S. Hrg. 109–526

HURRICANE KATRINA: WHY DID THE LEVEES FAIL?

HEARING

BEFORE THE

COMMITTEE ON HOMELAND SECURITY AND GOVERNMENTAL AFFAIRS UNITED STATES SENATE

ONE HUNDRED NINTH CONGRESS

FIRST SESSION

NOVEMBER 2, 2005

Printed for the use of the
Committee on Homeland Security and Governmental Affairs

HURRICANE KATRINA: WHY DID THE LEVEES FAIL?

S. Hrg. 109–526

HURRICANE KATRINA: WHY DID THE LEVEES FAIL?

HEARING

BEFORE THE

COMMITTEE ON HOMELAND SECURITY AND GOVERNMENTAL AFFAIRS UNITED STATES SENATE

ONE HUNDRED NINTH CONGRESS

FIRST SESSION

NOVEMBER 2, 2005

Printed for the use of the
Committee on Homeland Security and Governmental Affairs

U.S. GOVERNMENT PRINTING OFFICE

24–446 PDF WASHINGTON : 2006

For sale by the Superintendent of Documents, U.S. Government Printing Office
Internet: bookstore.gpo.gov Phone: toll free (866) 512–1800; DC area (202) 512–1800
Fax: (202) 512–2250 Mail: Stop SSOP, Washington, DC 20402–0001

COMMITTEE ON HOMELAND SECURITY AND GOVERNMENTAL AFFAIRS

SUSAN M. COLLINS, Maine, *Chairman*

TED STEVENS, Alaska
GEORGE V. VOINOVICH, Ohio
NORM COLEMAN, Minnesota
TOM COBURN, Oklahoma
LINCOLN D. CHAFEE, Rhode Island
ROBERT F. BENNETT, Utah
PETE V. DOMENICI, New Mexico
JOHN W. WARNER, Virginia

JOSEPH I. LIEBERMAN, Connecticut
CARL LEVIN, Michigan
DANIEL K. AKAKA, Hawaii
THOMAS R. CARPER, Delaware
MARK DAYTON, Minnesota
FRANK LAUTENBERG, New Jersey
MARK PRYOR, Arkansas

MICHAEL D. BOPP, *Staff Director and Chief Counsel*
THOMAS R. ELDRIDGE, *Senior Counsel*
JOYCE A. RECHTSCHAFFEN, *Minority Staff Director and Counsel*
DAVID M. BERICK, *Minority Professional Staff Member*
TRINA DRIESSNACK TYRER, *Chief Clerk*

CONTENTS

WITNESSES

Wednesday, November 2, 2005

Alphabetical List of Witnesses

Appendix

HURRICANE KATRINA: WHY DID THE LEVEES FAIL?

WEDNESDAY, NOVEMBER 2, 2005

U.S. SENATE,
COMMITTEE ON HOMELAND SECURITY AND
GOVERNMENTAL AFFAIRS,
Washington, DC.

The Committee met, pursuant to notice, at 9:37 a.m., in room 342, Dirksen Senate Office Building, Hon. Susan M. Collins, Chairman of the Committee, presiding.

Present: Senators Collins, Voinovich, Coleman, Warner, Lieberman, Akaka, Carper, Dayton, Lautenberg, and Pryor.

OPENING STATEMENT OF CHAIRMAN COLLINS

Chairman COLLINS. The Committee will come to order. Today, the Committee continues its investigation into the preparation for and response to Hurricane Katrina. Our focus at our fifth hearing this morning will be on why the levee system in and around New Orleans failed.

This flood-control system was not constructed as Katrina bore down on New Orleans. It is a project that dates back 40 years and was first authorized by Congress in the Flood Control Act of 1965. It is a project that has consumed $458 million of the taxpayers' money. Yet the project still is not complete, and key elements failed when put to the test.

While some of the floodwalls and levees were overtopped, something much more catastrophic happened that was not anticipated. Some levees and floodwalls failed outright, leaving gaping holes through which water rushed uncontrollably into the neighborhoods of New Orleans.

The result was a city more than 80 percent underwater. Estimates by experts tell us that this was approximately twice the percentage that would have flooded solely from overtopping and that, even in those parts that were expected to flood, the levee breaks caused the floodwaters to be far deeper.

This flooding caused enormous destruction and tragic loss of life. It made inoperable a land-based relief plan and aggravated the suffering and deprivation of the survivors. It caused far more devastation than would have occurred if the levees had held.

Our four witnesses today are the leaders of forensic teams that are investigating why the levees and floodwalls failed. These teams are sponsored by the State of Louisiana, the National Science Foundation, the American Society of Civil Engineers, and the U.S. Army Corps of Engineers. The National Science Foundation and the American Society of Civil Engineers teams will be releasing a joint interim report detailing their initial findings at this hearing.[1]

The testimony we will receive today demonstrates that many of the widespread failures throughout the levee system were not solely the result of Mother Nature. Rather, they were the result, it appears, of human error in the form of design and construction flaws, as well as a confused and delayed response to the collapse.

For example, at the 17th Street and London Avenue Canals, the evidence suggests that the design and construction of the floodwalls did not adequately account for layers of unstable soil beneath these walls that became, literally, "slippery when wet." Built on a weak foundation, these floodwalls could not stand up to the force of the water brought by the storm.

We will hear that the flooding east of the Industrial Canal in New Orleans East and in the lower Ninth Ward was caused in part by the storm surge from the hurricane that flowed over the top of the levees and floodwalls protecting those parts of the city. But we will also hear that this flooding was made worse by poor design and a lack of a uniform, comprehensive approach to levee construction.

In addition, our witnesses will testify that some of the levees in St. Bernard Parish apparently were built with inferior material that washed away as Katrina hit, allowing the surge waters to flow more easily into that parish.

We will also hear troubling concerns that the Army Corps' ongoing repair and reconstruction efforts have been insufficient. At least one of the team's leaders believes that these rebuilt levees may be at risk of failing in another storm, a disturbing finding that raises serious questions about the safety of the city's returning residents.

This Committee's investigation of Hurricane Katrina has already exposed many flaws in what we thought was a coordinated homeland security system that has been built during the past 4 years. Our hearing today will demonstrate that these flaws go beyond ineffective coordination and communication among the various levels of government to the very structures that are supposed to protect the residents of New Orleans.

The people of New Orleans and the surrounding parishes put their faith in the levee system, and many of those people have lost everything. Unless the cause of this failure is investigated thoroughly and addressed, New Orleans will remain a city in jeopardy. Katrina was a powerful hurricane, but it will not be the last hurricane.

Senator Lieberman.

OPENING STATEMENT OF SENATOR LIEBERMAN

Senator LIEBERMAN. Thank you very much, Madam Chairman. Thanks to the expert witnesses that are before us today.

I do want to stress that these are expert witnesses. These aren't political people or elected officials. I must say, therefore, the collective weight of their expert testimony, as I have read it in preparation for this hearing, makes this, in my opinion, a very important

[1] The report appears in the Appendix on page 224.

hearing because the collective weight of the testimony and the findings that they will bring before us today, for me is as disheartening, as heartbreaking, as infuriating, and ultimately as embarrassing as the scenes of human suffering and degradation that we saw in the aftermath of Hurricane Katrina.

This was a powerful hurricane. Our Committee's investigation began to determine why the Federal Government and the State and local governments failed to adequately prepare for and respond to the hurricane so that some of the human suffering that we saw on television from this distance would not have occurred.

But today, your testimony tells us something different, which really is—it is just shocking, which is that, notwithstanding how strong Hurricane Katrina was, a lot of the flooding of New Orleans should never have happened if the levees had done what they were supposed to do. What we kept hearing leading up to the hurricane hitting landfall and, of course, afterward was that the levees had been built to withstand a Category 3 hurricane.

The testimony we are going to hear this morning, as I have read it in preparation, tells me that Hurricane Katrina may have been as weak as Category 1 when it hit the canals along Lake Pontchartrain. But the bottom line point here that cries out from your testimony is that, in fact, it was human error in the design and construction of the storm surge barrier system that caused nearly all of the flooding of downtown New Orleans from the Lake Pontchartrain canals. And that a significant amount of the flooding of the Ninth Ward in New Orleans, the lower Ninth Ward and of so-called New Orleans East, occurred from the storm surge, but a lot of it occurred because of the failure of the levees on that part of town to do what they were supposed to do.

This ultimately has to lead our Committee to ask some very tough questions of the Army Corps of Engineers since the Army Corps of Engineers, not singularly but significantly, as a Federal agency, was in charge over a long period of years of the construction of these levees. We will ask those questions.

I must say that I am troubled also to hear from some of the witnesses in the testimony and in remarks to the staff that investigators from the three independent teams feel that they have not had the kind of cooperation that they should have had from the Army Corps of Engineers in providing access to important facts and evidence. I hope that lack of cooperation will end. We will have a witness before us in a couple of weeks from the Army Corps of Engineers administrative wing, and I hope before then that the frustration that the investigators are feeling with the lack of cooperation from the Corps will end.

Also, as the Chairman has said, your expert investigations have now found that some of the work done to repair the levees, the reconstruction efforts after Katrina, was done, we all understand, in haste and in very urgent circumstances, was plagued by a lack of engineering oversight and perhaps by the use of substandard materials, and therefore, may not adequately, from what I read in your testimony, protect the City of New Orleans from high tides, let alone another hurricane.

Gentlemen, I truly appreciate what you have done here and what you are going to tell us this morning. It is not pleasant to hear it, but it is important to hear it. Because as we said at the beginning, the only way we are going to make sure that, to the best of our ability, the suffering that occurred as a result of Hurricane Katrina in New Orleans and throughout the Gulf Coast region doesn't happen again is by pursuing the truth of what happened here and then fixing it.

I thank each of you—forensic teams operated under the auspices of the State of Louisiana, the National Science Foundation, the American Society of Civil Engineers, and the U.S. Army Corps of Engineers. Respectively, from all that I know, you include many of the foremost experts in this country in the design and operation of levee systems and the impact of hurricanes and storm surge upon them. We are also very privileged to have the benefit of the joint preliminary report of the teams from the National Science Foundation and the American Society of Civil Engineers that is scheduled to be released this morning, and I want to extend a special thank you to Drs. Seed and Nicholson and their teams for their hard work in finishing that report in time for today's hearings.

I thank all the witnesses for rearranging also what I know are very demanding schedules to be here this morning.

As a Committee, we are going to ask some tough questions about why the levees failed and what needs to be done to repair and reconstruct them now to protect the people of New Orleans and to enable the reconstruction of that great American city. We ask that you answer those tough questions with the same frankness that you have shown in the testimony that you have prepared for this morning. Thank you very much.

Chairman COLLINS. Thank you, Senator.

I want to welcome, officially, our witnesses to this hearing. As Senator Lieberman indicated, we have assembled what is truly a world class panel of scientists to help us understand this issue.

Dr. Ivor van Heerden is the Deputy Director of Louisiana State University's Hurricane Center and Director of the Center for the Study of Public Health Impacts of Hurricanes. He has an undergraduate degree in geology and both a Master's and a Ph.D. in marine sciences. He currently is the lead investigator selected by the State of Louisiana to review the levee failures in the New Orleans area.

Dr. Paul Mlakar is a West Point graduate. He has both a Master's and a Ph.D. in engineering science. Dr. Mlakar has served as the Chief of the Concrete and Materials Division of what is now called the Army Engineer Research and Development Center. Dr. Mlakar led the Corps' performance study of the Pentagon after the September 11 attacks. He is the leader of the Army Corps of Engineers data gathering team investigating the levee failures.

Dr. Raymond Seed is a professor of civil and environmental engineering at the University of California at Berkeley. He is an expert on the stability of dams, embankment soils, and buried structures. He holds an undergraduate degree in civil engineering and both a Master's and a Ph.D. in geotechnical engineering, which I have never even heard of before. Dr. Seed is leading the National Science Foundation's investigation of the levees.

And finally, we will hear from Dr. Peter Nicholson, who is an associate professor of civil and environmental engineering and Chair of Graduate Programs at the University of Hawaii. He has undergraduate degrees in geology and geophysics and in civil engineering, and both a Master's and a Ph.D. in civil engineering, as well. Dr. Nicholson, who chairs the American Society of Civil Engineers Geo Institute Committee on Embankments, Dams, and Slopes, is leading the Society's investigation of the levee failures.

I spent some time going through the credentials of our witnesses to demonstrate what an extraordinarily well-qualified panel we have this morning. I think it is unusual for us to have four scientists testifying before this Committee, and we very much appreciate your sharing your expertise with us this morning.

I am going to ask that you all stand and raise your right hands so that I can swear you in.

Do you swear that the testimony that you are about to give to this Committee will be the truth, the whole truth, and nothing but the truth, so help you, God?

Mr. VAN HEERDEN. I do.

Mr. MLAKAR. I do.

Mr. SEED. I do.

Mr. NICHOLSON. I do.

Chairman COLLINS. Thank you. Dr. van Heerden, we are going to begin with you.

TESTIMONY OF IVOR LL. VAN HEERDEN, PH.D.,[1] HEAD, STATE OF LOUISIANA FORENSIC DATA GATHERING TEAM, DIRECTOR, CENTER FOR THE STUDY OF PUBLIC HEALTH IMPACTS OF HURRICANES, AND DEPUTY DIRECTOR, LOUISIANA STATE UNIVERSITY HURRICANE CENTER, BATON ROUGE, LOUISIANA

Mr. VAN HEERDEN. Can I have the first slide, please? This is a product from a model that we used to determine the surge, and this gives you an idea of what the flooding would have been in New Orleans if there hadn't been a breach in the levee. It is a model we run on our supercomputer. This was actually the first warning that we put out 30-odd hours before landfall that New Orleans would flood. Next slide, please.

Senator LIEBERMAN. Could you describe that just a little more? In other words, how different would the flooding in New Orleans have been if the levees did not break?

Mr. VAN HEERDEN. As a result of the breaches, a whole lot—the flooding was double what you see on that slide.

The next slide actually is a satellite image that will show you the extent of the flooding. That is all the blue. So if we hadn't had the breaches, this area wouldn't have flooded and large sections here and in here wouldn't have flooded. Next slide, please.

This gives you an idea of the water depth, and you see the maximum water depth is about 15 feet. If this hadn't occurred, the water depth would have been maybe five to seven feet. I want to draw your attention to this area here and talk very briefly about the levee overtopping in this area, which was where Lake Pont-

[1] The prepared statement of Mr. van Heerden with attachments appears in the Appendix on page 49.

chartrain actually flooded into part of New Orleans. Next slide, please.

This is a slide of the actual levee, and you can see its northern embankment, and right on the top here is a wreck line. That is the water line from the surge. But you will see the wall here is actually a few feet, a couple of feet lower. Next slide, please.

And this is what happens when you get overwash. You create a scour trench, and this was one of the areas that Orleans East flooded. Next slide, please.

I want to start with the 17th Street Canal and then go to London Avenue Canal. Next slide, please.

This is the basic design of the walls, the so-called I-walls. There is sheetpiling driven in the ground and then a concrete wall on top, a soil embankment on either side. Very often, that soil comes from the dredging of the canal, so it is the material that was in the canal. Next slide, please.

This is what we term a hydrograph. It gives you the height of the water with time, and I will draw your attention to the pink line. This is from the model. This is the water level that was experienced in the 17th Street Canal at its mouth. The arrow indicates when we believe the breach actually occurred, so it was after the peak of the surge. Next slide, please.

An aerial view right after the flood, and the important thing is right here in the middle, you can see a green bank and the wall. That is the area that slid. Next slide.

This is taken on the water on day two. You can see there is the wall. We tried to line ourselves down the wall. And there is the former bank, and that used to be over here. Here are the wall segments that moved 30-odd feet. Next slide.

And then between them, there were sky areas and the walls also blew out, as well. Next slide, please.

This is the actual soil that is left behind, the old embankment, and the thing that we saw was a lot of wood and organic matter in this bank, indicative that it was dredged out of the canal. Next slide, please.

And, of course, as all of this moved, it acted as a bulldozer, and this yard used to be about four or five feet lower, and you can see how the hummocky terrain and the buildings and everything have moved. This is the bulldozing effect as that levee let go. Next slide, please.

Underneath all of this is an old swamp, and you can see the cypress stumps that occur in this area about every 15 feet. So New Orleans was built on an old swamp, and it suggests that where the 17th Street Canal breach occurred, we were sitting on top of an old swamp deposit. Next slide, please.

In addition, we tried to get the monoliths and the sheetpiling removed. We couldn't, but this was something that disturbed us. It looks like the sheetpiling actually didn't extend into this monolith. Unfortunately, this whole area has now been covered with the repair material, but it raises questions. Next slide, please.

Right now, we are not sure exactly how the water got from the canal through onto the opposite side to soften the soils and lead to the actual sliding of the wall. There are three potential pathways, one in this highly organic old swamp material that was pumped up to form the bank, the actual peat and swamp layer, and also these clays down here have lots of parallel lenses in them. The important thing was that sheetpiling, from all the records we can find, only went to minus-ten feet below sea level Next slide, please.

An aerial sketch, if you will, of what happened. This levee section moved, and then these walls on either side collapsed. Next slide, please.

This is at London Avenue at Filmore. This is the Western breach, very similar sorts of features. I want to draw your attention to this little house and pine trees. Next slide, please.

This is what it was like before Katrina. The house was down at the toe of the levee. You can see the pine tree. Next slide, please.

And now it is way up, as a result of that heave, indicative again of the very similar failure at the 17th Street Canal of this section of the levee sliding outwards. Next slide, please.

On the opposite side from that breach, the walls are broken, tilted, cracked. Next slide, please.

There is evidence of what we call sand boils, where the water has come underneath the levee and blown up on the top, on the back side. Next slide, please.

And, in fact, there are also heaves you can see, not a good slide, but these planter boxes have moved and there was this little swimming pool that moved, as well. So some of the same features we saw at the 17th Street Canal, not as dramatic. Next slide, please.

And what we believe happened at Filmore was basically the same thing. The sheetpiling came down to 11-and-a-half feet below sea level and the water found its way through. What is interesting on the opposite side of the canal, where it didn't fail but it cracked the sheetpiling, we believe went down to minus 26 feet, seeming to suggest a deeper sheetpile would have helped. Next slide, please.

The Mirabeau break on London Avenue, the thing that really strikes you when you get there is the sand. This is the top of a car, so you have four to five feet of sand. It looks like a river, the whole area. Next slide, please.

And when you look at the actual break, the thing that struck us were the wall segments actually dipping down into what appeared to be a hole, and so perhaps a slightly different failure to the other areas. Next slide, please.

And what we suspect is that this is a blowout hole that the soil, that the water made its way underneath and blew out, created a void, and these wall segments collapsed into that hole. Next slide, please.

And again, the important thing at Mirabeau is you have this very thick layer of beach sand. It is very porous, very premeable, and it created, we believe, a conduit for the water to get from the canal under pressure and onto the other side, and the fact that you have all the sand amongst the houses, suggesting that this was the main failure mechanism. Next slide, please.

The Industrial Canal failed just before the peak, right at the time the water started overtopping. Next slide, please.

The breaches. Next slide, please.

Next slide.

Just to show you how it blew out, it removed all these houses, probably a 20-foot head of water. Next slide.

And on the ground, you see a scour trench where the pilings used to be, the wall used to be. Next slide, please.

And where it hasn't failed, there is this very typical scour trench all the way along, suggesting that it was just overwash that led to the failure of these sections of the levees. Next slide, please.

There is the question of the barge. Next slide.

What we found was evidence that the barge had gone through the wall. Next slide, please.

But it was after the wall had collapsed, and that was given to us that the wall is at 45 degrees and the sheetpiling where the barge perhaps did knock the wall is horizontal, suggesting the wall was down before the barge came through. Next slide, please.

What really struck us, though, was when you look down the length of the wall, it had these strange curves in it beyond where the actual breach is and then the signs of embankment failure in front of the walls. Next slide.

And what you see here is a tilted wall and examples of where the soil has dropped down in both cases. And in this area, we saw something that we call percolation holes, where it appeared the water had actually started to scour down underneath the sheetpiling. Next slide, please.

Again, swampy material. The bore hole data suggests that these are all soft or very soft clays. Next slide, please.

And again, there appears to have been a number of potential mechanisms for the water to get under to lead to the failure as well as the overtopping, and right now, our investigation is looking at both, this being a failure related to the soil as well as the overtopping. Next slide, please.

And being from Louisiana, I am obviously very concerned about what happens to the folk who trusted the system, and this is an example of how some of them actually got out. Thank you.

Chairman COLLINS. Thank you. Dr. Mlakar.

TESTIMONY OF PAUL F. MLAKAR, PH.D., P.E.,[1] SENIOR RESEARCH SCIENTIST, U.S. ARMY RESEARCH AND DEVELOPMENT CENTER, VICKSBURG, MISSISSIPPI

Mr. MLAKAR. Madam Chairman and Members of the Committee, I am Dr. Paul F. Mlakar, Senior Research Scientist at the U.S. Army Engineer Research and Development Center in Vicksburg, Mississippi, which is a component of the Corps of Engineers. I have spent most of my professional career of four decades in the Corps studying the response of structures to extreme loadings. This has included the performance of the Murrah Building in the Oklahoma City bombing and the Pentagon in the September 11 crash. I am a Fellow of the American Society of Civil Engineers and the recipient of their Forensic Engineering Award in 2003. I am also a Registered Professional Engineer, legally obligated to protect the health, safety, and welfare of our citizens.

As some of you know, the ERDC conducts research and development to enable the Corps to better perform its military and civil works mission in support of the Nation. We employ 2,500 people in seven laboratories located in four States. The staff is recognized

[1] The prepared statement of Mr. Mlakar appears in the Appendix on page 98.

nationally and internationally for its expertise in civil engineering and related disciplines. Our facilities include a number of unique devices that allow us to deliver technical solutions on the leading edge of science.

I am pleased to appear today on behalf of the ERDC and the Corps to provide information as requested in your letter of October 27. The Congressional interest in the performance of the storm damage reduction infrastructure in Hurricane Katrina is much respected and shared by the Corps. While we do not yet have the complete answers to all of the questions, we welcome this opportunity to share our progress with you.

The Corps takes its responsibility for the safety and well-being of the Nation's citizens very seriously. In the case of the New Orleans area, we are determined to learn what failed, how it failed, why it failed, and to recommend ways to reduce the risk of failure in the future.

So what have we done about these failures in Katrina? As the emergency operations wound down, the Corps asked me to lead in the collection of data for the study of the protection infrastructure affected. I deployed to New Orleans on the heels of Hurricane Rita and have spent most of the intervening period in the region. At various times, I have been joined by some 30 Corps staff and other colleagues. Our priority has been on the breaches in the metropolitan area that caused the greatest devastation, that is the 17th Street Canal, the London Avenue Canal, and the Inner Harbor Navigation Canal.

To document exactly what happened, we have been diligently recording the damages and measuring the post-Katrina conditions. To eventually explain how and why, we have examined physical evidence to establish the maximum water elevations at various locations. To establish the timeline of events, we have conducted detailed interviews so far with about 70 people who sat out the storm. To establish the soil properties, we have pushed a state-of-the-art instrumented cone to a depth of 80 feet at some 60 locations. We further collected samples of the soil at depth in 10 locations for laboratory testing. We have also electronically scanned 63 out of 235 boxes of documents dealing with the design, construction, and maintenance of the projects involved.

As we began, the American Society of Civil Engineers and a University of California team sponsored by the National Science Foundation approached the Corps about similar studies of infrastructure performance they were undertaking in hopes of applying lessons learned to the levee systems in California. In the spirit of openness and full transparency, we invited these teams to join us for inspections of the projects involved. We subsequently learned that the State of Louisiana would soon establish its own study team, and we invited the researchers from the Louisiana State University Hurricane Research Center to join us in advance of this official establishment. The Corps gratefully acknowledges the assistance provided by these teams in the collection of the data.

So what is the way ahead? Over the next 8 months, an interagency performance evaluation task force commissioned by the Chief of Engineers will conclude the collection of the data, deliberately analyze this information, and rationally test various hypotheses about the behavior of the infrastructure. This work will comprehensively involve the following technical topics on 360 miles of diverse infrastructure. The topics are geodetic reference datum, storm surge and wave modeling, hydrodynamic forces, floodwall and levee performance, pumping station performance, interior drainage and flooding modeling, consequence analysis, and finally, risk and reliability assessment.

The participants on this task force will be drawn broadly from Federal agencies, academia, State and local governments, professional societies, and international experts. We will communicate our progress periodically through news releases, press conferences, and web postings. The final results will include conclusions as to the causes of the failures and recommendations for the future design and construction of such infrastructure nationwide. These results will be independently reviewed by an external panel of the American Society of Civil Engineers. At the request of the Secretary of Defense, the National Academies will also independently assess the results and report to the Assistant Secretary of the Army for Civil Works.

Our scheduled completion date is July 1. In the meantime, our progress will be shared with and used by our colleagues in the Corps responsible for the reconstruction of the protection in New Orleans.

My written statement contains further information about your specific questions, and I request that it be entered into the record.

Chairman COLLINS. Without objection.

Mr. MLAKAR. In closing, I advise against reaching conclusions to the very important questions before appropriate analysis is accomplished. Speculation concerning the understanding of why damage occurred in Katrina is not adequate to build back a reliable flood protection system. My testimony illustrates the Corps' continuing commitment to the pursuit and use of sound science and engineering principles in the execution of our civil works mission.

On behalf of the Corps, thank you for allowing me the opportunity to present this testimony today.

Chairman COLLINS. Thank you. Dr. Seed.

TESTIMONY OF RAYMOND B. SEED, PH.D.,[1] PROFESSOR OF CIVIL AND ENVIRONMENTAL ENGINEERING, UNIVERSITY OF CALIFORNIA AT BERKELEY, ON BEHALF OF THE NATIONAL SCIENCE FOUNDATION-SPONSORED LEVEE INVESTIGATION TEAM

Mr. SEED. Can I get my first Power Point image? In fact, you can skip to the second one.

Madam Chairman and Members of the Committee, good morning. My name is Raymond Seed, and I am pleased to be asked to appear before you today to testify on behalf of the levee investigation team sponsored by the U.S. National Science Foundation. A large number of leading national and international experts with a tremendous amount of forensic experience in sorting through major disasters have worked very hard this past month, and I am pleased to be able to present you with the first copy of the preliminary re-

[1] The prepared statement of Mr. Seed with attachments appears in the Appendix on page 102.

port of the findings of the combined ASCE and NSF-sponsored field investigation teams.[1] I am very grateful for their tremendous efforts in getting this material ready for you today.

Our hearts go out to the many people who have lost everything, even in some cases their lives, in this catastrophic event. Our teams have had considerable previous experience in many other disasters, including numerous major earthquakes around the world, the recent Indian Ocean tsunami, floods and levee failures, the Space Shuttle Challenger disaster, and more. But we were not prepared for the level and scope of the devastation that we witnessed when we were in New Orleans. It must be the intent of our work that something like this will not be allowed to happen again. Next.

With that in our minds and in our hearts, I must make it clear that we know a great deal about what happened, and in many cases, why, and that it is my intent today to speak as openly as possible. Our team, to a man and to a woman, feels that the people of the New Orleans region and the Nation and our government at all levels need and deserve nothing less. Important decisions are being made that will affect people's lives for years to come. We recognize the importance of providing the best possible informed information, responsibly studied and professionally and thoughtfully synthesized, that we can at this early juncture. Better and more complete information will continue to evolve over the coming year, but that will be too late for many ongoing decisions being made right now today.

Our preliminary report presents a consensus document, and it presents the initial observations and findings that we were able to agree to release with all the team members and organizations involved. If you will ask, I will do my best to answer questions well beyond the scope of our initial preliminary report.

Why did the levees and floodwalls fail? This is a map of the Central New Orleans region, prepared initially by the U.S. Army Corps of Engineers and then modified to reflect additional findings of our investigation teams. It shows the locations of many levee breaches that occurred with stars and dots and serves as a good base map for our discussions today. Not shown on this map are the additional flood protection levee systems that extend down the lower reaches of the Mississippi River, which begins here and runs about to the floor of the room, providing a narrow, additional protected corridor down to the Gulf.

The storm surges produced by Hurricane Katrina resulted in numerous breaches and consequent flooding of approximately 75 percent of the metropolitan areas of New Orleans. Most of the levee and floodwall failures were caused by overtopping as the storm surge rose over the tops of the levees and their floodwalls and produced the erosion that subsequently led to failures and breaches. Overtopping was most severe at the east end of the flood protection as the waters of Lake Borgne were driven west, producing a storm surge on the order of roughly 20 feet in the area right here and massively overtopping the levees across this stretch. Next photo.

[1] The report appears in the Appendix on page 224.

This photograph and the one which follows it—next—show two sections of those levees, or at least two sections where those levees had previously existed. They are massively eroded. There is virtually nothing left of these levees along some parts of this stretch.

A very severe storm surge also occurred farther to the South, along the lower reaches of the Mississippi River, and significant overtopping produced additional breaches in this region, as well. Next.

That is the section off the bottom of the map. Next.

These are some of the homes in that area. This photograph shows houses in the Plaquemines Parish corridor where the levee on the left, just off the photograph, breached and overtopped, and the storm surge carried the houses across and deposited them on the right-hand levee, which fronts the Mississippi River just to the right and has the main rip-rap and slope protection across the front face here. This was a catastrophic breach. Next slide.

Overtopping was lesser in magnitude along the Inner Harbor Navigation Channel and along the Western portion of the MRGO Channel, which are the two main conduits through here and along here. But the consequences were no less severe. This overtopping again produced erosion and caused numerous additional levee failures. Next.

This photograph shows the well-known breach at the West end of the Ninth Ward. I didn't show this earlier, but we spent some time figuring out the answer to the chicken and the egg question here, and it is our preliminary opinion that the infamous barge was a passive victim which was drawn into a breach that was already open at this location. Most of the failures in the Central New Orleans area were the result of overtopping, and one of the common failure modes was simply water cascading over the concrete floodwalls and then carving sharply etched trenches on the back sides of these walls. The next photo. The next photo.

This is an example of that, one of many. There is a large breach just in the background here. This is just West of the Port of New Orleans. Many failures of this type. This reduced the lateral supports at the back sides of the walls and left them vulnerable to the high water forces on their outboard faces.

Another repeated mode of failure and distress throughout the central region were problems at transition sections, where two different levee or wall systems joined together. The next slide. This is one of those sections. You can see here a structural wall which carries a gate structure over here for a road to pass through. It meets an earthen levee over here with a rail line crossing it, so there are three different intersections here. The intersection itself was a soft spot. Each of the individual sections was better designed, but they didn't join well. This was a common problem. There is a need to better coordinate these connections and their details.

Farther to the West, in the East Bank Canal District, three levee failures occurred on the banks of the 17th Street and London Avenue Canals, and these failure levels occurred at water levels well below the tops of the floodwalls lining these canals. These three levee failures were likely caused by failures in the foundation soils under the levees, and the fourth distressed section on the London

Avenue Canal shows signs of having neared the occurrence of a similar failure prior to the water levels having receded. Next.

This photograph actually shows a breach on the 17th Street Canal being closed, and Dr. van Heerden showed earlier, this is the original inboard half of the embankment which just slid to the right, roughly 45 feet at the location of the piece of chain-link fence right here, a massive lateral translation as a result of foundation instability.

The section across the canal on the East bank of the London Avenue Canal, North failure section, was very seriously distressed. Dr. van Heerden showed that one. In our view, it was at the point of incipient failure and was only saved by lowering of the water in the canal, possibly as a result of the other two breaches. That section is very seriously damaged and requires remediation before it can again safely hold high waters, and that will be another question which we will deal with later in this talk.

The road forward. Major repair and rehabilitation efforts are underway to prepare the New Orleans flood protection system for future high water events. The next hurricane season will begin in June 2006. We have a hurry on our hands. Based on our observations, there are a number of things we would like to point out.

Although it is somewhat customary to expect levee failures when overtopping occurs, they are not a requirement. There are things that can be done in terms of design details that would have provided better overtopping protection. Inboard face scour protections, splash slabs, rip-rap protection, even paving would have made a big difference at some of these sites and might have prevented some of the failures we observed.

As the system is being repaired and rebuilt, it would be advantageous to better coordinate the crest heights of the various sections. Better coordination between individual units would be a good idea.

Areas in which piping and internal erosion occurred are now weakened segments. There is a need to go back and assess the remaining segments that did not fail and be sure they still have their full integrity. Some of them will be found to have been damaged, in all likelihood.

Levees are series systems, where the failure of one component, one single segment, means the failure of the whole system. The failure of several levees at less than their full designed water height in this hurricane warrants a thorough review of the overall system.

In the short term, as repairs continue, we would like to see the sheetpiles, which are currently being operated as floodgates at the north end of the canals, continue to operate in that fashion. The Corps of Engineers does have good plans for moving forward on the five main downtown breach repairs, and we think they should operate those canals in that fashion until those can be implemented.

The Corps, like other public agencies, routinely hires outside boards of consultants for critical dam projects where public safety is at interest. We are not aware of any major dams in the United States which basically protect larger, more vulnerable populations than the New Orleans levee system, and we hope the Corps will be encouraged to empanel such a body to oversee their work in New Orleans.

The U.S. Army Corps of Engineers are stretched very thin right now, trying to respond and effect emergency and interim repairs in the wake of this catastrophe. It must be the job of the Federal Government and oversight committees such as yours to ensure they have the adequate resources and technical capabilities on hand to get the job done safely and well. The Corps has responsibility for many potentially high-hazard dams and levee systems, and we must all be able to have high confidence in their ability to perform these tasks.

The ASCE and NSF teams have been drawn in inadvertently into some of the ongoing levee repair work, and we feel that right now, the Corps of Engineers is stretched very thin in the New Orleans region.

This concludes my testimony. Thank you.

Chairman COLLINS. Thank you, Doctor. Dr. Nicholson.

TESTIMONY OF PETER NICHOLSON, PH.D., P.E.,[1] ASSOCIATE PROFESSOR OF CIVIL AND ENVIRONMENTAL ENGINEERING AND GRADUATE PROGRAM CHAIR, UNIVERSITY OF HAWAII, ON BEHALF OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS

Mr. NICHOLSON. Thank you, Madam Chairman, Members of the Committee. Good morning. My name is Peter Nicholson, and I am pleased to appear before you today to testify on behalf of the American Society of Civil Engineers as you examine the effects of Hurricane Katrina on the infrastructure of Coastal Louisiana, particularly on the levee system that protects the City of New Orleans.

I was asked by ASCE to assemble an independent team of experts to travel to New Orleans to collect data and make observations to be used to assess the performance of the flood control levees.

One of the goals of the assessment team was to gather data and attempt to determine why certain sections of the levee system failed and why others did not. These determinations may help to answer the question of whether the failures were caused by localized conditions and/or whether surviving sections of the system may only be marginally better prepared to withstand the type of loads that were generated by this event. Could I have the next slide, please.

The team that we assembled consisted of professional engineers from ASCE with a wide range of geotechnical engineering expertise in the study, safety, and inspection of dams and levees. While in New Orleans and the surrounding areas, we examined levee failures as well as distressed and intact portions of the levee system between September 29 and October 15.

Our levee assessment team was joined by another ASCE team of coastal engineers and another team primarily from the University of California, Berkeley, under the auspices of the National Science Foundation. Our three teams were joined in the field by the U.S. Army Corps of Engineers Engineering Research and Development

[1] The prepared statement of Mr. Nicholson appears in the Appendix on page 121.

Center Team, led by Dr. Paul Mlakar, and we would like to thank Dr. Mlakar and the ERDC team for their logistical support.

What we found in the field was very different than what we had expected, given what we had seen in the early media reports. Rather than a few breaches through the floodwalls in the city caused largely by overtopping, we found literally dozens of breaches throughout the many miles of the levee system. As geotechnical engineers, we were particularly interested to find that many of the levee problems involved significant soil-related issues. Next slide, please.

We have seen many of these same slides. Dr. van Heerden and Dr. Seed have stolen a little of my thunder. Playing clean-up here is going to be a little tough. We have seen this slide before, the 17th Street Canal breach, and we observed, as said, intact soil blocks that had experienced large translation and heave. Next slide.

We have seen slides like this. Here is the translated section we have seen before. It used to be over here. Next slide.

And here again, just a slightly different view looking the other way than the former slides, where the levee had been here, and here is that elevated section or block with the chain-link fence. This movement would be consistent with the failure of the soil embankment or the foundation soils beneath. While we cannot yet determine conclusively the exact cause of the breach itself, the type of soil failure may well have been a significant contributing factor. Next slide.

We have also seen London Avenue Canal breach, another view of the clubhouse, here from a different view, here taken from the top of the temporary repair that used to be down in the backyard of the house below. Next slide, please.

Again, in that same area, we saw a tremendous amount of sand deposited, and we believe this material to be either from the foundation material beneath the embankment as well as material that may have been scoured from the canal. Next slide.

Again, we were very interested in the non-failed section across the canal where we observed this floodwall and underlying embankment in severe distress. You can see it is out of alignment. Next slide, please.

It was observed that we saw tilting on the inside of the wall, cracking, as we had seen before. This wall was badly out of alignment. And as a result of the tilt, there were gaps between the wall and the supporting soil on the canal side. We also observed that there was evidence of soil movement, seepage, and piping as indicated by a number of close examinations. Next slide.

Sinkholes behind the wall near the crest of the embankment. Next slide.

As well as we have seen the examination of sand boils and heave. We have seen slides like this before. Next slide.

Further to the South, we had the second breach of the London Avenue Canal. Here, as they were trying to close the repair, dropping sandbags into the open hole. Next slide.

And again, we have seen the buried car with huge volumes of sand deposited, much more than could have come from the embankment, and we believe these were scoured from the canal itself.

By the time we got there, there was very little evidence left to examine the mechanisms at this site.

It is very important that the impact of the levee breaches outside of the City of New Orleans not be overlooked, and many of the sections of the system were severely tested by overtopping, as we have heard earlier. Many portions of the levees were breached or severely distressed, causing significant heavy flooding, in many cases complete destruction of the thousands of neighborhood homes.

The hurricane produced a storm surge that varied considerably depending on location, including the combined effects of orientation, geography, topography with respect to the forces of the passing storm. Hydraulic modeling of the surge, courtesy of LSU and Dr. van Heerden's group, and I have a few of his slides, as well. Next slide, please.

We have seen this before, the hydrograph showing essentially two different levels of storm surge, as we have heard, in the Industrial Canal and much less in the city, significantly different levels of the storm surge as the storm passed. Next slide.

As the storm passed to the East of New Orleans, the counterclockwise swirl, essentially, of the storm generated a large surge from the Gulf of Mexico and Lake Borgne that impacted the Eastern-facing coastal areas of the New Orleans area and the lower Mississippi delta. Next slide.

The surge was, as we have seen this, as well, courtesy of the Hurricane Center, concentrated into this funnel area here up through the MRGO Channel into the Industrial Canal or the Inner Harbor Navigational Canal, and much less so to the north in Lake Pontchartrain.

As shown by these models and the field evidence, this surge, which impacted the lakefront and the three canals within the central part of the city, was noticeably less severe. Field data indicated that the surge levels from the lake did not reach the elevation of lakefront levees and was well below the top of the height of the floodwalls bordering the interior canals, where three notable breaches occurred.

Where the storm surge was most severe, causing massive overtopping, the levees experienced a range of damage from complete obliteration to intact with no signs of distress. Much of the difference in the degree of damage can be attributed to the types of levees and materials that were used in their construction. The most heavily damaged and/or destroyed earthen levees that we inspected were constructed of sand or shell fill, which was easily eroded. Next slide.

And we have seen this slide, as well, before. This was the area along the MRGO that took the brunt of the storm as it came in, or the brunt of the surge through Lake Borgne from the East and just took out this section of the wall. Next slide.

This is another aerial view showing where the flooding occurred, color coded here with the deepest flooding in dark blue, getting lighter to the yellow. So we can see the massive storm surge coming in from the East, or from the right in your picture, coming over that destroyed levee and also overtopping walls and breaching both on either side of MRGO as well as from the canals within the city.

Senator LIEBERMAN. Can you do us a favor and define MRGO? It is the Mississippi River——

Mr. NICHOLSON. Mississippi River Gulf Outlet, MRGO.

Senator LIEBERMAN. Right.

Mr. NICHOLSON. Next slide, please.

This is just a lot of the embankments that were obviously overtopped. This is a photograph that we got from personnel at the energy plant, which watched through the storm. There is actually an earth embankment under here being overtopped by the flood wave. Next slide.

This is another example of one of the earthen levees that had essentially been gutted by the overtopping flow. Next slide.

We have seen this same slide when Professor Seed shared a lot of the slides. Essentially, nothing left of that embankment levee. Next slide.

This is an example of some of the embankments which were overtopped but survived quite well. In this area, we had a significant area of marshland in front, essentially helping knock down or keep the storm surge or the waves to a lesser extent.

Senator LIEBERMAN. Where was that one?

Mr. NICHOLSON. This is in the first line of defense on the Eastern edge of New Orleans East. Next slide.

Moving back into the Industrial Canal, we have seen some of these slides, as well. Next slide.

We have seen this slide twice, I think, already. We can go to the next one.

We have seen the type of damage. This is just inside of that breach in the lower Ninth Ward. Next slide.

And we have also seen a similar slide like this showing the scour on the backside of those walls that are overtopped as well as the misalignment of those I-walls or floodwalls just to the North of the lower Ninth Ward breach. Next slide.

Again, the scour behind the overtopping. The soil line used to be up here. This soil has all been removed, essentially destabilizing behind the wall. Next slide.

This is on the North side of the MRGO, overtopping, severely scoured out behind and caused breaches and failure of those walls. Next slide.

We also saw a lot of problems with transitions. We can see two different problems here, different materials, and different heights. Oftentimes, there was a weak connection between the two, but in addition, the lower heights would direct the water to flood over sometimes the weaker material first. Next slide.

If this was earth versus concrete, obviously the earth loses. Next slide.

This is what happens if that is allowed to go further. The earth line was up here. This was earth embankment, which has now been severely scoured away and breached through, essentially. Next slide.

More concrete to sheetpile, again, with the difference in height, directed the flow over this area first, and sheetpile being weaker than concrete, sheetpile loses. Next slide.

We also saw this type of very complex transition where we had all the different problems, different material types, concrete to pavement on soil to ballast under railroad tracks to earth embankment. We had breaches on this side and this side. This raises another question of where we have the types of transitions between parts of the levee system that were maintained, designed, and constructed by different authorities or different agency groups. Here we had an earthen levee constructed by one group, the railroad taking care of their own business, different heights, so we have a complete mix of things happening there. I am finished.

Well, I think we can answer the rest as we end. Madam Chairman, this concludes my testimony, and we will be pleased to take questions. Thank you.

Chairman COLLINS. Thank you. Your testimony was very helpful.

Dr. Seed, I want to begin my questioning with you today. At least twice, you wrote to the Army Corps of Engineers, on October 11 and October 18, to raise very serious concerns about the adequacy and the integrity of the repairs that the Army Corps and its contractors were making to the levees and the floodwalls, and I want to read for the record—we will put the entire letter of October 11—and the e-mail of October 18—into the record, but I want to read some excerpts.[1]

On October 11, you wrote that the situation at the 17th Street Canal "warranted an urgent response" because the repair was "actively eroding." In this same letter, you wrote that the "current embankment section was poorly configured with regard to the ongoing risk of failure." You wrote that certain repairs were leaking. In the case of the 17th Street Canal repairs, you wrote that "rapid erosion and blowout would become likely." At the Southern London Avenue break, you said that it was leaking into the city more than at the other two breaks and you called it a "potential hazard." You urged "urgent and resolute further action."

You also flagged the fact in your subsequent e-mail that contractors working on some of the levee repairs were not doing it properly and that there was inadequate oversight from the Army Corps. In that same e-mail, you said to the Army Corps, you warned of a "significant flow" of water and that there was no possibility of controlling storm surge rises at sections of the Industrial Canal levee so that further action may be urgently warranted.

These raise very serious questions in my mind about the integrity of the repairs that have been undertaken and whether the returning residents of New Orleans are still at risk. What is your assessment today of the sufficiency of the repairs, and do you think there is a serious public safety issue still in New Orleans?

Mr. SEED. Those are two separate questions.

Chairman COLLINS. Yes, and I shouldn't have combined them.

Mr. SEED. That is all right. I am a professor. We do that for a living.

The first question is the most complex. We haven't been on the ground in New Orleans now for several weeks and more, and so we are not entirely clear what the details of those current configurations are.

In response to the first letter, which you discussed, the Corps did respond quickly and very well, and those sections were rapidly im-

[1] The letter and e-mail appear in the Appendix on page 208.

proved. Behind that, though, was a week of back-and-forth interaction between our team and the Corps in which the responses, in our view, were insufficient and sometimes misdirected, and it became clear to us that they were struggling to get the right kind of people put in charge of the projects to get our concerns addressed. My understanding from their last response is they do, in fact, have the right kind of people now directing these projects, and so we have a better feeling about them.

The second letter addresses the two breaches on the Industrial Canal at the West end of the Ninth Ward, which when we left the sites had been further remediated, but which, in our view, were not adequate for a high-water incident, for instance, another hurricane storm surge as the storm season isn't yet behind us, or even a very high tide. A week ago Monday, October 24, they developed a large seep at one of those two sections, the northern of the two, and that, in our view, was not entirely unexpected.

The Corps does now have five contracts let and, I believe, signed, and they have five outsourced engineering firms doing the final design work on more permanent closure sections. These will all involve sheetpile curtains, which will be far deeper than the original sheetpiles that were installed in these sites, and the configurations will be far more stable than they were before. So there do seem to be suitable patches on their way to being in place at these five locations. So with regard to these five particular sites, I don't believe there is a long-term significant risk to the City of New Orleans.

The other half of the question, though, is what is the state of the overall safety of the City of New Orleans, and the answer there is the section that crossed along the North breach has not yet been addressed nor remediated. It is clearly a very weakened situation, and it was probably at the point of incipient failure in this last event. It certainly hasn't had its situation improved by the suffering it went through. It has, in fact, deteriorated. And there are many sections around the system that need to be investigated more thoroughly.

There are also ongoing repairs of literally, as Dr. Nicholson said, dozens of breaches, and the section up along what we like to call as locals the MRGO section is vastly eroded. That is a very difficult construction project, simply in terms of time, if the race is to get things put back together for the next storm season in June. So there is a tremendous logistical difficulty and the Corps of Engineers is working very hard at all this. They are also stretched very thin. It is a challenge for anybody. It is a very difficult challenge.

Chairman COLLINS. Dr. Nicholson, what is your assessment of the current state of repairs and the adequacy as far as people coming back into New Orleans to live and work?

Mr. NICHOLSON. Well, as Dr. Seed had mentioned, the repairs of the damaged sections, of the breached sections in town seem to be coming along quite well and seem to be adequate, with perhaps the exception of the Industrial Canal area, which we hope they are going to be taking care of fairly soon.

As far as the safety of the entire New Orleans area, as engineers, we look at safety or risk on a scale or as a factor of safety. So there are different levels of safety. There are always going to be some risks, particularly in a large storm.

For the short term, my opinion is that short term, without a storm, they are probably adequately safe. Certainly with a large storm, as we are not yet out of hurricane season, as Dr. Seed had just mentioned, and certainly for the next hurricane season, there are significant risks and safety. With evacuation, proper evacuation, certainly the property is at risk and there is a large degree of safety to the property, but I believe as far as the safety of returning there with the potential to evacuate, I see that there is adequate safety.

Chairman COLLINS. Dr. van Heerden, Senator Lieberman mentioned in his opening statement that we have heard time and again that the levees were constructed to withstand what I understand is called a standard project hurricane, and that is usually stated to be a Category 3 hurricane. We have also heard, well, the reason the levees failed is Katrina was a Category 4 hurricane that simply overwhelmed the design of the levees. But it is my understanding that your analysis suggests that the hurricane was not that strong. Could you elaborate on that and tell us what your assessment showed?

Mr. VAN HEERDEN. Certainly. If you look at New Orleans, there was basically two different surges. The surge on the right side of the eye was the sort of surge you would expect with a Category 3 storm, and that was where we saw the 18 to 20 feet of water in the funnel. But on the left-hand side, or the West side of the eye, the winds were much lower, more of the order of a Category 1 storm. The surges were not Category 3 surges. If Katrina had gone to the West of New Orleans, we would have seen about 15 feet of water in Lake Pontchartrain and obviously flooded a much greater area.

So as far as we could see, based on the model, and we have also spent many hours going out and measuring the heights of water lines, the surge in Lake Pontchartrain wasn't that of a Category 3 storm, and nor did it exceed the design criteria of the standard project hurricane.

We have tried to understand what the standard project hurricane is, and if one uses the frequency that is in the Corps of Engineers definition, that is one is to 200 years, then you are talking about a Category 5 storm. If you use the central pressure of 27.6 inches, then you are talking about the potential of a Category 4 storm.

In terms of the definition of the winds, we found two different definitions, and it is very difficult to work from those definitions to come up with the Saffir-Simpson. However, in the 1965 document, they talk about trying to design to the 1915 hurricane. The 1915 hurricane was a Category 4 hurricane. In 1969 documents, they talk about designing to Hurricane Betsy, again, which was a Category 4 storm.

So there is some confusion, exactly what is the standard project hurricane, but in our opinion, the design criteria on the 17th Street and London Avenue Canals were not exceeded.

Chairman COLLINS. So to summarize before I move on to Senator Lieberman, is it fair to say that the levees should have survived Hurricane Katrina, given that Hurricane Katrina by the time it struck New Orleans was at a lesser category than the standard project hurricane?

Mr. VAN HEERDEN. Madam Chairman, yes, it is fair to say that they should have stood the surge.

Chairman COLLINS. Thank you. Senator Lieberman.

Senator LIEBERMAN. Thanks, Madam Chairman.

Dr. van Heerden, let me pick up from Senator Collins' line of questioning. I understand you to be saying that, because as we all remember, Hurricane Katrina went more to the East of New Orleans than it was originally thought. That on the Eastern part of New Orleans, there was a significant surge and perhaps the hurricane was at a Category 3 or higher at that point. But the point that strikes me as very significant here is that insofar as Lake Pontchartrain is concerned, it, in your opinion, was significantly less than what we are calling a Category 3 hurricane, is that correct?

Mr. VAN HEERDEN. Yes, sir, that is correct.

Senator LIEBERMAN. And if I understand this correctly, most of the flooding of downtown New Orleans came from Lake Pontchartrain. Obviously, there was other significant flooding to the East in the New Orleans East, lower Ninth Ward, but when it came to downtown New Orleans, the 17th Street Canal, the Industrial Canal, and I believe it is the London Street Canal, those fed the flooding of downtown New Orleans, is that right?

Mr. VAN HEERDEN. Downtown was principally the 17th Street Canal and the London Avenue Canal——

Senator LIEBERMAN. London Avenue——

Mr. VAN HEERDEN [continuing]. As well as some breaches on the Industrial Canal. When you get to Orleans East, the flooding occurred not only from the Industrial Canal, but also from the breaches that the others have spoken about along the Gulf Intercoastal Waterway.

Senator LIEBERMAN. Correct. Let me come back and focus on Lake Pontchartrain because now you have told us that by your estimate, expert estimate, Hurricane Katrina was well below Category 3 as it hit Lake Pontchartrain. So do I correctly conclude that your determination is that the water of Lake Pontchartrain did not overtop the levees along the canal? In other words, the water did not reach a level to overtop those levees along Lake Pontchartrain?

Mr. VAN HEERDEN. In the 17th Street Canal and the London Avenue Canal, the waters did not get high enough to overtop those levees from——

Senator LIEBERMAN. Right.

Mr. VAN HEERDEN. I went up in a boat on the 17th Street Canal, and what we saw were water lines that indicated that the maximum water level was about three feet below the top of the wall.

Senator LIEBERMAN. So the fact that the water came surging through those levees and those canals from Lake Pontchartrain was the result of a failure of the levees, not that the water went over them?

Mr. VAN HEERDEN. That is correct, sir.

Senator LIEBERMAN. Dr. Seed and Dr. Nicholson, do you and your investigation agree with those conclusions? Here, I am focusing on Lake Pontchartrain, that the water—the flooding didn't occur from the water overtopping the levees, but that the levees simply failed. Is that your conclusion, Dr. Seed.

Mr. SEED. Our preliminary conclusion on all three of those sections is that the failure was produced somewhere in the foundation or the lower levels of the embankments themselves, but certainly the earthen embankments became unstable and the floodwalls were no longer supported.

Senator LIEBERMAN. And Dr. Nicholson.

Mr. NICHOLSON. I concur with the other two.

Senator LIEBERMAN. And this led to my conclusion from your testimony that I stated at the outset, that it was human error in the design and construction of the levees that led to a significant part of the flooding of New Orleans, that, in fact, if the levees had done what they were supposed to do, notwithstanding the strength of the storm on the East part of town, on Lake Pontchartrain, it wasn't that strong. If the levees had done what they were designed to do, a lot of the flooding of New Orleans would not have occurred, and a lot of the suffering that occurred as a result of the flooding would not have occurred. Am I correct in drawing that conclusion, Dr. Seed and Dr. Nicholson?

Mr. SEED. The latter part of your conclusion is unequivocally correct.

Senator LIEBERMAN. Which is—just to clarify——

Mr. SEED. Which is that the levees would have been expected to perform adequately at these levels if they had been designed and constructed properly. The opening sentence was a little bit troublesome inasmuch as you said it would be the result of human error. It may not have been the result of human error. There is a high likelihood that it was, but we are receiving some very disturbing reports from people who were involved in some of these projects, and it suggests that perhaps not just human error was involved, but there may have been some malfeasance. Some of the sections may not have been constructed as they were designed.

Senator LIEBERMAN. Yes.

Mr. SEED. That needs further investigating.

Senator LIEBERMAN. That is very important. So it was not only an error, or might be called technical judgment about what was necessary there, but that, in fact, the construction work done on those levees was not up to the design specifications, is that what I am hearing you say?

Mr. SEED. We are pursuing stories of that, in fact, and we are seeing evidence from what we saw in the field versus some of the design drawings we have been able to obtain so far that would suggest that some of those stories might bear some fruits. We are continuing to study it.

Senator LIEBERMAN. And help us understand, leaving that aside for a moment, the malfeasance possibility, what the errors in design were here. Was it a failure—I have heard you refer at different times to the soil configuration. Was it a failure to allow for the unique qualities of the soil there?

Mr. SEED. Somebody asked me about a month ago the difference between a dam and a levee.

Senator LIEBERMAN. Yes.

Mr. SEED. In principle, a dam is tall and narrow and a levee is short and very long. The real difference is that with a dam, we pick our sites and we pick them very carefully. We build levees usually at the edge of swamps, sometimes in swamps. We routinely get very poor foundation conditions, so the poverty of the foundation conditions is not unexpected.

Senator LIEBERMAN. Not unusual. That is where levees are built. Right.

Mr. SEED. Not unusual and we are used to that. What makes the New Orleans levees unusual is the high stakes involved in terms of the inboard population being protected. These are very high-risk levees with regard to consequences. In a system with several hundred miles of levees, it is very difficult to do suitable investigation and basically to nail all the details. The problem with the levee system is if you leave one detail unnailed, you leave a vulnerability which may in the end bring the whole system down.

The local conditions at the sites of the three main breaches on the canals, the one on 17th and the two on London, were very challenging local conditions.

Senator LIEBERMAN. Right.

Mr. SEED. There was some accommodation of that in the design, and we are studying very hard right now to determine if, in our opinion, the accommodation was suitable. Performance would be suggesting that it might not have been.

And the other half of the question is whether they were actually built the way they were designed, and there are some issues there. We are hoping very much to be able to, for instance, pull some of the sheetpiles and see what length they actually are. We have several sets of design documents which suggest different lengths, and we have several reports that perhaps none of those lengths is the correct answer. But these things are still out there and pulling a couple of sheetpiles is a clear step.

Senator LIEBERMAN. And you are still at work on it, but I hear you say that notwithstanding the unique circumstances of the soil in the vicinity of the construction of those levees to protect New Orleans, particularly facing Lake Pontchartrain, within your field, within your expertise, that was not an impossible task, that it could have been done, from what you know now, a lot better than it, in fact, was done, so that the levees would have withstood the water surge.

Mr. SEED. There was a second message, though, in what I said, and that is that borings were spaced at intervals, many miles of levee were being designed, and at some cost and some price, it would be possible to do a better and safer job. An important issue to get to later in the studies is whether, in fact, the level of protection that was paid for was delivered. But I think we have to also acknowledge the fact that the budgets were tight, people were squeezed, and we may not have been paying for enough protection. So it may be a double-ended question.

Senator LIEBERMAN. Well, that is an important question for us as elected officials, particularly those who fund the Army Corps of Engineers. But it is just an infuriating conclusion here, if what stands in the remaining investigations, that, in fact, a lot of the damage to New Orleans from Hurricane Katrina flooding was preventable. And it would have been prevented if the design and construction of the levees, particularly along Lake Pontchartrain and, to some extent, to the Eastern part of the city, had been done according to professional standards and specifications.

Mr. SEED. They were done according to professional standards and specifications. I want to be very careful there. They weren't necessarily done in the way, in hindsight, we would have liked to have them be done, and that is because professional standards, and so on, cover some range. But there certainly was the possibility to have engineered the system to perform better.

Senator LIEBERMAN. Dr. Mlakar, I apologize because I have only got about a half-minute left, but I hope there is time for you to respond insofar as you are able at this point in your investigations. I do want to say that I was troubled—I understand the difficulty and I caught your words of rational conclusions here. One of the problems we are facing is the movement of the calendar. If your report is not coming until July 1 of next year, and the hurricane season begins again on June 1, by which time the Corps has said it would restore the levees to at least the pre-Katrina levels, how is your report going to be helpful, or as helpful as it should be?

Mr. MLAKAR. We will be sharing our interim progress with my colleagues in the Corps of Engineers who are responsible for the reconstruction. So while the final report, due to the serious deliberations and complexity of the problem, will take until July, the interim progress will be shared much before that as the decisions have to be made.

Senator LIEBERMAN. OK. Thank you. Thanks, Madam Chairman.

Chairman COLLINS. Thank you. Senator Voinovich.

OPENING STATEMENT OF SENATOR VOINOVICH

Senator VOINOVICH. Thank you, Madam Chairman, for holding this hearing and raising important questions about the levees in New Orleans, and I just want to thank this panel. You have been terrific. It is nice to have such expertise before us today and coming from an objective point of view without any kind of axe to grind, as so often is the case when we have hearings before this Committee and many other committees.

I think it is important to learn from our mistakes and not to repeat them in the future. Today's testimony confirms what I have known since I was chairman of the Subcommittee on Transportation and Infrastructure. That was my first 2 years in the Senate. I lucked out, and I was chairman of the Transportation and Infrastructure Subcommittee. I had the Army Corps of Engineers under our jurisdiction, and at that time, I concluded that we were not funding the Army Corps of Engineers to the extent that they should be funded. We can sit here and we can criticize, but I think we should look at ourselves in the mirror and the administrations, not only this Administration, but previous administrations should do the same thing.

In the 1960s, we were spending, in 1999 dollars, about $4 billion on projects, $4 billion. Today, the last average from 1999 has been about $1.5 billion. Our operation and maintenance, in 1999, we were behind about $250 million. Today, it is $1.250 billion. The real question is, had we done our job, had the administrations asked for the money that the Army Corps of Engineers should have received and had this Congress responded to that, and I kept saying, we need it, we need it, please, from the head of the Army Corps of Engineers, ask for the money. It just wasn't there.

And, by the way, we then added on to them these ecological restoration projects. In other words, in addition to just the Army Corps of Engineers work, we are saying now we have these environmental restoration projects. We are going to throw that on top of you.

Yes, sir, Dr. Seed.

Mr. SEED. The Corps of Engineers knows how to build levees and how to make them safe. Euphemistically, we say somebody wrote the book. The Corps of Engineers literally wrote the book repeatedly on the creation and the safe creation of levees. Their compaction standards, their design standards are widely copied and emulated throughout the country and throughout the world.

The Corps of Engineers is also struggling right now to repair failures in the New Orleans area, and it is painfully clear to our investigation team that they are struggling for lack of technical manpower, and we find that to be very daunting. We haven't done a formal study of the national staffing of the Corps yet, but we hope to engage in that. We have been taking personal surveys among our friends and colleagues, former students. The assistant coach of my soccer team is also a geotechnical engineer, and he is working on a big Corps levee project in Yuba City, California.

And in all of our contacts, we are finding a shortage of geotechnical engineering capability and the elongage of cost efficiency, which is people with degrees in economics and management and a lack of engineering. The stunning parallel to us is NASA before the Challenger disaster and NASA afterwards, where they reinstituted their engineering and scientific capabilities at the cost of cost efficiency.

I think we need to take a very strong look at ourselves as a Nation. We have strangled the Corps of Engineers in terms of budgets and support. They have responded by doing what was necessary to get their jobs done as best they could. But I think the human error issue in New Orleans is not going to be something which we can be pointing fingers at the Corps for. I think the finger pointing will be at ourselves when we are all done.

Senator VOINOVICH. Well, the National Academy of Sciences has come out with some recommendations, ten recommendations on what we need to do to deal with the lack of scientists and engineers in this country, and I am hopeful that the Senate and the House and the Administration will adopt their recommendations and spend the money and make the sacrifice that we need in order to deal with this ongoing problem.

This Committee has spent its time on looking at the issue of human capital, and if you go back to almost any problem we have, it is not having the right people with the right knowledge and skills at the right place and at the right time. Go back and look at it. We have neglected human capital on the Federal level forever, and it is time for us to change that, and I am glad that you brought up the lack of folks that they need to get the job done.

Here we are today, and we have to make decisions about New Orleans. Are we going to go to a level three and rebuild this thing and get it so that we can get to level three, and if we were to do that and we decided to go to level five, would we do it differently? Do you understand the question? In other words, we have concrete, and we have under-soil that shouldn't be there. We are going to get in there and make it better, assuming you have the resources to do it. But the question is, if you go to a level three and the decision then is to go to a level five, would you do it differently in terms of going to the level three? In other words, can you take it to level three, do it right, and then say, if we go to level five, can you build on top of that, or if you are going to go to level five, would you do it differently right from the get-go?

Dr. Mlakar or any of you, chip in on it.

Mr. MLAKAR. Thank you, Senator. Probably if we decided to go to level five from the get-go, there might be some different options open to us than if we first went to level three and then went to level five. I am here primarily to talk about the fact-finding we are doing to figure out exactly what happened, but as a general answer to your question, yes, there are probably some different options on which way you want to authorize us to go.

Senator VOINOVICH. And then the question is, if you go to level three and then the decision is to go to level five, what is the time span, and then what do you do in the interim period? What if we have another hurricane? If we don't rebuild to level three the way it is supposed to be done, then the folks will still be very vulnerable in New Orleans. Can I have some comments from some of the other witnesses?

Mr. VAN HEERDEN. I would respectfully encourage to go to a level five to start. From the hurricane statistics side, in the last 50 years, a major hurricane has come close to New Orleans on about eight different occasions, and just a slight change in the track of any of those hurricanes would have created a similar sort of flooding. Southeast Louisiana is a hurricane-prone area, and speaking as a Louisianan, I would encourage that we go to Category 5 from the beginning. Thank you.

Senator VOINOVICH. Dr. Seed.

Mr. SEED. Speaking as a Californian and as an American, therefore not from Louisiana, I think if you do a Category 3 first design and then go to a Category 5, many of your design elements will be compatible and extendable. Some of them will not. There will be some sunk costs which will essentially be a temporary, interim measure.

Designing for a full Category 5 is no walk in the park. It probably involves restoration of offshore barrier islands and a lot of issues that are going to be well beyond concrete and rebar and sheetpiles and earth levees. It is a very complex issue and a very difficult one, and in the end, you are also still going to have a system which will be untested until it is tested. One of the great problems with levee systems is there is no way to do a dry run to see how you are doing.

Mr. VAN HEERDEN. Could I make one more comment?

Senator VOINOVICH. Sure.

Mr. VAN HEERDEN. We heard in the testimony that those levees that were faced by wetlands weren't eroded, and we saw that in the slide. So I would encourage that at the same time we restore the levees, we restore our coastal wetlands. These wetlands are our outer line of defense. These wetlands are what take the stuffing out of the hurricanes, the barrier islands and the wetlands. Perhaps this is a unique opportunity to both reconstruct the levees and get the coastal restoration program going.

Senator VOINOVICH. Dr. Nicholson, would you like to comment on this?

Mr. NICHOLSON. Well, as Dr. van Heerden just mentioned, we did observe that where the wetlands gave you a first line of defense, not necessarily line of defense, but it certainly helped reduce the wave heights and the impact on those levees. We saw that very clearly. So that restoring the wetlands would certainly give you a front line to help reduce the impact.

Senator VOINOVICH. The conclusion I get from all of you, then, is that if you were in our shoes and having to make a decision, even if we decided that we were going to build to a level five, then it is incumbent on us to build to level three and do it the right way.

Mr. SEED. Probably the safest and secure answer to that is there is no way to do a level five quickly, and the people of New Orleans will need protection before that can be completed.

Senator VOINOVICH. Thank you.

Chairman COLLINS. Thank you. Senator Akaka.

OPENING STATEMENT OF SENATOR AKAKA

Senator AKAKA. Thank you very much, Madam Chairman.

I want to add my welcome to all of our witnesses, and I would like to add a special aloha to Dr. Nicholson, who, as Senator Collins mentioned earlier, is a professor at the University of Hawaii at Manoa. Dr. Nicholson, I want you to know that I am honored that you are leading the American Society of Civil Engineers team and lending your expertise to this worthy cause. I am pleased to have you join this hearing today.

Dr. van Heerden, you have written movingly about the situation in the State of the Emergency Operations Center, that Monday evening, as you realized the levees were falling, you assumed that "the Corps of Engineers, who basically owned the levees, would be warning everyone" and you thought that "the Corps must be monitoring the levees" and that they would sound the alarm. Have you learned why the Corps did not warn everyone and why they weren't monitoring the levees?

Mr. VAN HEERDEN. No, we haven't. The first call that we got that indicated something was amiss was when I was at the State Emergency Operations Center, and that was around eight o'clock on Monday evening, and quite honestly, at that time, everybody was congratulating themselves that we had dodged the bullet. We first heard of a nursing home somewhere, they had two feet of water in it and the water was rising half-a-foot an hour. They weren't sure where it was and they weren't sure if it was salt or fresh water, which would have been a key. Then, as far as I know, they lost telephone contact. But whether a warning was given, certainly at eight o'clock in the State Emergency Operations Center, we were unaware of it.

Senator AKAKA. Dr. Mlakar, I know you are not here to represent the Corps, but I would like to give you a chance to comment, if you are willing to do that, on this.

Mr. MLAKAR. Thank you, Senator. Yes, I am here as a technical expert leading the collection of the data to figure out exactly what happened, and I am really not prepared to answer this question on our emergency response but will be very pleased to get back with you for the record on that point.

Senator AKAKA. Thank you very much.

Dr. van Heerden, I understand that in the summer of 2004, you and others from the Louisiana State University Hurricane Center participated in a simulation of a Category 3 storm hitting New Orleans. That exercise predicted that flooding would leave 300,000 people trapped in New Orleans. On Sunday, August 28, just over a year later, your LSU team warned FEMA and other disaster officials that there would be a significant event in New Orleans. What was FEMA's reaction when they were warned both in the summer exercise and immediately prior to the levees breaking that there was a disaster in the making?

Mr. VAN HEERDEN. That is a hard one to address. In the 2004 exercise, I think for the most part, this was the first time anybody had ever really thought about the consequences of a flooding event of New Orleans, maybe the first time that some of the agencies really understood what the consequence could be if the city was flooded.

The only comment I had was I knew from our public opinion surveys that 68.2 percent of the people would leave and that would leave about 300,000 behind, and if you flooded the city, you would have over 800,000 homeless. And so we tried to press with FEMA the need to perhaps preposition tents and to perhaps find the properties in Louisiana, whether it was State parks or farmland, where you could erect these tents for these evacuees as the first line, and I was told very bluntly that Americans do not live in tents, and I was obviously very disappointed because I knew that we would have this problem that we had where citizens were bused all over the place, families were split up, and in many cases, there wasn't the first-line medical surveillance that could happen if you had an organized tent city or series of cities.

In terms of FEMA in response to New Orleans, we made all our predictions, our storm surge model outputs available to FEMA officials via the Internet, and at the State EOC, we briefed them, briefed everybody there, including FEMA, and then the *Times-Picayune Newspaper* on the Sunday morning before the storm took one of our storm surge outputs and created a color graphic and indicated then that the flooding was going to happen.

Senator AKAKA. I was particularly interested in what response or reaction FEMA had about your findings and what had happened there.

Dr. Seed, a member of your team was quoted in the press stating that your team was denied access to certain Army Corps of Engineers employees. Can you comment on these reports and describe exactly what your team requested from the Army Corps of Engineers and also what responses you received from them?

Mr. SEED. We have had highly variable levels of cooperation from the Corps of Engineers. It has fluctuated with regard to the units of the Corps we have been in contact with, the locality of those people, and also the time of the week.

We had a marvelous experience in the field for 2½ weeks, where the various teams arrived, we were squeezed as to numbers of people we were allowed to bring in because there were questions about ingress and safety and also whether, in fact, investigation teams might be in the way as emergency operations were proceeding. When we arrived on the ground, we learned rapidly that the situation was bigger than we could handle, and we pooled our resources. The Corps team, the investigation team led by Dr. Mlakar, literally worked shoulder-to-shoulder with the rest of the teams, and we did as much study as we could quickly because bulldozers were scooping up and burying vital data. So cooperation and collaboration of teams on the ground in the critical 2½ weeks of the field studies was superb.

We were routinely promised we would be able to meet with local representatives from the Louisiana District, who have an intimate knowledge of the history and the evolution of many of these sites, which is fundamentally critical if you are working under those kinds of time constraints and you only have limited manpower. We never actually met any of those people at any of the sites. They were always busy doing other emergency work, and that was very disappointing to us. That was the source of Dr. Bea's concerns.

We received a wonderful inbriefing document with maps and some cross-sections of some of the levees, which was tremendously useful. We were, however, not able to obtain any of the subsequent follow-on documents that we had requested, in fact, a list of documents which we had developed jointly amongst the various teams, including input from the ERDC team, until this past Saturday, when all of a sudden many documents were posted electronically on a website.

So the Corps of Engineers seems to be moving in fits and starts. Sometimes, they are very cooperative. Sometimes, they are not. I was listening with painstaking diligence to Dr. Mlakar's comments in the opening session. The Corps of Engineers has repeatedly promised to provide documentation and access to all the teams. This involves background design documents and design memoranda, construction memoranda, maintenance and inspection reports. It also extends to ongoing studies they are doing right now, the borings and sampling and the test data. A lot of that stuff is very important. They have consistently promised that stuff will be forthcoming.

In his comments today, that last piece was missing. He announced an intent to develop this information, but he did not announce an intent to share it with the other investigation teams. I am hoping that was an omission, not a deletion.

Senator AKAKA. Do you think the Corps was deliberately keeping you from meeting people?

Mr. SEED. The Corps of Engineers has just suffered a major blow. The people that work for the Corps of Engineers do so because they have a desire to do good things and make people safe, and when your work doesn't go well in that regard, it is a very difficult situation.

I think the Corps is struggling to get its hands around all of this at many levels, locally and at the national level. To their credit, as time passes, we do see them consistently making the right steps in the end. We did see the interim levees repaired in fits and snatches for a while, and then when we pointed out the flaws, the flaws were rapidly and appropriately addressed.

It did take us many weeks of struggle to get our investigation teams in and on the ground. The Corps was expressing concerns about the safety of the teams and logistical issues and the possibility they might interfere with the operations. Members of our team have directed these types of operations. They certainly know their way around a levee and around construction equipment. There is no way they would be an obstruction in the field, and their personal safety was not much of an issue. We have been to countries like the Northwest corner of India up against the Pakistan border and many of us who have had 12 inoculations are immune even to mosquitoes from the Louisiana area, to a large extent. So we thought that was perhaps also a delaying tactic. We would have liked to have gotten in quicker. But in the end, the teams were let in. That doesn't always happen.

So it is a very mixed bag. We are seeing mixed responses, but we are seeing the Corps consistently in the end responding adequately to get the job done. That lifeline hasn't been cut yet. We are concerned, though, that as the heat goes away, they continue to respond adequately to get the job done. There are a great many documents, and so on, we are going to need in the months ahead, and the data they are currently developing is, of course, fundamentally important.

Senator AKAKA. Thank you, Dr. Seed. Thank you, Madam Chairman.

Chairman COLLINS. Thank you.

Before I call on Senator Warner, let me address the issue of documents. It is very troubling to this Committee that the forensic teams that are looking into the failures of the levees have not received complete and total cooperation from the Army Corps. I do want to point out that Dr. Mlakar is not the individual making document decisions, but I also want to assure you, Dr. Seed, and others involved in these reviews, that this Committee is committed to making sure that you have all the documents that you need from the Corps to complete your analysis. That is absolutely critical to your work. It is also critical to our work. And we, too, have had difficulty in receiving the documents that we need from the Army Corps and from the Department of Defense, in general. So this is an issue that this Committee will follow up on, and it is appropriate that I now call on the distinguished chairman of the Armed Services Committee who perhaps can assist us in this matter, also.

OPENING STATEMENT OF SENATOR WARNER

Senator WARNER. Thank you, Madam Chairman.

First, the Senate has approached, I think in a very reasonable way, the extraordinary broad analysis that we must provide about this natural catastrophe to our Nation and the human suffering it involved. There are four of us on this Committee who serve on the Environment and Public Works Committee, and the distinguished Ranking Member being one of the four, Senator Voinovich, Senator Carper, and myself. I want to say from the outset what I am sure everybody knows, that the Corps has the primary responsibility for issues relating to these levees and so forth. We all recognize that.

I have personally talked to General Strock. I have a high regard for his professional capabilities. He has forthrightly said, we haven't had the time yet to develop the answers that are needed, and they are busy doing so. As a matter of fact, I think almost each of you are in some form of consultation with the Corps on this. So time is needed. But I will join with others on this Committee to assure the Chairman and Members of this Committee that such documents in the possession of the Corps are made available to this Committee and in a timely way.

But I think I have listened very carefully, and this is an excellent panel, by the way. I commend the Chairman and the Ranking Member for bringing it here, very competent individuals. I draw on a modest background of civil engineering in my college and university years. You are quite right about going, Senator Voinovich, from a level three to a level five. Ideally, the footings and so forth required for a level five are probably markedly different than what you need for a level three in many instances. Nevertheless, we are not here for that question.

But I did want to just lay a benchmark about the Corps, and they are working very hard on this, and the Environment and Public Works Committee has purposely allowed them more time before they are brought before us as witnesses, but we will assure you that this Committee is well served by their documents.

I would like to go to another matter, Madam Chairman, and that is one that Dr. Ivor van Heerden raised, and others, about if we go to a level five and so forth, we have to rely on much more than what man can devise. It is what nature can devise by way of these natural barriers, which through the years there has been some erosion, and the loss of the natural sediment from the river has not provided the help that nature needs to reestablish itself.

So this brings me to the channel called, as I understand it, MRGO, the Mississippi River Gulf Outlet, a manmade navigation channel that provides a direct shipping lane from the Gulf of Mexico to the marine terminals in New Orleans. I wonder if that should not be reexamined in the light of the overall approach to the revitalization of this whole area.

It is my understanding that over the years, experts have worried that the Mississippi River Gulf Outlet would allow a severe storm surge to give a direct hit at New Orleans. Is there any data to support that did happen in this instance? That concern appears to have been one that we have got to address. This project also has disrupted the natural flow of sediment, which is critical in providing the buffer zones that you referred to.

So, therefore, I just wonder, do you feel as we address this problem, and given that there has been some reduction in the navigation use of this outlet and it has become somewhat less significant now—I have just been told that, I cannot corroborate it, but I will—should the MRGO be a part of the solution to providing for the future preservation of this area in the face of natural disasters?

Mr. VAN HEERDEN. Senator, yes, we believe that a really hard look needs to be put on MRGO, whether it is actually needed, and certainly from our computer modeling, we know that where MRGO joins the Gulf and Coastal Waterway, the area known as the funnel is where we really get the amplification of the surge. If MRGO was to be abandoned, there is the potential of using parts of it as a conduit to funnel sediments elsewhere. Obviously, you can't have sediment in a channel that you have still got navigation.

Senator WARNER. Thank you.

Mr. MLAKAR. First, Senator, I would like to thank you for your acknowledgement that there is a great deal of effort involved in providing this information, and General Strock and all of us are, indeed, committed to be absolutely open and transparent in this study.

As far as MRGO and the natural barriers and this larger picture, I am really here as a technical expert on what happened in Hurricane Katrina. We will have some information about that in our final conclusions, to what extent the loss of the wetlands, to what extent MRGO might have played a role in that. Others in the Corps are looking at these larger questions, and perhaps I would like to defer to them to answer.

Senator WARNER. Thank you very much. Dr. Seed.

Mr. SEED. We haven't studied yet, the degree of vulnerability introduced by the MRGO, but it doesn't appear to have been a large issue in this particular case. The larger question is to how to move forward to something like a higher degree of protection, possibly a Category 4 or 5 system as is being discussed. It is a broader issue than reconfiguring something as simple as the MRGO when the barrier islands—it probably involves reconfiguring how that was even created in the New Orleans area and how they are coordinated.

It involves the need to have somebody be in charge of the overall system and resolve the differences between the different groups who have to interact at connections and cross-connections. It involves handling issues like the Corps of Engineers, who build levees and then nominally turn them over to locals after some period of time and those interfaces. There are a lot of organizational issues which need to be resolved to move the city safely forward.

Senator WARNER. Thank you.

Mr. NICHOLSON. Similarly, the hydraulics of MRGO and the funnel factor are a bit out of my purview. As a geotechnical engineer, we are looking at other issues as far as the levees were concerned. But certainly, this is an area where there has been a lot of discussion and should be looked into further. I have seen some of the modeling done by the LSU Hurricane Center that has suggested that may certainly help at least part of the protection, or could be a buffer zone, if you will. But that is an area which is really beyond the scope of what we are looking at.

Senator WARNER. I thank the Chairman.

Chairman COLLINS. Senator Carper.

OPENING STATEMENT OF SENATOR CARPER

Senator CARPER. Again, our thanks to each of you for joining us today.

I appreciate the use of the technology and all the maps and the photos that you showed, and you used a pointer of some kind, a laser pointer that was actually difficult to follow. I do pretty well in my color blindness tests and so forth, but it was just hard to pick it up on the charts, so I just share that with all of you so that next time it might be even more helpful to all of us.

Dr. van Heerden, if I could start off with the first question for you, please. Last month, at a hearing on another committee that I serve on, the Environment and Public Works Committee, a Lieutenant General whose name is Strock, Carl Strock—I don't know if you know him, but he is the Chief of Engineers. He stated that the path of Hurricane Katrina was such that the wetland loss was not an issue in this particular storm. I would just ask for you to react to that comment.

Mr. VAN HEERDEN. If we had the wetlands we had in the 1870s now——

Senator CARPER. In the when?

Mr. VAN HEERDEN. I say 100 years ago, the surge would have been dramatically less, and there are two very important reasons for that. First off, if you imagine a hurricane moving forwards with very strong winds, the winds that are blowing on land are on the right-hand side and that is blowing the water towards the land. But on the left-hand side, the winds are blowing offshore and that is blowing the water away from the land.

So if you have very significant and healthy wetlands and barrier islands on the left-hand side, you start to suck the wind energy out of that storm. On the right-hand side, if you have substantial wetlands and barrier islands, you add significant friction to that surge. And if you have ever had the opportunity to go into the Louisiana cypress swamps, which used to be very——

Senator CARPER. I have never had that opportunity.

Mr. VAN HEERDEN. Do come down. But if the cypress swamps that used to exist where MRGO, along the course of MRGO that got destroyed by the salt, what you see is a 60 to 70-foot high wall of gray tree stumps, and when that water tries to flow through that, there is a lot of very significant friction, and you lose that flow.

An example of how valuable the wetlands are, Hurricane Andrew made landfall in Louisiana in 1992, I believe it was, and made—its path came up the central part of Louisiana where we have extremely healthy wetlands and two new emerging deltas, two areas of net land growth, and the surge in Morgan City, which was some 20-odd miles inland, was only seven feet. So to me, that is—and in terms of the wind between the coast and Morgan City, the wind lost 50 percent of its energy. That is an example of how valuable those wetlands are in reducing hurricane impacts, both wind and surge.

Senator CARPER. How do we go about rebuilding the wetlands?

Mr. VAN HEERDEN. If you look at it, all of coastal Louisiana was built by the Mississippi River and the sediment in the river is, in essence, a renewable resource. The river floods every year. All we have got to do is find efficient methods to get that sediment out of the river and back into the wetlands. In our toolbox, we can have major diversions, perhaps diverting 50 percent of the river. We know that used to happen every 1,000 years and that is what built large parts of Louisiana. There may be opportunities to do that now in the lower part of the river system, maybe into the Breton Delta.

The next tools in our toolbox are siphons and minor or smaller diversions, and we have a couple of those, and that is where you simulate the distributory channels that used to operate when the river flooded, and you can get the sediment a little further, and greater volumes.

Another important way would be to use what we call mini-siphons. These are very small siphons spaced every few miles down the river that would in many ways simulate a natural flooding event because you would put—you wouldn't flood anybody locally, which is a concern, but you would put significant amounts of fresh water and especially the nutrient-rich waters into the wetlands.

And then also in the toolbox is the restoration of our barrier islands, and in Federal waters, there are some fantastic sand resources that are there that could be mined and that sand then used to build barrier islands. I believe it is very doable and would really aid Louisiana in terms of hurricane impacts.

Senator CARPER. All right. Thanks very much.

I have a question that I would invite any of the panelists to answer. I will give you a break, Mr. van Heerden, for a moment, but I would ask any of the others who would like to take a shot at this to do so.

Many of the Corps' calculations regarding how to build levees to protect New Orleans from a Category 3 hurricane were done, I think someone said, in the 1960s, and since then, New Orleans has subsided, but there has been a great deal of additional development, as we all know, and hundreds of square miles of wetlands have been lost. An independent analysis was done, I think for the *Times-Picayune Newspaper* back in 2002. I think it was called "Washing Away." It showed that therisk might now be twice as large as the Corps had estimated.

How has this affected the Corps' assumption and design recommendations? Is there any attempt to review and update the assumptions regarding the design? Mr. Mlakar.

Mr. MLAKAR. Yes, sir. I would say that we don't have an answer or conclusion about that right now, but that is certainly going to be a subject of our study.

Senator CARPER. I am sorry, say that one more time.

Mr. MLAKAR. We don't have the answer to that right now, but I think we will have something to report on that at the end of our study.

Senator CARPER. And that will be roughly when?

Mr. MLAKAR. The study will be done July 1.

Senator CARPER. All right, thank you. Yes, sir, Mr. Seed, an easy name for me to pronounce.

Mr. SEED. And I apologize for my name being so simple. People tend to remember it, although sometimes I get called "Bird" several years later. [Laughter.]

I have a partial answer for that, and our sense is the partial answers are important at this early stage. Hydrology has advanced considerably over the past half-century, and there are numerous projects, Corps projects, Bureau projects, and projects owned by neither involving levees and also large and high-risk dams whose hydrology needs to be updated and the ramifications of which need to be studied.

The difference between levees and dams is that dams tend to get reassessed every 5 and 10 years in a fairly formal system. There is a National Dam Safety Program which foments that. We don't have a National Levee Safety Program. It is a missing piece, and we would like to see one established.

Many levees are beginning to protect large populations. Levees used to exist in the swamps, which were unpopulated. We have a huge problem in California with our Sacramento Delta, where people are now moving into the delta because the real estate around the delta is both built in and hugely expensive, and we are projecting having over 200,000 people move into that area in difficult and tenuous situations over the next 10 years alone. The prudence of that is also a political issue in California.

We also have in California a city, Sacramento, with levee flood protection, nominally engineered by the Corps. The design level of flood protection intended for New Orleans was to be a so-called 200-year level of protection, which means about once every 200 years, you would expect to lose it in a major hurricane. As the Picayune said, the better estimate today might be roughly half that. We have levee systems in Sacramento which are nominally engineered to a 75-year level of protection, and the local understanding is it may be half of that. There are efforts to raise Folsom Dam now to help staunch some of the flooding and raise those levels. But we have levee systems throughout the United States at various levels of protection, and it is possible that those all need to be reassessed in terms of their levels of prudence.

Senator CARPER. Mr. Nicholson, do you want to add anything?

Mr. NICHOLSON. Yes, just two things. First of all, I am not in a position to comment on what the Corps is doing or has understood about reevaluating the effect of the wetlands, but I did want to concur that the ASCE also believes that support of a National Levee Inspection Safety Program similar to the National Dam Safety Program that exists now would certainly be important, particularly in protecting those large urban areas. It is vitally important as they have been neglected to a much greater extent than our national dams.

Senator CARPER. One last quick one for you, Dr. Seed. You stated in your testimony that some inexpensive modifications to the levees and floodwalls could have prevented some of their failures. What would be the reasons for choosing not to undertake those modifications?

Mr. SEED. It is almost a policy issue. The Corps of Engineers was authorized, which is a very specific term, to provide a certain level of protection for the people of New Orleans, and they specially sized the elevations of the tops of the levee and floodwall systems targeted at that. They typically overbuilt them in many areas by a foot and sometimes two to allow for long-term settlement, and the region is also subsiding. But by and large, that was the target, and they met it.

It was not their policy to think about what would happen if you got one or two more feet of water. Therefore, there was no design provision for one or two more feet of water, but it may well be that with some inexpensive additions that might have added, at best, a few percent to the overall project cost, one or two or sometimes three feet of water for a few hours might have been accommodated safely. Our sense is that there is a bit of a policy issue there which needs to be evaluated.

Senator CARPER. All right. Thanks to all of you. Thanks very much.

Chairman COLLINS. Thank you. Senator Coleman.

OPENING STATEMENT OF SENATOR COLEMAN

Senator COLEMAN. Thank you, Madam Chairman, and thank you for holding this important hearing. Gentleman, though I didn't have the time to listen to your testimony, I have read your statements. Just a couple of questions. I am still trying to understand what happened here.

We have heard a lot of talk about building to a level five and the timing that would take and the cost that would take, but my kind of basic question as I kind of listened to the testimony, I think all of you have commented that the levee failure—I think, Mr. van Heerden, I think you talked about geotechnical engineering failure and talked about high porosity and permeability of soils. I think, in fact, every individual talked about the soil being an issue, that it wasn't the surge, as you read the paper, that the surge overcame, but there were issues with the soil, geotechnical issues, I think is the phrase that was used.

So my first question is, did the levees break because they were not geared to deal with a Category 5 hurricane, or, in fact, what we really dealt with was something less than a Category 5 here? I am trying to understand why. Is there anybody here who is saying that the reason for the failure was because the levees were not adequate to protect against a Category 5 hurricane?

Mr. SEED. There are two pieces of that. As Dr. Nicholson said, there were several dozen levee failures, breaches, and distressed sections. A majority of them were the result of overtopping, and that simply means that the hurricane was bigger than the levees were built to take and that will be a policy issue. You could pay more and get bigger, taller systems that would have taken more storm surge.

But three of the particularly devastating failures, the ones on the 17th Street and London Avenue Canals, failed at far less than designed water surge levels because they were on the left flank, far away from where the hurricane was, and the water surge wasn't so big there. So those were, in fact, foundation failures.

Senator COLEMAN. So those, just to understand, if they were built to level 3 but didn't have the foundation failures, we would not have seen the extent of damage that occurred?

Mr. SEED. A considerable fraction of the flooding and some of the loss of life would have been prevented.

Senator COLEMAN. I don't want to get into any finger-pointing here, but how would that have been prevented? What should have gone on that didn't go on to have prevented those structural failures?

Mr. NICHOLSON. I will take that one. First of all, I think I would be careful with the use of "structural failure." As geotechnical engineers——

Senator COLEMAN. I am not a geotechnical, so give me the right phrase. It is important that we define this. And again, my concern is that there is so much talk about Category 5, but as I read your reports—and there are cost issues, let me just say, there are cost issues. I fully agree with my colleague from Ohio about the need to have more scientists, more engineers, but I don't agree that the issue is simply more funding, and I don't believe—I would say, respectfully, Mr. Seed, that this kind of conflict, if we put more into cost efficiency, that somehow that takes away from efficiency. In the private sector, it doesn't work that way. You can get cost efficiency and have people do the right job. So I am not a believer that if we would have thrown more money in, necessarily. If that is the case, I would support that.

So I am trying to understand the nature of the problem, why the problem was there, and what I am least clear on, that it wasn't necessarily a problem because we weren't at Category 5, the ability to deal with Category 5. We had less than that, and yet we still saw the breaches. So help me understand why that occurred and how that could have been prevented.

Mr. NICHOLSON. OK. Well, in fact, this is a multi-faceted issue because we had a number of different types of flood control structures. We had different heights of storm surge in different areas. And so this discussion of Category 3, Category 5, as Dr. van Heerden said, really is a term that is used for the size of the storm, and there are a couple different definitions which make it even more complicated. Really, the individual flood protection is designed for a certain level of storm surge.

As Senator Lieberman had asked, if they had performed as they were intended, certainly, we would have seen a lot less flooding. Exactly what went wrong and what failed is precisely what we are trying to do, and we certainly need additional studies. We, in the field, observed many different types of failure mechanisms. There is not one thing that went wrong. In different areas, in different types of levees, we saw different types of failures.

So in some cases where we saw the overtopping, it is fairly easy. It is the more difficult ones, such as those floodwalls in town on the 17th Street and London Avenue Canals where we, in fact, have some pretty good ideas of what had gone on. We understand or we can observe some of the mechanisms that had led to the failures. But exactly what went on, and again, we aren't looking at finger-pointing at this point.

Senator COLEMAN. Let me ask you, who has the responsibility for checking the soil——

Mr. SEED. Can I tackle that next because I think I have the answer you are looking for, and I think the question you asked is the one that we were all hoping to hear today. It is certainly why I flew out from California on the red-eye.

Senator COLEMAN. I have taken that flight. [Laughter.]

Mr. SEED. That is the only way we get to Washington from Berkeley.

Throwing more money into the bucket is not going to fix the problem. For more money, you can buy higher levees, and for more money, you can buy an increased level of safety, but what you need is an increased level of assurance of safety, and to get an increased level of assurance of safety, you need to make some fundamental changes as to how levee systems in the New Orleans area are designed and built and maintained.

No one is in charge. You have multiple agencies, multiple organizations, some of whom aren't on speaking terms with each other, sharing responsibilities for public safety. The Corps of Engineers had asked to put flood gates into the three canals, which nominally might have mitigated and prevented the three main breaches that did so much destruction downtown. But they weren't able to do that because, unique to New Orleans, the Reclamation Districts who were responsible for maintaining the levees are separate from the Water and Sewerage District, which does the pumping. Ordinarily, the Reclamation District does the dewatering pumping, which is separate from the water system. These guys don't get along. The Sewerage District was so concerned they wouldn't be able to pump through gates which had to be opened and closed that in the end, the Corps, against its desires, was forced instead to line the canals, which they did with some umbrage, and the locals bore a higher than typical fraction of the shared cost as a result of that.

The constant interaction between different groups who fight over turf, pride, and other issues to the detriment of public safety needs to be stopped. There needs to be some overall coordination. Levees in the New Orleans area are at different heights. You can stand—we have a photograph in our report at one section where you can clearly see five different elevations, all within 100 yards of each other. If you have five different elevations within 100 yards, the person who built the lowest section wins because they become the public hazard. There is a need to coordinate these things.

At a more global level, if someone is to be in charge, in all likelihood, it needs to be somebody very much like the Corps of Engineers, quite likely the Corps of Engineers. The Corps of Engineers needs to have the manpower and the technical expertise in terms of boots on the ground to get that job done.

Standing in the field, we saw sections which just didn't look entirely prudent. These weren't individual sections of a levee or of a wall, these were sections where a levee and a wall joined together and the joint didn't look right. Now, we had the benefit that nature had highlighted that for us by scouring around the edge so we could all see that there was a scour path, but we all thought, looking at them, maybe we would have foreseen the scour path had we been standing there before the hurricane. Hindsight is 20/20, but we think perhaps we would have noted that. It doesn't seem to us that people stood there and looked at that. There seems to have been a shortage of boots on the ground.

We are seeing design documents which are signed off and initialed and checked by just one individual and not by several, as would be customary, and we are seeing the Corps stretched very thin, trying to do the work to build and to complete the building of a very complex system, and it doesn't feel like the manpower and especially the technical expertise is entirely at the level we would like to see it at to get a job of this nature and this sensitivity accomplished.

Senator COLEMAN. Mr. van Heerden.

Mr. VAN HEERDEN. I met with Colonel Wagenaar last week, the District Engineer in New Orleans, and recognizing, as Professor Seed does, that perhaps they don't have all the technical expertise they need at this point in time, we offered from the University of Louisiana to help. We have got, obviously, a lot of engineering departments, geotechnical engineers, and so maybe as a beginning or a short gap or whatever, we suggest that the Corps of Engineers reach out to academia and try and capture some of the talents and expertise in the universities.

Senator COLEMAN. If I may, and this is just a comment, Madam Chairman, I served as Mayor of St. Paul, Minnesota. We are at the beginning of the navigable headwaters. The Mississippi starts there and is navigable right down to New Orleans. When I was Mayor, we had floodings that came very close to flooding situations. We have a major power plant on the Mississippi, and we were within a short level of major problems. I worked extensively with the Corps. We actually built a gate and a floodwall around one of the neighboring islands, which was the Corps really going outside of the way they usually operate so that citizens could use this island when there wasn't a problem with the flood, but you could close the gate and provide protection. They showed great flexibility.

But I really do appreciate two things that I have heard here, and one of which reminds me of what we heard in the post-September 11 hearings. Who is in charge? If you see a problem, how do you get it done? We are all listening to this and saying, we have heard this before, the kind of silo effect in government.

So I would just say thank you, one, for expressing the need to coordinate, and then the second piece, which we have heard before, too, is the need for government to reach out. Whether it is FEMA calling Wal-Mart and figuring out how to position supplies or the Corps working with academia and others, and we did that in our development, to take advantage of the talent that is out there. So it isn't necessarily just throwing more money. I am not against that where it is needed. But it is about how you use it efficiently and how decisions are made, and so I do appreciate your response.

Mr. SEED. Could I add a third piece to that, though, and that is something we saw with NASA and the Challenger and we see in other agencies. It is important that we don't just simply reach out to academia. The Corps, in streamlining its operations, is outsourcing an increasing fraction of its work in engineering and especially in geotechnical engineering. I should welcome that because, of course, I could do work for the Corps and I could get paid for it as opposed to doing these investigations where we are all volunteers and my wife is nuts. [Laughter.]

But against my own better judgment, I am going to tell you that, I think, the Corps of Engineers needs to have a very strong internal capability because what happened to NASA was they lost the ability to keep track of the outsourced engineering. You bring elegant people in from the outside. If you can't deal with them on a level playing field, you have a hard time checking what they are doing and problems can arise. It is important that the Corps have an internal capability which matches the problem, as well.

Senator COLEMAN. You have made that point quite clear today. Thank you.

Chairman COLLINS. Thank you, Senator Coleman. You brought up an incredibly important issue. Our full Committee investigation has already revealed that there was a great deal of confusion among the Army Corps, the Levee Board, the State Department of Transportation, and the Water and Sewer District on who was responsible for what, and that is an issue that we are going to be pursuing in a subsequent hearing because there is also evidence uncovered by our investigators that that confusion about who is responsible for what delayed the response when the levees failed, and it is incredibly important that we pursue that issue and focus not just on the specifications that are needed for the new, improved levee system, but also the organizational issues that will clearly designate an agency to be in charge. So I appreciate your raising that issue.

I do want to follow up on that issue with Dr. Nicholson because we have had a number of experts, including Dr. Seed today, who have suggested that the failure to have one department or agency with clear control and responsibility for the designing, the building, and the maintenance of the levees contributed to the damage from Hurricane Katrina. From your perspective, what would be some of the problems from a civil engineering standpoint associated with the lack of a comprehensive effort and with a lack of a clear role designating responsibilities?

Mr. NICHOLSON. I see that really as a two-part question, or two-part answer. Certainly, we observed in the field where you had different organizations in charge of the design, maintenance, and even the construction of certain parts of levees, where they came together, that was one of the transition problems we saw and——

Chairman COLLINS. If I could just interrupt you for a second, is that the issue with the transition points that both you and Dr. Seed referred to, where you have very different materials being used, where the seams don't seem to go together in a logical way once they are uncovered?

Mr. NICHOLSON. Well, certainly we find that each individual organization will do as they see fit, and when the two sections of the flood control system operated or owned, designed, and maintained by each of those different organizations come together, they may be in two different manners. They may have two different heights. They may be two different materials.

And so the transition from one to the next needs to be more continuous. We need to maintain or improve the connection between those two. If they are at different heights, if they are different materials, those are two of the big transition problems. As I showed in my last slide there, we have also got different organizations such as the railroads coming in with a very different purpose and aspect of what they believe is their greatest importance. They may not have in their mind the same, not just agenda, but the same comprehension of what their part of the responsibility is. And so that is a very difficult question or problem that we see.

How to answer that, as has been brought up, perhaps the solution would be to put one organization in charge and to oversee and essentially be responsible for that, and overseeing and essentially having authority over the other organizations.

Chairman COLLINS. Dr. Seed, do you agree with that?

Mr. SEED. Yes. The important analogy here is that building a levee system is like building a boat or building a Space Shuttle. You have a lot of pieces that have to fit together perfectly because if you have a flaw, you are going to lose the whole thing. It is not necessarily reasonable to think you can build 80-some-odd miles of levees in a ring if you have got a half-dozen or more different parties involved and if you do it in 143 individual projects. It is perhaps better to have an overall vision and one group responsible, like the captain of a ship, whose job it is to be sure that the ship is seaworthy before it sails.

Chairman COLLINS. Dr. Mlakar, what is your opinion on that?

Mr. MLAKAR. I think the results of our studies, I believe, ma'am, you began by saying we need to really investigate this thoroughly, and I think the final results will have some recommendations along those lines.

Chairman COLLINS. You are withholding judgment for now.

Dr. van Heerden, what do you think? Should we have one agency with clear, overall responsibility?

Mr. VAN HEERDEN. Madam Chairman, my comment is going to politically raise some hackles in Louisiana, but I believe there should be one Levee Board. It is a scale of efficiency. It is a scale of expertise. And it becomes a case of when you have all these different agencies, one hand doesn't know what the next hand is doing. So in my opinion, yes, we need one Levee Board, and they should be controlling all the levee systems, not a large number of levee boards, each funded in a different way, each appointed in a different way, in many cases, levee board members not being engineers or having experience in drainage or understanding some of the models.

Chairman COLLINS. Thank you.

Dr. Nicholson, just one final question. Dr. Seed raised the issue of possible malfeasance or corruption in the construction or the materials used for some of the levees as opposed to the specifications not being adequate, but of perhaps the case where the specifications were adequate but the contractor did not comply. Did you see any examples of the inferior materials being used in the levees as part of your review?

Mr. NICHOLSON. We don't have exact information to answer the first part of that question as far as what was specified or not used as specified. We did see what we considered to be inferior materials in some cases, perhaps, but that may well have been allowed in the specifications.

Chairman COLLINS. Could you give us an example of the inferior materials?

Mr. NICHOLSON. I think the best example of that was using sand and the so-called shell fill as embankment material, the highly erodible materials that may have been sufficient if you had not had any erosion, but as soon as you start that erosional process, they quickly disappear, and we saw wide evidence of large sections of the levees simply gone.

Chairman COLLINS. Thank you. Senator Lieberman.

Senator LIEBERMAN. Thanks, Madam Chairman. Thanks again. The panel has been really superb. I thank you for your public service and what you are doing in coming before us.

I want to take you to a different part of your investigations, which is to say the Committee has obviously focused on why the levees failed, but also, for various reasons, when the levees failed. Knowing when the levees failed will help give us some understanding of the specific period during the storm when the breaks happened and the different water levels and forces at work at that time.

Second, knowing when the levees were overcome or failed will help us understand when different parts of the city and the surrounding parishes began to flood and help us assess how and when the State, local, and Federal officials learned of these breaks and responded to them.

So if I could start with you, Dr. van Heerden, if you would please walk us through your best estimates this morning of when the various levees failed causing the flooding of New Orleans.

Mr. VAN HEERDEN. We set up something called our stop-clock program where we created a hotline for people to phone us when they returned to their homes to tell us the times on hand-face clocks, and working—this is now just preliminary data——

Senator LIEBERMAN. Right.

Mr. VAN HEERDEN [continuing]. But we started in the lower Ninth Ward. It appears that they started to flood from the East, in other words, from the area of the funnel, as early as 5 a.m., and by 6 a.m., it had reached Tennessee Street, which is very close to where the two big breaches occurred.

Senator LIEBERMAN. Right.

Mr. VAN HEERDEN. At 5 in the morning, there was—where the railroad crosses the Industrial Canal at Interstate 10, from the water level record in that area, we understand that the sandbags that they had used to seal the levees at the railroads blew out. That was, we believe, around 5 a.m.

In terms of the two large breaches on the Industrial Canal, apparently they occurred between 7:15 a.m. and 7:30 a.m., and that is just from testimony. We don't have the clocks here.

Senator LIEBERMAN. Right.

Mr. VAN HEERDEN. In terms of the London Avenue Canal, again, this is all very preliminary data, the Mirabeau breach, the one on the South, the one closest into the city, we believe occurred between 9 a.m. and 9:30 a.m. The one at Filmore Street, between 10 and 10:30 a.m. We have got a number of clocks at 10:15 a.m. And then at the 17th Street Canal, between 10 and 10:30 a.m. But this is very preliminary data. We are still getting lots of phone calls.

Senator LIEBERMAN. It is very significant because based on the data you have, the preliminary conclusions, the major levee failures had occurred by mid-morning on August 29 and the flooding, therefore, had begun. Part of what we are pursuing here is when—of course, it was a chaotic situation, very difficult in many ways to determine what was happening, but for various reasons, word did not apparently reach people at the top of the Federal Government until, by some estimates, Tuesday, and that may have affected, obviously, what the response would be.

Do any of the others of you on the—yes, Dr. Mlakar, do you have some conclusions about the time of the levees——

Mr. MLAKAR. We don't have conclusions yet, but we are looking into that issue, exactly when it did fail.

Senator LIEBERMAN. Yes.

Mr. MLAKAR. That is very important to understanding how and why it failed. Like Dr. van Heerden, we have been looking at clocks. We have got on the order of 50. You know, the clock might stop when it loses power, the clock might stop when it is flooded. There are some issues there that we have got to sort through.

We have talked to 70 eyewitnesses out of an identified group of 100—that is still growing—to get their recollections. As you can well imagine, we might have one person recall 8 a.m. and the person across the street is sure that it was still dry at 10 a.m., so we have got some issues in resolving the witness testimony.

And then finally, in addition to that, we have identified some security cameras that were operating that should have a very good field of view on what was happening, and we are in the process of acquiring their tapes.

Senator LIEBERMAN. Security cameras that were there for that reason, or just for reasons——

Mr. MLAKAR. For some other reason, perhaps a 7-Eleven, a bank, or whatever is just surveiling and you happened in the field of view to have an area that is eventually breached and flooded. So we are in the process of synthesizing all that information, and as part of this, we will be getting together with my colleague from LSU and combining their information with our information to give all of us the best estimate of when. And while we are primarily interested in that information for helping us understand the how and the why——

Senator LIEBERMAN. Because you will relate it to what the storm was doing at that point.

Mr. MLAKAR. Exactly. It will also be information useful for your slightly different purpose.

Senator LIEBERMAN. Absolutely. Dr. Seed and Dr. Nicholson, do you reach independent judgments about the times at which the levees broke?

Mr. SEED. We have been funneling our information in terms of witnesses' statements, and so on, to the other two groups because we lack the manpower and resources to really do a full processing of that. But the timelines described by Dr. van Heerden would make sense with the geotechnical observations we see in the field, and so they are consistent.

Mr. NICHOLSON. I would have to agree with that, as well.

Senator LIEBERMAN. Thank you all. Thanks, Madam Chairman.

Chairman COLLINS. Thank you. Senator Coleman.

Senator COLEMAN. Thanks, Madam Chairman. Just a couple of other areas of inquiry.

Mr. Seed, you have talked a lot about NASA and the comparisons to NASA. One of the things that you have in the NASA program is you have redundancies, and levees don't appear to have redundancies, though I am wondering, and perhaps you can educate me on this, what are the redundancy options, doable options? Is it wetlands? Is it barriers? Is that what one would call a redundancy? This investment, I keep coming back to the cost issue, the former mayor in me. I guess I am going through the protection about Category 3 versus Category 5. Does the existence of redundancies, does that move something from a Category 3 to a Category 5 or does it just strengthen the ability to withstand a Category 3? Help me understand this redundancy issue.

Mr. SEED. Not necessarily. Redundancy is hugely expensive in the context of levees. The only really thorough redundant system in the world is that of Holland, which in the mid-1950s the entire Nation was flooded by a North Sea storm, and so they have tremendous incentive, literally the entire country was flooded. They operate in polders, which are essentially like the containment compartments in a ship, so that if their exterior coastal defense is breached, you flood only a section and then you hit a second levee. And so they have defense in depth. But if that is the single leading issue for your nation, you can put a large fraction of your national resources into that.

I don't think we can get a large fraction of our national resources into the New Orleans levees in the next week or two. I don't think that is going to happen. So redundancy is very expensive. More likely, we are going to have to build levees which are vastly more secure. In California, we have a few places where we have sacrificial islands. We have things that are designed to fail like a fuse in an electrical system, which will reduce water levels and take water levels down. So there are a lot of options we can look at there, but by and large, in the New Orleans area, given the geometries, redundancy would be very difficult to achieve.

Senator COLEMAN. Do you other gentlemen want to comment on that issue?

Mr. VAN HEERDEN. Only that restoring the wetlands would, in essence, act in a small way as a second barrier.

Senator COLEMAN. Let me just touch on two other points. One, is there—and this may not be for your panel, but I am interested, are any lessons to be learned here about the relationship between FEMA and the Corps? Is there anything anybody wants to comment on regarding FEMA and the Corps in terms of interaction, communication, efficiency of what one does helping the other, or perhaps hindering the other?

Mr. SEED. Two separate operations, in our view, speaking for our team, the Corps' job is to prevent these things from happening in the first place and then to fix them afterwards, and FEMA does the middle piece, which is the emergency.

Senator COLEMAN. Is there a notification piece, though? What I am hearing, clearly, the Corps has a question about timing or has a part in saying, hey, we have a problem. And again, this may not be your area of expertise, but at a certain point, knowing there is a problem and then being able to respond, I think there would be some issues there.

Mr. SEED. Well, I guess the heart of the issue we discussed earlier, if the lines of responsibility and who is in charge aren't clear, it is very hard to decide who needs to be issuing warnings and public notices, and the Corps' policy is to build these systems and then turn them over to locals. They don't remain the proprietors forever. So there are some difficult issues there.

The turning over is also problematic. California has a great many Corps-built levees which are now turned over to locals who then have deep pockets liability for these kinds of things. You, of course, can't sue the Corps of Engineers as a Federal agency. They have tremendous immunity for water-related and safety-related projects. So when they get turned over to the locals, the locals aren't necessarily all that pleased to be getting them because they acquire the liability, whereas while the Corps operates them, they are a little bit protected.

Senator COLEMAN. And they acquire the maintenance responsibility, also.

Mr. SEED. They do, but it is the liability which is crushing. So there are some issues as to how levees happen in the United States. I am hoping that all this will trigger an investigation at a more global level of where levees are, what the conditions of levees are, and more fundamentally, how levees happen, how they are designed and built, how they are constructed and maintained, and how people allow decisions with regard to who lives where and who lives above sea level and the levels of protection and so on. It is a huge, festering national issue which has been off the radar screen.

As my wife likes to tell me, levees are currently sexy for maybe a month or two, but by and large, when these disasters aren't hitting, levees are just big piles of dirt. They are not all that attractive. They don't get much attention.

Mr. MLAKAR. Sir, I believe your question was about the relationship between FEMA and the Corps. We certainly appreciate your interest in that, but I think you are right. There are probably others in the Corps that are much more qualified to speak to that than I.

Senator COLEMAN. Let me just say, Madam Chairman, you raised the issue about inferior materials, malfeasance, corruption, and I just want to say, I think we really have to look into that. I was in Armenia not too long ago, and things are falling apart there because everything was built with, like, 15 percent less rebar because it went into the pockets of someone. That is corruption on a clear level.

And we hear a lot of murmuring, and maybe folks don't want to talk about it, we hear murmuring about New Orleans, Louisiana has had a history of corruption in public officials. It has happened. I don't want to offend anybody, so I think we have to get beyond the murmuring and take a very close look, a very earnest look. Is that an issue? Contractors, were they not putting in the materials they were supposed to? And again, we don't have the answers. We clearly saw inferior materials. But I think we have to have the courage to take a look at that and not to point a finger or to offend, but to say we have an obligation to make sure that what was done was done right.

Thank you, Madam Chairman.

Chairman COLLINS. Thank you. Senator Akaka.

Senator AKAKA. Thank you very much, Madam Chairman.

Let me ask this fast question before I ask my last one, and this is to Dr. Seed. You stated that throwing money at the Corps will not solve the problem, but you also said that the Corps is lacking staff, or the quote is "boots on the ground." To clarify, is there a way to fix the staffing issue without additional funding, in your opinion?

Mr. SEED. No. My comment was intended in the other direction. I don't think simply putting additional funding in guarantees you are getting good boots on the ground. You can spend that money in other ways. I am hoping that there is some oversight capability, and I am hoping that if funding is injected, there will be some reorganization and some rebuilding of some of the engineering expertise, which was formerly very impressive in those areas of endeavor.

Senator AKAKA. My final wrap-up question, Madam Chairman, is for Dr. Nicholson and Dr. Seed. You both made specific recommendations for what can be done to improve the New Orleans levee system in the future, and I want to open this question also to the two other witnesses. Which recommendations can be implemented in the short term and are relatively inexpensive, and which recommendations require more time and resources to implement? Also, if you care to respond, which measures the Corps of Engineers should have implemented prior to Katrina. Dr. Seed.

Mr. SEED. Those are three different questions. I guess I am inferring a third one there. The things that can be done quickly aren't necessarily the ones that need to be done as quickly. There is an urgency to some of them, and the third one is the easiest question.

The Corps of Engineers were given operating instructions. They were given orders. They were authorized for certain things, and they strove to fulfill those specifications. It would be good if their instructions were more flexible. It wasn't their job to do the kinds of things that we see that could have been done better. That wasn't part of their task. It wasn't their assignment. So it is a little bit unfair to do finger-pointing because something was omitted. More troubling are the three canal failures, which appear to be foundation issues. That will be a tougher issue.

What can be done quickly, you can get yourself more protection by installing splash pads on the inboard faces of a lot of the floodwalls. That would be a very inexpensive and rapidly implementable fix.

Some things are much harder than that, but they are more urgent. Getting the MRGO levee segment back up and operating is hugely vital. That was the back door. It is across 15 miles of swamp from the developed areas, but the water came across that swamp, and it didn't even slow down. It was not interested in doing so. And so the Ninth Ward and the St. Bernard Parish were essentially toast from the first time that flood hit. Getting those levees rebuilt is hugely urgent and very difficult to do in a timely manner.

At a more global level, if the system is going to work, putting somebody in charge is important. It is not very expensive to put somebody in charge necessarily, but it is going to take some time to achieve that because you are going to have to enact legislation and take some level of control, probably at a Federal level.

And finally, if the Corps of Engineers is going to be that someone, and they would appear to be the only suitable candidate, the Corps of Engineers is also going to have to do some restructuring and some rebuilding of some of its capabilities, and that will not be a short-term issue. It is much easier to whittle down an organization than it is to rebuild it. You can do a lot of damage in 3 or 4 years that might take a decade or longer to repair.

Senator AKAKA. Dr. Nicholson.

Mr. NICHOLSON. I would agree with much of what Dr. Seed said as far as overtopping protection and getting the MRGO length of levee restored, as that is the front line of protection for much of that area. Certainly the whole St. Bernard Parish area took that as their—or lost that front line of protection.

But to go a little step further, for quick and inexpensive, those are very difficult things. Those two options are maybe the two that would be quick and inexpensive. But at the next level, and this may not be quick and not all that inexpensive, would be, as I think we both agreed earlier, would be the enactment of a National Levee Safety Program which would oversee New Orleans at about the same cost, and I believe that is about $10 million a year for those two programs, to have a levee protection program in New Orleans, as well as in California. It would help to get more attention paid to those vital infrastructure elements.

Mr. SEED. And not just New Orleans and California. We have levees in a lot of places. Most States have levees. We have massive levee systems up and down the Mississippi and Ohio Valleys. We have levees in the Charleston area. So I would hope it is something which would have some national interest at this point.

Mr. NICHOLSON. I should say, even Hawaii has a small section of levees.

Senator AKAKA. Dr. Mlakar.

Mr. MLAKAR. Yes, thank you. Rather than speculate as we are just getting into this of what we need to do in the short- and the long-term, I would like to answer your question by reiterating the Corps' commitment here in a thoroughly open and transparent manner to getting to the answers and finding out the how and the why it happened, and then I think the answers to your questions will be clear.

Senator AKAKA. Dr. van Heerden.

Mr. VAN HEERDEN. I have two comments. One is the academics of how the soil failure actually occurred don't detract from the fact that we had soil failure and you can very visually see those levee systems slid many tens of feet. So what I would ask is that we identify other areas in our levee systems that perhaps didn't fail or could have failed where we have similar soil conditions and perhaps come in and drive a secondary line of sheetpile down to 50, 60, 70 feet, whatever the case may be, to create that barrier to stop the seepage.

The second thing is, and very important to Louisiana, some of our parishes, some of the levee boards do not have a very strong or robust economic base in which to get funds. Just as the Federal Government took over the building of the levees after the 1927 flood on the Mississippi, and they paid for them and built them, perhaps this is a time in terms of some of our jeweled cities like

New Orleans for the Federal Government to offer the same level of support and come in and build the levees without us having to rely on the limited incomes of some of these parishes and levee boards in Louisiana.

Senator AKAKA. Thank you very much, Madam Chairman.

Chairman COLLINS. Thank you.

I want to thank all of our witnesses today for truly excellent testimony. Your testimony and statements have been extremely helpful to us as the Committee continues its investigation into the preparation for and response to Hurricane Katrina. It is absolutely critical that we get a better understanding of why the levee system failed and you have helped us to do so today.

I want to assure you that your full statements and any additional material that you may wish to submit will be included in the hearing record. In addition, Members of the Committee may have some additional written questions which we will be submitting to you. I very much appreciate the efforts that all of you made to be here today.

The hearing record will remain open for 15 days. I want to also thank our staff for their hard work on this investigation.

Senator Lieberman.

Senator LIEBERMAN. Thanks, Madam Chairman. Very briefly, I join in the thanks. It strikes me, as I have listened to you this morning and read your papers, that you are men of science and you speak in technical terms and very reasoned tones, but the testimony that you have given really cries out to us to act decisively. And if I might add, generously in terms of support for the Army Corps, to make sure that nothing like this ever happens again because you do deepen, in your testimony and your investigation, you deepen the tragedy of Hurricane Katrina and the failure associated with it because you now tell us that not only was it a failure of governmental preparation and response to the flood, but the flood itself could have been significantly prevented had the design and construction of the levees been what they should have been.

I would ask you this as you go forward in continuing your work. It may be that what you find not only helps us understand what happened, but as you have suggested a few times today, you may also come across some indications of, for want of a better term, what I would call a ticking time bomb, some other vulnerability, as I think you said at the end, Dr. van Heerden, that didn't fail this time but might again. And, we want to work together to make sure that it doesn't next time.

But I know most of you are working with, talk about not much resources, a lot of you are giving your own time, and this is an enormously important contribution you are making that only people of your experience and expertise can make, so thank you very much.

Chairman COLLINS. Thank you. This hearing is now adjourned.

[Whereupon, at 12:19 p.m., the Committee was adjourned.]

APPENDIX

FAILURE OF LEVEE SYSTEMS SURROUNDING GREATER NEW ORLEANS DURING HURRICANE KATRINA.- PRELIMINARY ASSESSMENT

Committee on Homeland Security and Governmental Affairs - U.S. Senate

Written Testimony, Ivor Ll. van Heerden, Ph.D.
Head, State of Louisiana Forensic Data Gathering Team
Director, Center for the Study of Public Health Impacts of Hurricanes
Deputy Director, LSU Hurricane Center
Louisiana State University
Baton Rouge, LA 70803

2nd November 2005

Abstract
Hurricane Katrina made landfall in Louisiana at 6:10 am on Monday 29th of August, 2005. After the storm 85 % of greater New Orleans was flooded, and about 1000 persons had lost their lives and approximately 100,000 families were homeless, being mostly families that had heeded the evacuation orders. The hurricane protection system that all residents of New Orleans depended upon; their security from surge floods; had failed catastrophically with over twenty breachings or breaks.

The flooding of New Orleans represents two separate flooding events, distinct in time, space and intensity. In eastern New Orleans levee failure accompanied a surge overtopping event, flooding surrounding communities; in western New Orleans catastrophic levee failure caused the flooding. Preliminary findings by the State of Louisiana Forensic Data Gathering Team are that in the case of the 17th Street Canal, London Ave Canal and the Industrial Canal, levee collapse and flood breaching reflected unstable soil conditions and a lack of foundation support and water percolation seals, given the soft, porous and highly organic nature of the soils. In the case of the Industrial Canal, levee overtopping may have hastened the structure's collapse.

ADCIRC Storm Surge Modeling
The Hurricane Public Health Research Center at LSU has developed an operational version of the ADCIRC storm surge model that has been in use since 2002 in support of hurricane emergencies. Basically, we take an official advisory from the National Hurricane Center and then convert that meteorological data via a super computer and the necessary numerical computational code into a graphic that represents the expected surge for that particular advisory. Each surge model run takes 5-7 hours to complete from the time of the National Hurricane Center advisory is posted on the Internet till the time we put our output on the Internet (www.hurricanne.lsu.edu/floodprediction/). Our output is sent to a large listserve consisting of emergency management officials from Federal, State, and local government, NGO's and the media. The same product is sent to the Louisiana State University (LSU) staff at the State Emergency Operations Center (EOC) in Baton Rouge where all officials are briefed on the latest surge model outputs. At 10:00

pm on Saturday 28th August 2005, 32 hours before landfall, we put out an email and warned that New Orleans would flood as the surge would overtop the levee system especially in Orleans East and St Bernard Parish. We warned that we expected levee erosion. We also reminded the emergency managers assembled at the State EOC that during Hurricane Betsy (1965) the Industrial Canal had been breached and that if we lost levees the flooding would be far more severe than the model depicted.

The ADCIRC model is an ideal forensic tool as it allows us to hindcast the actual surge conditions for any hurricane at any point in the study area and can generate a hydrograph – a graph of how the water level changed with time during the surge event.

Nature of the Surge Event

The surge due to Hurricane Katrina consisted of two distinct flooding events, separated in time, space and intensity. East of the track the surge of 15-18 feet above sea level reflected that caused by the winds of a Category three or four storm (120 mph). West of the eye and especially over Lake Pontchartrain the maximum surge was 10-11 feet and winds those of a Category 1 storm (72-76 mph). The surge on the east side rose much quicker and peaked before that on Lake Pontchartrain. We have been collecting data from stopped hand dial clocks in order to determine just when each levee section failed. While the 'stopped clock' data is still preliminary we will present some of the times.

General "I" Wall Levee Design

The "I" wall levees consist of linked steel pilings approximately 18 inches wide hammered into the ground to a set depth and then a concrete wall (monolith) is built over the upper few feet of the steel pilings. Reinforcing bars are passed through holes in the sheet piling and then cemented into the monolith structure. At least one contractor complained the structure was not stable due to the soft soils.

The 17th Street Canal Breachings

The original canal was dredged in the 1890's and the material excavated from the canal placed along the banks. The "I" walls that failed were built in the early 1990's. At the time of construction the original sheet piling was driven down into the ground. Shortly thereafter, because off an approaching storm, the pilings were all pulled out back up to their original elevations. Once the storm threat was over the pilings were then pushed back into the soft soil. These actions of push, pull, and then push greatly weakened the soils. Based on the design memorandum that we found in the files of the Louisiana Department of Transportation and Development, the pilings at the breach extended to a depth of 10 feet below sea level. At or around the time the pilings were being resunk the canal was dredged to a depth of 18.5 feet below sea level. Thus there was a linear depth of 8.5 feet of canal that was not "blocked" by sheet piling allowing the potential of a lateral flow of water under the pilings from the canal. According to local residents, their back yards adjacent to the canal were at times quite wet even when there had been no rains, suggestive of a canal seep, i.e. water making its way from the canal via seeps into their yards – a sign of trouble to come?.

The 17th Street breach occurred at approximately 10:15 am on the 29th August, 2005, one hour after the peak of the surge when the water level was about 9 feet above sea level. During Katrina a 200 foot section of the levee slid sideways 35 feet in a classical example of a lateral slide failure – a pressure burst. Adjacent to this slide the levee wall segments, that were not interlocked, were flattened by the flow, a number seemingly shearing off their piling foundations. A lateral slide of this nature with some rotation of the levee wall segments during the slide occurs because of foundation failure. A 200 linear foot length of levee slide is indicative of catastrophic structural failure. The backyards of residents adjacent to the levee were heaved up and a former flat terrain was now made up of hummocky dunes – homes, cars and buildings were all heaved up into strange skewed juncture positions by the 'bull dozing' of the levee slide.

The levee at the breach was built on top of a highly organic marsh and peat with soft clays – a very porous and weak medium. This highly organic soil was used to create the levee embankment when the canal was originally excavated. A sand layer is present 30 feet below the surface. Once this former swamp was drained for development, the organic matter in these originally flooded soils would have decomposed rather rapidly due to exposure to the air (oxygen) and would have lost some of their strength as well as becoming more porous. Potential conduits for water percolation from the canal between the bottom of the pilings and the canal floor, under pressure of the Katrina surge, would have been via the porous and weak soil embankment; the peat old marsh layer; and even the deeper lying sands. Our preliminary finding is that this canal levee "I" wall design in these very weak soils and substratum, was an accident waiting to happen. At the very least the sheet piling should have been sunk to 60 feet below sea level.

London Ave (West) Filmore Breach

The "I" wall design of the levee at this breaching is basically the same as that at the 17th Street Canal site. The steel pilings appear to have extended to about 11.4 feet below sea level. Once again the canal floor was substantially deeper than the piling being 18-19 feet below sea level. The levee breach is a smaller version of what happened on the 17th Street Canal, there was a lateral slide of the levee embankment and "I" wall and a heave of the back yards of local residents adjacent to the heave. The wall segments on either side of the slide collapsed downwards with the flow. Because the underlying substrate consisted predominately of old beach sands, an enormous amount of sand was carried by the flood into the subdivision at the breach.

The levee at the breach was built on top of a highly organic marsh and peat – a very porous and weak medium. This highly organic soil is believed to have been used to create the levee embankment when the canal was originally excavated. A 50 foot thick sand layer is present 10 feet below the surface. These sands are very porous. Once this former swamp was drained for development, the originally flooded organic soils would have decomposed rather rapidly due to exposure to the air (oxygen) and would have lost some of their strength as well as becoming more porous. The sand layer appears to have been exposed on the floor of the canal after it was dredged around 1990. Potential conduits for water percolation from the canal between the bottom of the pilings and the canal floor, under pressure of the Katrina surge, would have been via the porous and weak soil embankment; the peat old marsh layer; and especially the deeper lying sands. Sand boils and even blowouts through the substrate under the sheetpile will explain most of the sand in the adjacent residents' back yards. Our preliminary finding is that this canal levee "I" wall design in these very weak soils and substratum, was an accident waiting to happen. At the very least the sheet piling should have been sunk to 80 feet below sea level.

The east bank levee of the London Ave canal at Filmore is bowed, tilted back and cracked in a number of places. There is evidence of sand boils, heaves, and other signs of soil instability. The question could be asked why the walls did not fail at this point? It appears that the sheet piling was sunk to a depth of 26 feet on the east side of the canal at Filmore as against the 11.4 feet where the west breach occurred. This relative difference in sheet piling depth may indicate why the east side at Filmore did not fail, but nevertheless even sheet piling to a depth of 26 feet below sea level was not sufficient.

London Ave (East) Mirabeau Breach

The "I" wall design of the levee at this breaching is basically the same as that at the 17th Street canal breaching. The steel pilings appear to have extended to about 26 feet below sea level. The levee breach is similar to that of Filmore except the extent of any heave is unknown. Because the underlying substrate consisted predominately of old beach sands, an enormous amount of sand was carried by the flood into the subdivision at the breach.

The levee at the breach was built on top of a highly organic marsh and peat – a very porous and weak medium. This highly organic soil is believed to have been used to create the levee embankment when the canal was originally excavated. A 50 foot thick sand layer, very porous, is present 10 feet below the surface. Once this former swamp was drained for development, the originally flooded organic soils would have decomposed rather rapidly due to exposure to the air (oxygen) and would have lost some of their strength as well as becoming more porous. The sand layer appears to have been exposed on the floor of the canal after it was dredged around 1990. The main conduit for water percolation from the canal under these 26 foot deep pilings, due to the pressure of the Katrina surge, would have been via the beach sands. The walls segments all sag and dip down towards the center of the breach. Those in the center appear to have collapsed outwards. The sagging and dropping (lowering) of the wall segments as one approaches the center of the breach suggests that there was a blowout due to water under pressure escaping from the canal below and under the pilings using the porous sand layer as the pathway. The blowout and subsequent loss of sand substrate would create a void that the wall segments would then collapse into and in this way the structural integrity of the "I" wall segments was destroyed. The huge amounts of clean white sand to be found in the subdivision adjacent to the breach attest to this failure mode. So even though the sheet piling was deeper than at the Filmore West breach, it was still not deep enough. Thus it can be considered that the bowed and tipping wall segments, with sand boils and small heaves on the east bank opposite from the Filmore breach, are indicate of an earlier stage of the Mirabeau breach. If it had not failed at Mirabeau it would have failed at Filmore on the east side. Again this explains most of the sand in the adjacent residents' back yards.

Our preliminary finding is that this canal levee "I" wall design in these very weak soils and substratum, was an accident waiting to happen. At the very least the sheet piling should have been sunk to 80 feet below sea level.

Industrial Canal Breachings

The "I" wall design of the levee at this breaching is basically the same as that at the 17th Street canal breaching. The steel pilings appear to have extended to about 10 feet below sea level. The canal is much deeper than 10 feet below sea level. There are two major breachings on the Industrial Canal south of its junction with the Gulf Intra Coastal Waterway. The breachings appear to have occurred before the peak of the surge when the water level was at the top of the levee wall (7:15 am).

On first inspection, because of the scour trench (generally 3x4 feet) behind the levee wall (landward side), one can assume that the failure was due to the scour trench excavating its way down to the base on the pilings and then the whole system failed catastrophically due to the pressure of the water. However, if one inspects the wall segments between the two breaches, the scour trench seems to be fairly uniform in size but one sees that the levee wall has two areas with very distinct bows and the walls are tilted backwards - features similar to the London canal on its east side at Filmore. Inspection of the soil embankment on the canal side of these bowed sections reveals that the soil is highly cracked, that long wide sections of soil have slipped down about 12 – 18 inches and there is evidence of 'down percolation holes'. These are scour-like structures created when the water under pressure moves down the cracks and eventually finds its way under the piling and starts to scour a passageway leading to sand boils which then sets the stage for a failure.

The levee at the breaches was built on top of a 10-foot thick highly organic marsh and peat with very soft clays – a very porous and weak medium. This highly organic very soft clay soil is what was used to create the levee embankment when the canal was originally excavated. A layer of very soft to soft clays with silt and sand lenses is present 15 feet below the surface. Once this former swamp was drained for development, the originally flooded organic soils would have decomposed rather rapidly due to exposure to the air (oxygen) and would have lost some of their strength as well as becoming more porous. Potential conduits for water percolation from the canal between the bottom of the pilings and the canal floor, under pressure of the Katrina surge, would have been via the porous and weak soil embankment; the peat old marsh layer; and even the deeper lying clays with porous sand and silt lenses. The down percolation holes created due to the tilting of the walls under pressure of the surge would also have weakened the levee system. It is very important to note that the soil borings all indicate very soft or soft clays, not ideal foundation material.

While the ADCIRC data indicate the failure of these Industrial canal levees occurred at the time overtopping had just started to occur; overtopping would have helped to weaken the soil embankment behind the levees. Just why the levees failed exactly where they did is still a question to be answered, but the failure of the Industrial Canal levees is indicative that this canal levee "I" wall design in these very weak soils and substratum, was an accident waiting to happen. At the very least the sheet piling should have been sunk to 70 feet below sea level.

Conclusions

While Hurricane Katrina was a major hurricane, our preliminary findings are that failure of the 17th Street and London Ave canal levees was due to a design that did not account for the very weak nature of the soils. The design criteria of these levees was not exceeded. The design also did not take into account the very high porosity and permeability of these soils. It was a geotechnical engineering failure.

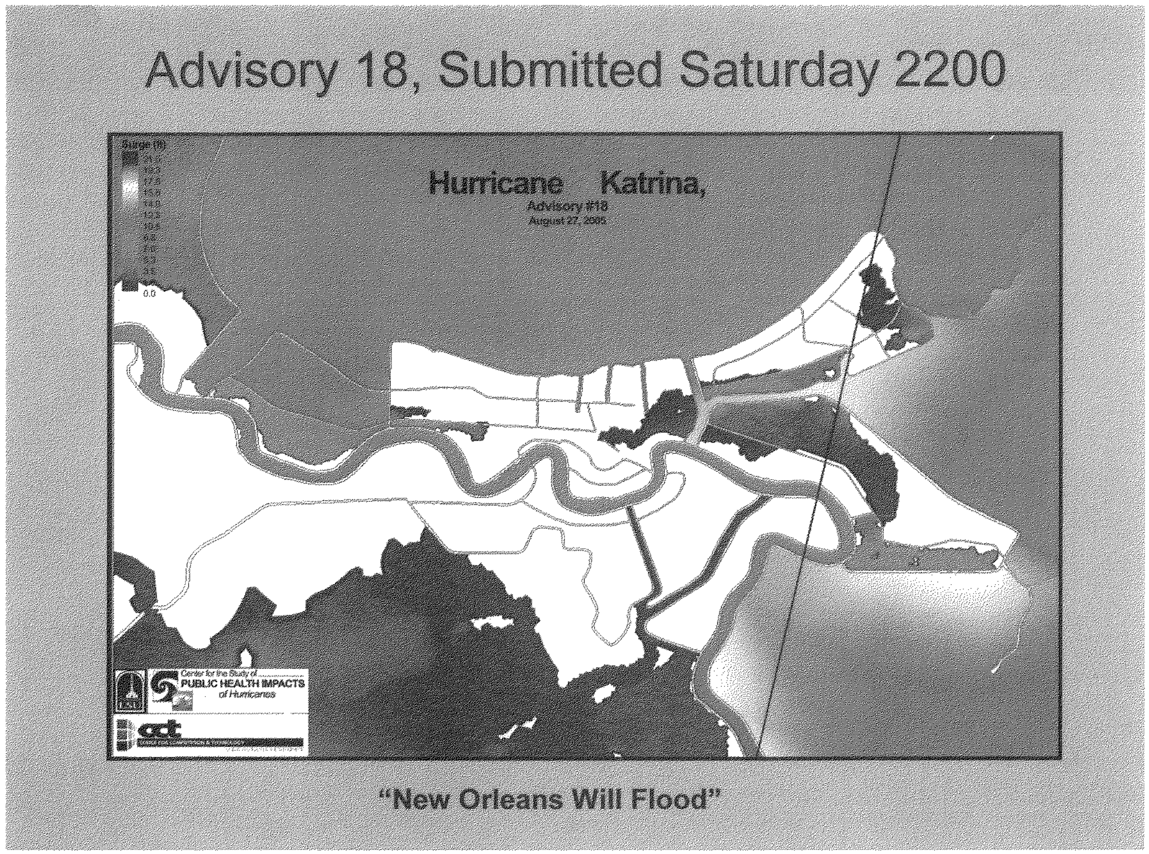
The same conclusion can be made for the Industrial Canal levees that failed during Katrina, although surge overtopping no doubt enhanced their collapse.

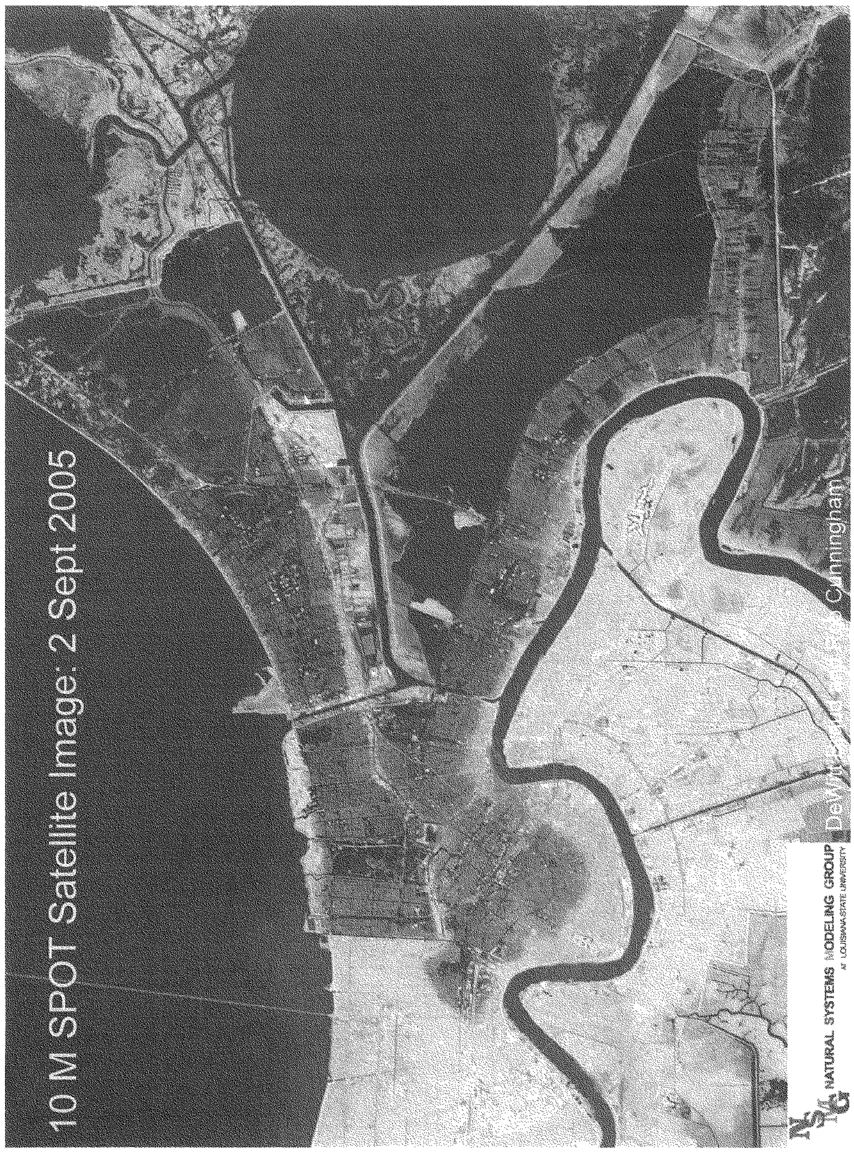
Most of the flooding of New Orleans was due to man's follies. Society owes those who lost their lives, and the approximately 100,000 families who lost all, an apology and needs to step up to the plate and rebuild their homes, and compensate for their lost means of employment. New Orleans is one of our nations jeweled cities. Not to have given the residents the security of proper levees is inexcusable.

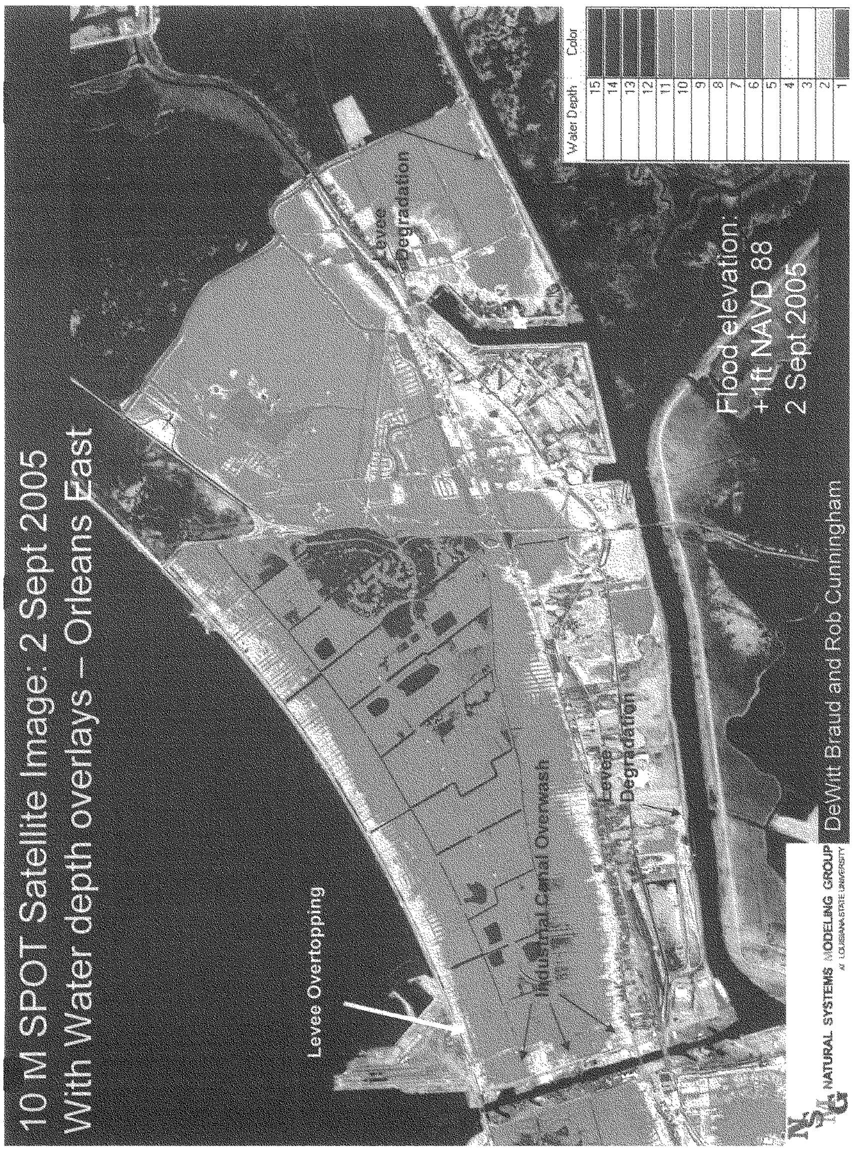
Preliminary Data – Hurricane Katrina Canal Breachings, 17th Street, London Avenue and Industrial Canal

Dr. Ivor van Heerden
Director Center for the Study of Public Health Impacts of Hurricanes, Deputy Director
LSU Hurricane Center
Louisiana State University

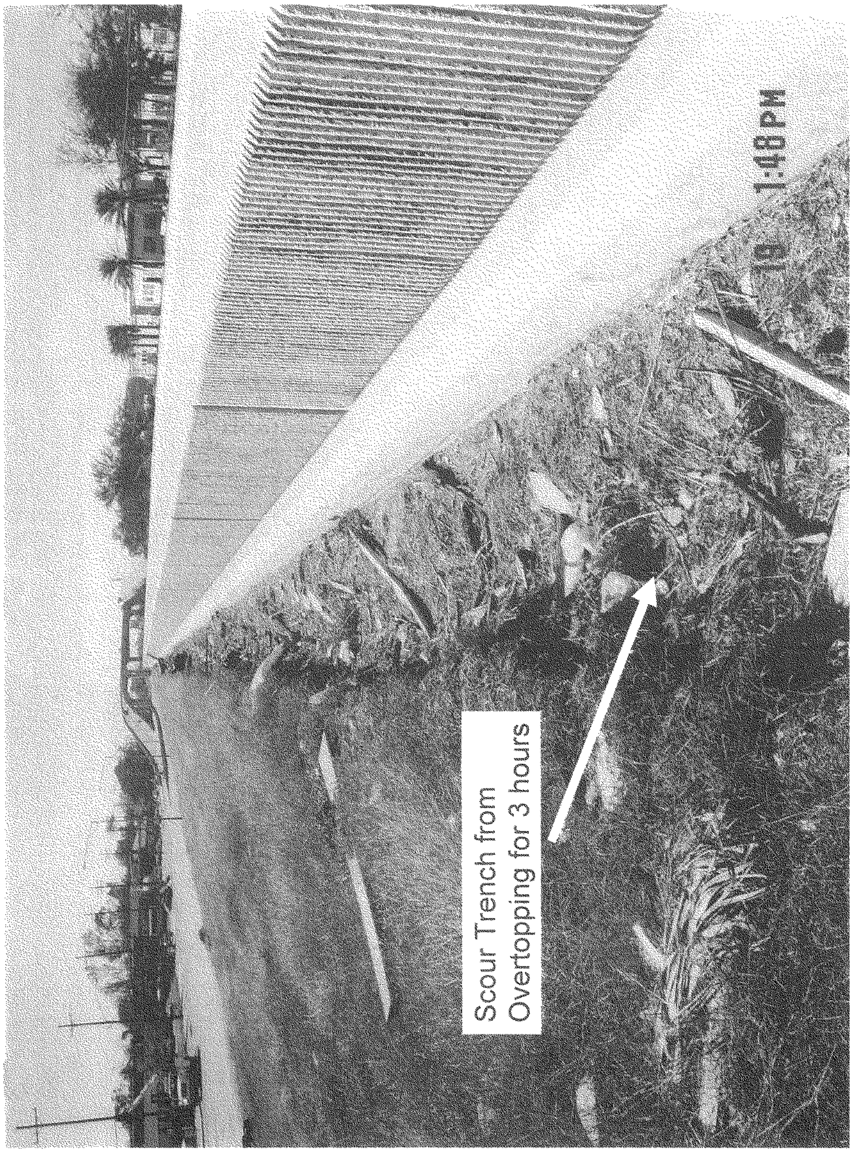
Center for the Study of
PUBLIC HEALTH IMPACTS
of Hurricanes

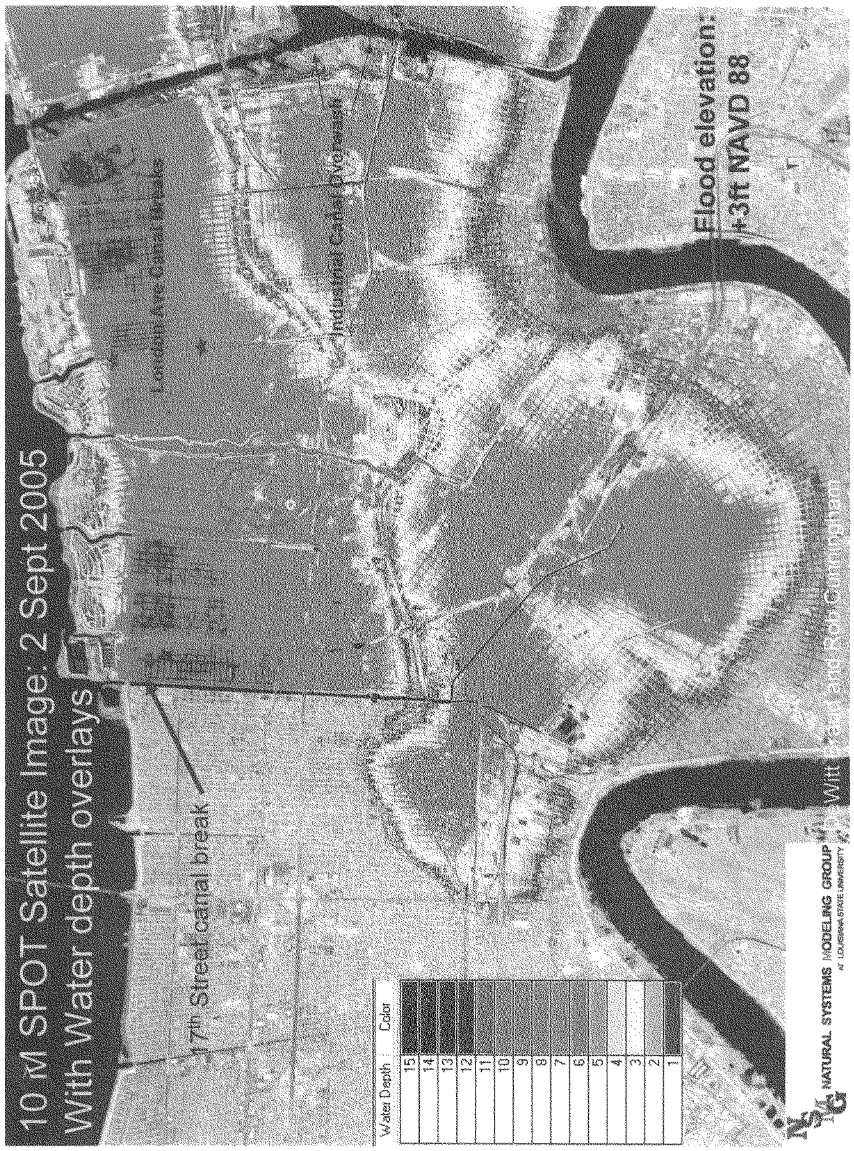

Advisory 18, Submitted Saturday 2200
Hurricane Katrina,
Advisory #18
August 27, 2005
Surge (ft)
0.0
Center for the Study of
PUBLIC HEALTH IMPACTS
of Hurricanes
"New Orleans Will Flood"

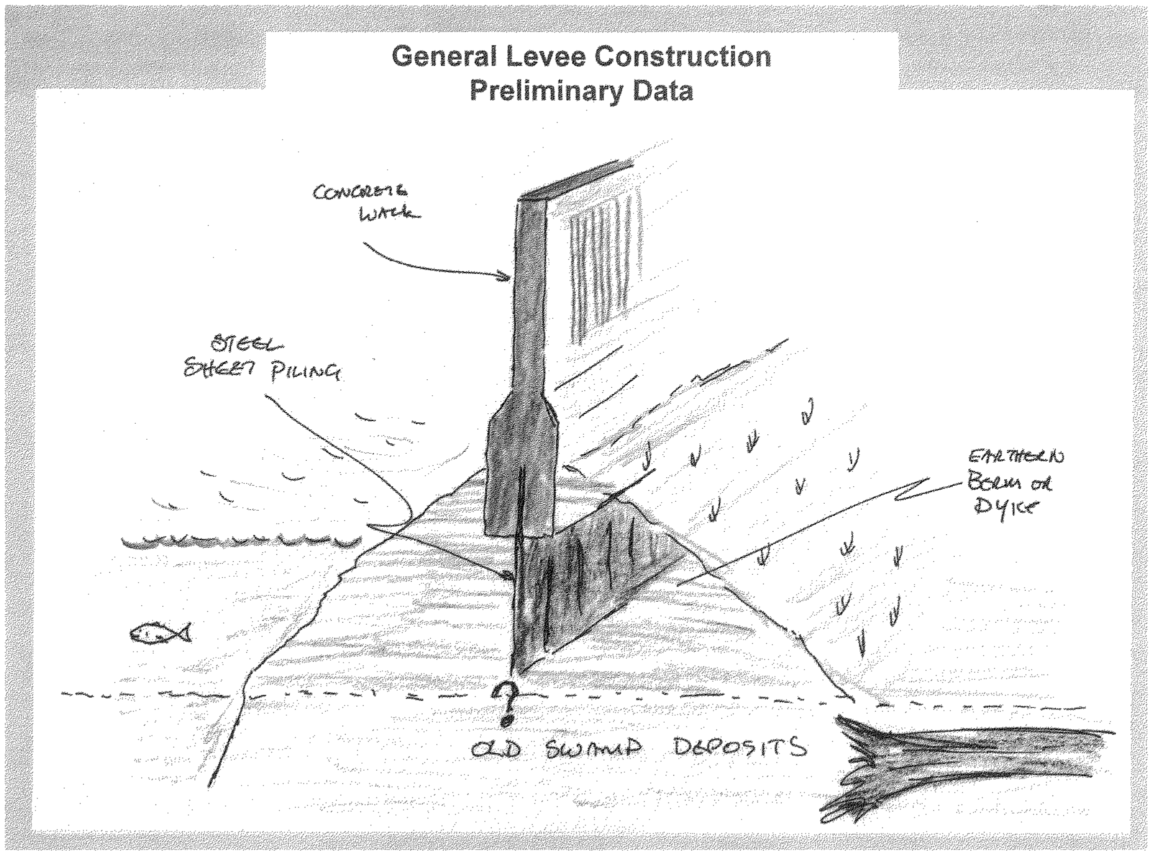

10 M SPOT Satellite Image: 2 Sept 2005
NATURAL SYSTEMS MODELING GROUP

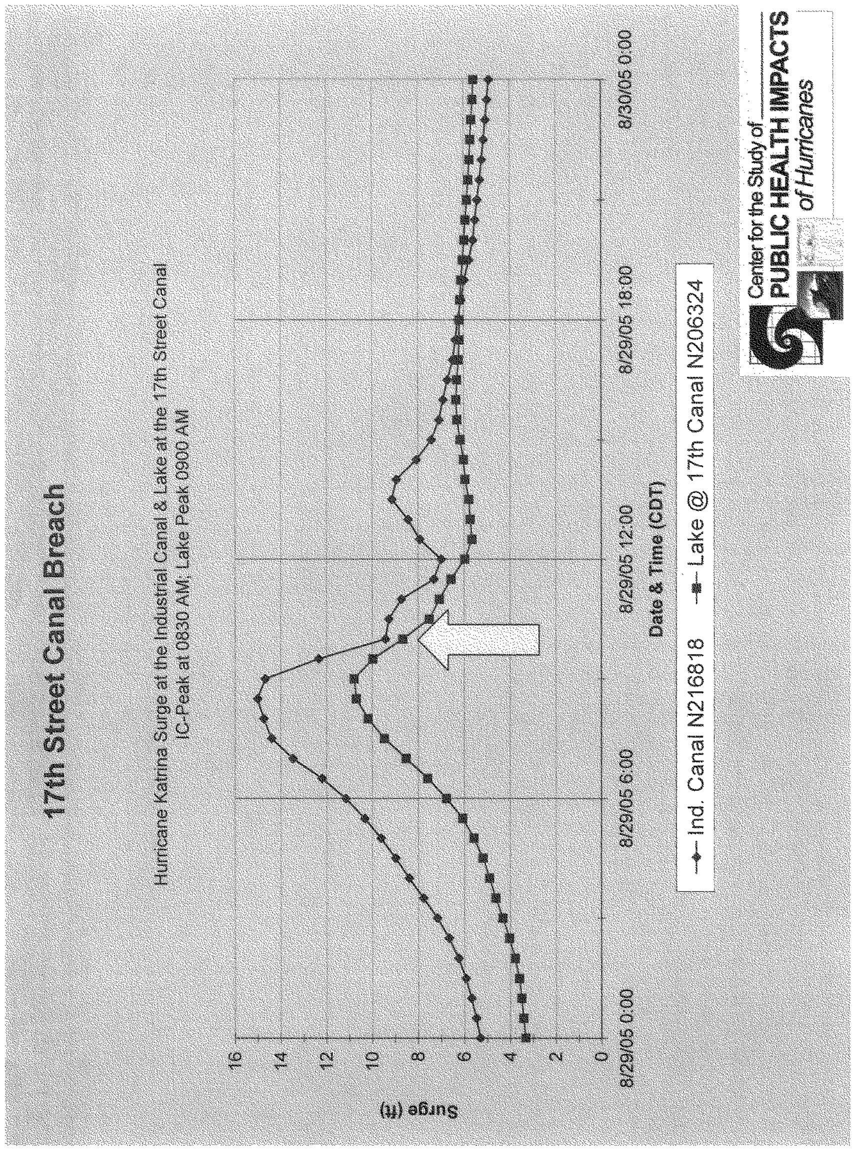

10 M SPOT Satellite Image: 2 Sept 2005
With Water depth overlays – Orleans East
Levee Overtopping
Industrial Canal Overwash
Levee Degradation
Levee Degradation
Flood elevation:
+1ft NAVD 88
2 Sept 2005
Water Depth
Color
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
NATURAL SYSTEMS MODELING GROUP
AT LOUISIANA STATE UNIVERSITY
DeWitt Braud and Rob Cunningham

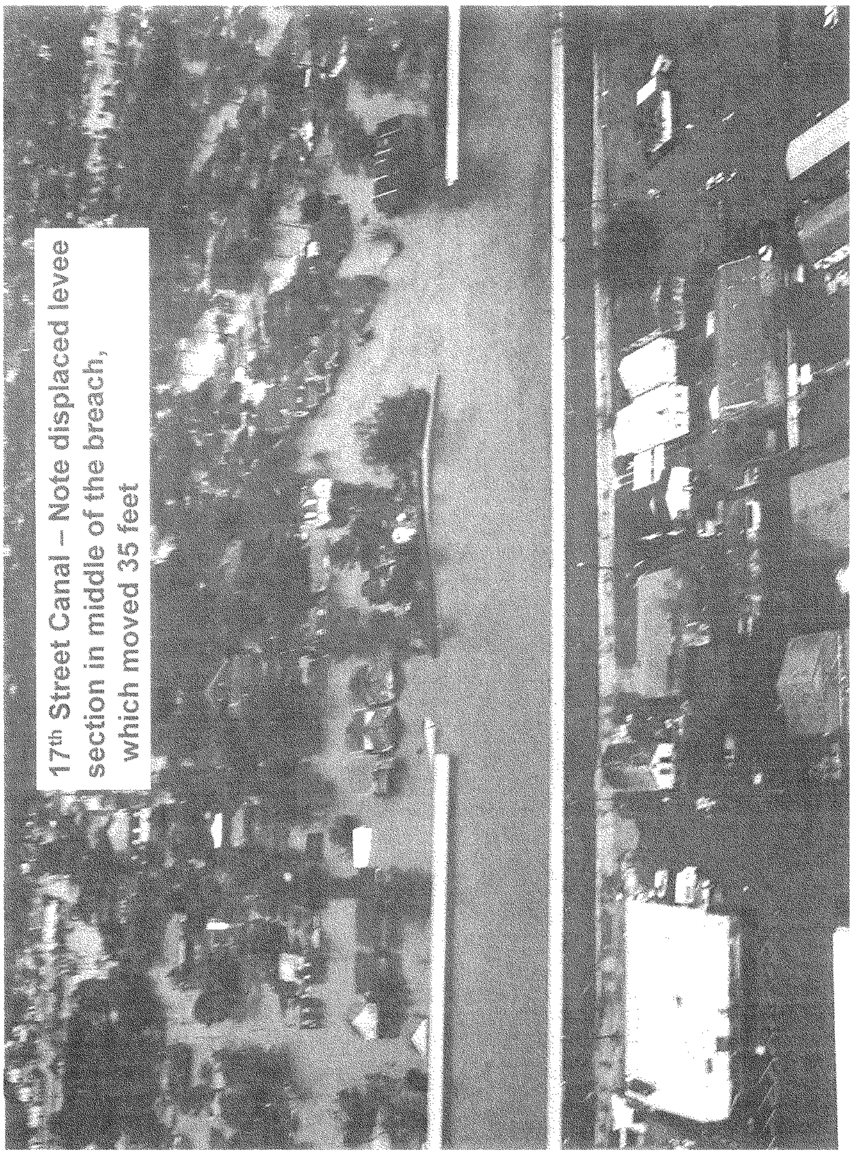

2:56PM


Scour Trench from
Overtopping for 3 hours
1:48PM

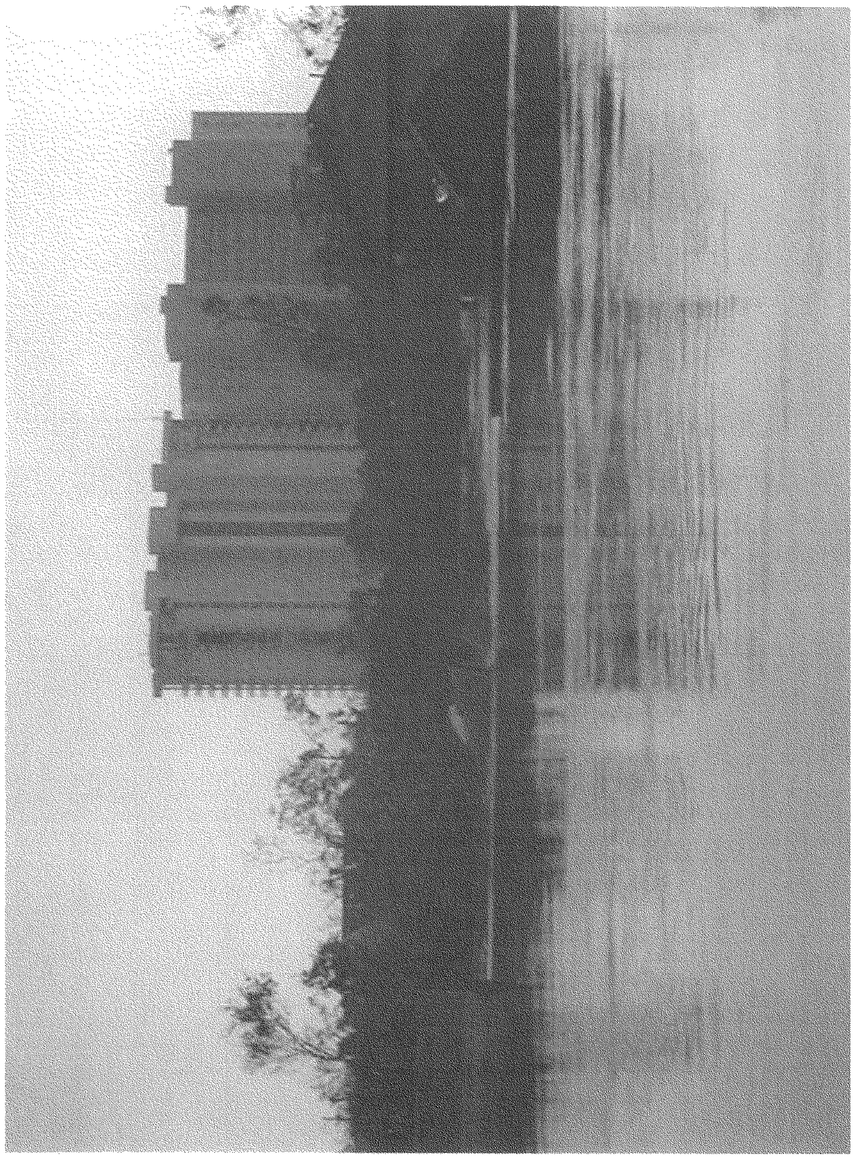

10 M SPOT Satellite Image: 2 Sept 2005
With Water depth overlays
17th Street canal break
London Ave Canal
Industrial Canal Overwash
Flood elevation:
+3ft NAVD 88
Water Depth
Color
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
NATURAL SYSTEMS MODELING GROUP
AT LOUISIANA STATE UNIVERSITY

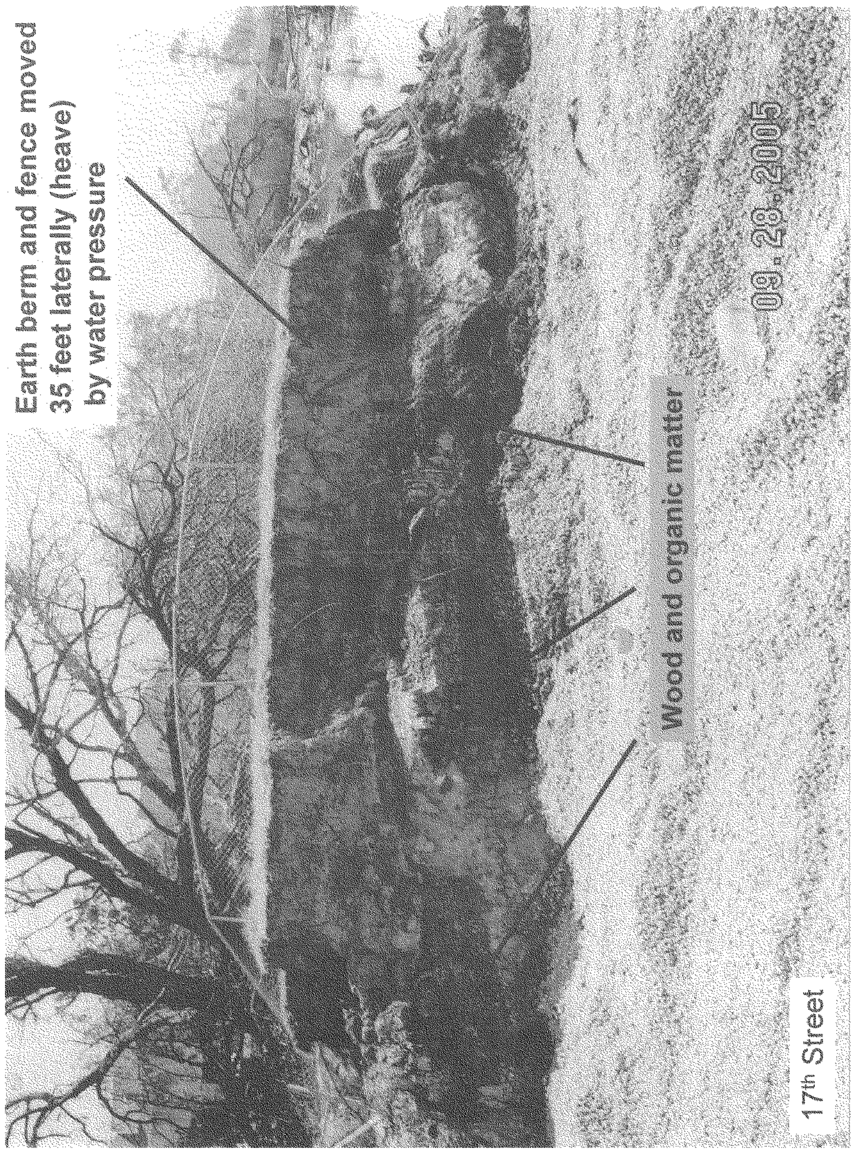

General Levee Construction
Preliminary Data
CONCRETE WALL
STEEL SHEET PILING
EARTHERN BERM OR DYKE
OLD SWAMP DEPOSITS

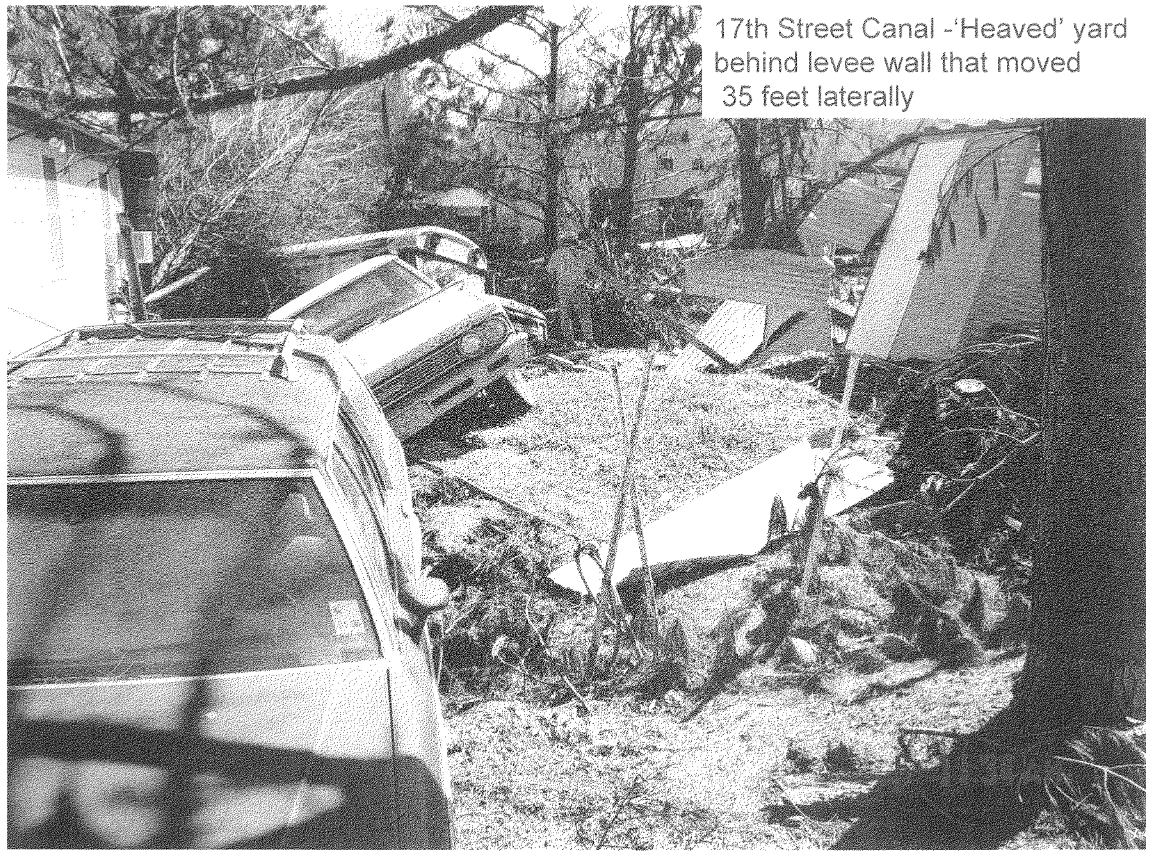

17th Street Canal Breach
Hurricane Katrina Surge at the Industrial Canal & Lake at the 17th Street Canal
IC-Peak at 0830 AM; Lake Peak 0900 AM
Surge (ft)
16
14
12
10
8
6
4
2
0
8/29/05 0:00
8/29/05 6:00
8/29/05 12:00
8/29/05 18:00
8/30/05 0:00
Date & Time (CDT)
Ind. Canal N216818
Lake @ 17th Canal N206324
Center for the Study of
PUBLIC HEALTH IMPACTS
of Hurricanes


17th Street Canal – Note displaced levee
section in middle of the breach,
which moved 35 feet

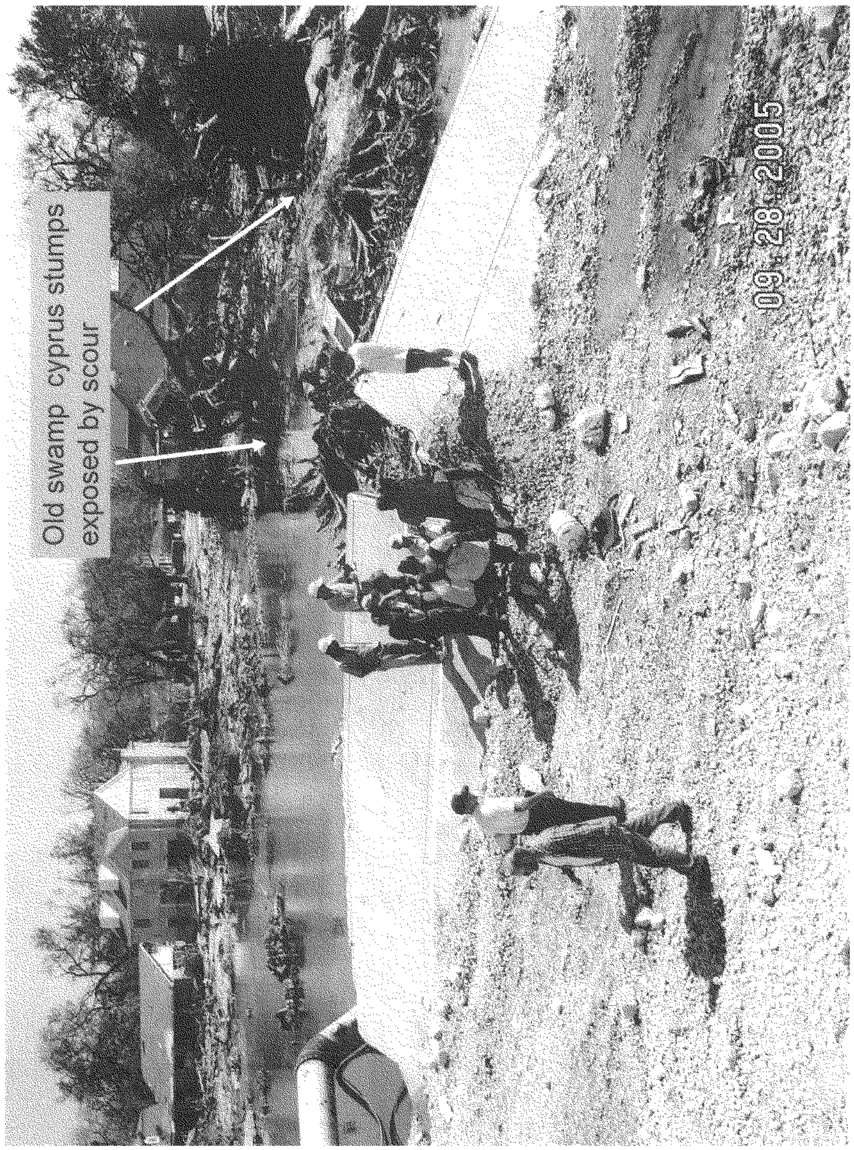

08/30/05

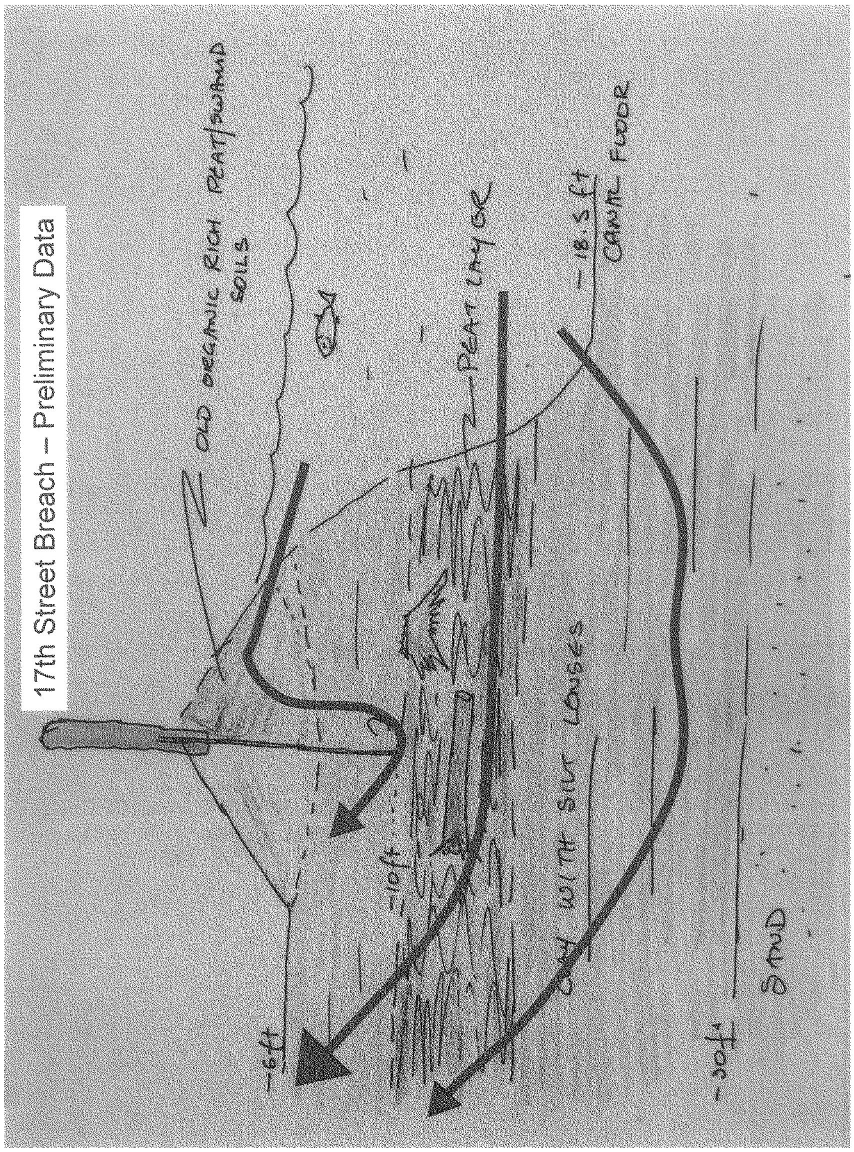


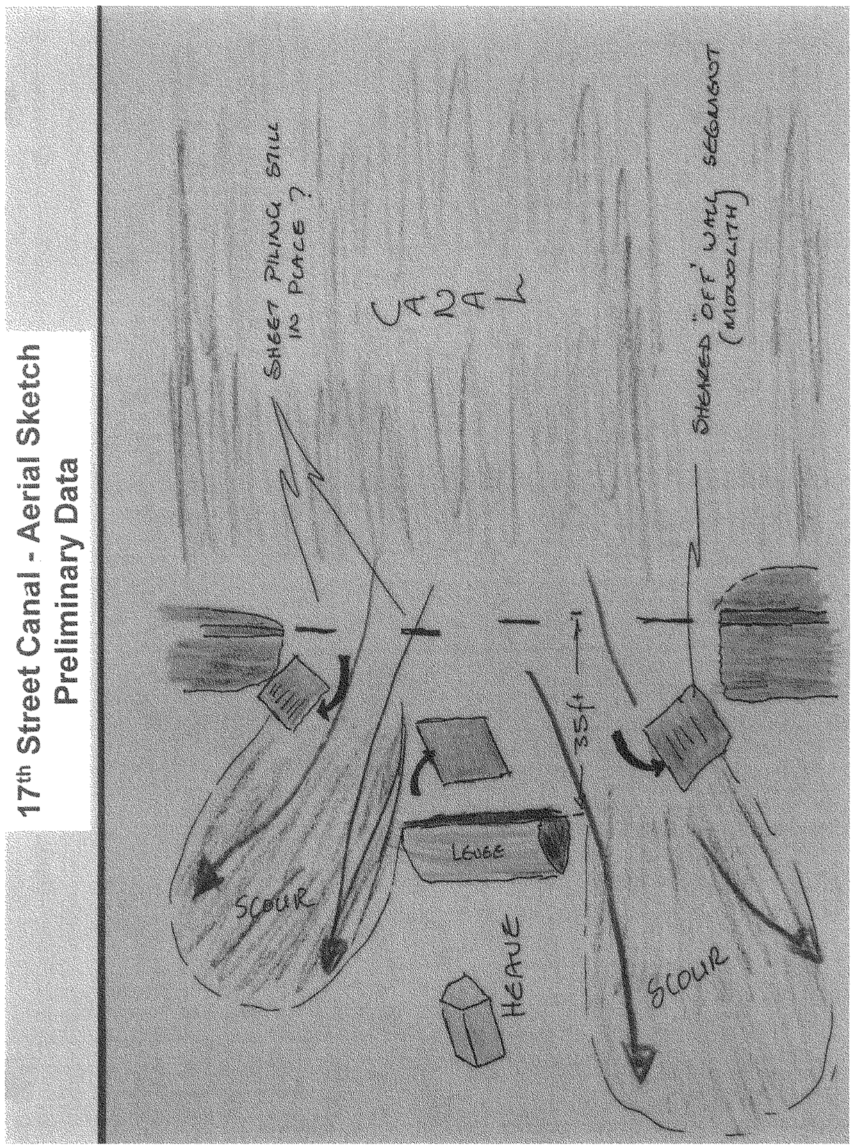

Earth berm and fence moved
35 feet laterally (heave)
by water pressure
Wood and organic matter
09.28.2005
17th Street

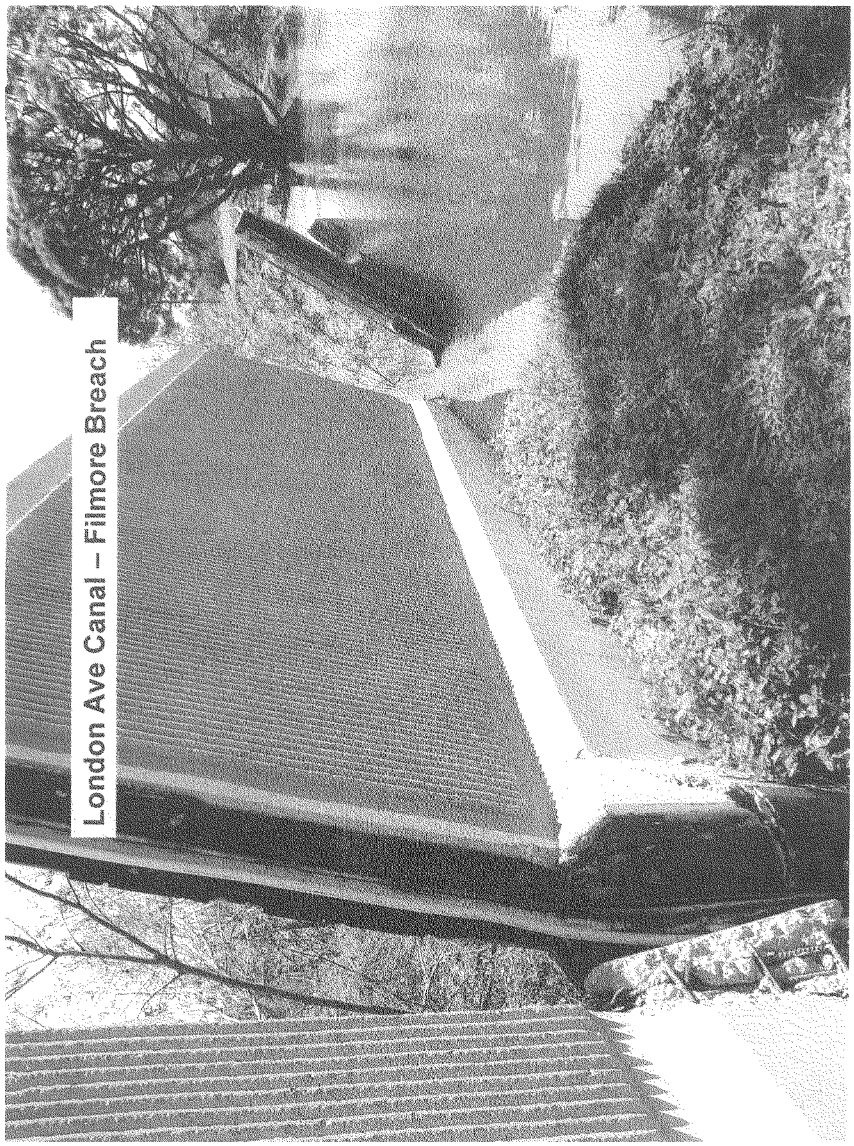


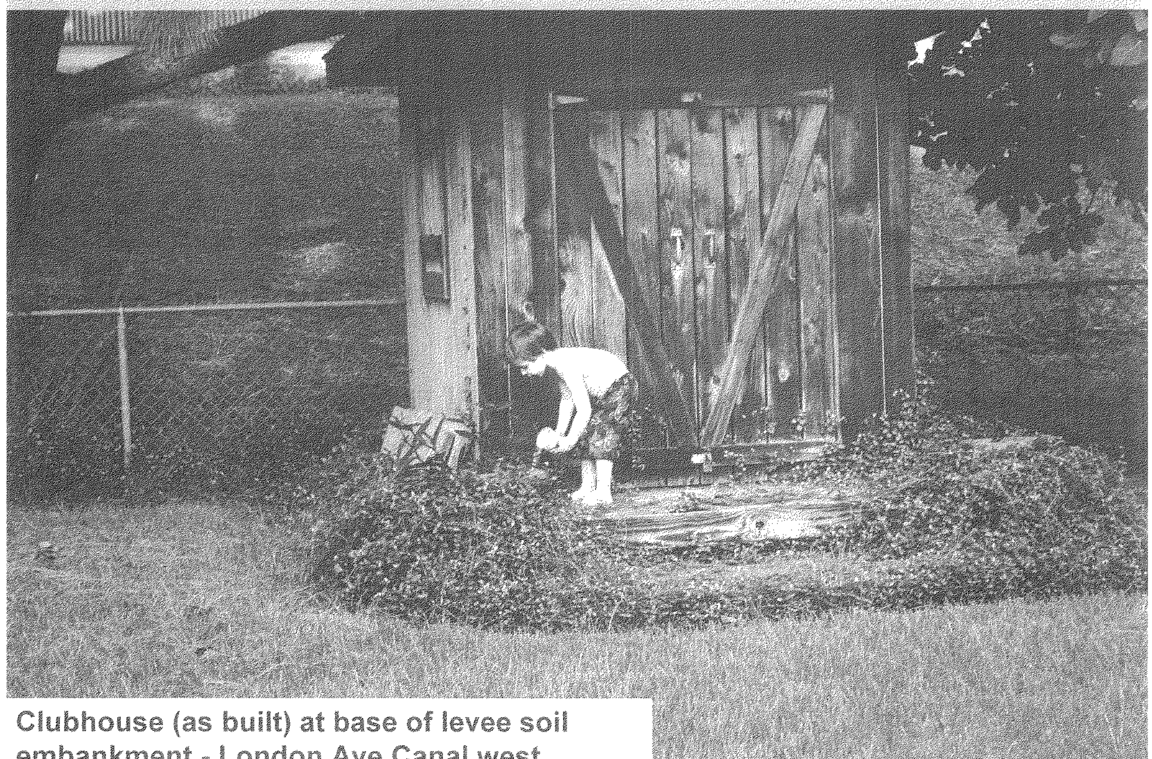
17th Street Canal -'Heaved' yard behind levee wall that moved 35 feet laterally


Old swamp cyprus stumps
exposed by scour
09 28 2005


17th Street Breach – Preliminary Data
OLD ORGANIC RICH PEAT/SWAMP SOILS
PEAT LAYER
-18.5 ft CANAL FLOOR
-6 ft
-10 ft
-30 ft
SAND


17th Street Canal - Aerial Sketch
Preliminary Data
SHEET PILING STILL IN PLACE ?
CANAL
SHEARED 'OFF' WALL SEGMENT (MONOLITH)
35ft
SCOUR
HEAVE
SCOUR

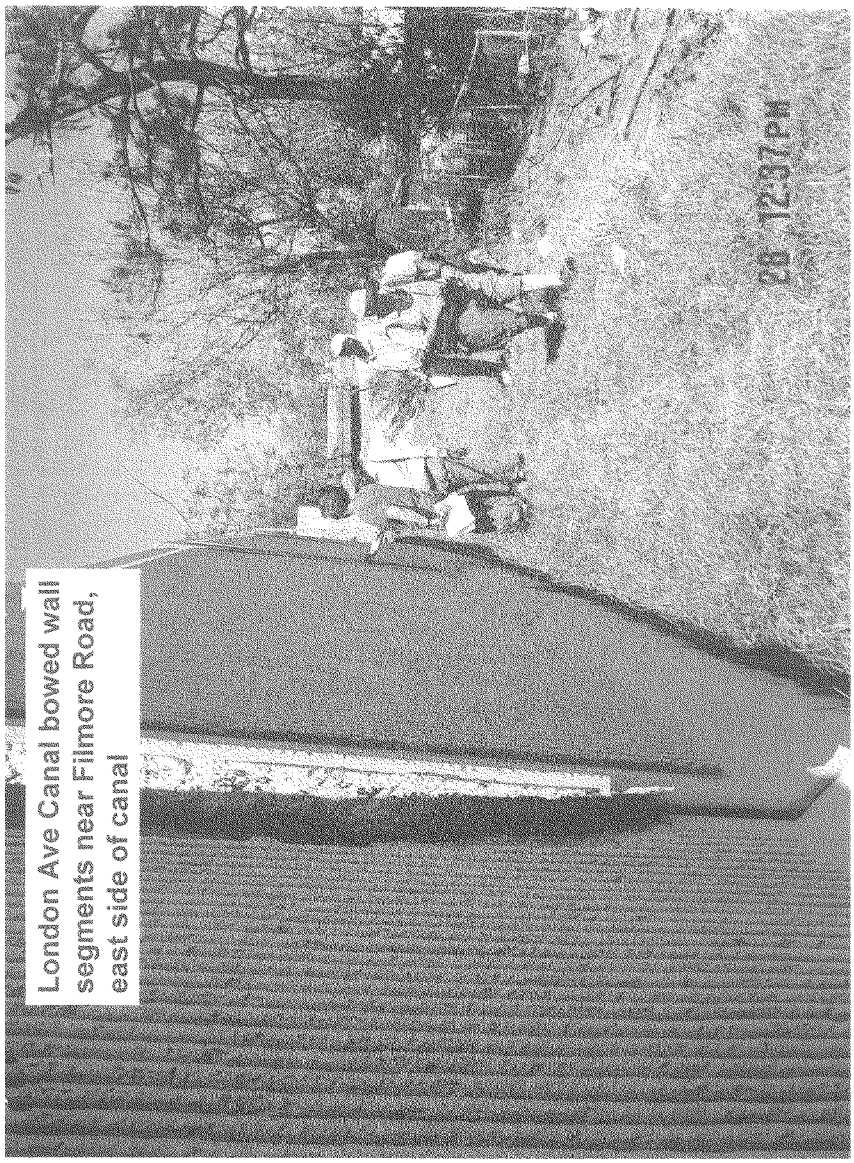

London Ave Canal – Filmore Breach



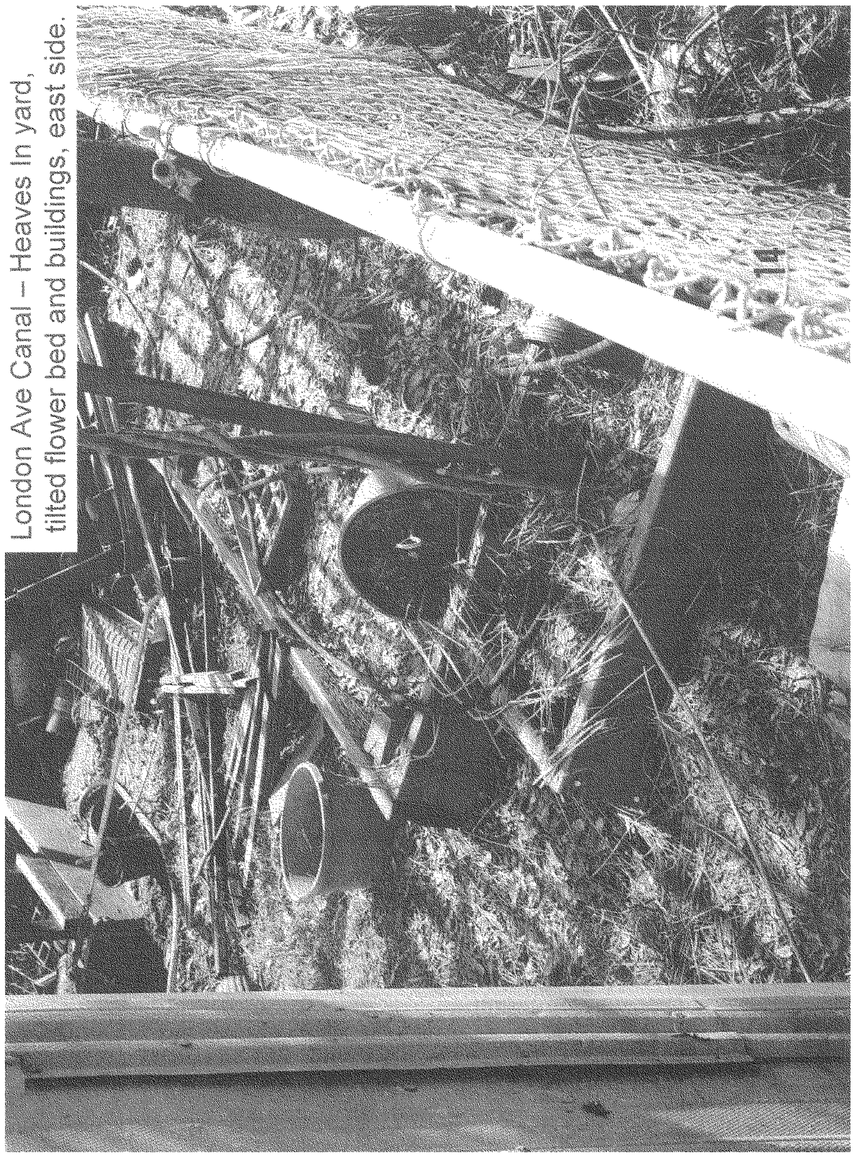
Clubhouse (as built) at base of levee soil embankment - London Ave Canal west breach. Note pine tree location on left.

Daniel Cantrell

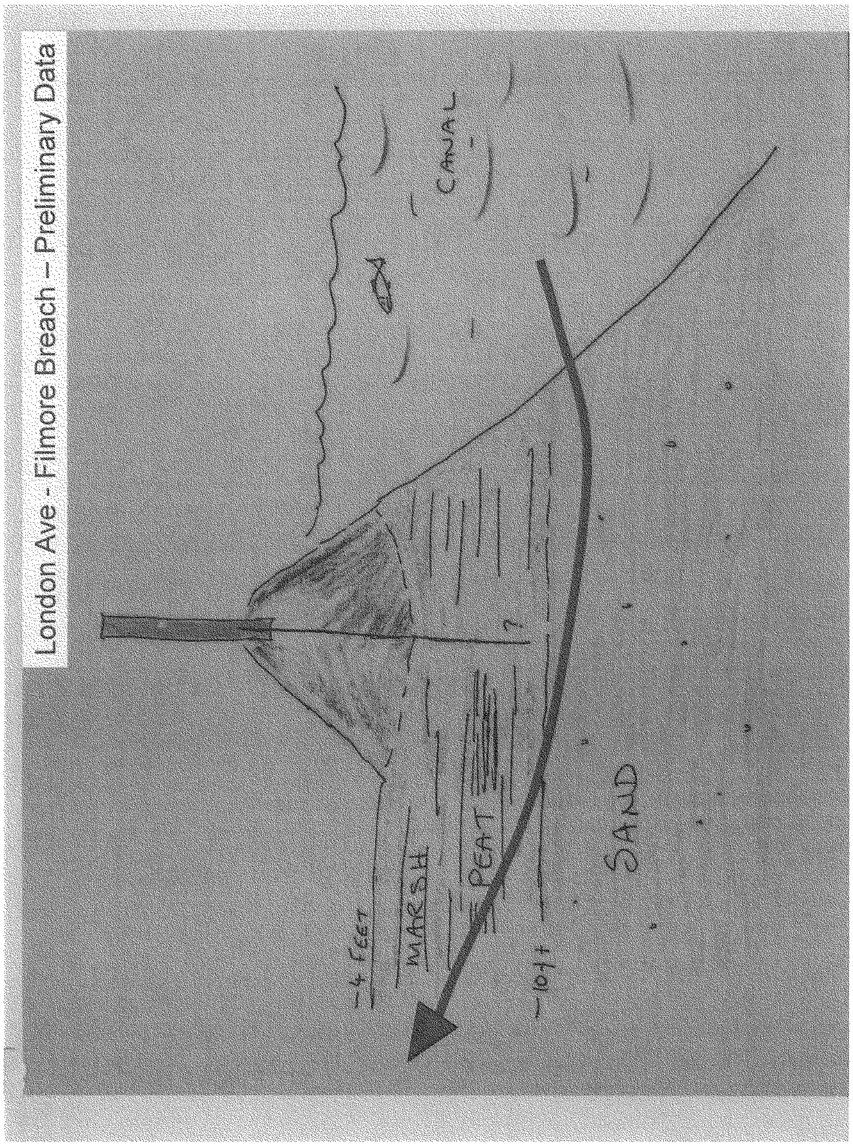

Club house and pine tree after heave –
London Ave Canal west breach, rose 6-8 feet!
Daniel Cantrell

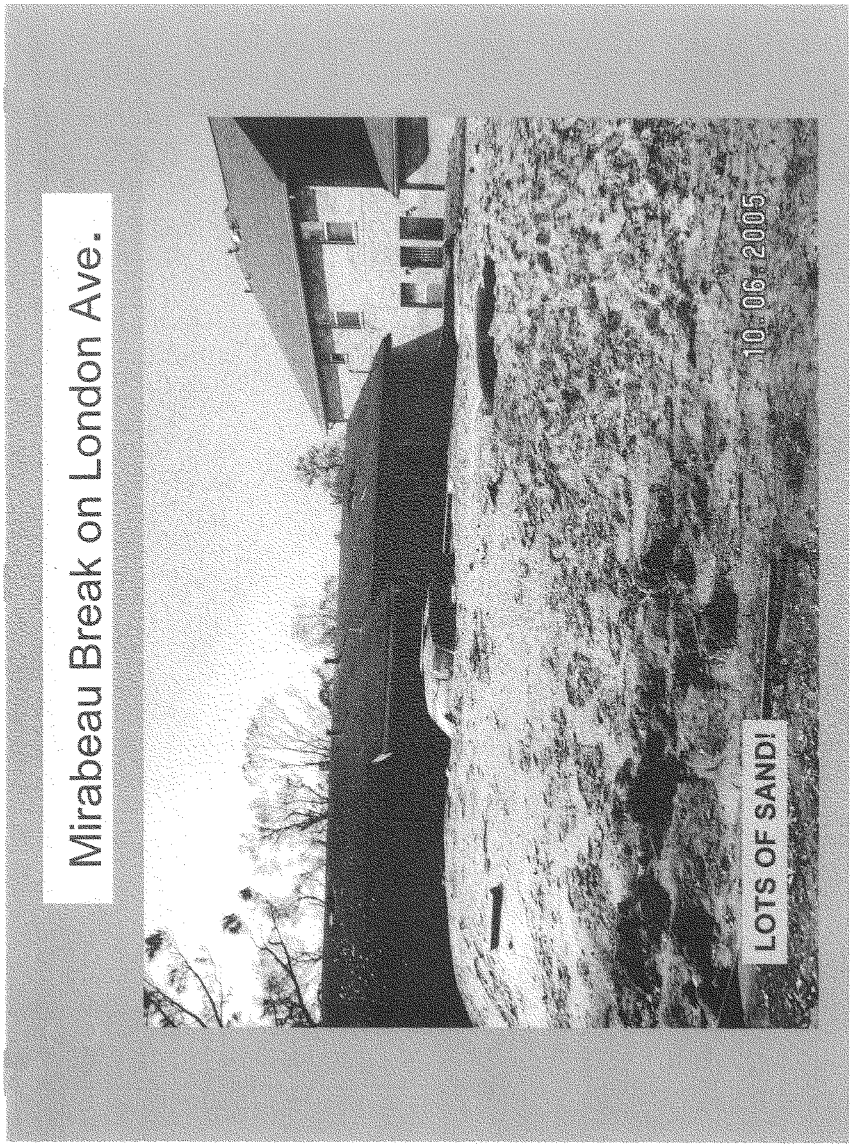

London Ave Canal bowed wall
segments near Filmore Road,
east side of canal
28 12:37 PM

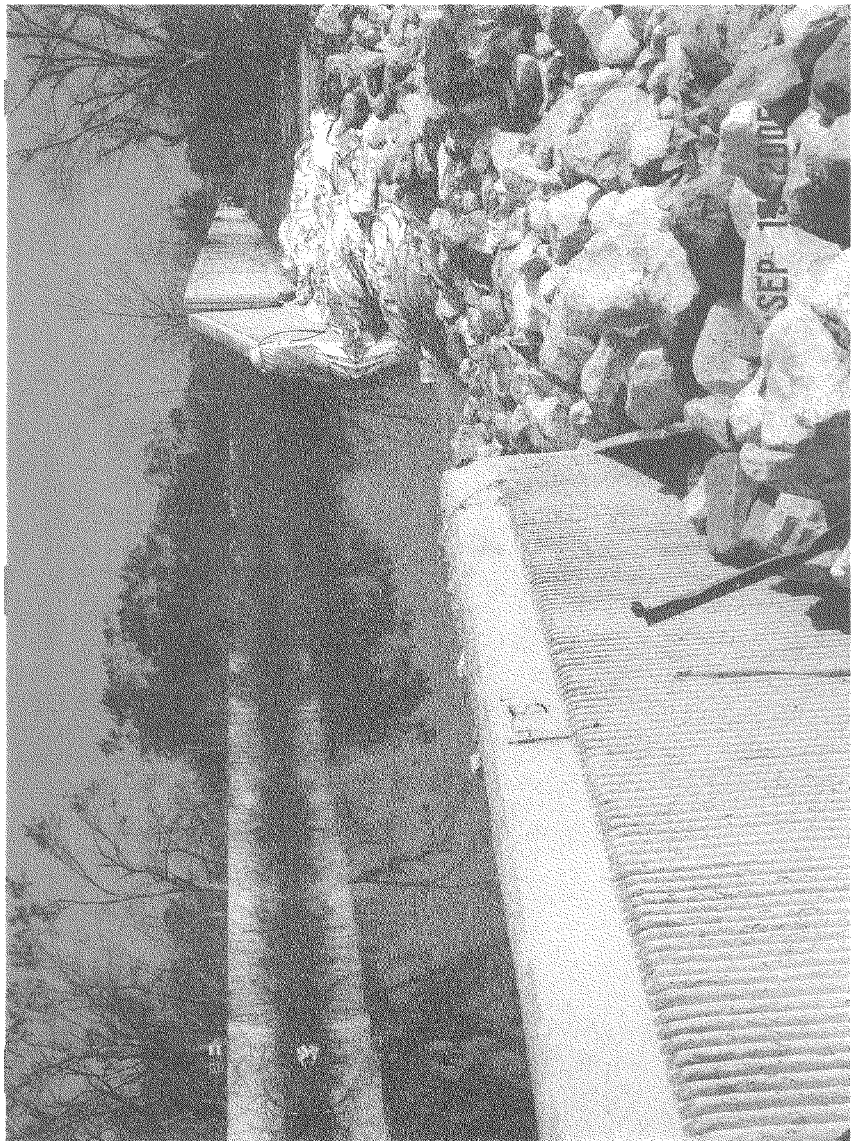
London Ave Canal – Large 'sand boil' at base of levee soil embankment, east side



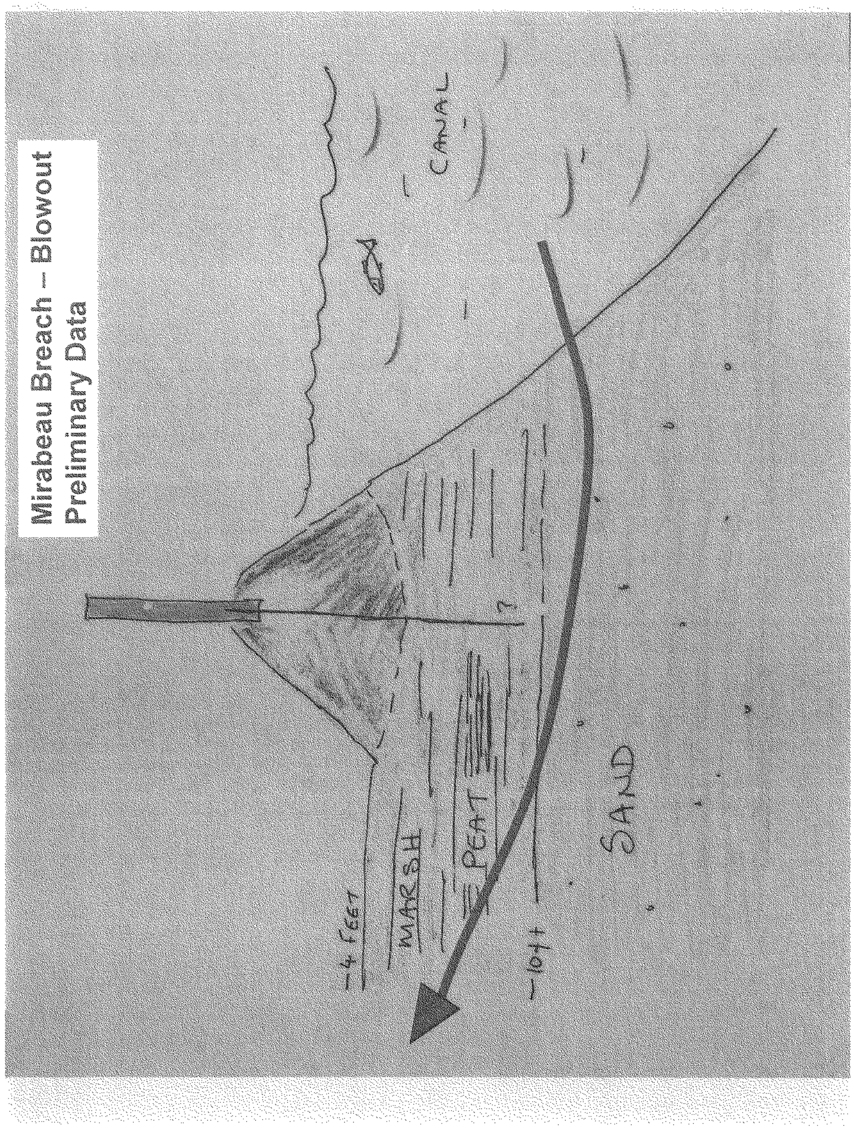
London Ave Canal – Heaves In yard, tilted flower bed and buildings, east side.

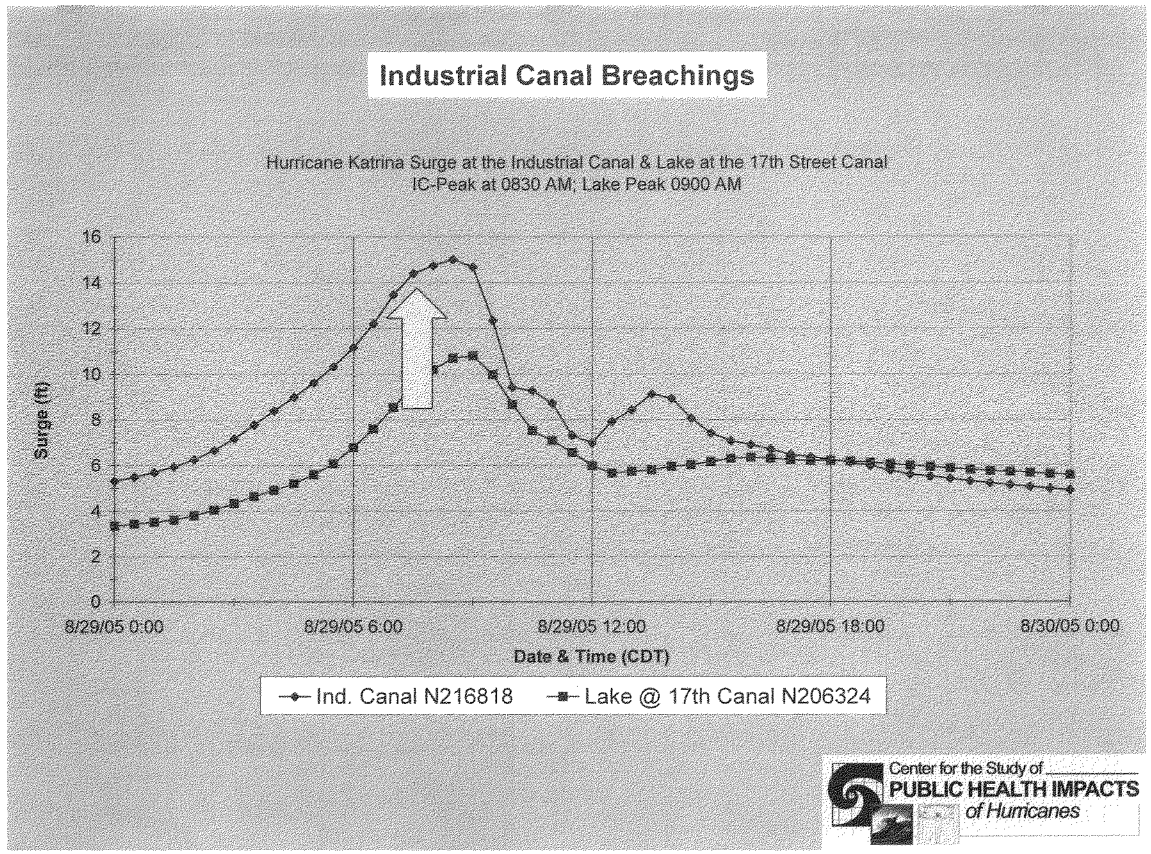

London Ave - Filmore Breach – Preliminary Data
CANAL
-4 FEET
MARSH
PEAT
-10 ft
SAND

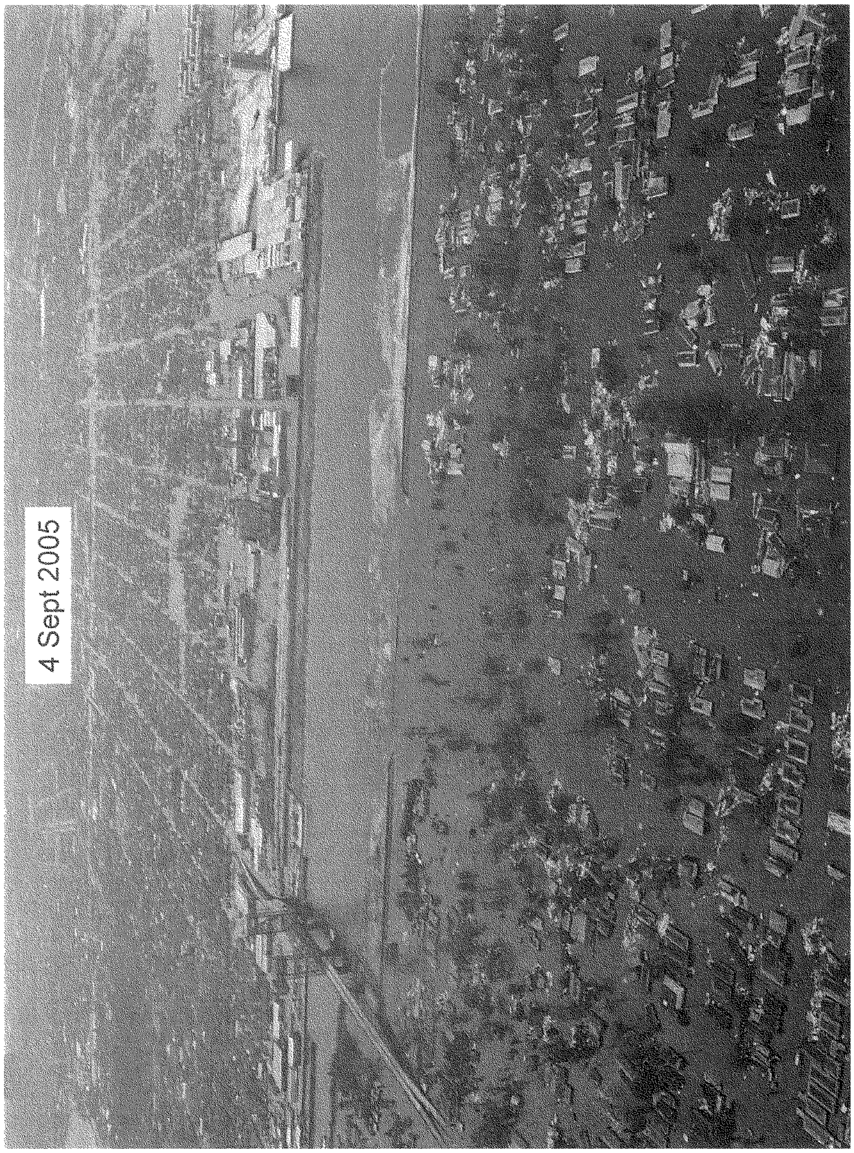

Mirabeau Break on London Ave.
LOTS OF SAND!
10 06 2005



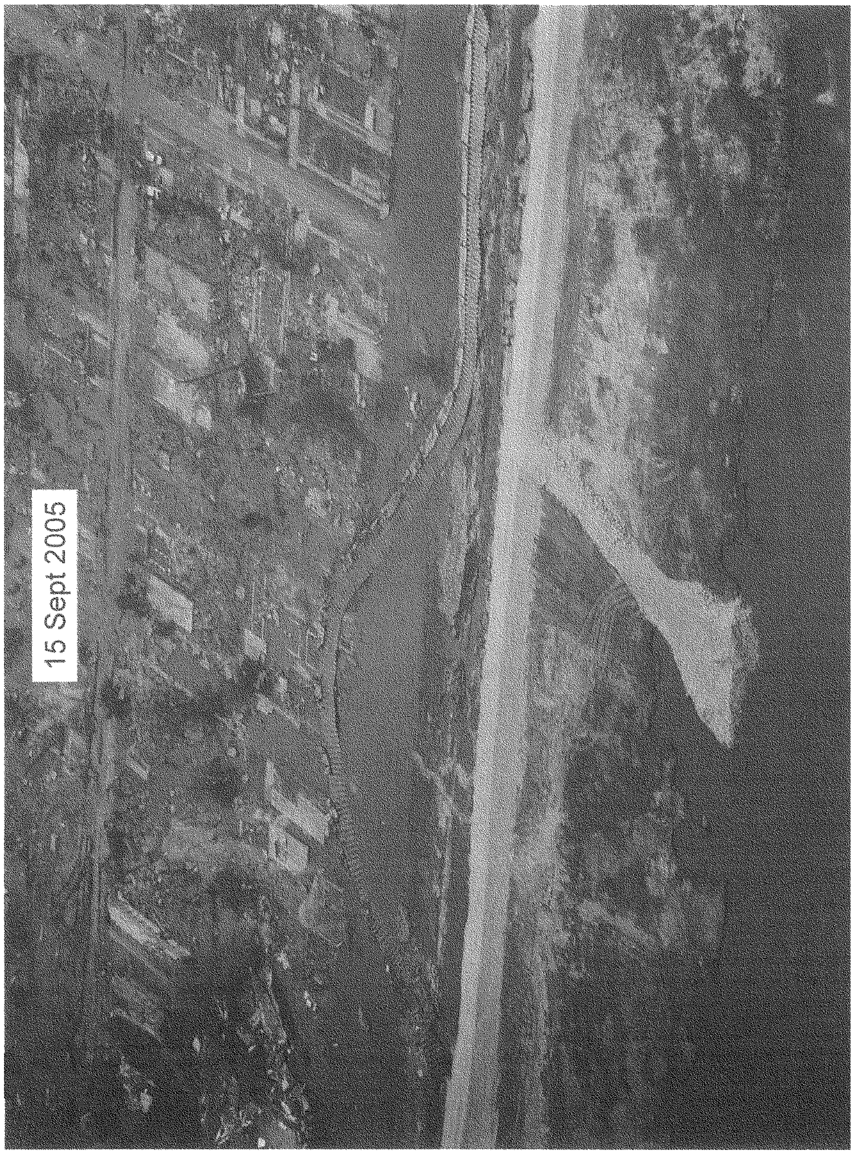

Blowout hole?

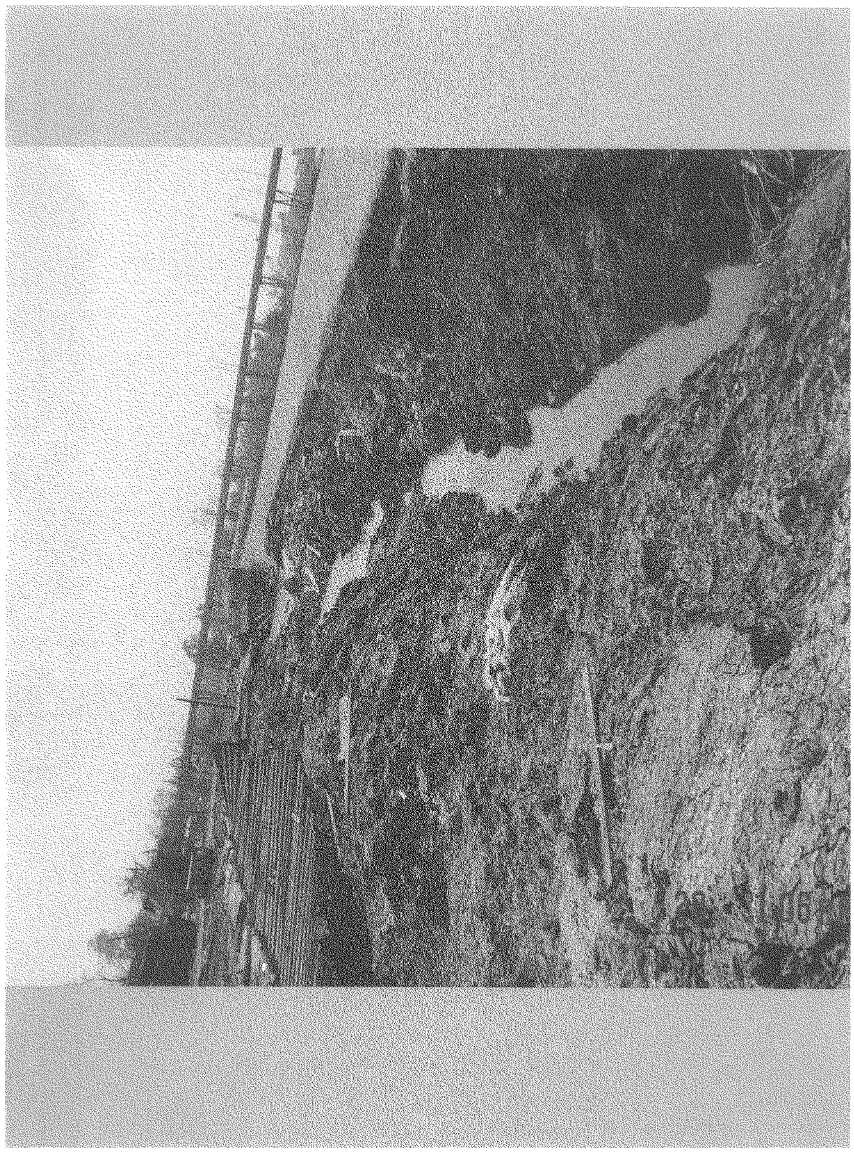

Mirabeau Breach -- Blowout
Preliminary Data
CANAL
-4 FEET
MARSH
PEAT
SAND

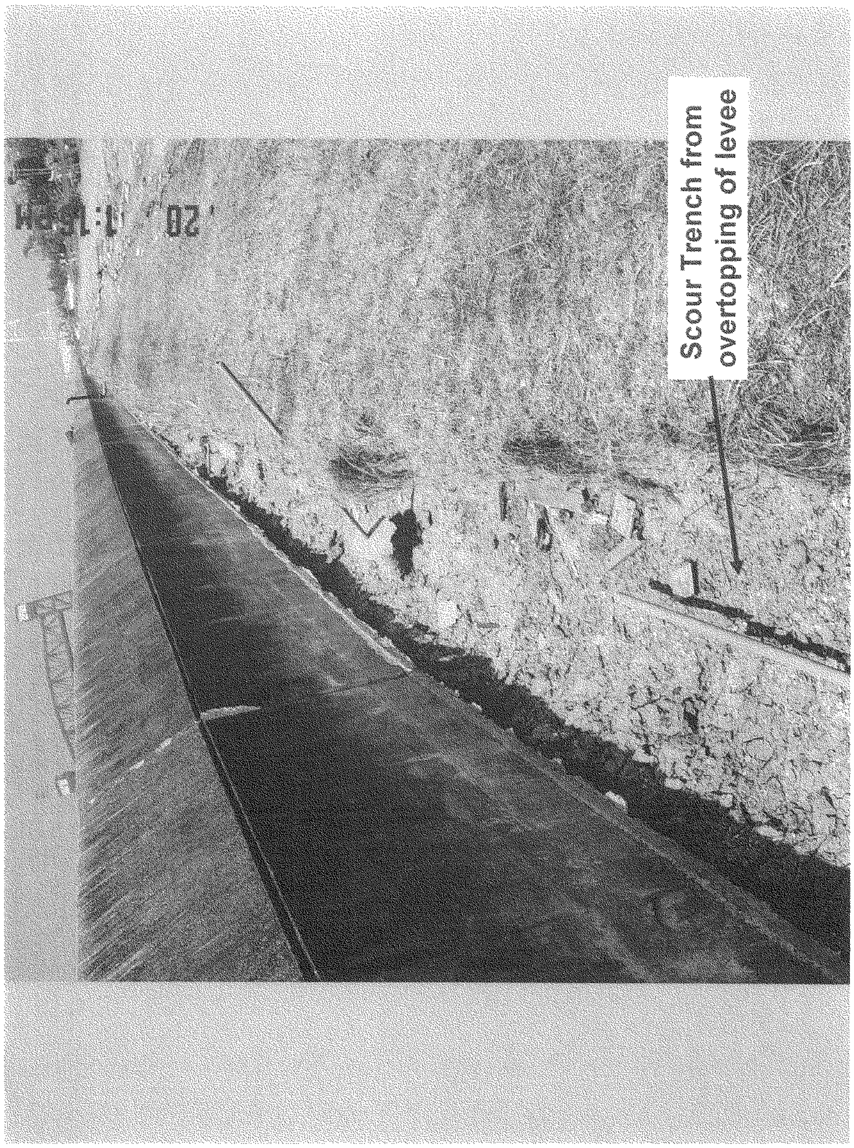

Industrial Canal Breachings
Hurricane Katrina Surge at the Industrial Canal & Lake at the 17th Street Canal
IC-Peak at 0830 AM; Lake Peak 0900 AM
Surge (ft)
16
14
12
10
8
6
4
2
0
8/29/05 0:00
8/29/05 6:00
8/29/05 12:00
8/29/05 18:00
8/30/05 0:00
Date & Time (CDT)
Ind. Canal N216818
Lake @ 17th Canal N206324
Center for the Study of
PUBLIC HEALTH IMPACTS
of Hurricanes

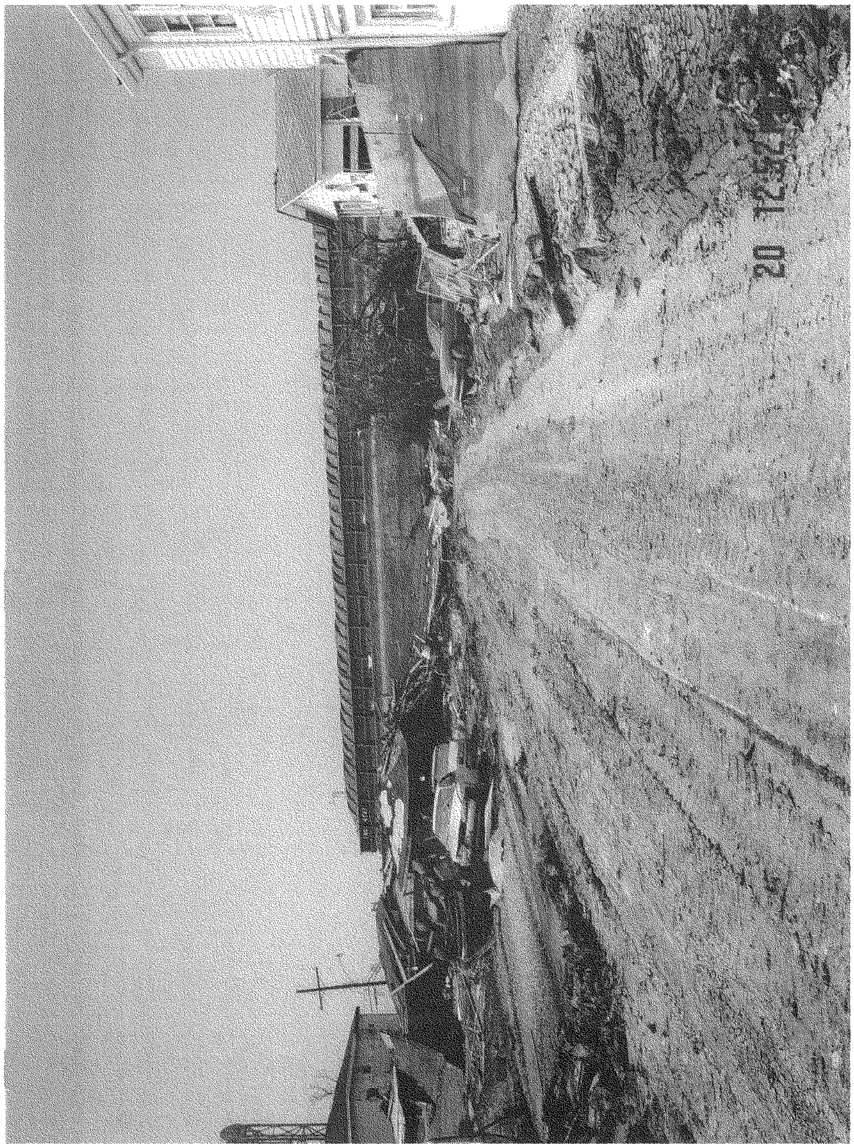

4 Sept 2005

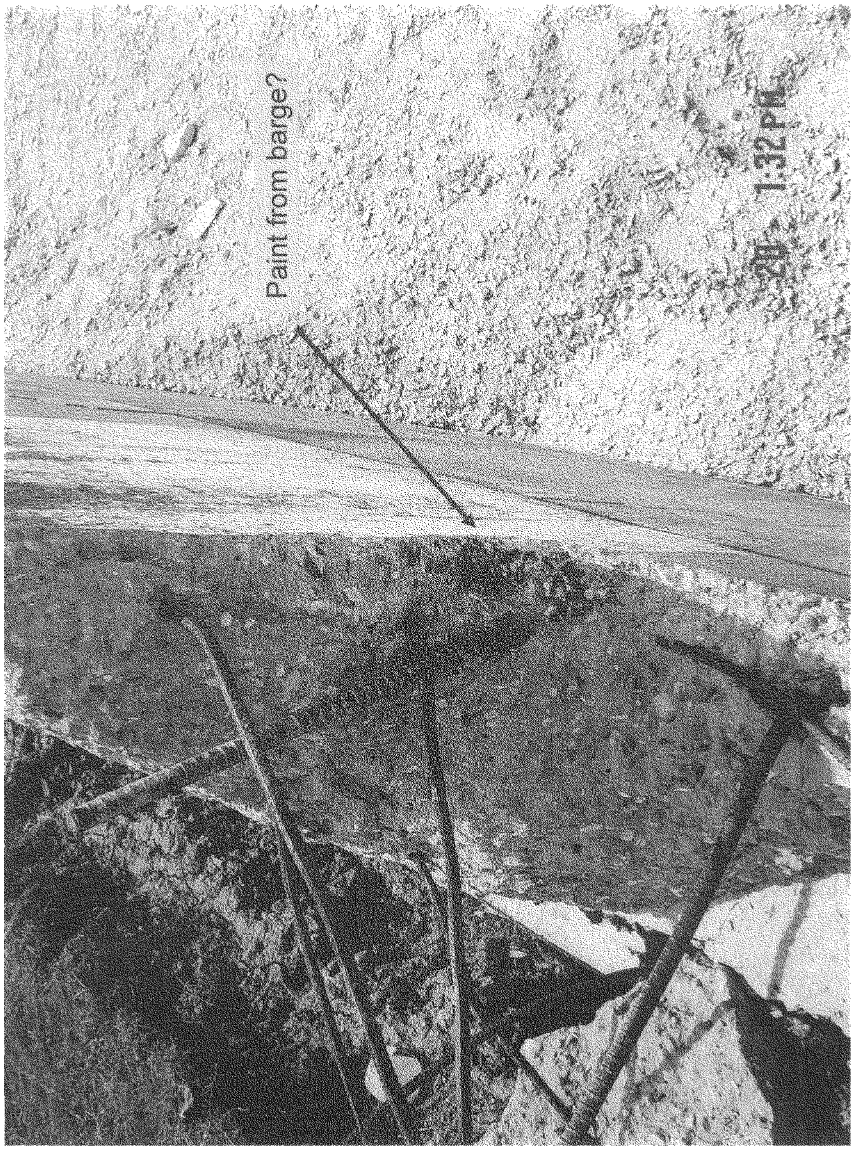

Levee Failure on East Side of Industrial Canal
09.02.2005

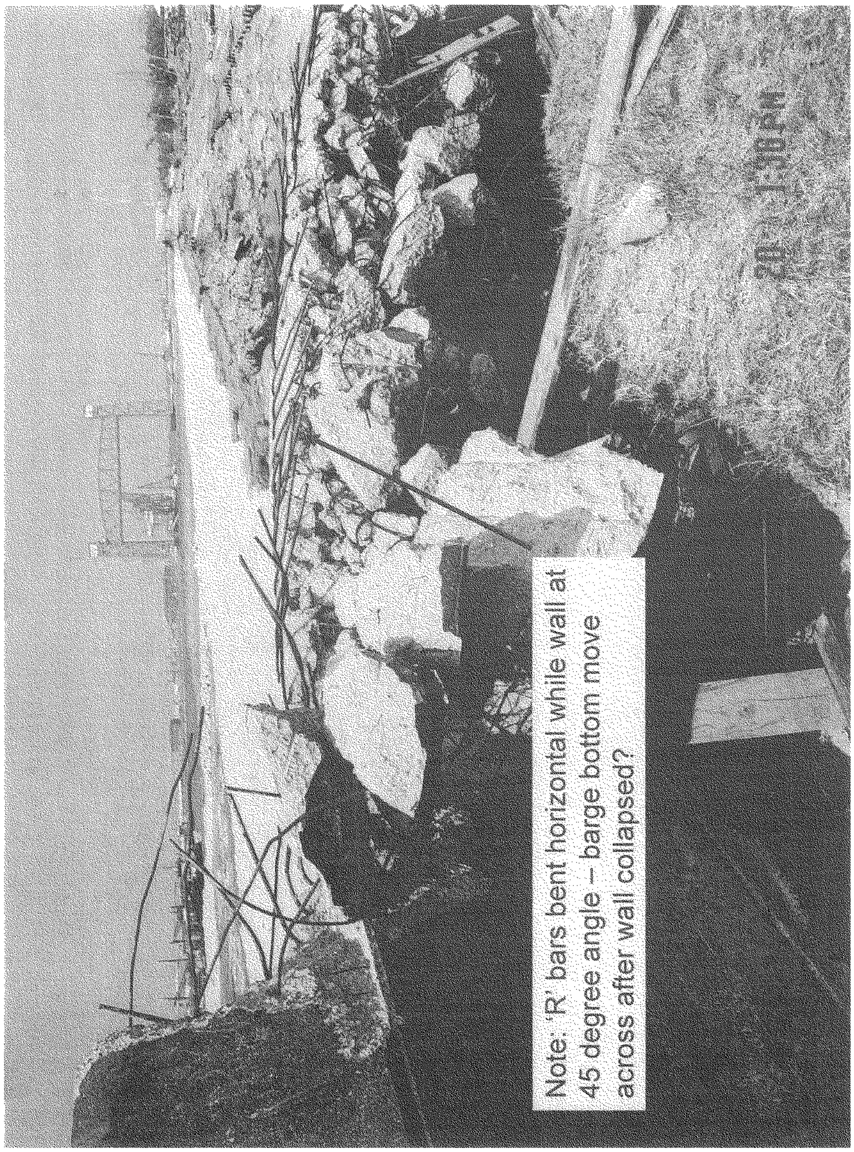

15 Sept 2005

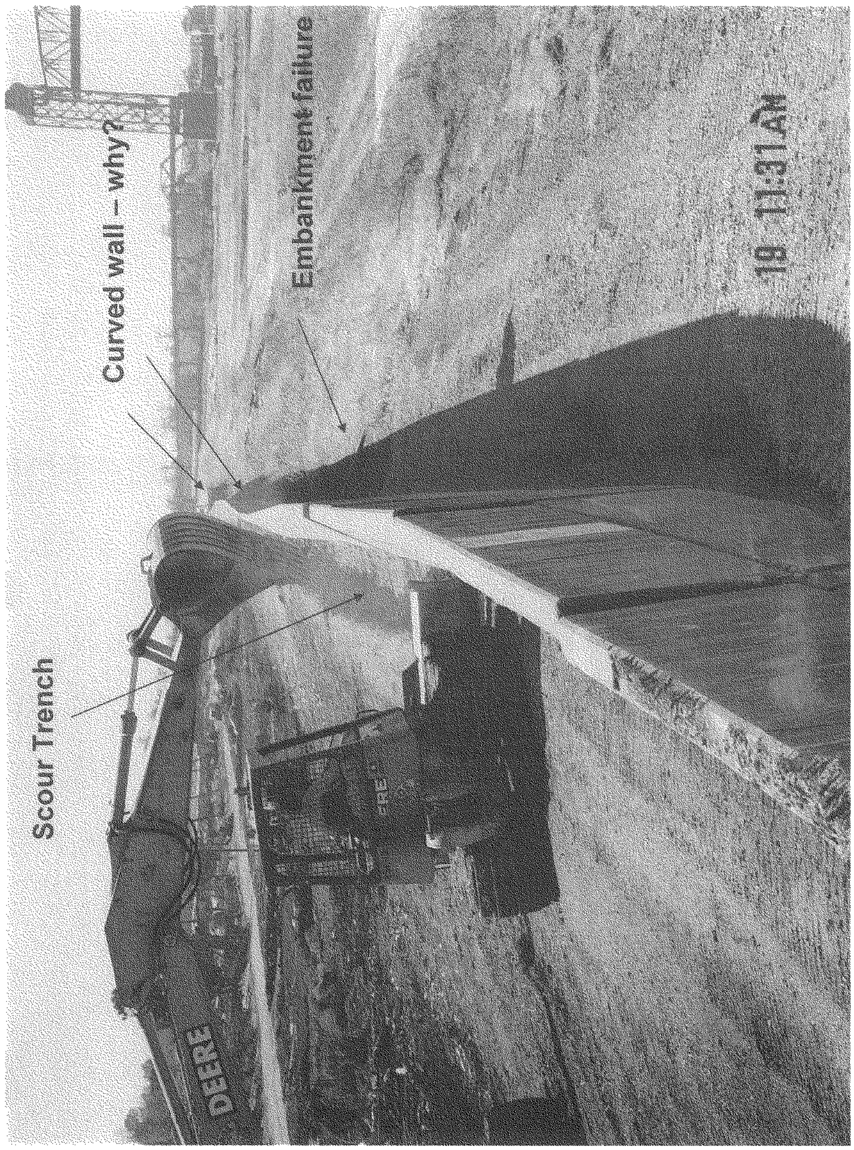


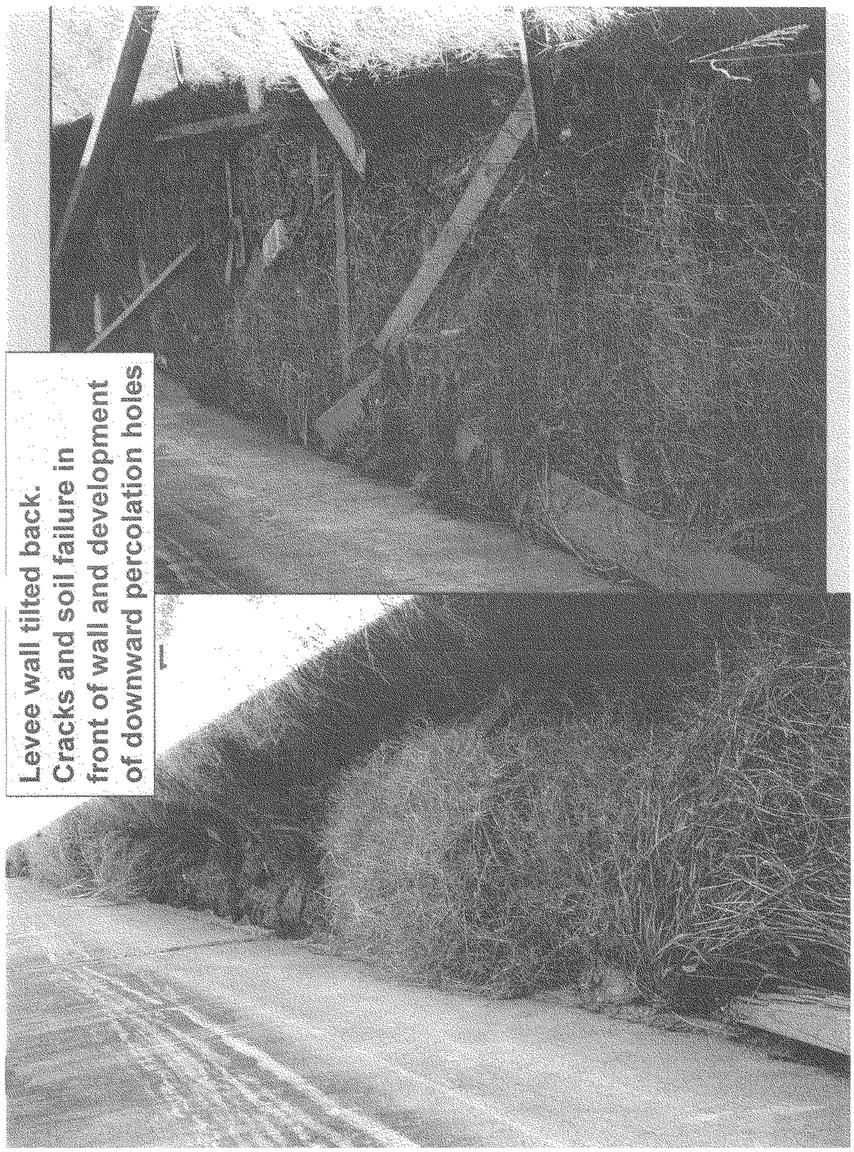

Scour Trench from overtopping of levee

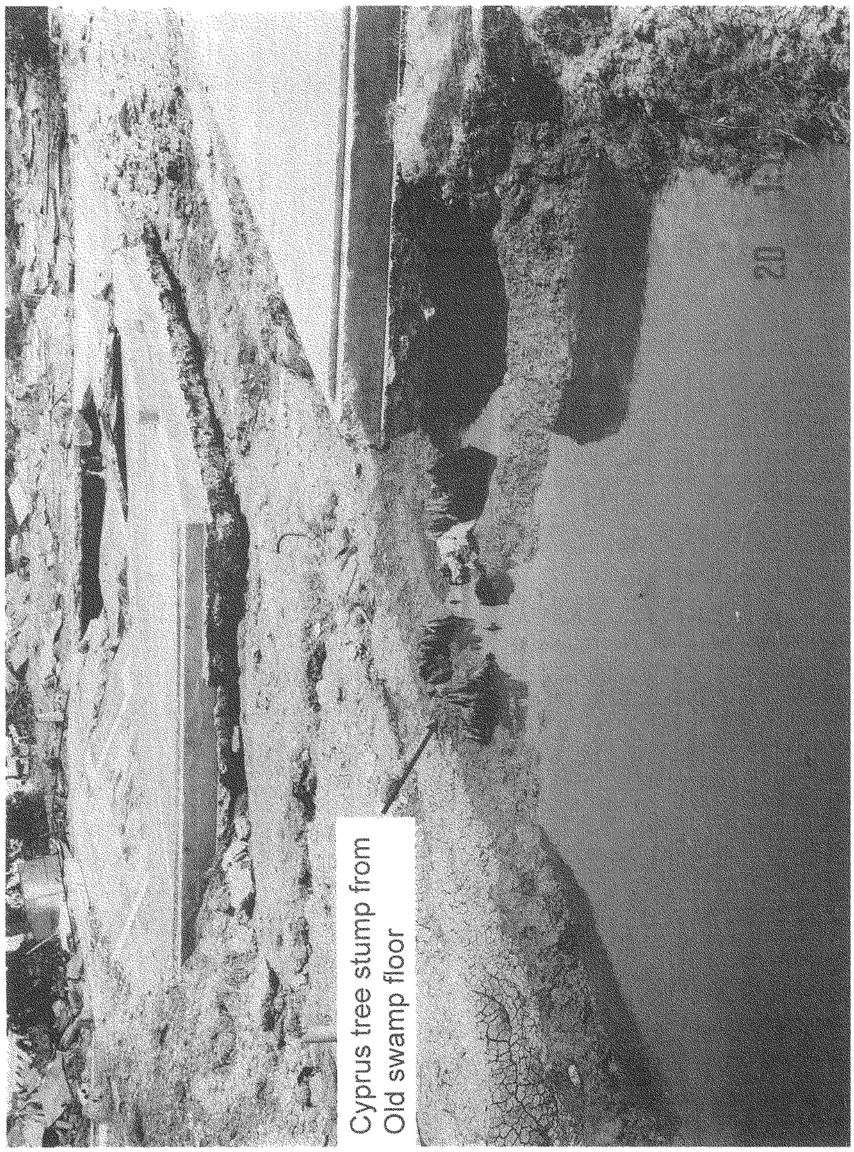


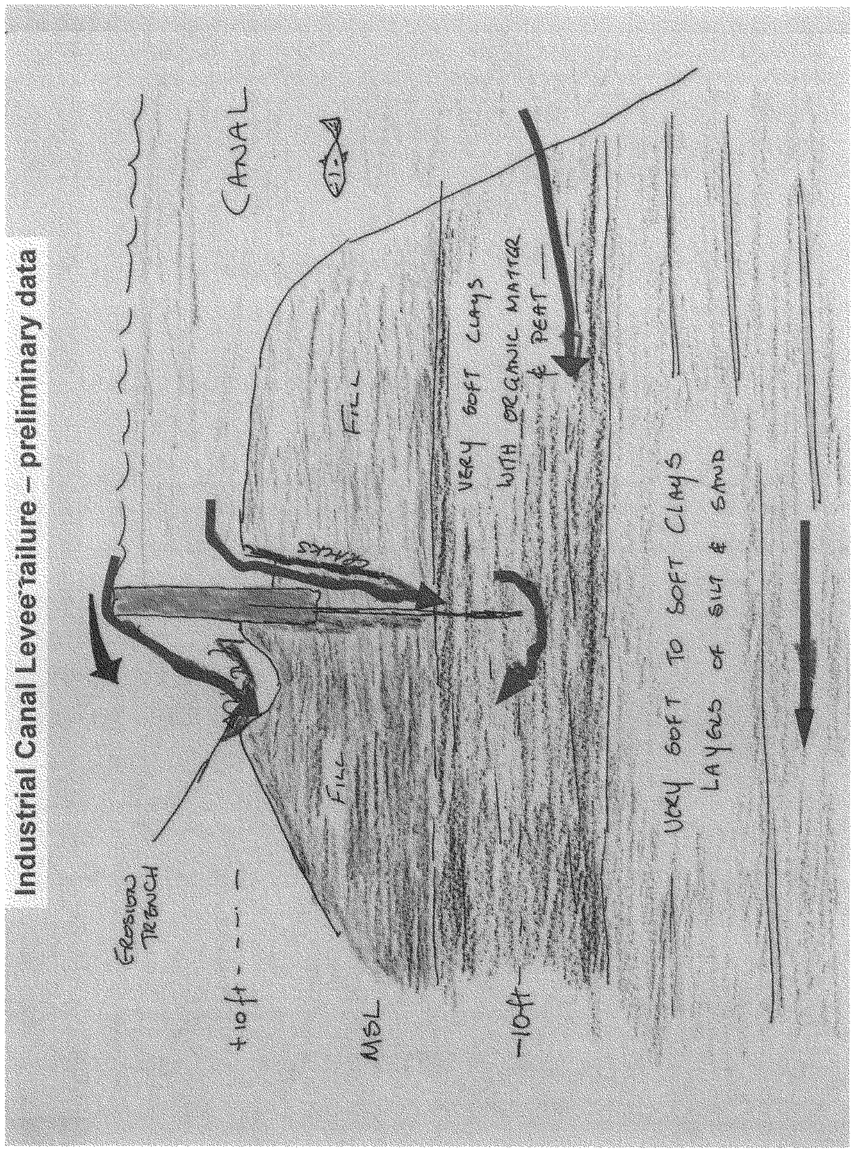

Paint from barge?
1:32 PM

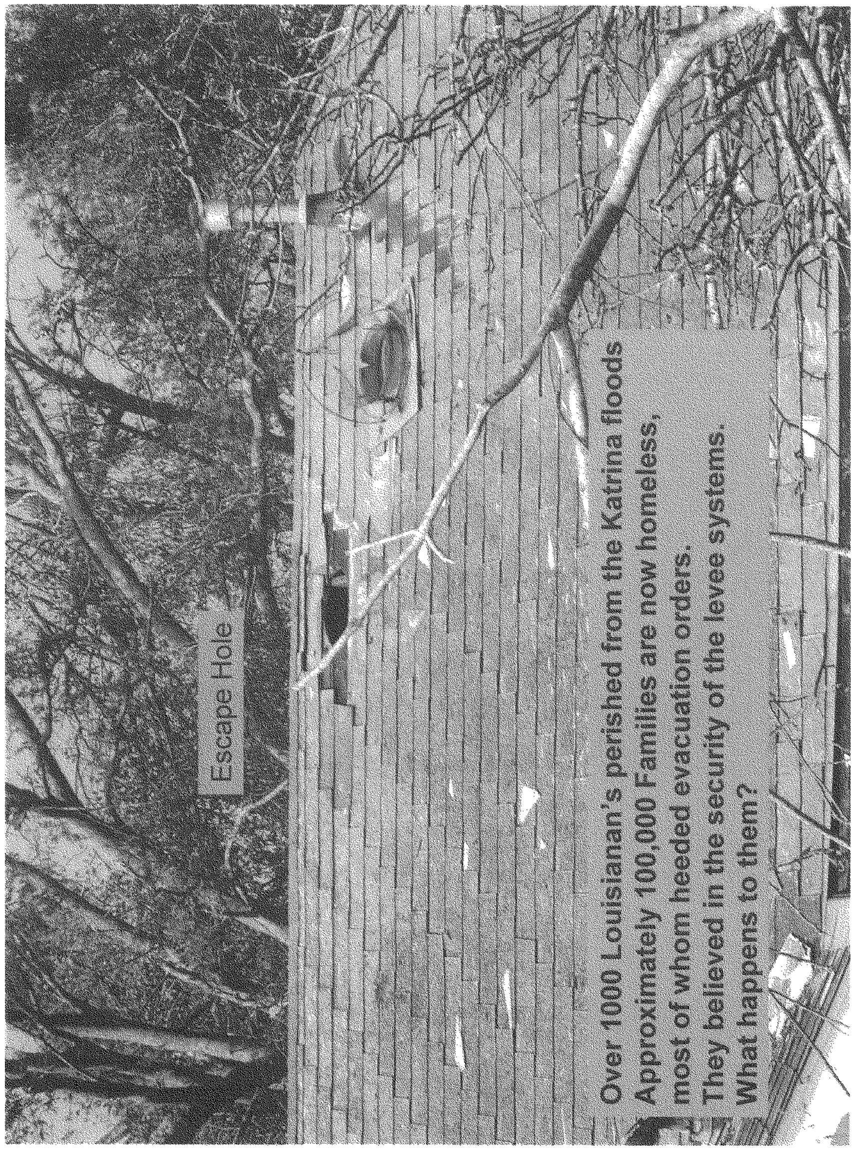

Note: 'R' bars bent horizontal while wall at
45 degree angle – barge bottom move
across after wall collapsed?


Scour Trench
Curved wall – why?
Embankment failure
19 11:31 AM
DEERE


Levee wall tilted back.
Cracks and soil failure in
front of wall and development
of downward percolation holes


Cyprus tree stump from
Old swamp floor


Industrial Canal Levee failure – preliminary data
CANAL
FILL
FILL
CRACKS
EROSION TRENCH
+10ft
MSL
-10ft
VERY SOFT CLAYS
WITH ORGANIC MATTER
& PEAT
VERY SOFT TO SOFT CLAYS
LAYERS OF SILT & SAND


Escape Hole
Over 1000 Louisianan's perished from the Katrina floods
Approximately 100,000 Families are now homeless,
most of whom heeded evacuation orders.
They believed in the security of the levee systems.
What happens to them?

Paul F. Mlakar, Ph.D., P.E.
Senior Research Scientist
US Army Research and Development Center

Testimony Before the
Committee on Homeland Security and Governmental Affairs
United States Senate

Hearing on
Hurricane Katrina: Why did the Levees Fail?

November 2, 2005

Madame Chair and Members of the Committee

Introduction

I am Dr. Paul F. Mlakar, Senior Research Scientist at the US Army Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi, which is a component of the US Army Corps of Engineers (the Corps). I have spent most of my professional career spanning four decades in the Corps studying the response of structures to extreme loadings. This has included the performance of the Murrah Building in the Oklahoma City bombing and the performance of the Pentagon in the 9/11 crash. I am a Registered Professional Engineer, a Fellow of the American Society of Civil Engineers, and received their Forensic Engineering Award in 2003.

As some of you know, the ERDC conducts research and development to enable the Corps to better perform its military and civil missions in service to the Nation. We employ some 2548 people in seven laboratories located in four states. This staff is recognized nationally and internationally for its expertise in civil engineering and related disciplines. Our facilities include a number of unique devices that allow us to conduct analyses and experiments on the leading edge of technology.

I am pleased to appear today on behalf of the ERDC and the Corps to provide information as requested in your letter of invitation dated 27 October 2005. The Congressional interest in the performance of the storm damage reduction infrastructure in Hurricane Katrina is much appreciated and shared by the Corps. While we do not yet have the answers to all of the questions, we welcome this opportunity to share our progress with you.

The Corps takes its responsibility for the safety and well-being of the Nation's citizens very seriously. In the case of the New Orleans area, we are determined to learn what failed, how it failed, why it failed, and to recommend ways to reduce the risk of failure in the future.

On September 22, 2005, the Corps asked me to lead in the collection of data for the study of the storm damage reduction infrastructure affected by Hurricane Katrina. On September 26, 2005, I deployed to New Orleans on the heels of Hurricane Rita and have spent most of the intervening time in the region. At various times I have been joined by some thirty colleagues from the Corps. Our priority has been on the breaches in the metropolitan area that caused the greatest devastation, i.e. the 17^{th} Street Canal, the London Canal, and the Inner Harbor Navigation Canal.

We have been diligently recording the damages and measuring the post-Katrina conditions. We have examined physical evidence to establish the maximum water elevations at various locations. To establish the timeline of events, we have conducted detailed interviews with about 70 people who sat out the storm. To establish the soil properties, we have pushed a state of the art instrumented cone to a depth of 80 feet at 56 locations. We further collected samples of the soil at depth in 10 locations. We have also electronically scanned 63 out of 235 boxes of documents dealing with the design, construction, and maintenance of the projects involved.

As we deployed, the American Society of Civil Engineers and a University of California team sponsored by the National Science Foundation approached the Corps about similar studies of infrastructure performance they were undertaking in hopes of applying lessons learned to the levee systems in California. In the spirit openness and full transparency, we invited these teams to join us beginning on September 29, 2005 for inspections of the projects involved. On September 30, 2005, we learned that the State of Louisiana would soon establish its own study team and we invited the researchers from the Louisiana State University Hurricane Research Center to join us in advance of this official establishment. The Corps gratefully acknowledges the assistance provided by these teams in the collection of the data.

Over the next eight months, an Interagency Performance Evaluation Team commissioned by the Chief of Engineers will examine and analyze these data, and rationally test various hypotheses about the behavior of the infrastructure. The work currently planned will include the following tasks:

Geodetic Reference Datum
Storm Surge and Wave Modeling
Hydrodynamic Forces
Floodwall and Levee Performance
Pumping Station Performance
Interior Drainage/Flooding Modeling
Consequence Analysis
Risk and Reliability Assessment

We will seek the collaboration of other agencies and academia as we proceed with this factual study.

The final results will include conclusions as to the causes of the failures and recommendations for the future design and construction of such infrastructure nationwide. These results will be independently reviewed by the American Society of Civil Engineers and, at the request of the Secretary of Defense, the National Academies/National Research Council will independently review the results as well. Our scheduled completion date is July 1, 2006. In the meantime, our interim results are being shared with our colleagues in the Corps responsible for the repair of the storm damage reduction system in New Orleans and will be taken into consideration in the design and repair of the existing levees and floodwalls.

In response to your specific questions we are able to offer the following responses at this time:

Why did the levees fail?

There is no single answer to this question as there were multiple breaches of levees and floodwalls at a number of locations and the exact failure mechanism of each is likely to be different. The answer to this will follow from a thorough analysis of the data we are now collecting. In some cases, e.g. the Inner Harbor Navigation Canal, we have observed evidence of overtopping that may have played a role. In other cases, e.g. the 17th Street Canal, we have observed evidence of massive soil movement that could have been a factor in how these levees failed. There is a need for considerable analysis to answer this question. Until we can compare the evidence to an understanding of the hydrodynamic environment that resulted from the storm, the forces generated by the resulting surge and waves, how those forces were applied to individual structures and how the structures, given their design intent and capacities, should respond to those forces, we will only be speculating as to why they failed.

What was the physical process that caused these failures?

The physical processes that caused the breaches will be determined from the comprehensive analysis of the data that we are collecting. What we have to date is evidence of what happened; we can see the final result of the structural behavior, but we cannot yet determine why. That will require more understanding of the design intent of each structure, its condition prior to the storm, the forces to which it was subjected (static and dynamic) and the ability to at least simulate how the structure would respond to those forces. This is the objective of our current interagency analysis efforts.

What role did human error play in these failures?

Through a thorough analysis of the data that we are collecting, we will explore whether human error played any role in the performance of the infrastructure.

Have we found any errors in the design or construction of these systems?

We have not yet determined whether the failures were caused by errors in the design or construction of these systems, or by some other means. Our analysis will help establish the cause. We are examining the ability of the structures as designed to deal with the forces applied by the storm. Those forces in some cases may have been well beyond the design capacity. In other cases, the structure may not have performed as expected and we will determine why. Until we can relate the performance to the forces, with accepted engineering analysis, we are not comfortable speculating on the adequacy of a design.

What can these failures and the efforts to repair them tell us about the level of protection the remaining flood and hurricane protection systems provide to residents of New Orleans and the surrounding parishes?

The results of our study will provide a better indication of the extent to which the remaining system can be expected to reduce the risk of future storm damage. We will be examining and providing analysis on the performance of the entire storm damage reduction system, to understand the failures that occurred, to understand other components of the system that may have been degraded in their capacity to protect against future storms and to understand where the system performed successfully. We will be developing information on risk and reliability of the system as it will be after we complete repairs.

In conclusion, I want to caution against reaching conclusions to your very important questions before appropriate analysis is accomplished. Speculation concerning observed damage is one thing, but we are not yet in a position to understand why that damage occurred. I hope that my testimony illustrates the Corps' past and continuing commitment to the pursuit and use of sound science and engineering principles in the execution of our civil works missions.

On behalf of the Corps, thank you for allowing me the opportunity to present this testimony today.

Hurricane Katrina: Performance of the Flood Control System

Testimony of
Raymond B. Seed, Ph.D.
Professor of Civil and Environmental Engineering
University of California at Berkeley
On behalf of the
NSF-Sponsored Levee Investigation Team
Before the Committee on Homeland Security and Government Affairs
U.S. Senate
November 2, 2005

Madam Chairman and Members of the Committee:

Good morning. My name is Raymond Seed, and I am pleased to be asked to appear before you today to testify on behalf of the Levee Investigation Team sponsored by the U.S. National Science Foundation.

A large number of leading national and international experts with a tremendous amount of forensic experience in sorting through major disasters have worked very hard this past month, and I am pleased to be able to present you with the first copy of the preliminary report of the findings of the combined ASCE and NSF-sponsored field investigation teams.

I am very grateful for their tremendous efforts in getting this material ready for you today.

I. Katrina and the Flood Control System

Our hearts go out to the many who have lost everything, even in some cases their lives, in this catastrophic event. Our teams have had considerable previous experience in many other disasters, including numerous major earthquakes around the world, the recent Indian Ocean tsunami, floods and levee failures, the space shuttle Challenger disaster, and more. But we were not prepared for the level and scope of the devastation that we witnessed when we were in New Orleans.

It must be the intent of our work that something like this not be allowed to happen again.

With that in mind, and in our hearts, I must make it clear that we know a great deal about what happened, and in many cases why, and that it is my intent today to speak as openly as possible. Our team, to a man and to a woman, feel that the people of the New Orleans region, and the Nation, and our governments at all levels, need and deserve nothing less. Important decisions are being made that will affect people's lives for years to come. We recognize the importance of providing the best possible informed information, responsibly studied and professionally and thoughtfully synthesized, that we can at this early juncture. Better and more complete information will continue to evolve over the coming year, but that will be too late for many ongoing decisions being made right now, today.

Our preliminary report represents a consensus document, and it presents the initial observations and findings that we were able to agree to release with all the team members and organizations involved. If you will ask, I will do my best to answer questions well beyond the scope of our initial Preliminary Report.

II. Why Did the Levees and Floodwalls Fail?

This is a map of the central New Orleans region, prepared initially by the U.S. Army Corps of Engineers and then modified to reflect additional findings of our investigation teams. It shows the locations of many of the levee breaches that occurred, and serves as a good base map for our discussions today. Not shown on this map are the additional flood protection levee systems that extend down the lower reaches on the Mississippi River, providing a narrow additional protected corridor down to the Gulf.

The storm surges produced by Hurricane Katrina resulted in numerous breaches, and consequent flooding of approximately 75 percent of the metropolitan areas of New Orleans. Most of the levee and floodwall failures were caused by overtopping, as the storm surge rose over the tops of the levees and their floodwalls and produced erosion that subsequently led to failures and breaches.

Overtopping was most severe at the east end of the flood protection system, as the waters of Lake Borgne were driven west producing a storm surge on the order of 18 to 25 feet that massively overtopped levees immediately to the west of this lake. This photo shows one piece of a six mile section of levees at the northeast corner of the MRGO channel that were massively overtopped and eroded by this storm surge, which then sent floodwaters racing towards St. Bernard Parish. There is virtually nothing left of these levees along some parts of this stretch.

A very severe storm surge also occurred farther to the south, along the lower reaches of the Mississippi River, and significant overtopping produced additional breaches in this region as well. This photo shows homes that were carried across the narrow protected corridor in southern Plaquemines Parish by a breach on the west levee, and then thrown astride the crest of the Mississippi Riverfront levee.

Overtopping was lesser in magnitude along the Inner Harbor Navigation Channel and along the western portion of the MRGO channel, but the consequences of this overtopping were again severe. This overtopping again produced erosion and caused numerous additional levee failures. This photo shows the well known breach at the west end of the Ninth Ward. We spent some time figuring out the answer to the chicken and the egg question, and it is our preliminary opinion that the infamous large barge was drawn in through a breach that was already open.

Most of the failures in this central New Orleans area were the result of overtopping, and one of the common failure modes was simply water cascading over concrete floodwalls and then carving sharply etched trenches at the back sides of these walls. This reduced the lateral support at the back sides of the walls, and left them vulnerable to the high water forces on their outboard faces.

Another repeated mode of failure and distress throughout this central region were problems at "transition" sections where two different levee and/or wall systems joined together. There is a need to better coordinate these connections, and their details.

Farther to the west, in the East Bank Canal District, three levee failures occurred along the banks of the 17th Street and London Avenue Canals, and these failures occurred at water levels below the tops of the floodwalls lining these canals. These three levee failures were likely caused by failures in the foundation soils underlying the levees, and a fourth "distressed" levee/floodwall segment on the London Avenue Canal shows signs of having neared the occurrence of a similar failure prior to the water levels having receded. This photo shows the north breach at the London Canal. The section directly across the canal, on the east bank, was very seriously distressed and also requires remediation before it can safely hold high waters again.

III. The Road Forward

Major repair and rehabilitation efforts are underway to prepare the New Orleans flood protection system for future high water events. The next hurricane season will begin in June of 2006. Preparing the levees for the next hurricane season, however, should also include a review of how the system performed during Hurricane Katrina, so that key lessons can be learned and then used to improve the performance of the system.

Based on our observations, a number of initial comments are warranted concerning the rebuilding and rehabilitation of the levee system.

Although it is somewhat customary to expect levee failures when overtopping occurs, the performance of many of the levees and floodwalls could have been significantly improved, and some of the failures likely prevented, with relatively inexpensive modifications of the levee and floodwall system details. The addition of overtopping erosion protection at the landside toes of the floodwalls through the provision of rip-rap, concrete splash slabs, or even paving of the ground surface at the inboard faces of the levee crest floodwalls might have been effective in reducing this erosion, and might have prevented some of the failures observed.

As the New Orleans regional flood protection system is now being repaired and rebuilt, it would appear advantageous to plan crest heights in a systematic and deliberate way, so that if and when overtopping does occur, it occurs preferentially at the desired locations along any given section of levee/floodwall frontage. Similarly, the transitions between disparate levee/floodwall sections (e.g.: transitions between earthen levees, sheetpiles, and/or concrete wall sections) should be more robustly designed and constructed so that these transitions do not represent locations of potential weakness in otherwise contiguous perimeter flood protection system.

Areas in which piping erosion occurred, including reported instances of piping along the MRGO frontage, suggest that there are areas of foundation that were weakened to a state worse than "pre-Katrina" conditions. Similarly, there may be additional sections like the west bank across from the North breach on the east side of the London Avenue Canal that were distressed (but did not fully breach) and are in need of remedial work. It is important to remember to check, and to repair as necessary, levee sections that may have been damaged but that did not fail as part of the current repair operations.

Levees are "series" systems, where the failure of one component (one levee segment) means failure of the whole system. They have less redundancy than many other engineered systems. And the consequences of failure are high. The failure of at least several levees at less than their design water height in this hurricane warrants an overall review of the design of the system.

In the short-term, as interim levee repairs continue, consideration should be given to retaining the use of sheetpiles placed against the bridges at the north ends of the 17^{th} Street and London Avenue canals to control storm and tidal surges. Until the levees in these canals are more fully repaired or more permanent canal surge check structures are emplaced, having the ability to rapidly prevent storm surges down these canals is still needed.

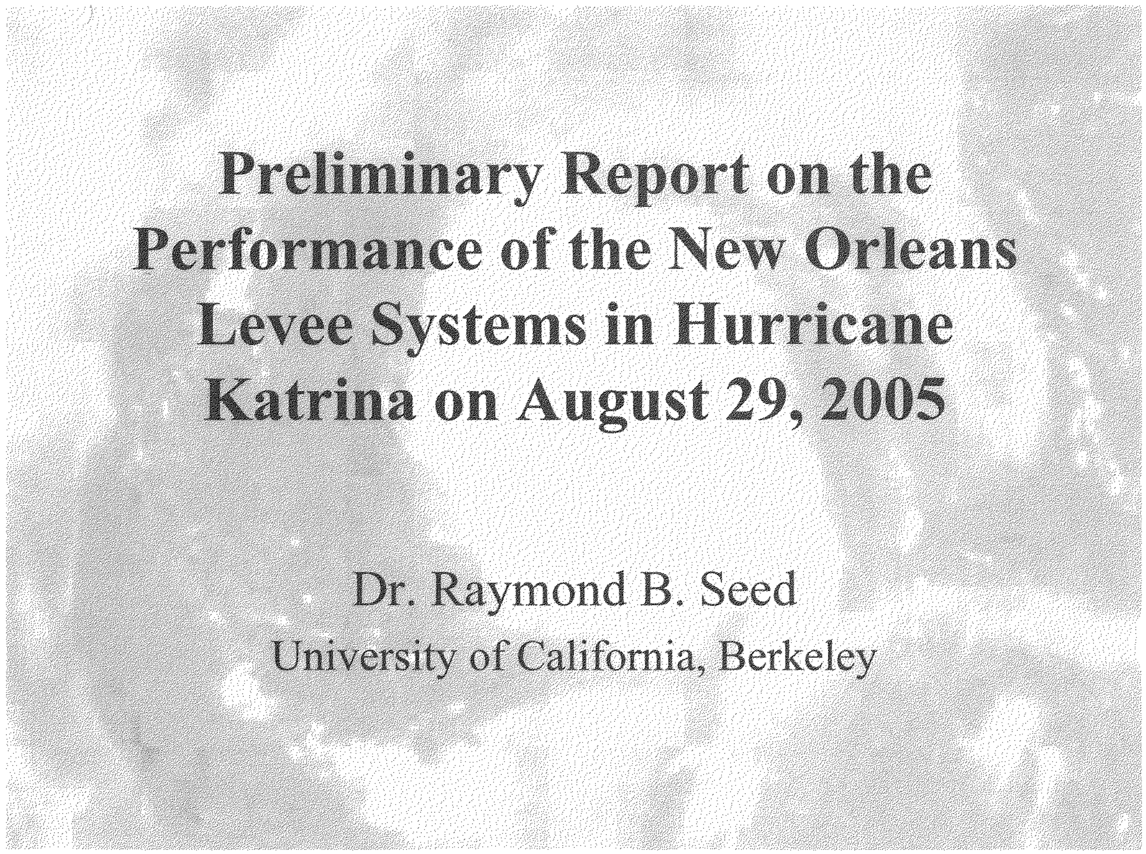
The USACE, like other public agencies, commonly uses Independent Boards of Consultants to review the adequacy of the design and construction (and remediation) of major dams. The levee system in New Orleans actually protects more life and property than almost any major dam in the United States. We recommend that the Corps should retain an Independent Board of Consultants to review the adequacy of the interim and permanent levee repairs being carried out in the aftermath of Hurricane Katrina.

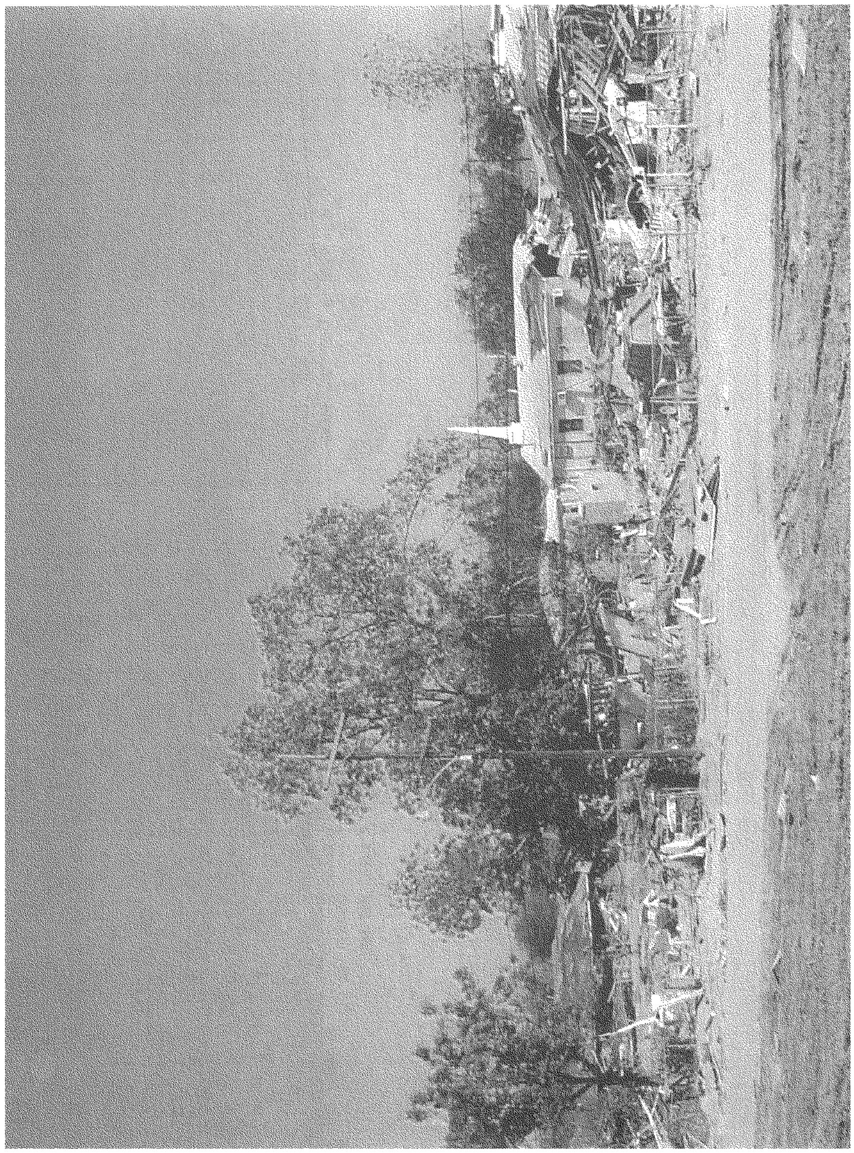
The U.S. Army Corps of Engineers are stretched very thin right now, trying to respond and effect emergency and interim repairs in the wake of this catastrophe. It must be the job of the Federal government, and oversight committees such as this one, to ensure that they have the resources and technical capabilities to get their job done safely and well. The Corps have responsibility for many potentially high hazard dams and levee systems, and we must be able to have high confidence in their ability to perform these vital tasks.

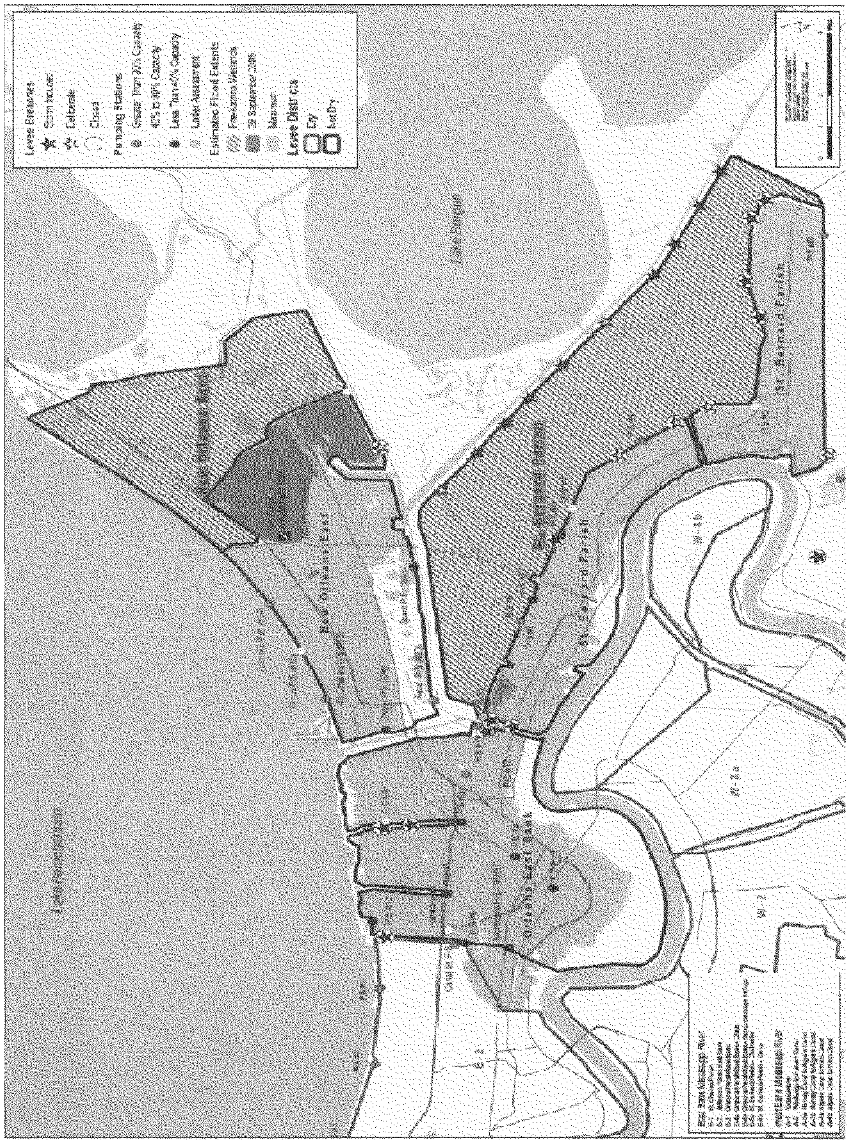
The ASCE and NSF-sponsored levee assessment team(s) have already been instrumental in providing insights and recommendations for mitigating potentially serious deficiencies in the temporary/emergency repairs at a number of breached sections. It is anticipated that additional important lessons will be learned in the months ahead as these investigations continue, and that some of these lessons are also likely to be useful in moving forward with the ongoing repair and long-term rebuilding of the New Orleans regional flood protection systems. Such lessons will continue to be passed along as quickly as practicable.

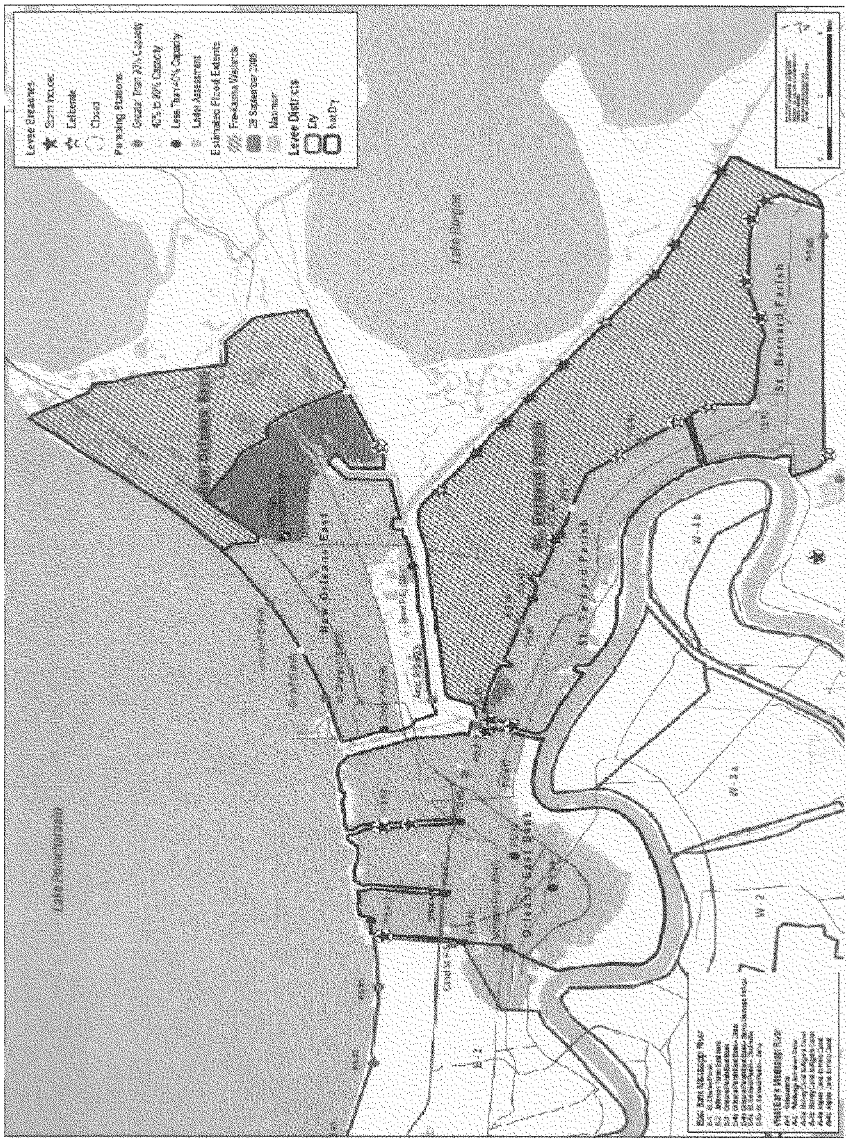
As much of the population is currently being permitted to re-occupy portions of the New Orleans area, doing everything possible to ensure the safety of these people and their neighborhoods must continue to be the highest priority.

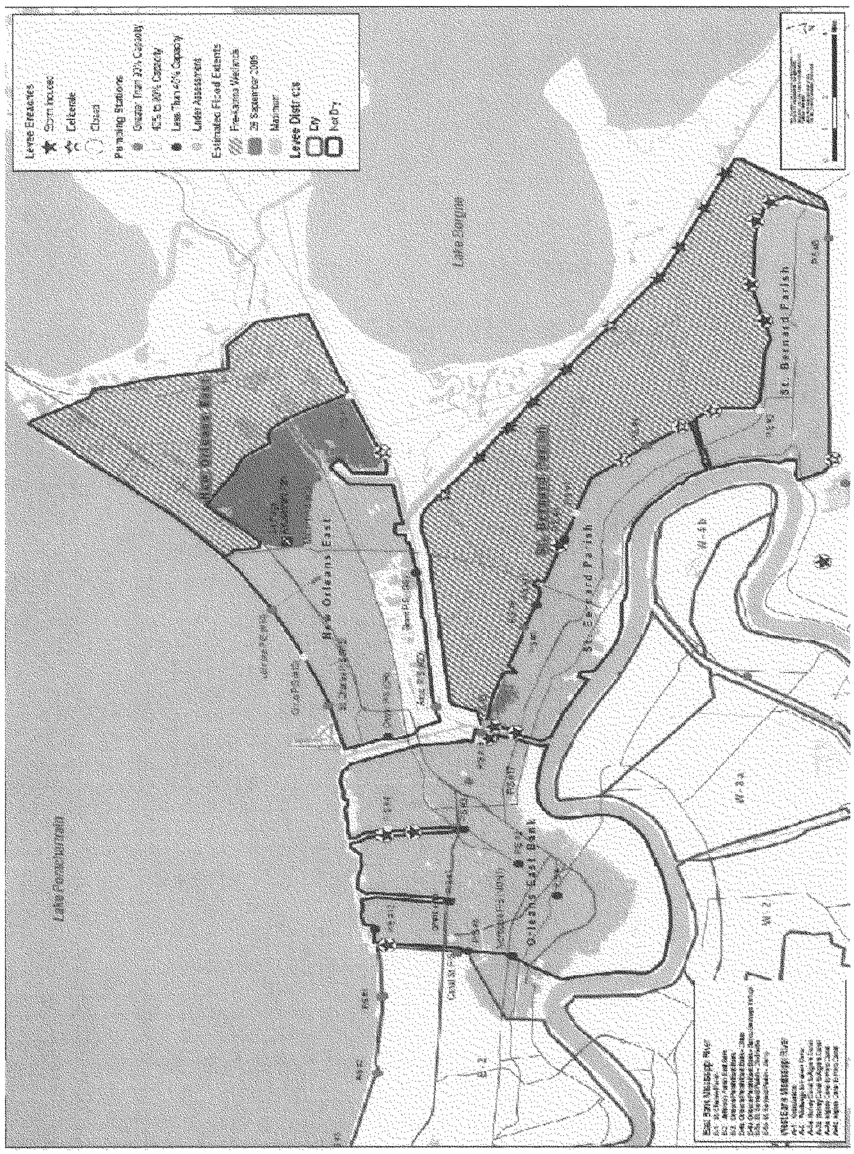
This concludes my testimony. Thank you.

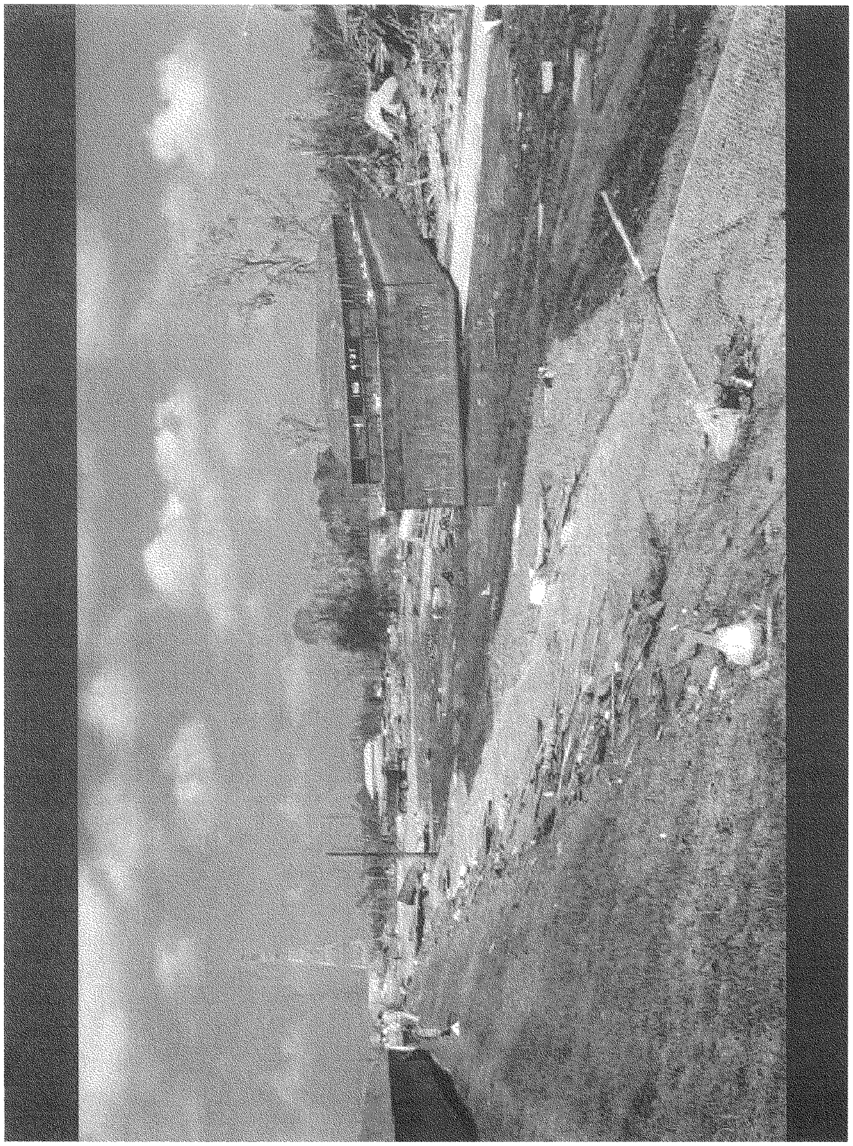

Preliminary Report on the
Performance of the New Orleans
Levee Systems in Hurricane
Katrina on August 29, 2005
Dr. Raymond B. Seed
University of California, Berkeley

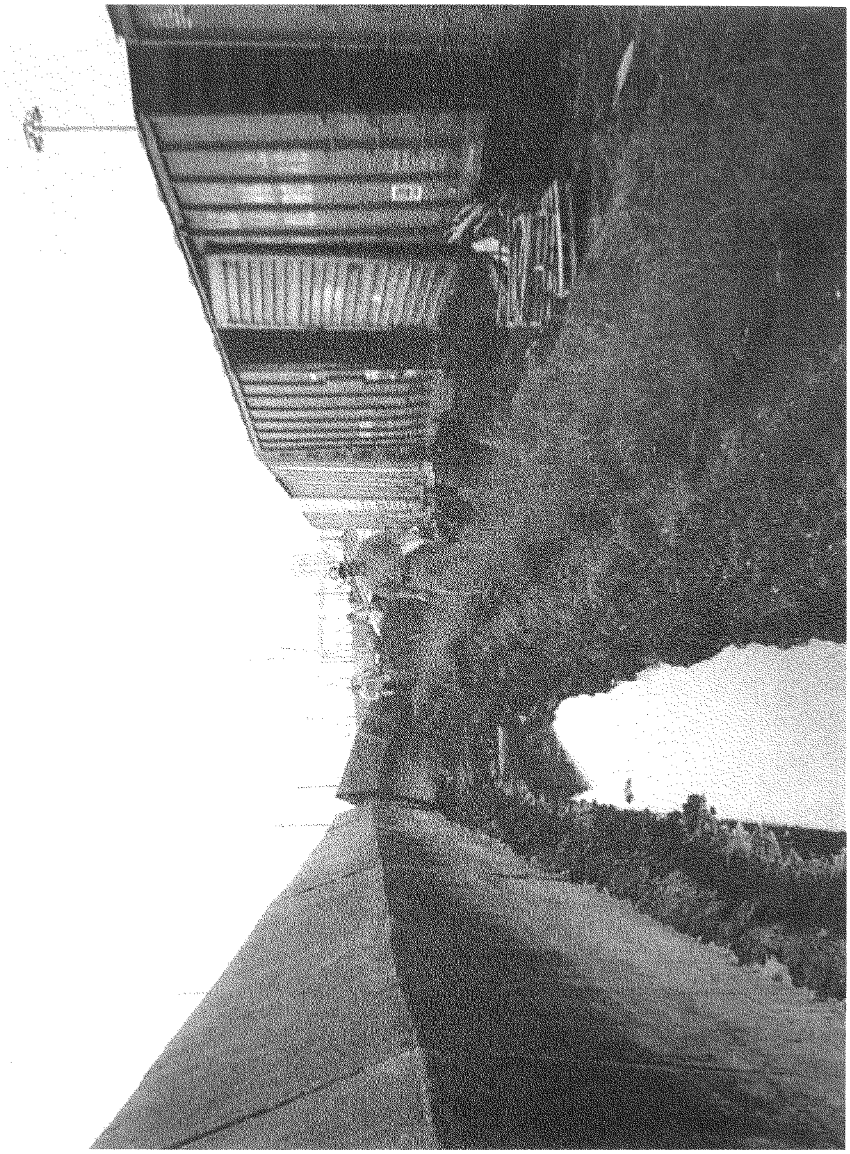


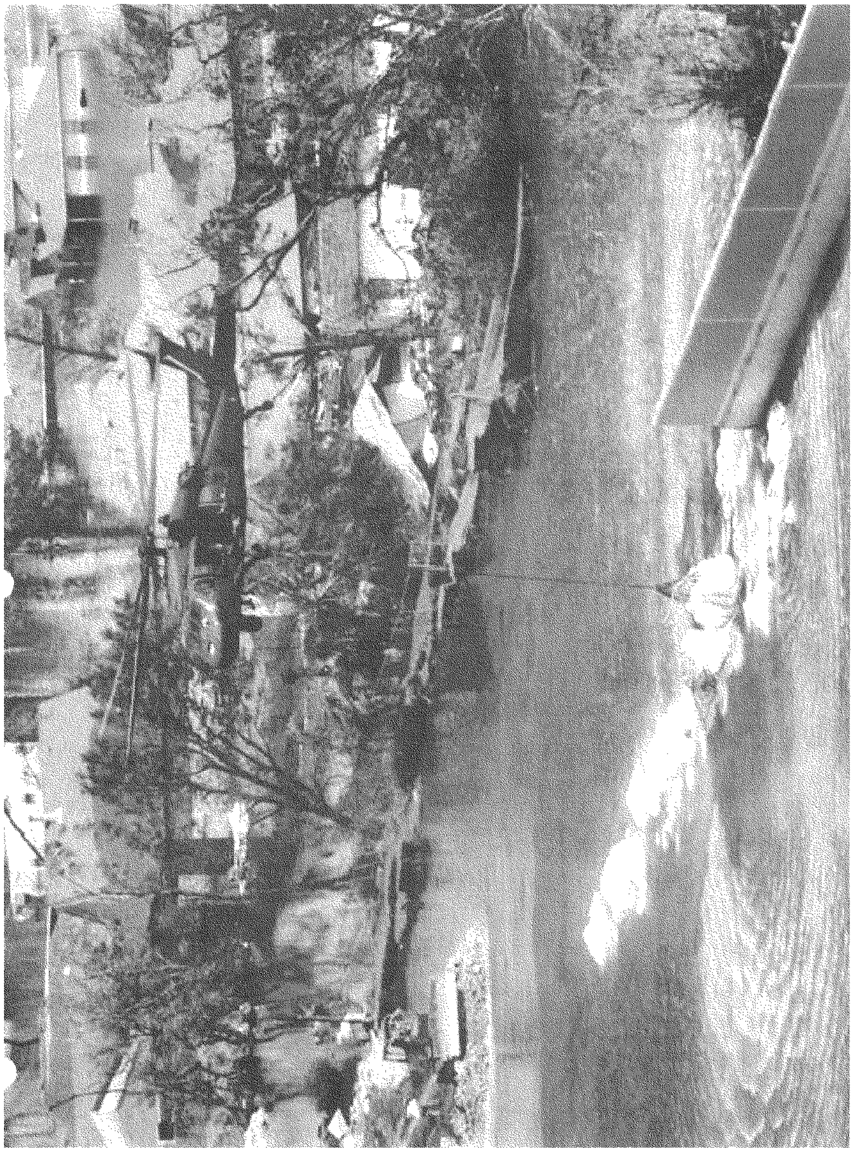

Levee Breaches
Pumping Stations
Estimated Flood Extents
Levee Districts
Dry
Not Dry
Lake Pontchartrain
Lake Borgne
New Orleans East
Orleans East Bank
St. Bernard Parish


Levee Breaches
Storm Induced
Deliberate
Closed
Pumping Stations
Estimated Flood Extents
Levee Districts
Dry
Not Dry
Lake Pontchartrain
Lake Borgne
New Orleans East
St. Bernard Parish
Orleans East Bank


Levee Breaches
Pumping Stations
Estimated Flood Extents
Levee Districts
Dry
Not Dry
Lake Pontchartrain
Lake Borgne
New Orleans East
St. Bernard Parish
Orleans East Bank







ASCE
American Society of Civil Engineers

Washington Office
101 Constitution Ave., N.W.
Suite 375 East
Washington, DC 20001
(202) 789-7850
Fax: (202) 789-7859
Web: http://www.asce.org

Hurricane Katrina: Why Did the Levees Fail?

Testimony of

Peter Nicholson, Ph.D., P.E.

Associate Professor of Civil and Environmental Engineering and Graduate Program Chair

University of Hawaii

On behalf of the

AMERICAN SOCIETY OF CIVIL ENGINEERS

Before the

Committee on Homeland Security and Governmental Affairs

U.S. Senate

November 2, 2005

Hurricane Katrina: Why Did the Levees Fail?

Testimony of
Peter Nicholson, Ph.D., P.E.
Associate Professor of Civil and Environmental Engineering and Graduate Program Chair
University of Hawaii
On behalf of the
AMERICAN SOCIETY OF CIVIL ENGINEERS
Before the
Committee on Homeland Security and Governmental Affairs
U.S. Senate
November 2, 2005

Madame Chairman and Members of the Committee:

Good morning. My name is Peter G. Nicholson, and I am pleased to appear before you today to testify on behalf of the American Society of Civil Engineers[1] (ASCE) as you examine the effect of Hurricane Katrina on the infrastructure of coastal Louisiana, particularly the levee system that protects the city of New Orleans.

I am a member of ASCE and the chair of the ASCE Geo-Institute's Committee on Embankments, Dams and Slopes. I was asked by ASCE to assemble an independent team of experts to travel to New Orleans to collect data and make observations to be used to assess the performance of the flood control levees.

As engineers, our paramount concern is for the safety, health and welfare of the public. We believe there is a tremendous opportunity to learn from the tragedy of New Orleans to prevent future loss of life and property.

The purpose of our site visit was to make observations and gather information about the failure of the levees, including that data that would be lost ("perishable data") during the process of levee repair and the passage of time. This included evidence such as high water marks and indicators of overtopping, and evidence of any foundation movement or failure.

---

[1] ASCE, founded in 1852, is the country's oldest national civil engineering organization. It represents more than 139,000 civil engineers in private practice, government, industry, and academia who are dedicated to the advancement of the science and profession of civil engineering. ASCE carried out Building Performance Assessments of the World Trade Center, the Pentagon and the Murrah Federal Building, and its technical assessments following earthquakes, hurricanes, and other natural disasters. The New Orleans levee technical group includes representatives appointed by the ASCE Geo-Institute and ASCE Coasts, Oceans, Ports, and Rivers Institute. ASCE is a 501(c) (3) non-profit educational and professional society.

One of the goals of the assessment team was to gather data in an attempt to determine why certain sections of the levee system failed and why others did not. These determinations may help to answer the question of whether the failures were caused by localized conditions or whether surviving sections of the system may be only marginally better prepared to withstand the type of loads that were generated by this event.

Following the first week in the field gathering data, we presented a press release on October 7, 2005, describing our initial observations concerning the performance of the levee system during and after Hurricane Katrina. We believe that our joint team knows, at least in principal, how the levees in New Orleans failed; the exact details await further analyses.

I. ASCE New Orleans Levee Assessment Team

The team assembled consisted of professional engineers from ASCE with a range of geotechnical engineering expertise in the study, safety and inspection of dams and levees. While in New Orleans and the surrounding areas, we examined levee failures as well as distressed and intact portions of the levee system between September 29 and October 15.

Our levee team was joined by another ASCE team of coastal engineers, including two colleagues from the Netherlands and Japan, both countries challenged by their geography to design against natural disasters from the sea, and another team primarily from the University of California, Berkeley, under the auspices of the National Science Foundation. Our three teams were joined by a U.S. Army Corps of Engineers' Engineering Research and Development Center (ERDC) team, led by Dr. Paul Mlakar. We would like to thank Dr. Mlakar and the ERDC team for their logistical support.

II. Observations by Sites and Areas

What we found in the field was very different than what we had expected, given what we had seen in the media reports. Rather than a few breaches through the floodwalls in the city caused largely by overtopping, we found literally dozens of breaches throughout the many miles of levee system. A number of different failure mechanisms were observed, including scour erosion caused by overtopping, seepage, soil failure, and piping.[2] As geotechnical engineers, we were particularly interested to find that many of the levee problems involved significant soil-related issues.

A. 17th Street Canal

At the 17th Street Canal breach, we observed intact soil blocks that had experienced large translation and heave. This movement would be consistent with a failure either of

[2] Piping, sometimes referred to as internal erosion, is a channel caused by the flow of water through a dam or embankment. It may increase rapidly and cause catastrophic failure of the embankment.

the soil embankment or the foundation soils beneath. There was no evidence of overtopping at this site. While we cannot yet determine conclusively the cause of the breach itself, this type of soil failure may well have been a significant contributing factor. Further investigation, together with analyses and review of the design and construction documents, should be of tremendous assistance in ultimately making these kinds of determinations.

B. London Avenue Canal – North

At the north breach on the London Avenue Canal, we observed a large displaced soil mass, which had been heaved nearly vertically over six feet, apparently indicating the toe of a rotational-type soil failure. Again, there was no evidence of overtopping at this site. Field inspection also showed a large amount of sandy soil deposited in the neighborhood landward of the breach, which is believed to be material from the foundation beneath the embankment together with material scoured from the canal bottom. This is consistent with the soil profiles provided to us which showed sand in the subsurface near this location. Under high water pressure, the flow through this type of material can be significant, which is known to cause internal stability problems.

C. London Avenue Canal – North, Across from Breach

Of particular interest was the levee section almost directly across from the north breach on the London Avenue Canal, where we observed a floodwall and underlying embankment that was in severe distress.

This site provided an excellent case study demonstrating multiple, concurrent failure mechanisms. It was observed that this section of floodwall was distressed to the point that it appeared that it might have been approaching failure when the water loading was relieved as the other breaches occurred. The wall was badly out of alignment and tilting landward; as a result of the tilt, there were gaps between the wall and the supporting soil on the canal or waterside. Also observed were evidence of soil movement, seepage and piping, as indicated by a series of sinkholes near the crest, together with "boils"[3] and heave at or near the inboard toe[4] of the embankment.

D. London Avenue Canal – South

To the south was another breach on the London Avenue Canal. That breach had apparently cut so deeply that huge volumes of sandy material had been scoured from the canal bottom and then deposited up to five feet deep extending hundreds of feet into the neighborhood. Very little evidence remained to be gathered at this site and the causes and mechanisms of the breach may never be known. It was, however, again

---

[3] A boil (or "blow") is a flow of soil, usually in the form of fine sand or silt, into the bottom of an excavation. The flow is forced in by water or water and air under pressure. It may increase rapidly and cause catastrophic failure.

[4] The toe is the base of the slope (in the case of dam or levee) on the side away from the water.

demonstrated by high water marks that the floodwall most likely was not overtopped at this location.

E. Outside New Orleans
It is important that the impact of the levee breaches outside of the city of New Orleans not be overlooked. Many sections of the system were severely tested by overtopping from a direct onslaught of the storm surge. Many portions of these levees were breached or severely distressed, causing severe flooding and, in many cases, complete destruction of thousands of neighborhood homes. Some of the levee sections were nearly obliterated and were observed to have been constructed of highly erodable materials.

III. Hurricane Katrina: Why Did the Levees Fail?

A. The Levee Failures
Hurricane Katrina was a catastrophic storm that made landfall in the Gulf Coast near the Louisiana and Mississippi border with wind speeds near 150 mph. But the damage in New Orleans due to the high winds and rain paled in comparison to the devastation resulting from the flooding.

The hurricane produced a storm surge that varied considerably depending on location, including the combined effects of orientation, geography, and topography with respect to the forces of the passing storm. Hydraulic modeling of the surge, verified by the most part by our own field observations of high water marks, show that essentially two significantly different levels of storm surge impacted the levee system.

As the storm passed to the east of New Orleans, the counterclockwise "swirl" of the storm generated a large surge from the Gulf of Mexico and Lake Bourne that impacted the eastern facing coastal areas of the New Orleans area and lower Mississippi delta. The surge was then concentrated into the channels of the Mississippi River Gulf Outlet (MRGO) that fed into the Inner Harbor Navigational Channel (IHNC). The funneling of the surge in these channels resulting in widespread overtopping of the levees.

In contrast, a somewhat separate surge that originated in Lake Pontchartrain was generated in part by the flow in from the Gulf of Mexico but also from the north winds across the lake. As shown by the models and field evidence, this surge, which impacted the lakefront and three canals within the central part of the city, was notably less severe. Field data indicated that the surge levels from the lake did not reach the elevation of the lakefront levees and was well below the top height of the floodwalls bordering the interior canals where three notable breaches occurred.

Where the storm surge was most severe, causing massive overtopping, the levees experienced a range of damage from complete obliteration to intact with no signs of distress. Much of the difference in the degree of damage can be attributed to the types of levees and the materials used in their construction. The majority of the most heavily damaged or destroyed earthen levees that we inspected were constructed of sand or "shell fill" which was easily eroded.

At some of these locations the earthen embankments were simply gone. Those with embedded sheetpiles faired only marginally better and were often breached as well. Further inland, in the western portion of the MRGO and along the Inner Harbor Navigation Canal, the degree of overtopping was less severe but again resulted in a number of breaches. Many of these breaches occurred through I-wall structures that were severely scoured on the landside as a result of overtopping. These scour trenches undermined the support of the levee floodwalls and reduced the ability of the walls to withstand the forces of the water on their outer surfaces. Localized concentrations of overtopping water flow or possible localized weaker soils may have been responsible for why certain portions of the system were breached while others remained intact.

Another commonly observed problem was the frequent presence of "transitions" between different sections of the levees. There were a number of different types of these transitions that appeared to have caused problems, including inconsistent crest heights, change in levee type (I-wall vs. T-wall), change in material (concrete, steel sheetpile, earth), and transitions where certain rights-of-way resulted in penetrations of the flood control system.

Where levees were overtopped, the weaker material at the point of transition (i.e., earth to concrete, sheetpile to concrete, earth to sheetpile) would be more susceptible to failure. Many of the problems we observed appeared to have been related to transition details and were often exacerbated by inconsistent crest heights, particularly where the weaker material had the lower height. Many of these transitions were found at sections where infrastructure elements designed and maintained by multiple authorities, and their multiple protection elements, came together, and the weakest (or lowest) segment or element controlled the overall performance.

Finally, three major breaches, and at least one significantly distressed levee-floodwall section, were investigated at sites along the 17th Street and London Avenue canals which, as explained before, were clearly not overtopped.

Obvious soil failures within the embankment or foundation soils at or below the bases of the earthen levees had occurred at two of the breaches. At the distressed section, seepage and piping were evident. These types of soil instabilities appear likely to have been responsible for failure of these wall systems.

Evidence of piping erosion at one these sites serves to illustrate the severity of the underseepage at high water stages. Another possibility that also needs to be investigated, however, is the potential presence of a weak soil unit (either within the lower embankment, or in the underlying foundation soils) with sufficiently low shear strength that it may have failed.

Additional studies will need to be performed at these breached and distressed locations to better determine embankment and foundation soil conditions, and appropriate seepage flow and shear strength characteristics, so that the mechanisms that led to the observed failures at these sites can be conclusively determined.

B. Recommendations

Preparing the levees for the next hurricane season should include a review of how the system performed during Hurricane Katrina, so that key lessons can be learned to improve the performance of the system. Based on our observations, a number of initial comments are warranted concerning the rebuilding and rehabilitation of the levee system.

While levee failures may be expected when overtopping occurs, the performance of many of the levees and floodwalls may have been significantly improved, and some of the failures likely prevented, with relatively inexpensive modifications of the levee and floodwall system.

The following specific points need to be dealt with in New Orleans:

- The levees need additional overtopping protection at the inboard sides of the floodwalls to minimize erosion.

- Crest heights of the levees need to be planned in a systematic and deliberate way, so that if and when overtopping does occur, it occurs preferentially at the desired locations along any given section of levee's floodwall frontage where the walls are more robust or designed to better resist overtopping.

- Transitions should be improved so that they do not represent locations of potential weakness in otherwise contiguous perimeter flood protection systems.

In addition, larger issues should be addressed as well.

- ASCE believes that Congress should enact a National Levee Inspection and Safety Program modeled on the successful National Dam Safety Program. The levee program should include a national inventory of levees, particularly those that protect large, heavily populated urban areas.

- ASCE supports the efforts to reduce coastal land loss in the Louisiana coastal area, an area that has been named America's Wetland because of its national importance. ASCE urges continued support of the existing program for Louisiana coastal wetlands, funded by the Coastal Wetlands Planning, Prevention, and Protection Act (CWPPPA). ASCE also supports the ongoing effort to implement the comprehensive Louisiana Coastal Area (LCA) Program, which will further reduce land loss and provide additional preservation.

- We must discourage new development in the floodplain unless there is a pressing need for it and adequate protection can be provided. Population centers must be given a higher level of protection than most now have.

- We must use all the tools available to reduce damages. This means use of not only structural means such as levees, floodwalls, and dams, but also non-structural approaches such as flood resistant design, voluntary relocation of homes and businesses, revitalization of wetlands for storage, and use of natural barriers such as the Louisiana wetlands.

- Congress needs to consider seriously whether to establish a more stringent national flood control policy that emphasizes the need to protect human life from a 500-year flood.[5]

- The American Society of Civil Engineers (ASCE) believes Congress should establish an independent advisory panel to envision the future of the Gulf Coast and to recommend ways to begin the rebuilding of the areas that were devastated by Hurricane Katrina on August 29. The panel should consist of technical experts from a number of disciplines who would provide an objective review of all design and construction issues relating to the reconstruction of the areas covered by the President's major disaster declarations for Louisiana, Mississippi, and Alabama. The unpaid body would cooperate with and advise all federal, state, and local agencies involved in the reconstruction effort in the affected region.

  As we see it, the Advisory Group charter would:

- Work as the primary advisor to all state and local governments on the rebuilding of the region, with the primary goal of helping hundreds of thousands of present and future residents of the areas to enjoy a secure and prosperous future.
- Consist of experts from engineering, architecture, urban planning, and other design and construction-related fields.

---

5 A 500-year-flood is so big and rare that it will normally happen only once every 500 years. That doesn't mean that a 500-year-flood can't happen the year after a 500-year-flood. Every flood season has exactly the same chance—one in 500—of producing a 500-year-flood, even in area that experienced a 500-year-flood the season before. In other words, it is the flood that has a 0.2 percent chance of occurring every year. A 100-year flood, on the other hand, is used by the National Flood Insurance Program as the standard for floodplain management and to determine the need for flood insurance. A 100-year flood is based on a one percent chance of a flood's occurring in a given year.

- Develop recommendations that would include strategies to minimize the impact of future storm events and other natural hazards.
- Provide expert advice on the design and construction of the region's damaged public facilities, including port and harbor installations; lifelines; wastewater and drinking-water plants; airports and airfields; waste-management and disposal facilities; mass transit and public transportation services; roads, bridges, and tunnels; public buildings; and other key infrastructure.
- Ensure that the reconstruction efforts take into account the latest technologies in the prevention and mitigation of future harm to public and private buildings from severe windstorms and floods.
- Serve as link to federal agencies working in support of the reconstruction effort.
- Function in an advisory capacity only, having no authority to mandate particular design, construction, or environmental solutions.

IV. Conclusion

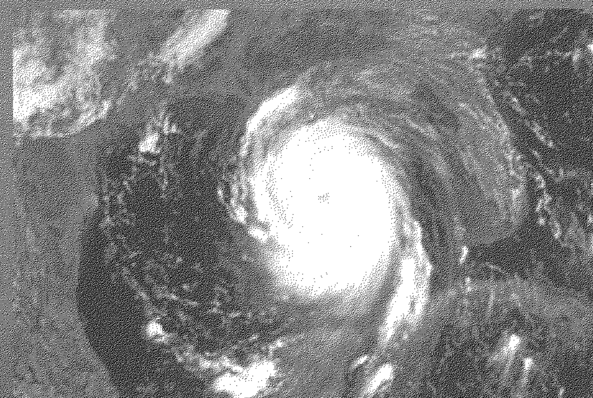
Other potentially important lessons will be learned in the months ahead, and that some of these are also likely to be useful in moving forward with the ongoing repair and long-term rebuilding of the New Orleans regional flood protection systems.

As much of the population is currently being permitted to re-occupy portions of the New Orleans area, doing everything possible to ensure the safety of these people and their neighborhoods must continue to be the highest priority.

Madame Chairman, this concludes my testimony this morning. I would be pleased to answer any questions you may have.

# # #

Performance of the New Orleans Flood Control System: Hurricane Katrina

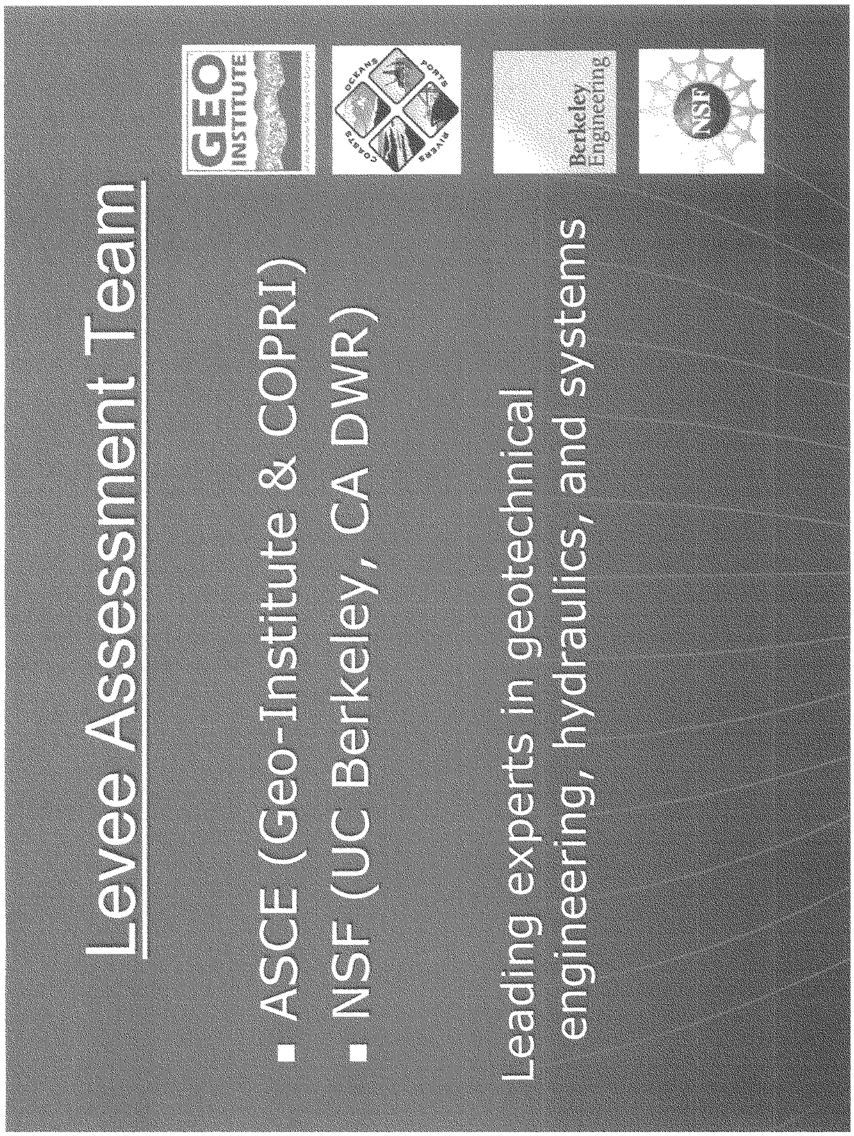


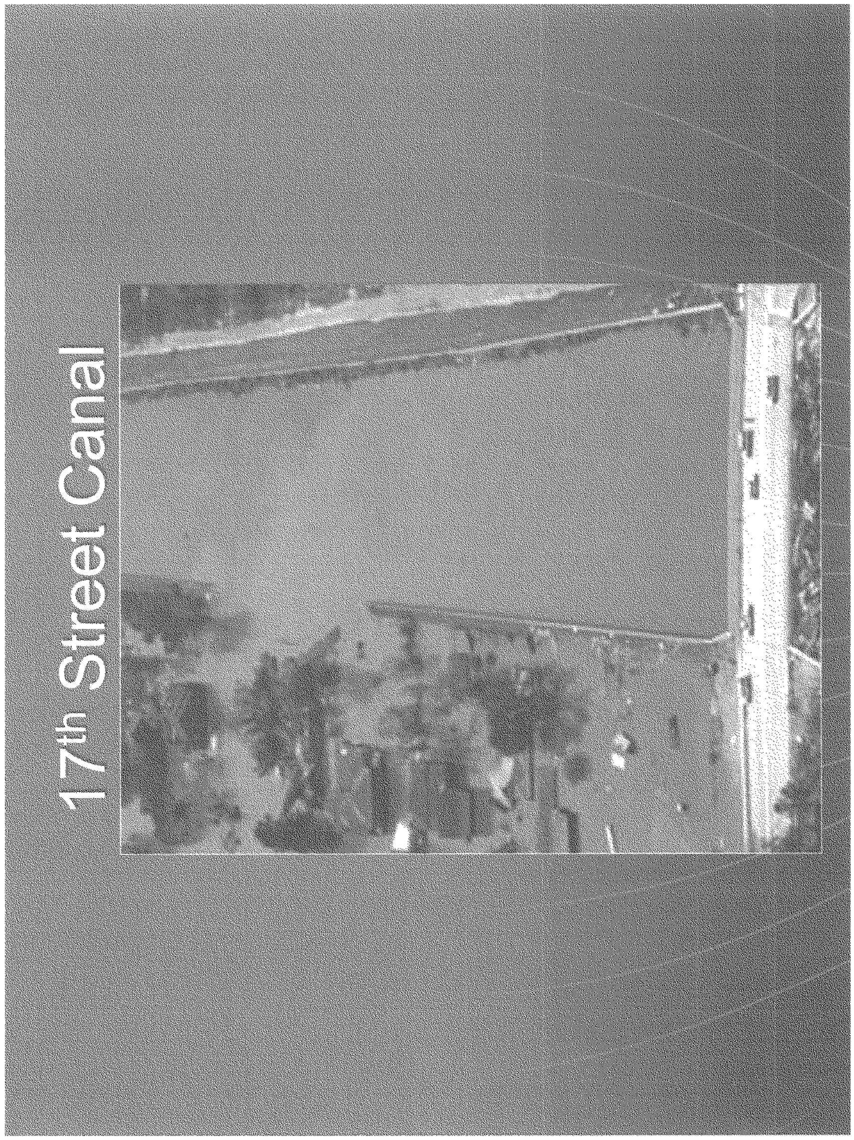
http://www.noaanews.noaa.gov/stories2005/s2506.htm

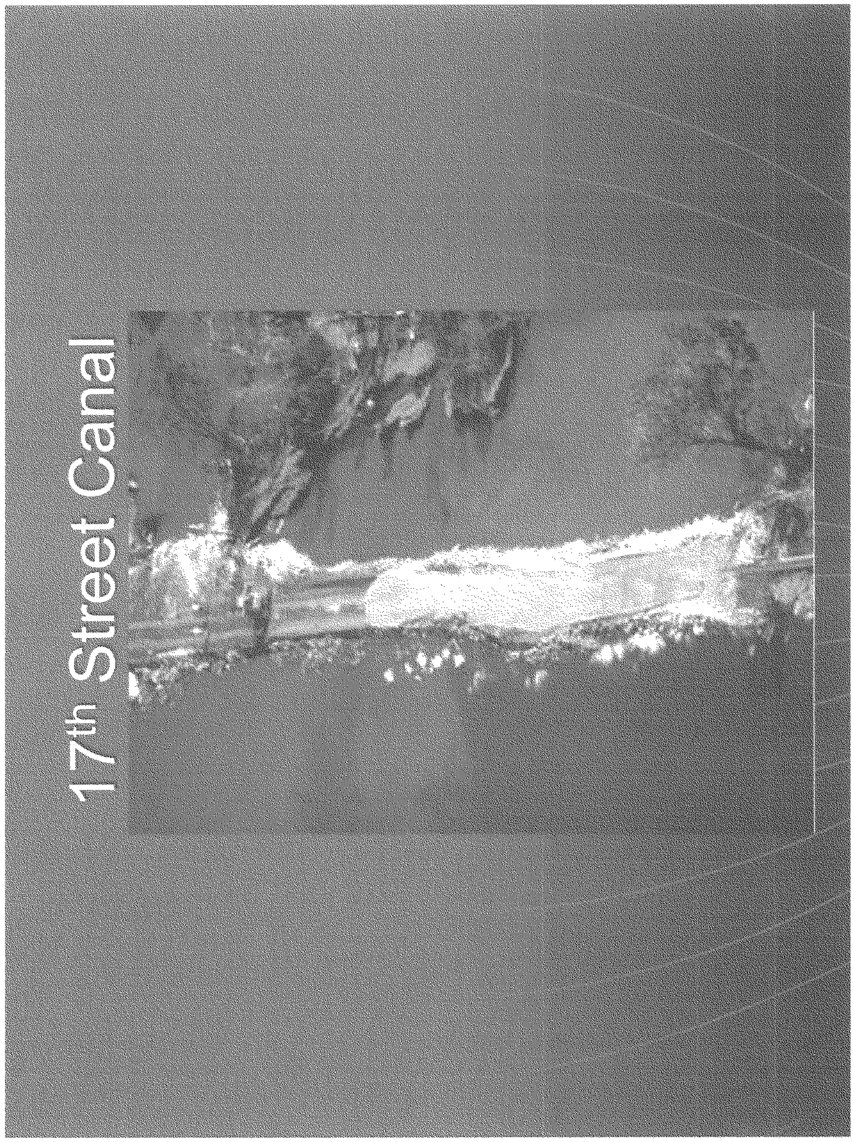
Presented to the Senate Committee on Homeland Security and Governmental Affairs

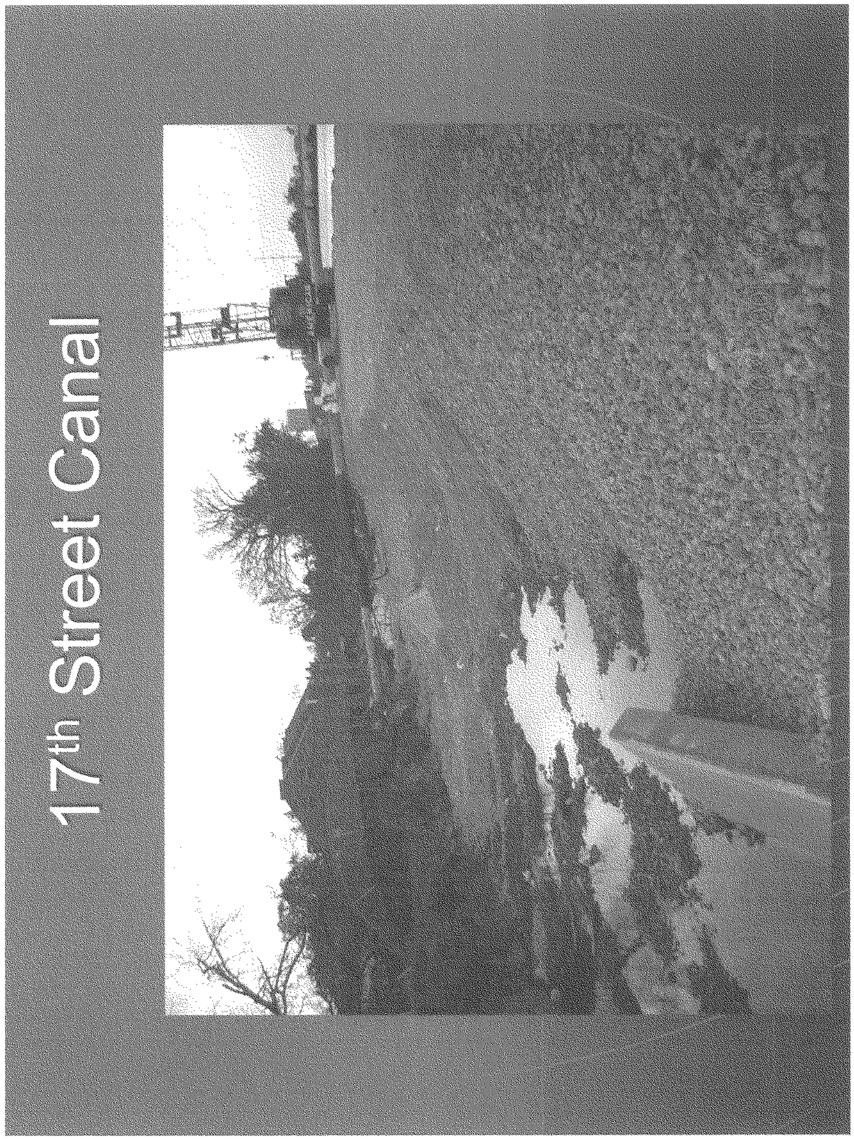
November 2, 2005

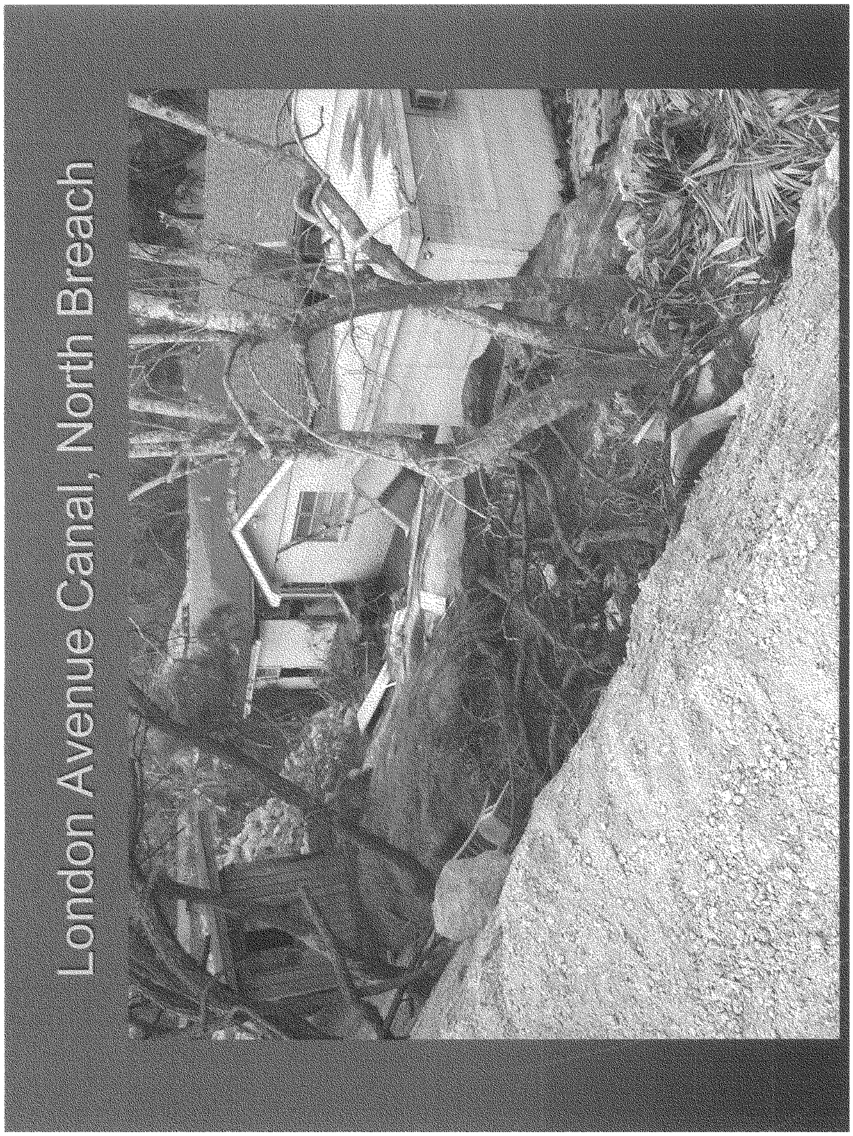
Washington DC

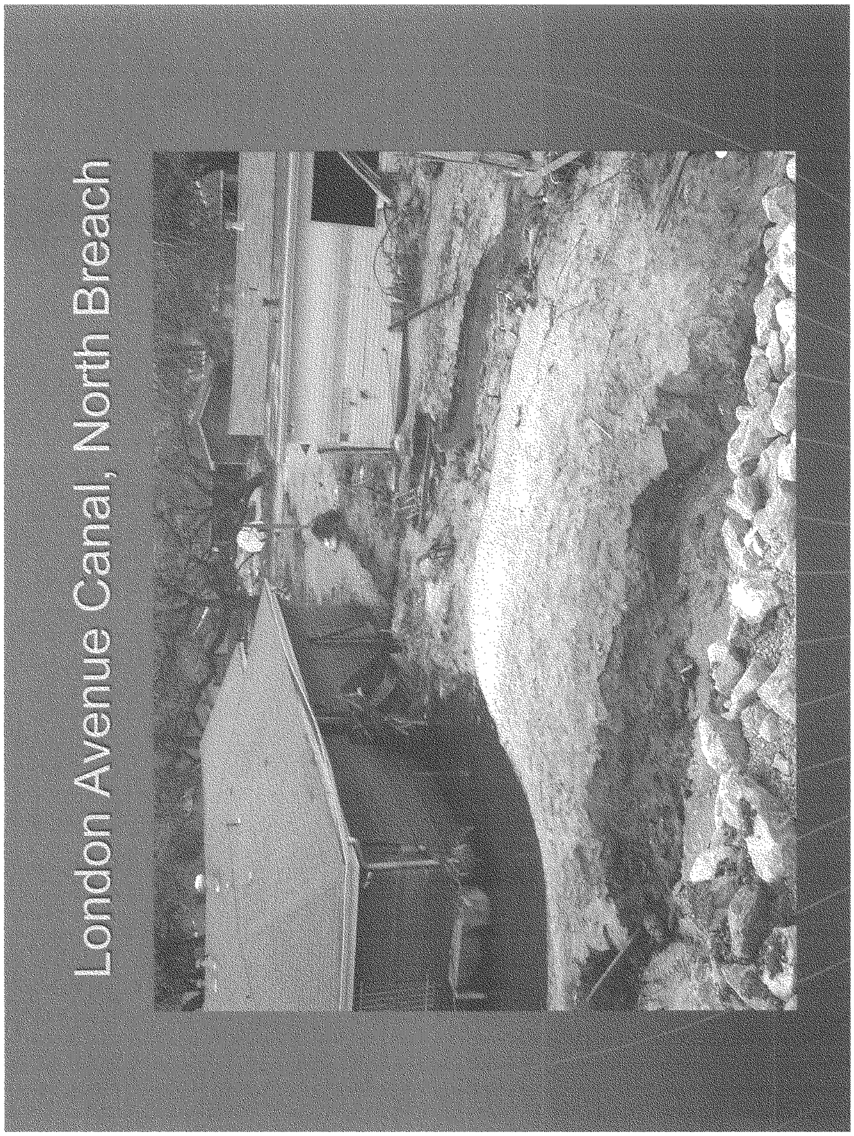

Levee Assessment Team
ASCE (Geo-Institute & COPRI)
NSF (UC Berkeley, CA DWR)
Leading experts in geotechnical engineering, hydraulics, and systems
GEO INSTITUTE
OCEANS PORTS RIVERS COASTS
Berkeley Engineering
NSF

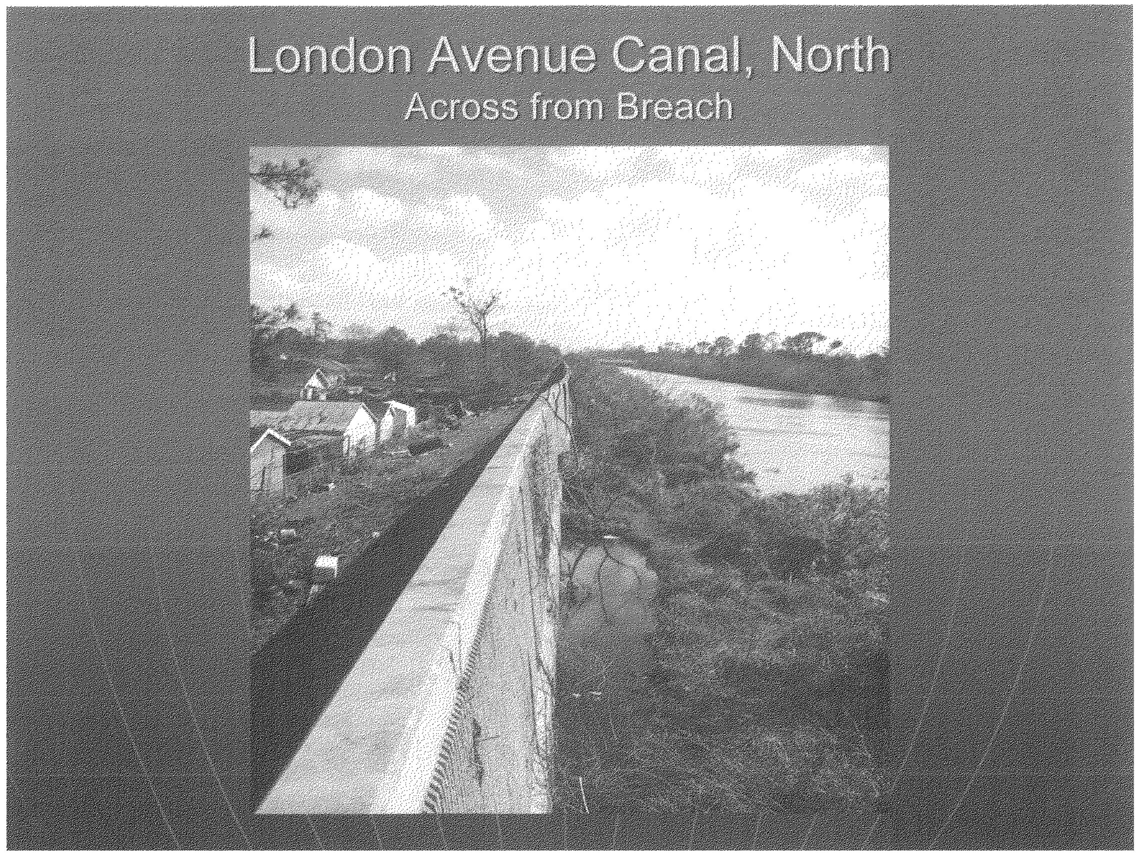

17th Street Canal

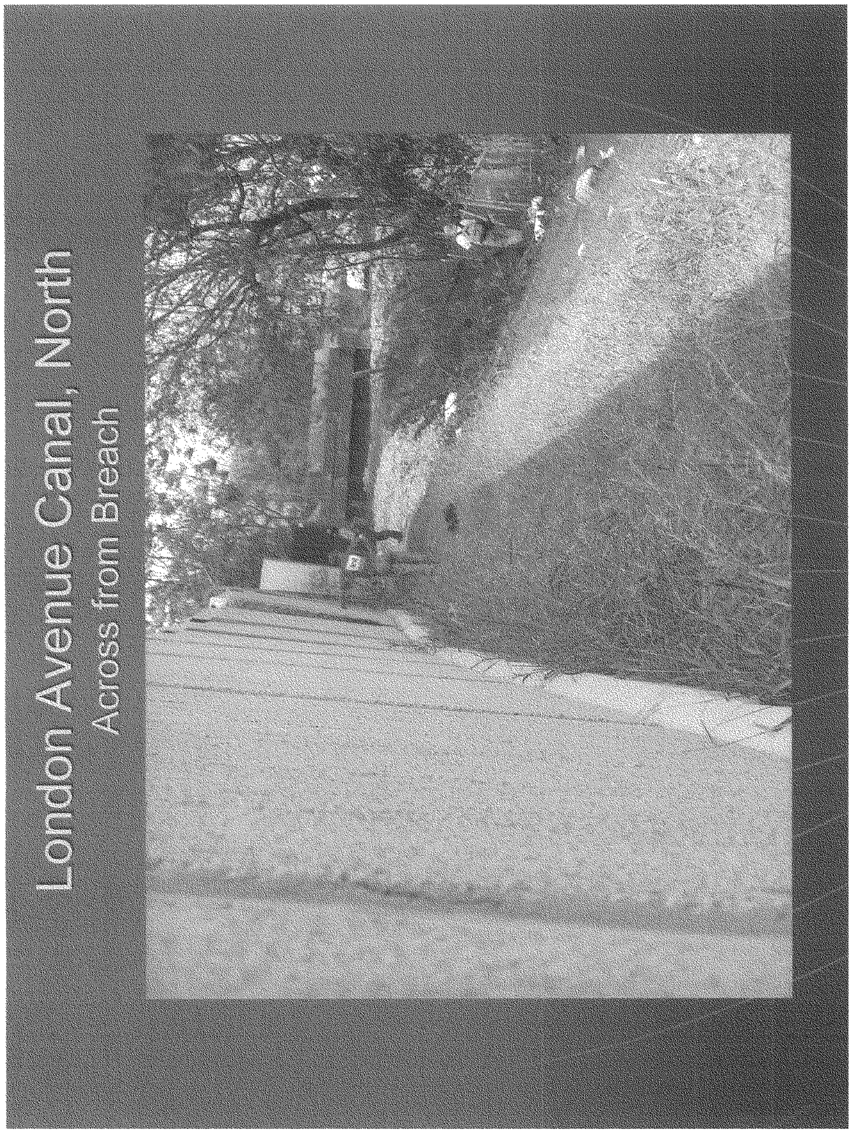

17th Street Canal

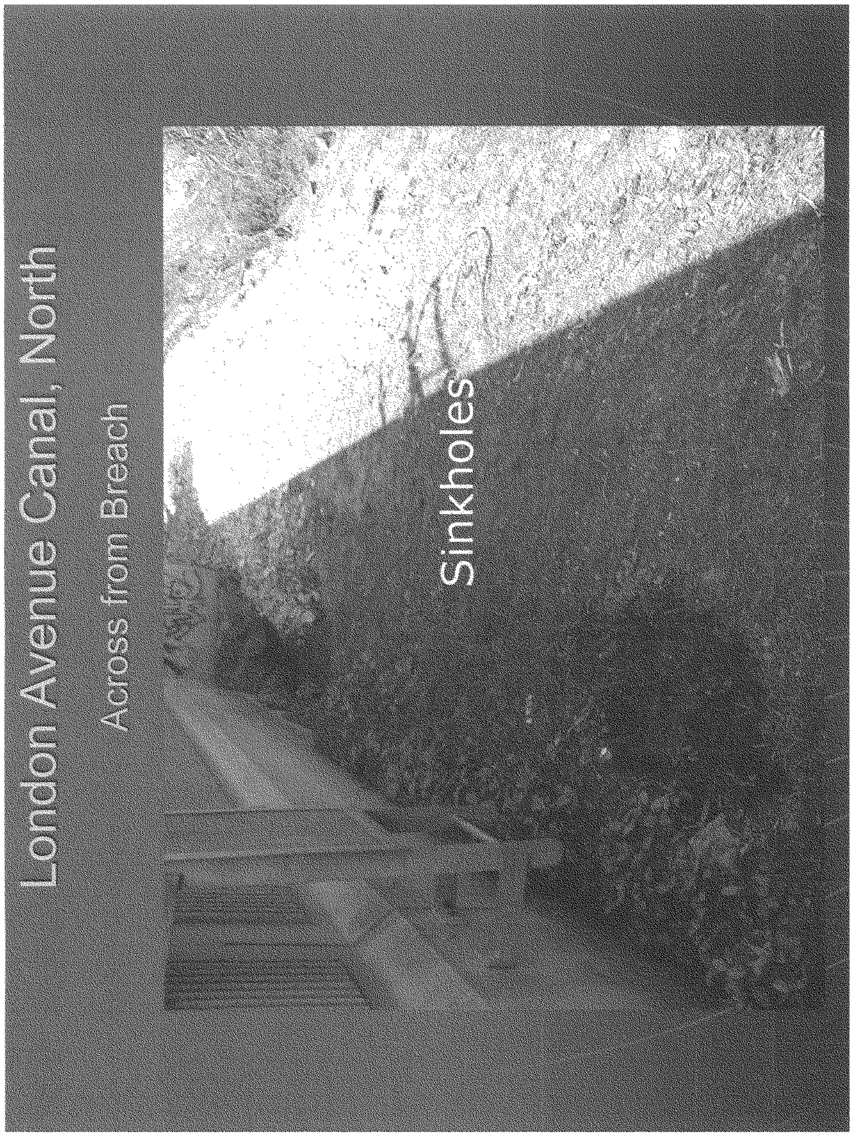

17th Street Canal

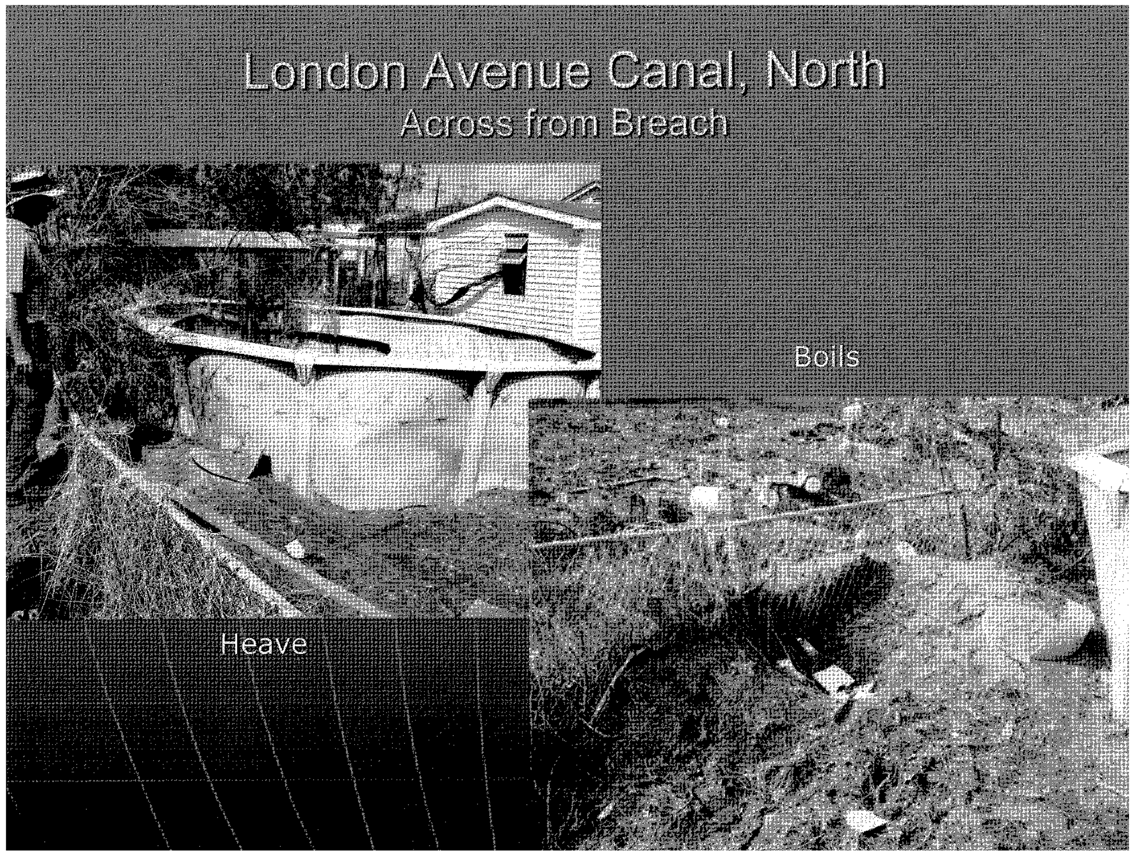

London Avenue Canal, North Breach

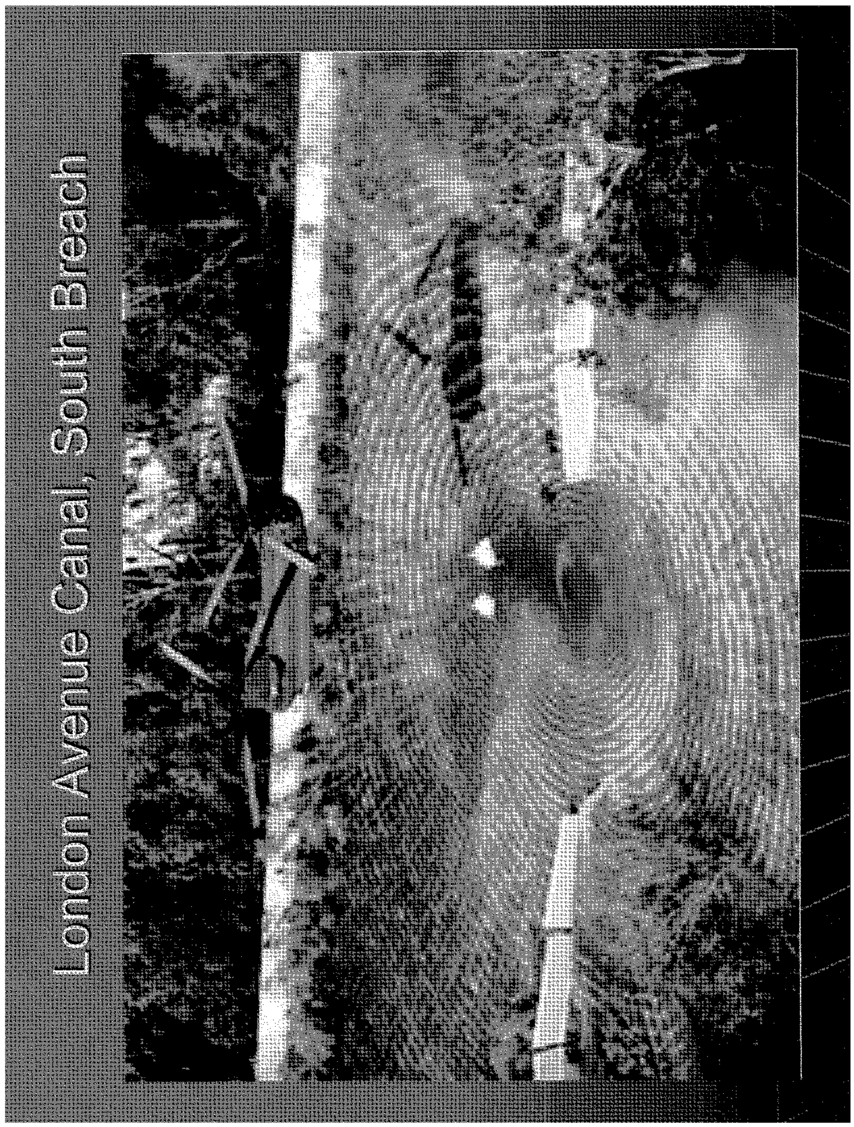

London Avenue Canal, North Breach

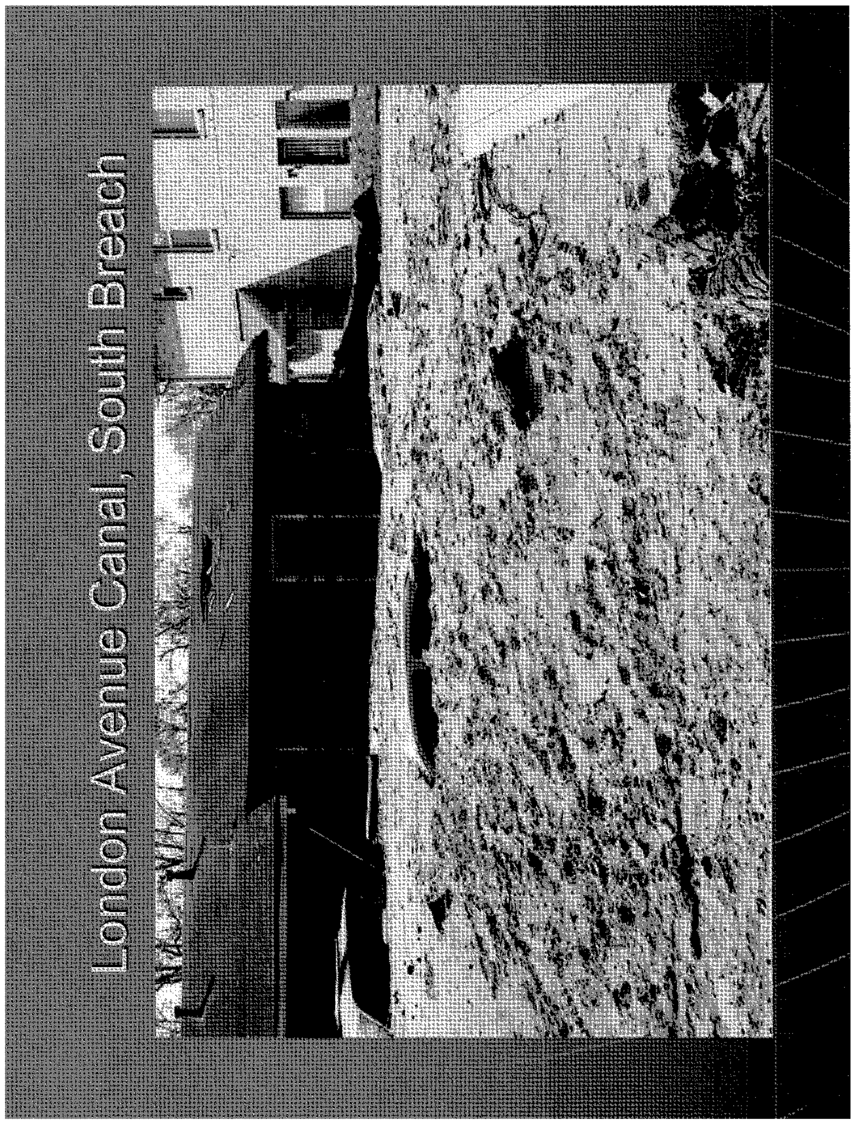

London Avenue Canal, North
Across from Breach

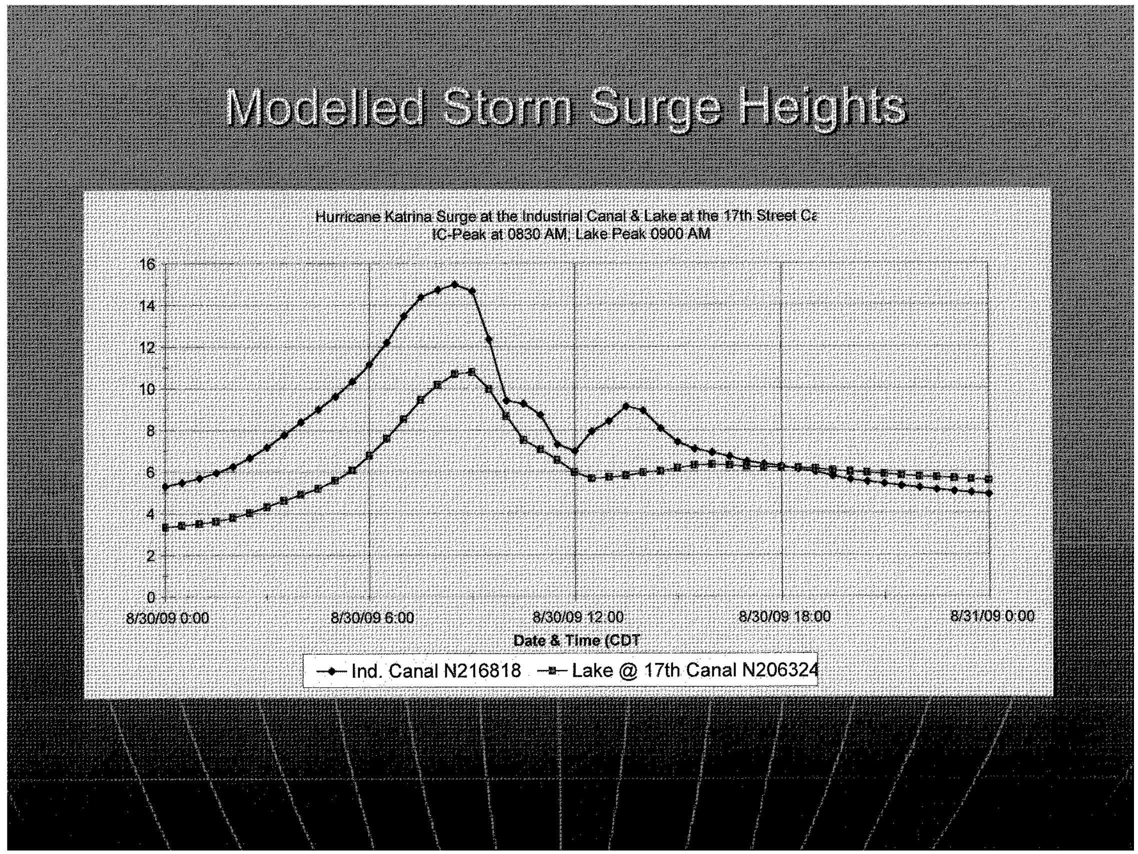

London Avenue Canal, North
Across from Breach

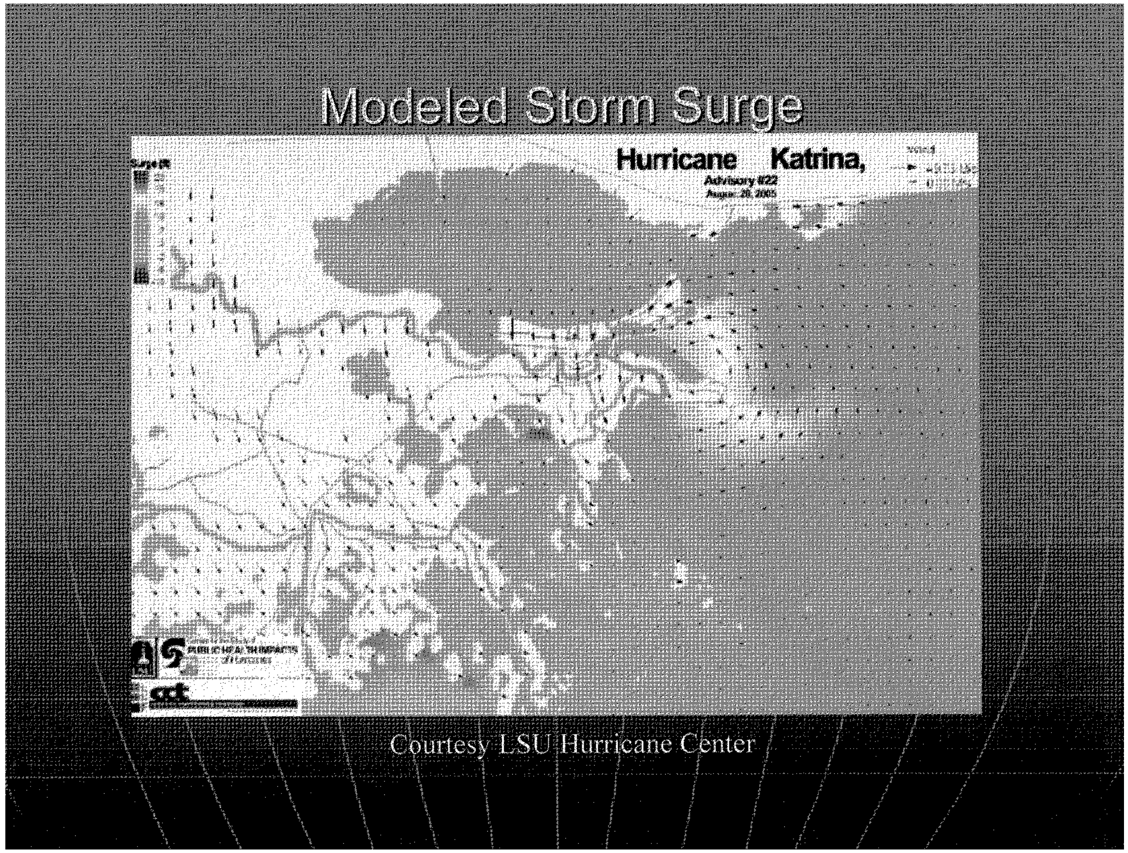

London Avenue Canal, North
Across from Breach
Sinkholes

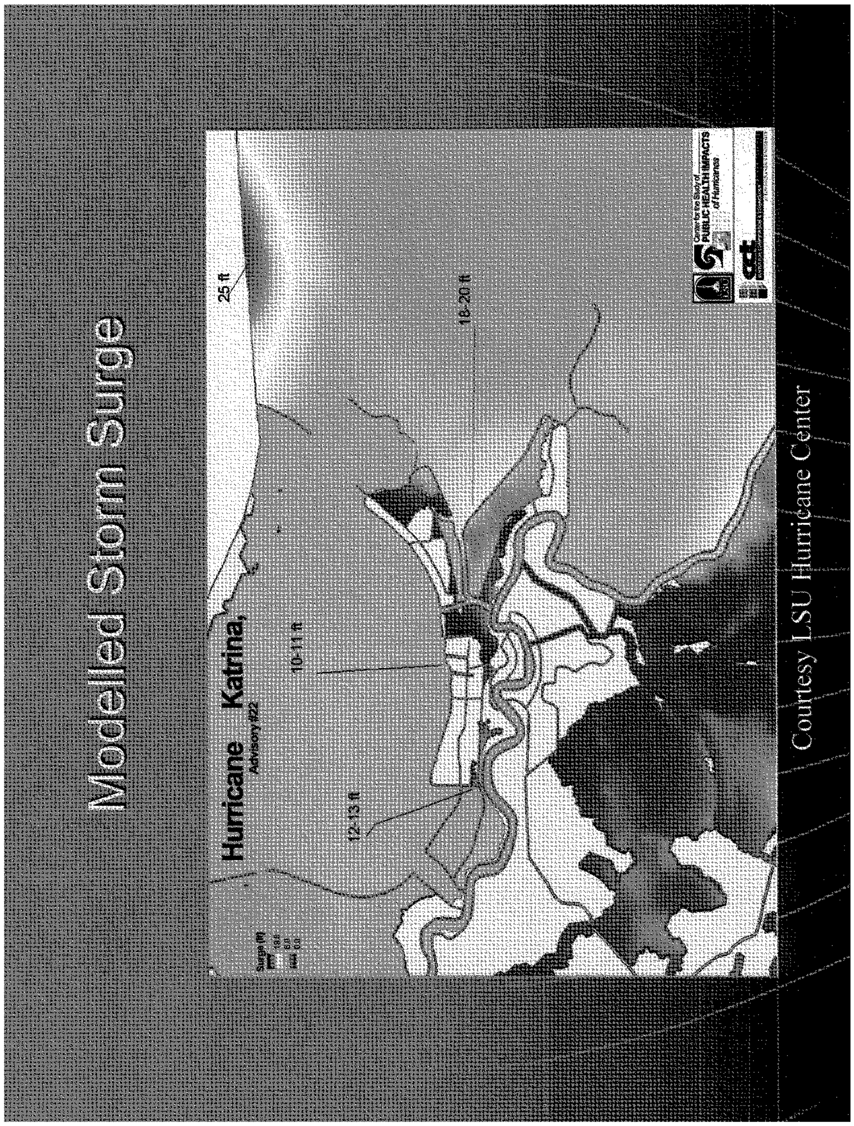

London Avenue Canal, North
Across from Breach
Boils
Heave

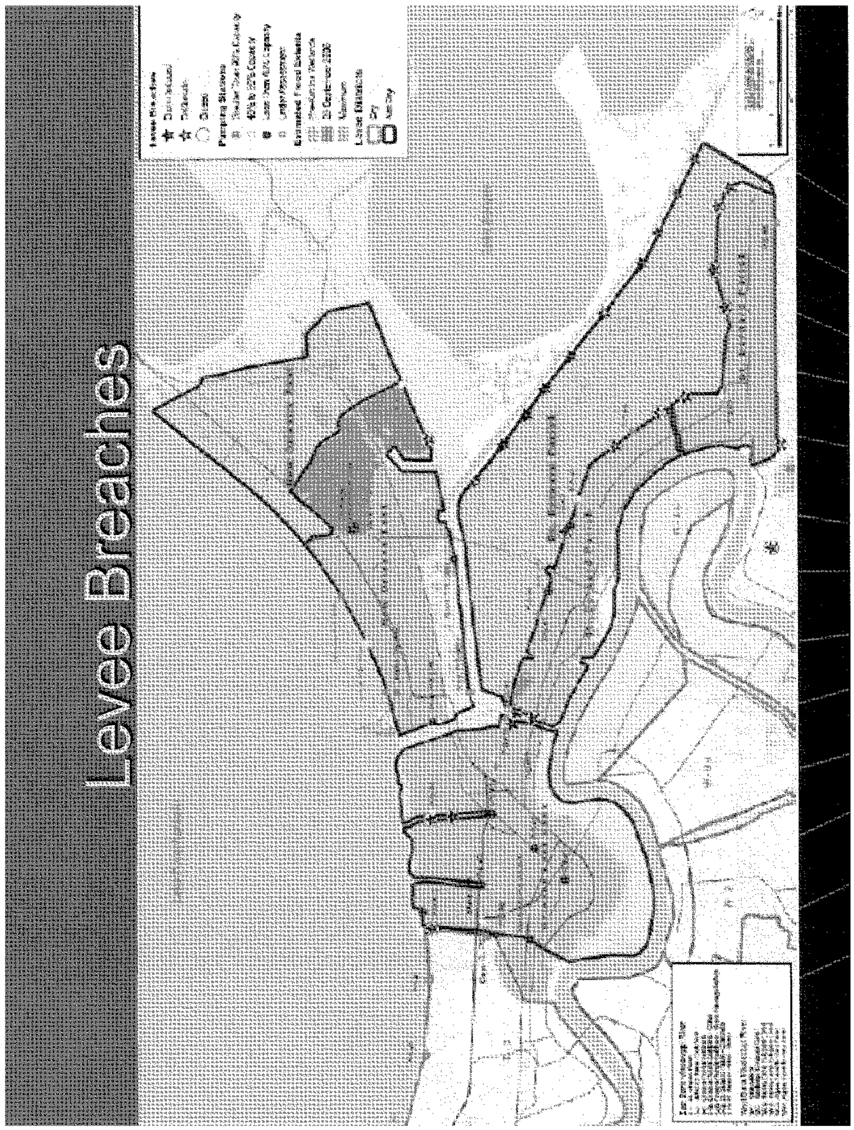

London Avenue Canal, South Breach

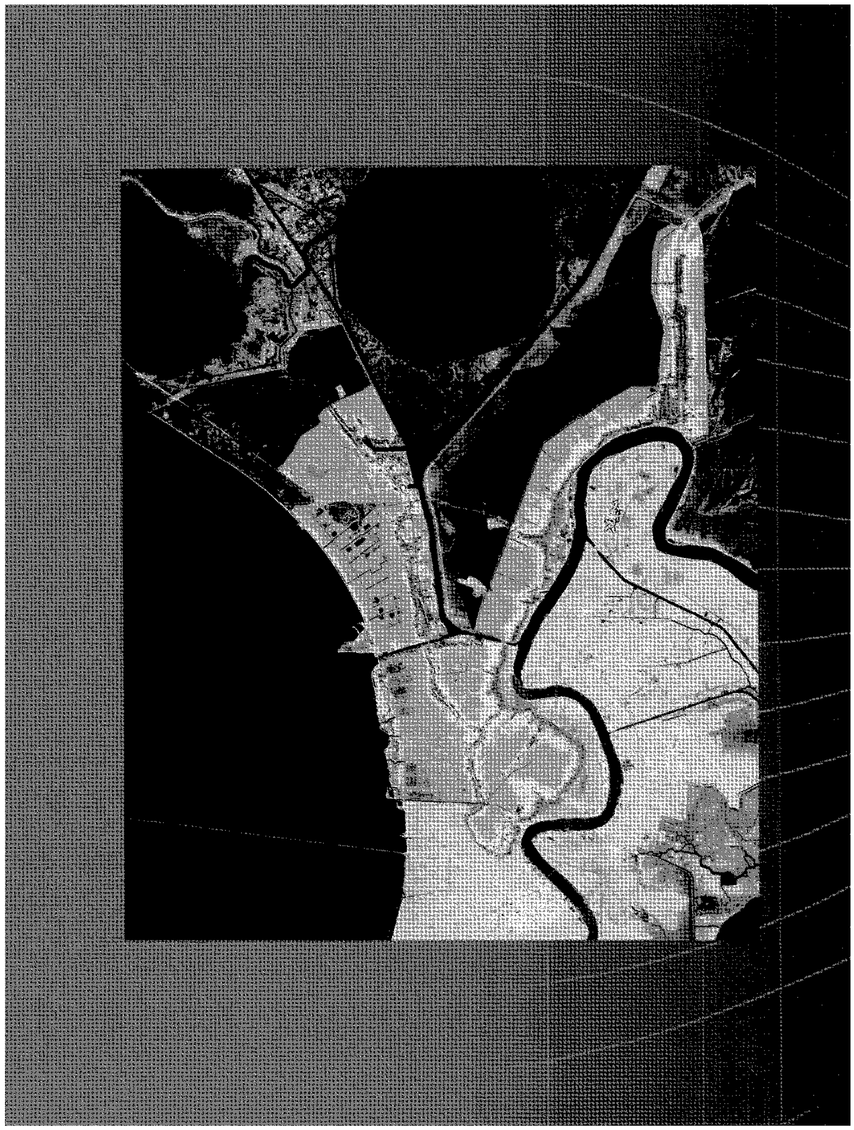

London Avenue Canal, South Breach

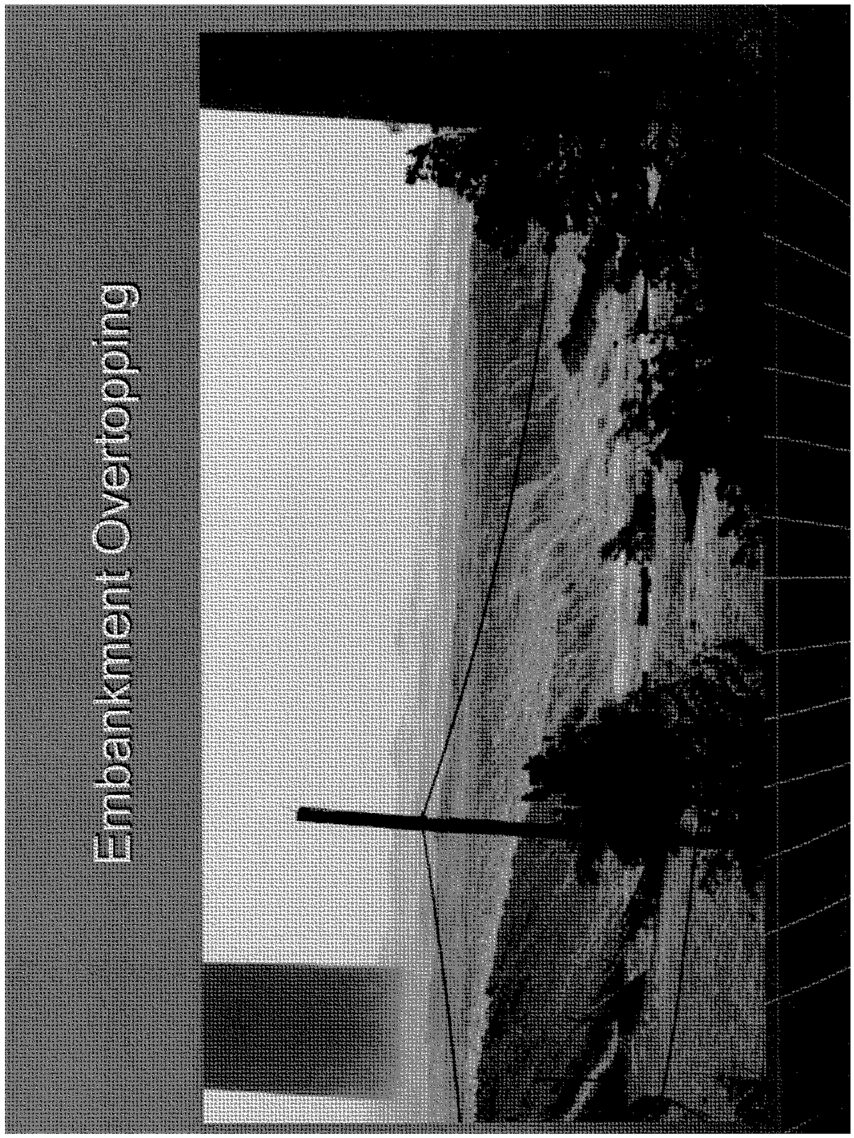

Modelled Storm Surge Heights
Hurricane Katrina Surge at the Industrial Canal & Lake at the 17th Street Ca
IC-Peak at 0830 AM, Lake Peak 0900 AM
16
14
12
10
8
6
4
2
0
8/30/09 0:00
8/30/09 6:00
8/30/09 12:00
8/30/09 18:00
8/31/09 0:00
Date & Time (CDT
Ind. Canal N216818
Lake @ 17th Canal N206324


Modeled Storm Surge
Hurricane Katrina,
Advisory #22
Courtesy LSU Hurricane Center


Modelled Storm Surge
Hurricane Katrina,
Advisory #22
25 ft
18-20 ft
10-11 ft
12-13 ft
Courtesy LSU Hurricane Center

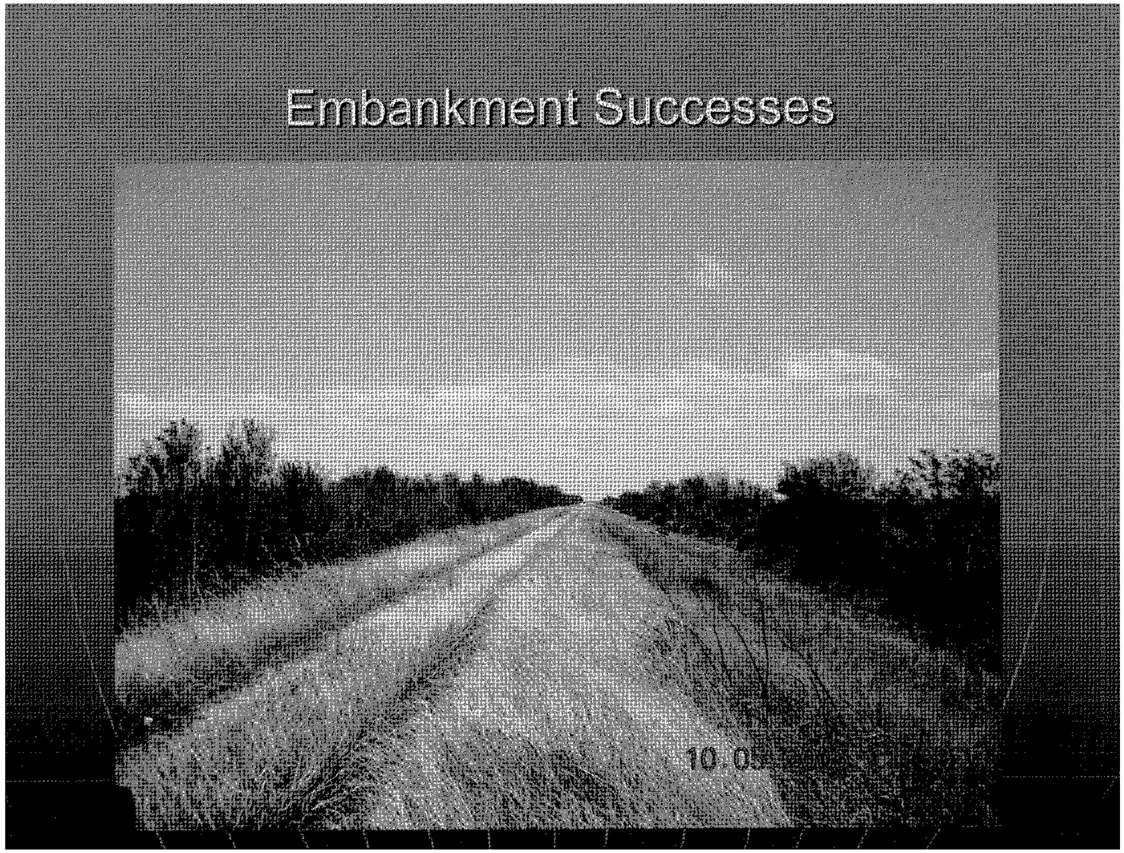

Levee Breaches

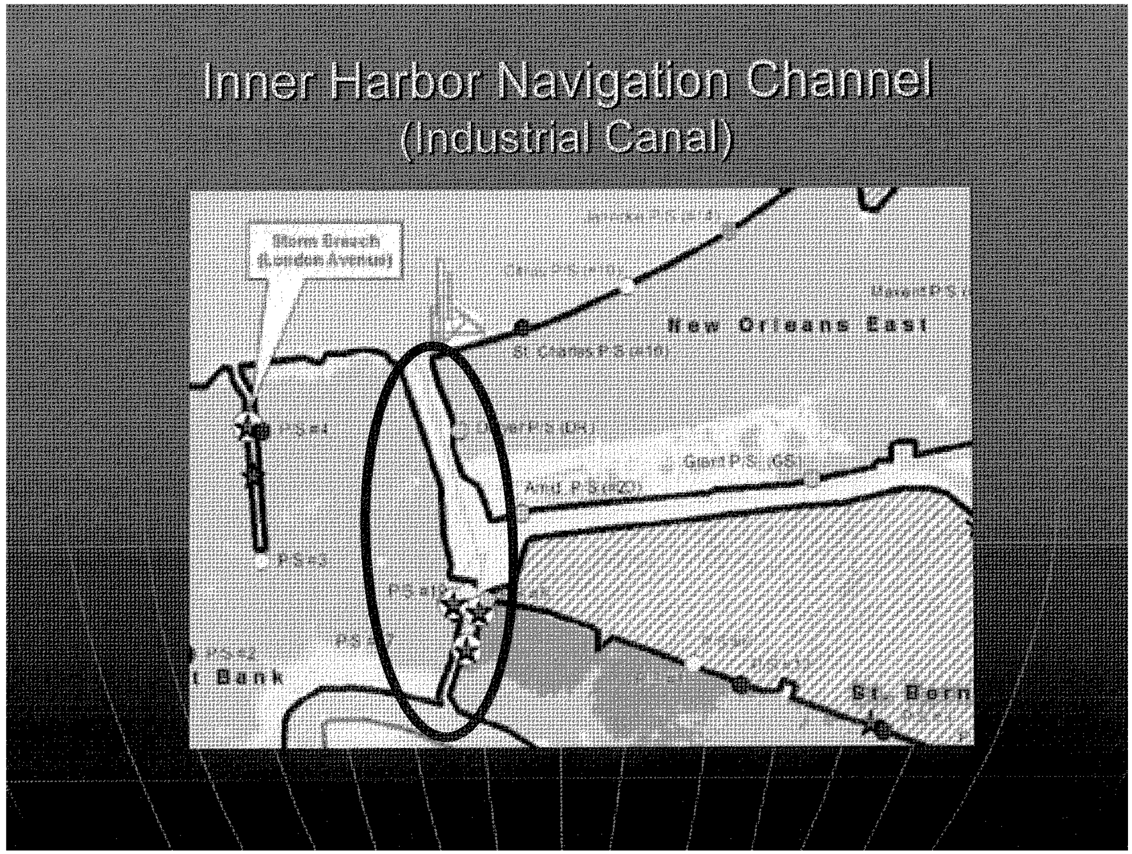


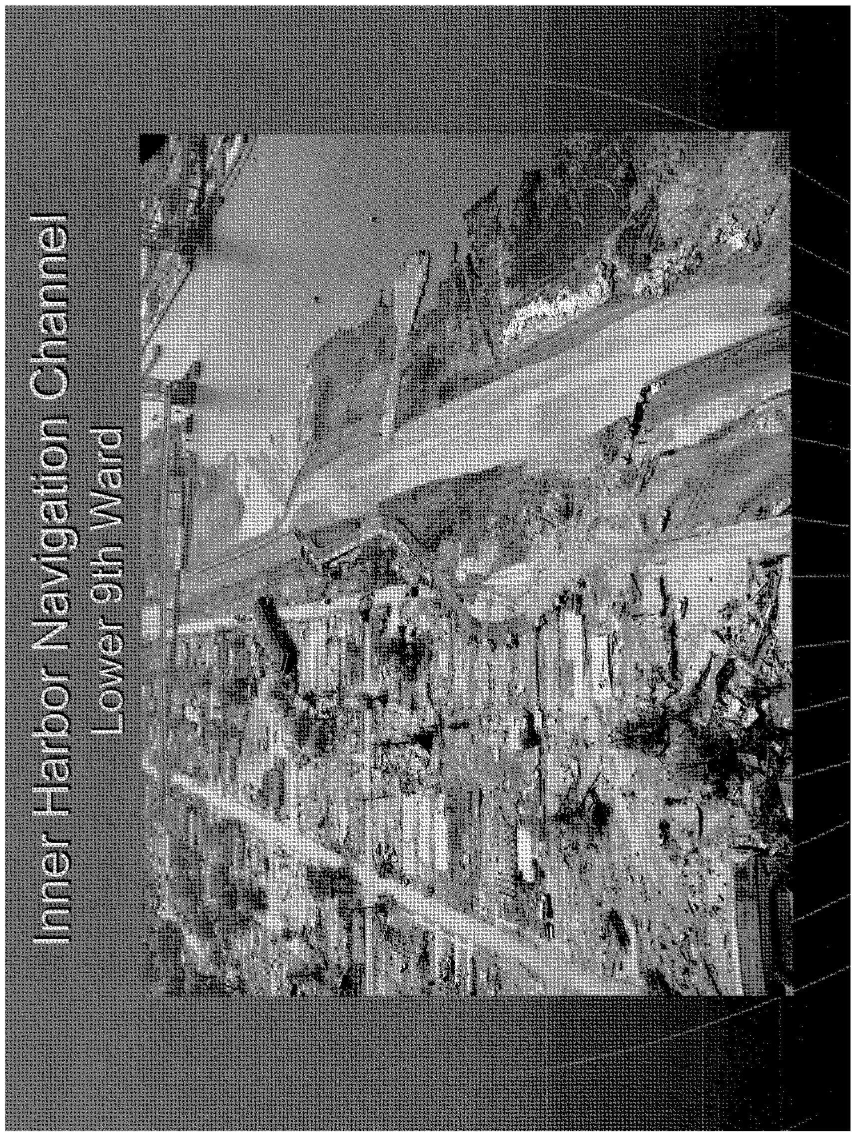

Embankment Overtopping

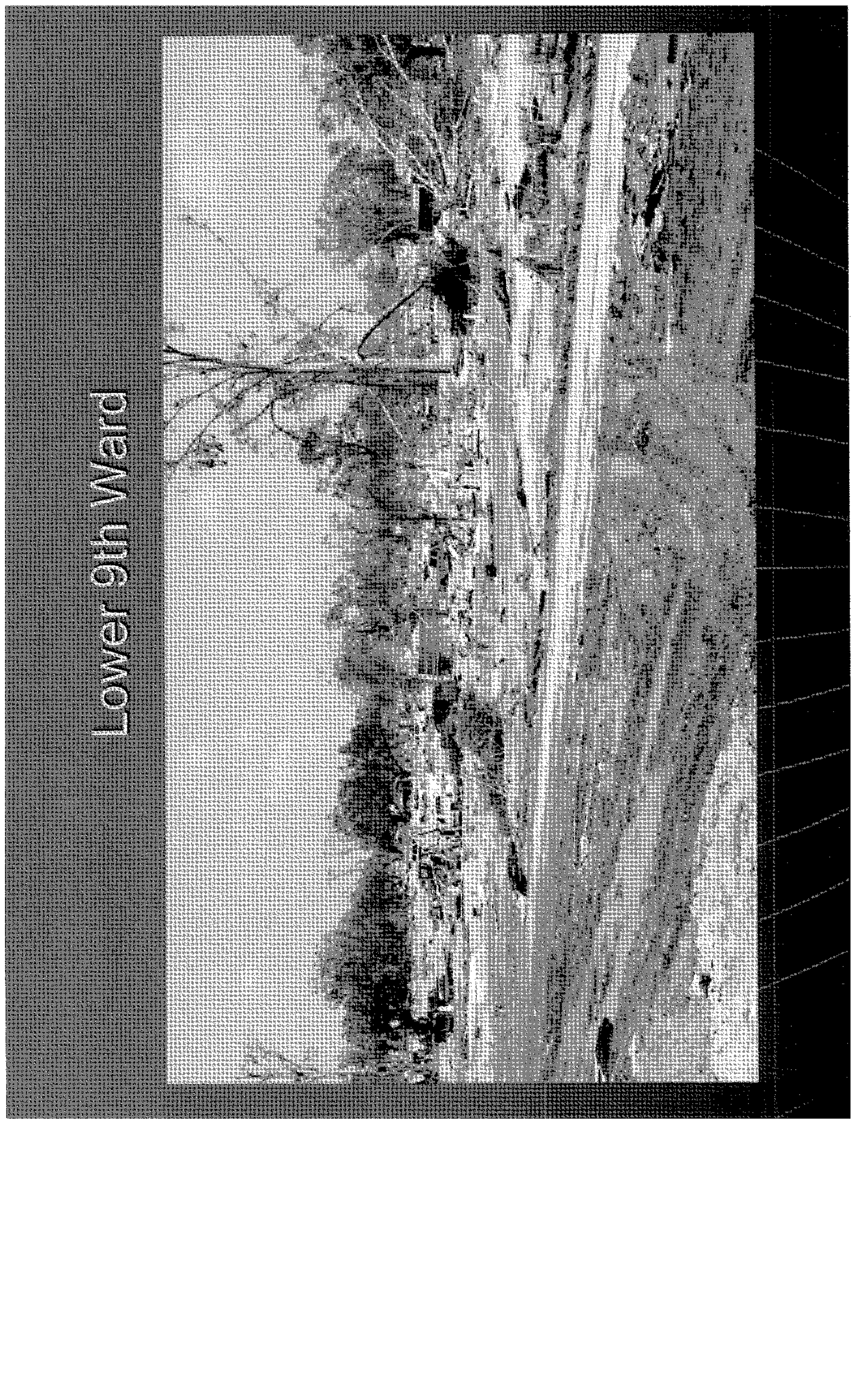

Overtopped Embankment (Sand Core)

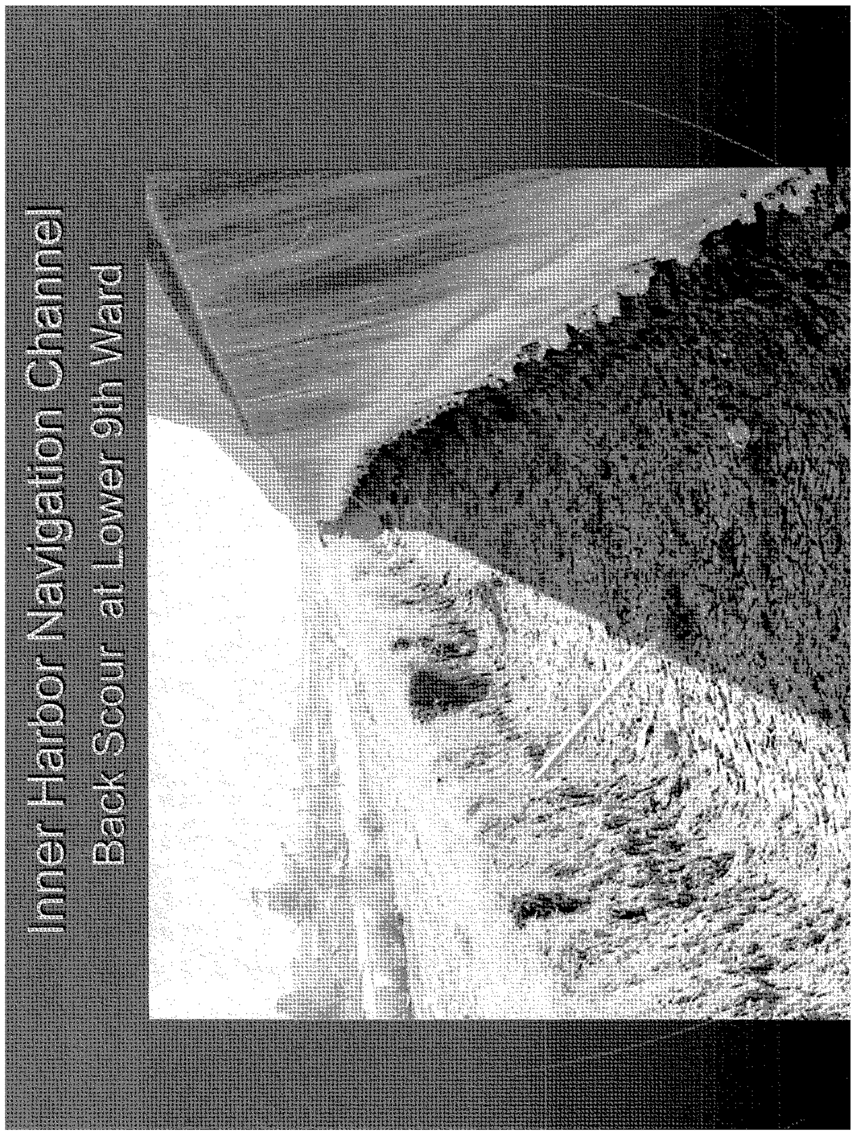

Overtopped Embankment (Sand Core)


Embankment Successes

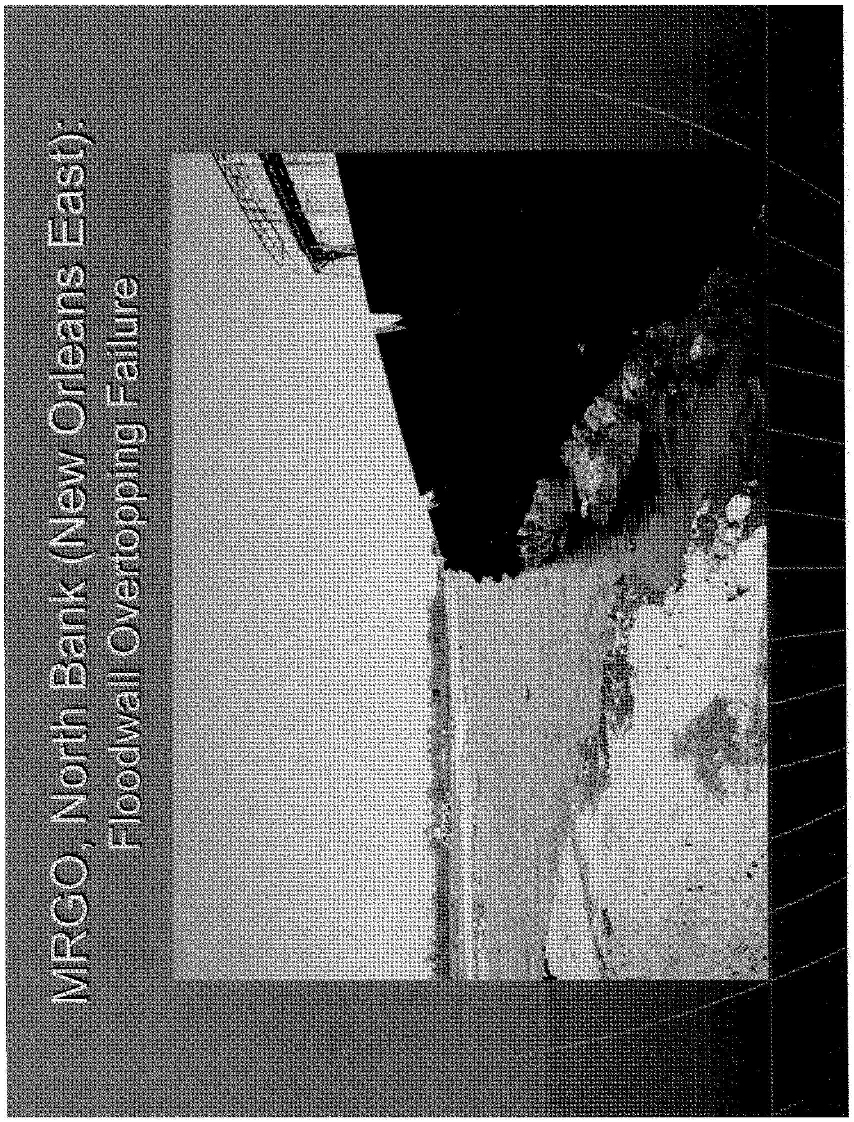

Inner Harbor Navigation Channel
(Industrial Canal)
Storm Breach (London Avenue)
New Orleans East
P.S.#4
P.S.#3

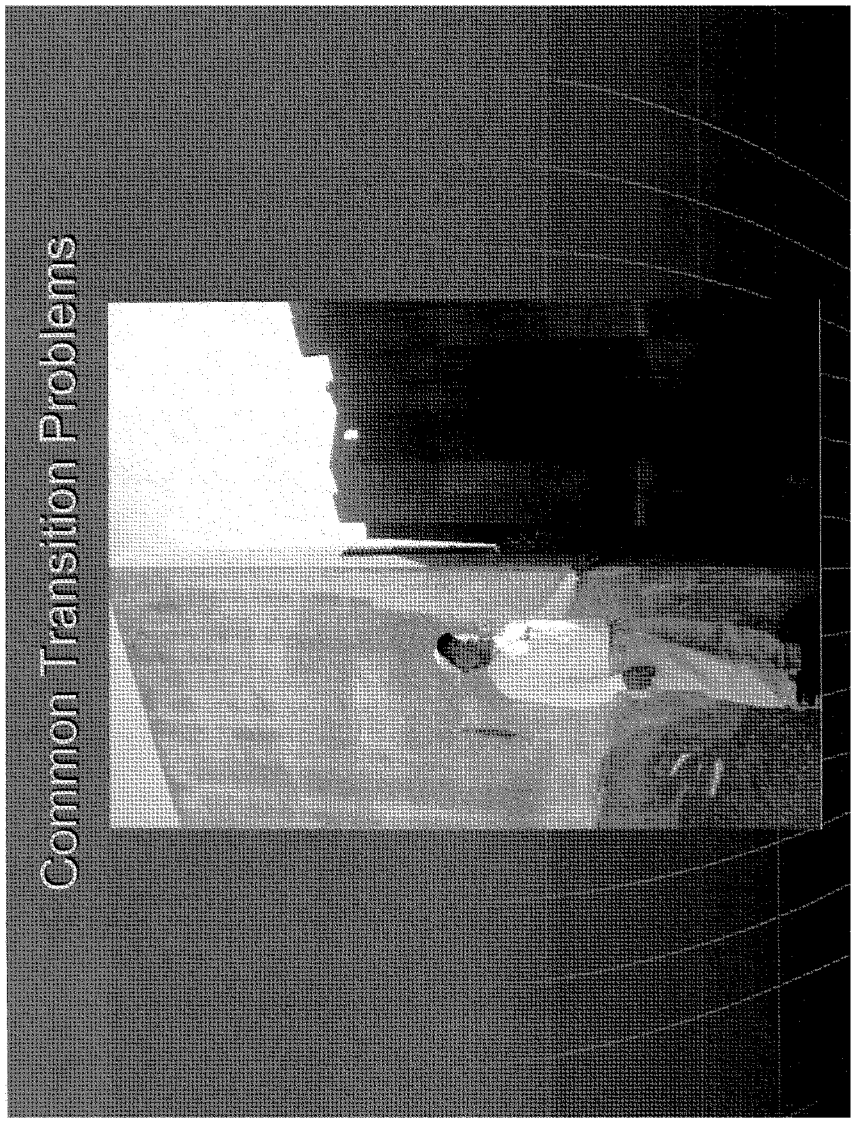

Inner Harbor Navigation Channel
Lower 9th Ward


Lower 9th Ward


Inner Harbor Navigation Channel
Back Scour at Lower 9th Ward

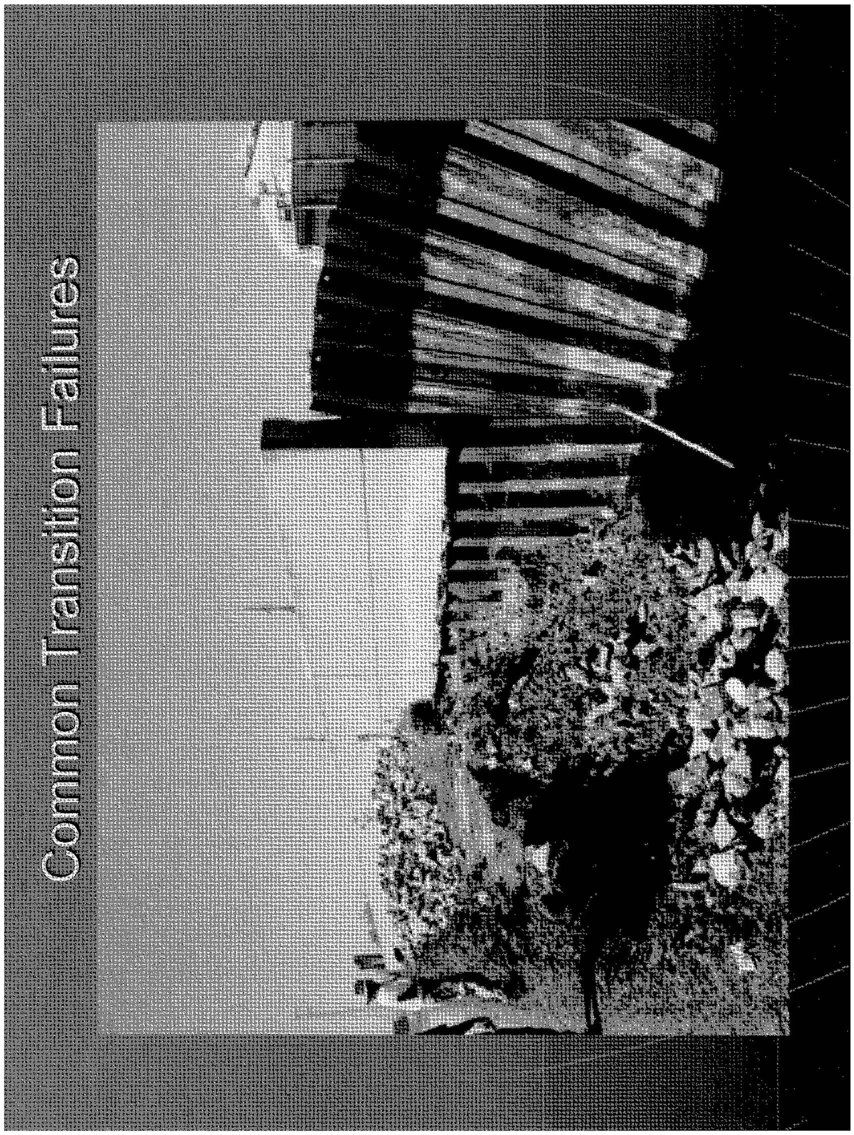

MRGO, North Bank (New Orleans East):
Overtopping Back Scour

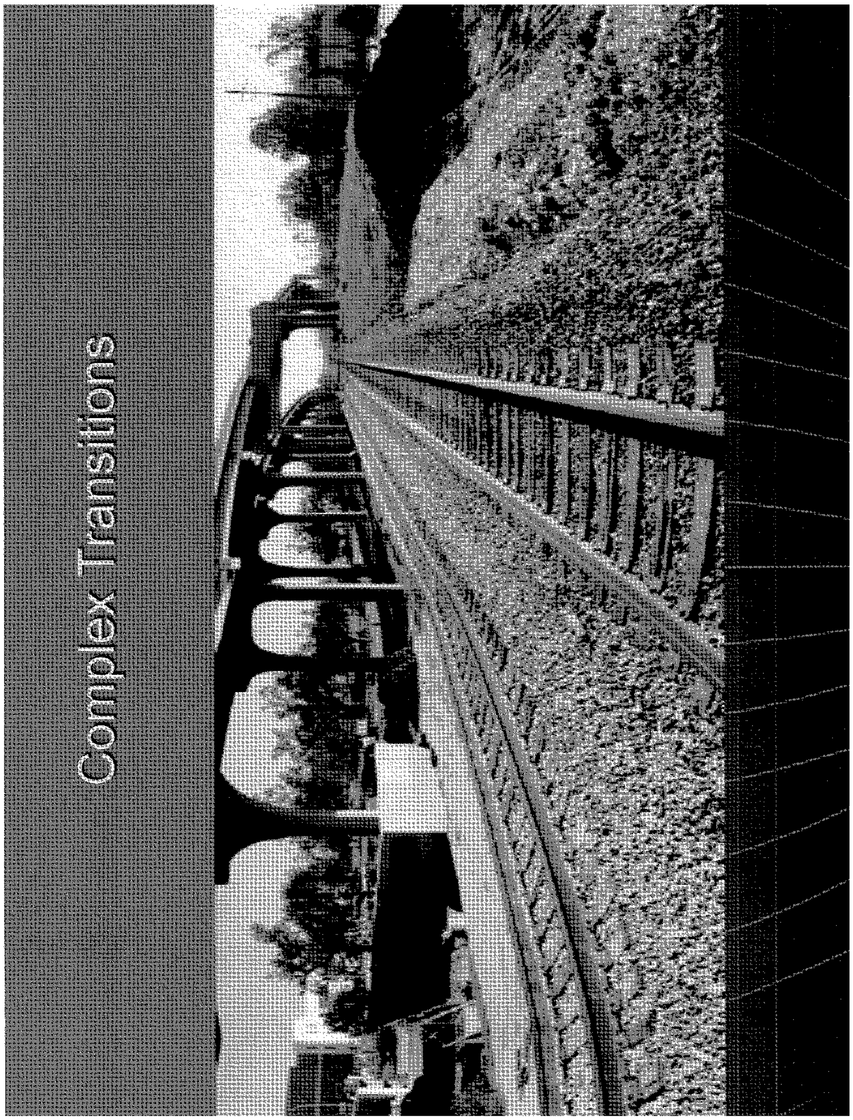

MRGO, North Bank (New Orleans East):
Floodwall Overtopping Failure


Common Transition Problems


Common Transition Failures


Common Transition Failures


Common Transition Failures


Complex Transitions

Response from Ivor van Heerden, Ph.D.,
LSU Hurricane Center
And
Leader "TEAM LOUISIANA"

to

Post-Hearing Questions for the Record
Submitted to Ivor van Heerden, Ph.D.
From Senator Susan M. Collins

"Hurricane Katrina: Why Did the Levees Fail?"

November 2, 2005

1. *One question that has not been answered is whether and when the Army Corps of Engineers should have known that the soil beneath the flood walls in New Orleans was weak and left the city more vulnerable to storms than had been believed.*

One possible indication that the Army Corps should have known of the weakness earlier is a 1997 lawsuit between Pittman Construction, a building contractor, and the Army Corps. In the suit, Pittman contended, and I quote from the opinion in that case, that, together with another factor, the "relative weakness of the soils permitted the concrete to shift during construction, resulting in monoliths that were not in alignment as required by the contract."

It would seem logical that the weaknesses identified in this 1997 lawsuit should have tipped off the Army Corps that the flood walls were more vulnerable than believed. However, a recent New Orleans Times-Picayune article quotes Pittman's expert witness, Herbert Roussel, as stating that the soil weaknesses, "in no way jeopardizes the integrity of the wall as far as flood protection is concerned."

Can you shed light on whether the soil weaknesses that caused flood walls to fail – particularly on the 17th Street and London Avenue levees – should have been known about and addressed perhaps years earlier?

<u>Ivor van Heerden Response</u>

In my opinion the soil data produced in the Pitman Lawsuit is one of the 'smoking guns' as concerns the levee failures.

The fact that the monoliths concrete shifted during construction due to the relative weakness of the soils is a very strong indication that something was wrong. Preliminary assessment of the soil strengths used by the Corps of Engineers (as obtained from borehole data collected in 1982) shows that the Corps averaged the data over a distance of about a mile. This meant that they used higher soil strengths (+/- 320 lbs/sq.ft. than actually was measured in the 1982 boreholes in the breach are, which were actually 180 lbs/sq.ft.) Thus the soils stability calculations to determine sheet pile lengths and the overall design were too high, resulting in a less than robust design.

In summary, when Pitman complained about the weakness of the soils and revealed the stability problems with the concrete, the Corps should have undertaken a detailed geotechnical investigation to better understand the problem. This investigation would surely have precipitated a different design and deeper sheet piles which most likely would have prevented the levee failure in the 17th street Canal during Katrina.

Ivor van Heerden

Response from Ivor van Heerden, Ph.D.,
LSU Hurricane Center
And
Leader "TEAM LOUISIANA"

to

Post-Hearing Questions for the Record
Submitted to Ivor van Heerden, Ph.D.
From Senator Pete V. Domenici

"Hurricane Katrina: Why Did the Levees Fail?"

November 2, 2005

1. *Are you a civil or mechanical engineer?*

I am an associate professor in the Department of Civil and Environmental Engineering.

2. *Can you please give us details on your education, background, and experience as it relates to engineering matters?*

My undergraduate studies consisted of two years of study in the Department of Civil Engineering at the University of Natal, South Africa, followed by three years of study in the Geology Department of the University of Natal. My Bachelor of Science Honors degree was in coastal processes and sedimentary geology.

My graduate degrees undertaken at the Coastal Studies Institute, Louisiana State University were in Marine Sciences with the focus on coastal process and dynamics. While a graduate student I was involved in numerous geotechnical surveys of the Gulf of Mexico seafloor for oil rigs and pipeline locations, as well as significant geological borehole and core interpretations and projects all across coastal Louisiana, from geology to oceanography.

I have many years of practical experience in engineering-related fields, as a engineering draftsman, military engineer, land surveyor, working with dredgers since 1969, investigation of failed river training levees as a consequence of major tropical cyclone-induced floods, coastal investigations of many kinds, marina and harbor developments, groundwater studies, and CEO of a major marine diamond mining company which involved numerous dredgers off the Skeleton Coast of southern Africa. I have also participated in the conceptual engineering design of many Coastal Wetlands Planning, Protection, and Restoration Act projects. I have many years of hurricane research experience as the Deputy Director of the LSU Hurricane Center and Director of the Center for the Study of the Public Health Impacts of Hurricanes. I established the ADCIRC storm surge model at LSU and am responsible for operational storm surge predictions (www.hurricane.lsu.edu/floodprediction/).

Our preliminary investigation has shown that the failure of the levees during Katrina did not reflect the mechanical collapse or fracture of concrete sections or other such mechanisms; rather, the failures reflected design problems related to the nature of the weak soils, the movement of subsurface waters beneath the structures, and erosion due to waves and currents. Accordingly, to understand what went wrong requires an intimate knowledge of Louisiana's Holocene geology (subsurface soil structure), fluid dynamics (waves and surges and numerical modeling), hydraulic gradients and some basic principles of geo-hydrology and geotechnical engineering design. I am fully qualified to do research in all these areas, but to ensure the best research possible, along with Louisiana Department of Transport and Development Secretary Johnny Bradberry, we put a research team together consisting of scientists and engineers from LSU as well as two experienced retired Louisiana geotechnical engineers (both of whom have taught at Louisiana universities) and one experienced construction engineer. I am the head of that team and its designated spokesperson.

3. When did you begin your investigation of the breached levees in New Orleans?

30th August 2005

4. Where are you at in the process of that investigation?

We have really just started, possibly 10 percent along the way.

5. How long do you believe your investigation will take?

It could take 6-9 months depending on how freely and quickly the Corps of Engineers releases data.

6. Might other data, information, or issues come to light that could change your current assessment?

No. I doubt it. The visual physical evidence in the field is very clear; the levees underwent at multiple locations "catastrophic structural failure".

7. Are any opinions you make today based only on your preliminary findings?

Yes.

Ivor van Heerden

Post-Hearing Questions for the Record
Submitted to Paul F. Mlakar, Ph.D.
From Senator Susan M. Collins

"Hurricane Katrina: Why Did the Levees Fail?"

November 2, 2005

1. One question that has not been answered is whether and when the Army Corps of Engineers *should have known* that the soil beneath the flood walls in New Orleans was weak and left the city more vulnerable to storms than had been believed.

   One possible indication that the Army Corps should have known of the weakness earlier is a 1997 lawsuit between Pittman Construction, a building contractor, and the Army Corps. In the suit, Pittman contended, and I quote from the opinion in that case, that, together with another factor, the "relative weakness of the soils permitted the concrete to shift during construction, resulting in monoliths that were not in alignment as required by the contract."

   It would seem logical that the weaknesses identified in this 1997 lawsuit should have tipped off the Army Corps that the flood walls were more vulnerable than believed. However, a recent New Orleans Times-Picayune article quotes Pittman's expert witness, Herbert Roussel, as stating that the soil weaknesses, "in no way jeopardizes the integrity of the wall as far as flood protection is concerned."

   Can you shed light on whether the soil weaknesses that caused flood walls to fail – particularly on the 17th Street and London Avenue levees – should have been known about and addressed perhaps years earlier?

   The Corps takes this legitimate question very seriously. We are collecting and analyzing all information about the soil beneath the flood walls that was available prior to Katrina, including the Pittman claim and the Roussel opinion. We are also conducting new exploration and testing of these soils to obtain further insight. Our answer will come from the Interagency Performance Evaluation Taskforce (IPET) established by the Corps no later than June 1, 2006. This group includes experts in geotechnical, structural, and hydraulic engineering from 40 government, academic, and private organizations worldwide. They are charged with evaluating the response of the overall hurricane protection system, including the soils beneath the floodwalls. The findings will be externally reviewed by a panel of the American Society of Civil Engineers and will be further scrutinized by a Committee of the National Research Council. An interim progress report as of January 10, 2006 is available at https://ipet.wes.army.mil/.

3/29/2006

Post-Hearing Questions for the Record
Submitted to Paul F. Mlakar, Ph.D.
From Senator Pete V. Domenici

"Hurricane Katrina: Why Did the Levees Fail?"

November 2, 2005

1. Are you a civil or mechanical engineer?

I am a civil engineer and further a registered Professional Engineer legally obligated to protect the health, safety, and welfare of our citizens.

2. Can you please give us details on your education, background, and experience as it relates to engineering matters?

I am a Senior Research Scientist at the US Army Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi, which is a component of the US Army Corps of Engineers. I have spent most of my professional career of four decades in the Corps studying the response of structures to extreme loadings. This has included the performance of the Murrah Building in the Oklahoma City bombing and that of the Pentagon in the 9/11 crash. I am a Fellow of the American Society of Civil Engineers and the recipient of their Forensic Engineering Award in 2003. For additional information on my education and background, please see the attached file that contains my bio.

3. When did you begin your investigation of the breached levees in New Orleans?

The Corps began planning the study of the performance of the hurricane protection system around September 1. I led the first elements of the taskforce into the region on September 26.

4. Where are you at in the process of that investigation?

On November 2, 2005, we had collected much of the ephemeral data, e.g. high water marks throughout the region. The Corps has also established an Interagency Performance Evaluation Taskforce (IPET) to deliberately and openly study the response of the hurricane protection system. This group includes experts in hydraulic, geotechnical, and structural engineering from 40 government, academic, and private organizations worldwide. A report of our interim progress as of January 10, 2006 is available at https://ipet.wes.army.mil/.

5. How long do you believe your investigation will take?

The final report will be available by June 1, 2006. A panel of the American Society of Civil Engineers is reviewing the work of the IPET and the study will be further scrutinized by a committee of the National Research Council.

6. Might other data, information, or issues come to light that could change your current assessment?

The observations that I shared on November 2 were preliminary. We have continued to collect further information with an open mind. Our final assessment will be based on a deliberate analysis of all the information.

7. Are any opinions you make today based only on your preliminary findings?

All of my testimony on November 2 was based solely on my preliminary observations to that time.

Paul F. Mlakar, Ph.D., P.E.

Dr. Mlakar is the Senior Research Scientist for weapons effects and structural dynamics at the U.S. Army Engineer Research and Development Center (ERDC). In this capacity he conducts original research, oversees that of other teams, and serves as an Army spokesman. Following the September 11 airliner crash into the Pentagon, Dr. Mlakar was selected by the American Society of Civil Engineers (ASCE) to lead a study of the structural behavior. The published results of this study are guiding the engineering profession in designing all structures to reduce the progression of collapse from extreme loadings.

From 2000 to 2003 Dr. Mlakar was the Technical Director of the ERDC responsible for innovations in military engineering to rapidly upgrade transportation infrastructure and assure cross country mobility. From 1995 to 2000 he served as the Chief of the Concrete and Materials Division of the U.S. Army Engineer Waterways Experiment Station (WES). In the winter of 1996, Dr. Mlakar acted as the Chief Engineer of a North Atlantic Treaty Organization Task Force that rapidly restored a war-damaged century-old bridge on the main line of supply for Operation Joint Endeavor in Bosnia.

From 1984 to 1995 Dr. Mlakar founded and guided the Structures Division of JAYCOR as a Vice President. This group researched and consulted on structural engineering and related problems for a variety of government and commercial clients. This work included the invention of a patented hardened air cargo container capable of resisting the effects of internal explosions. Other projects involved the design of structures to resist explosive effects including the protection of embassies and other visible targets against terrorist bombings. Dr. Mlakar also served on the ASCE team that assessed the structural performance of the Murrah Building in the 1995 Oklahoma City terrorist bombing.

As a research engineer for the WES, from 1973 to 1984, Dr. Mlakar was the contributing leader of a team that investigated the mechanics of structural elements. Projects included the seismic response of hydraulic structures, the behavior of field fortifications subjected to weapons effects, and the application of probability to structural design. During the period 1966 to 1973, Dr. Mlakar was an officer in the Corps of Engineers. This encompassed an Assistant Professorship at the U.S. Military Academy (USMA) at West Point, as well as troop command and staff service in Vietnam and the U.S.

Dr. Mlakar graduated 2nd in his class from USMA. Subsequently, he earned an M.S. and a Ph.D. in Engineering Science from Purdue University. Dr. Mlakar is a registered professional engineer and the author of 150 technical publications. He is a Fellow of ASCE and the past Chair of its Committee on Shock and Vibratory Effects. Dr. Mlakar serves on three technical committees of the American Concrete Institute. He is a past Vice President of the Society of American Military Engineers. Dr. Mlakar has received a number of prestigious honors including the 2003 ASCE Forensic Engineering Award and the 2004 Purdue Alumni Achievement Award.

15-Aug-06

Post-Hearing Questions for the Record
Submitted to Raymond B. Seed, Ph.D.
From Senator Susan M. Collins

"Hurricane Katrina: Why Did the Levees Fail?"

November 2, 2005

1. One question that has not been answered is whether and when the Army Corps of Engineers *should have known* that the soil beneath the flood walls in New Orleans was weak and left the city more vulnerable to storms than had been believed.

   One possible indication that the Army Corps should have known of the weakness earlier is a 1997 lawsuit between Pittman Construction, a building contractor, and the Army Corps. In the suit, Pittman contended, and I quote from the opinion in that case, that, together with another factor, the "relative weakness of the soils permitted the concrete to shift during construction, resulting in monoliths that were not in alignment as required by the contract."

   It would seem logical that the weaknesses identified in this 1997 lawsuit should have tipped off the Army Corps that the flood walls were more vulnerable than believed. However, a recent New Orleans Times-Picayune article quotes Pittman's expert witness, Herbert Roussel, as stating that the soil weaknesses, "in no way jeopardizes the integrity of the wall as far as flood protection is concerned."

   Can you shed light on whether the soil weaknesses that caused flood walls to fail – particularly on the 17th Street and London Avenue levees – should have been known about and addressed perhaps years earlier?

Response:

The Pittman lawsuit has been interpreted by some as a "red flag" indicating poor foundation soil conditions, but that does not mean that it should have alerted the Corps to particular conditions of concern with regard to overall stability at the 17th Street Canal and London Avenue Canal breach sites. The Corps had long been aware of generally poor foundation soil conditions at those sites, and it appears likely that the Corps generally believed that those poor conditions had already been accounted for in terms of overall stability.

That does not mean that the Corps did not have opportunity (or opportunities) to catch design short-comings at these breach sections. There were a number of questionable selections of soil shear strength parameters in some of the stability analyses performed at some of these sections, and the Corps had review responsibility for these analyses (the original analyses had been outsourced to non-Corps engineering firms.) During these reviews, mainly during about 1990-91, the Corps had opportunities to catch the use of what appear to have been optimistic soil shear strength parameters at several of these sections, and also to have caught the inappropriate use of strength parameter "averaging" along very long lateral stretches, and over considerable vertical depths, in soils well known to be notorious for their local variability with regard to shear strength. Use of more localized (near-lowest local) shear strengths would have been more appropriate in many cases.

There were a number of systematic problems in the designs, and in the design analyses, for the London Avenue and 17th Street Canal levees and floodwalls. We are continuing to study these, and their history, as best we can through the background documents, etc. that we are able to obtain.

There was some controversy within the Corps itself with regard to how some of these shear strengths were selected. Reviewers from the Corps' Vicksburg District appear to have raised questions in 1990 regarding the selection of shear strength parameters for some of these analyses, and we are tracking these back as best we are able. We are also performing our own interpretations of the data available at the time of the original design, and also the data being developed by post-Katrina field and laboratory testing investigations. We hope to have a report on all of this available by about early April, 2006.

Post-Hearing Questions for the Record
Submitted to Raymond B. Seed, Ph.D.
From Senator Pete V. Domenici

"Hurricane Katrina: Why Did the Levees Fail?"

November 2, 2005

1. Are you a civil or mechanical engineer?

Response: Civil Engineer

2. Can you please give us details on your education, background, and experience as it relates to engineering matters?

Response:

Please see attached C.V. This is not fully up to date, as I usually update it about every two years (and have been too busy this Fall to do this properly as yet.)

3. When did you begin your investigation of the breached levees in New Orleans?

Response:

Our studies began on August 29th, when Katrina arrived at New Orleans, but much of the early work was background study and logistical preparations for our initial field investigations. The serious investigation began in earnest on September 28th, when our first field team members were granted access to the sites of interest.

4. Where are you at in the process of that investigation?

Response:

Our Phase 1 studies were principally directed towards making initial sense of what happened, and why, and making this information available to Governmental bodies, agencies, and the many hundreds of thousands of affected people who had urgent need of some technically sound preliminary information in this regard. That effort was largely completed by the end of November, 2005.

We are now embarked on Phase 2 studies, directed primarily towards a more detailed study of the successes and failures at critical sections of the flood defenses. This involves tracing back through design documents and analyses, our own field studies, and also performing our own analyses using: (1) the data that was available for the original designs, (2) additional, post Katrina data developed by the IPET and Louisiana investigation teams, and (3) some additional field and laboratory work to be performed by our NSF-sponsored team. Our Phase 2 studies will also include some study and comments regarding institutional and governmental factors that affected the performance of the flood protection system.

5. How long do you believe your investigation will take?

Response:

We are targeting our next report for release in about early to mid-April, and currently plan to complete our Phase 2 studies by no later than the end of Summer, 2006.

6. Might other data, information, or issues come to light that could change your current assessment?

Response:

That is always conceivable.

7. Are any opinions you make today based only on your preliminary findings?

Response:

All of our findings to date should be considered to be preliminary. The Corps' IPET studies have performed (and published) a fairly thorough review of our initial Preliminary Report, and have found it to be very accurate. Our ongoing studies, since our initial Senate testimony of November 2nd, have added new findings, and further depth to some of our earlier understandings, but they have not yet resulted in significant changes in our earlier principal opinions or principal "preliminary" findings.

RAYMOND BOLTON SEED
Professor of Civil and Environmental Engineering
University of California, Berkeley

Dr. Raymond B. Seed was born in San Francisco on February 9, 1957. He received his Bachelor of Science Degree in Civil Engineering from the University of California at Berkeley in 1980, and his Master of Science and Doctor of Philosophy Degrees, both in Geotechnical Engineering and both from the University of California at Berkeley, in 1981 and 1983, respectively.

After working between 1980 and 1983 as an engineer for several geotechnical consulting firms, (Dames and Moore, Woodward-Clyde Consultants, and Converse Consultants), he joined the faculty of Stanford University where he served for four years as an Assistant Professor of Civil Engineering. He returned to U.C. Berkeley in 1987, where he is now a Professor of Civil and Environmental Engineering.

Since 1982, Professor Seed has served as a geotechnical consultant to numerous domestic and foreign engineering firms and government and civil agencies on problems spanning a number of areas including: geotechnical earthquake engineering, static and seismic stability evaluation of dams and embankments, numerical analysis of soil-structure interaction, design and performance of buried structures and conduits, stability and performance of waste fills and hazardous waste repositories, advanced geotechnical laboratory testing for a variety of applications, seismic risk analyses of lifeline systems, seismic response analyses, slope stability studies, liquefaction hazard assessment and mitigation, foundation design, and geotechnical finite element analyses of a variety of problems.

The author of more than 200 professional research publications, Professor Seed's research activities also span a wide range of subject areas. His research has had a significant impact on geotechnical practice in a number of areas including: analysis of compaction-induced stresses and deformations, seismic stability and performance evaluation for dams and embankments, analysis of soil liquefaction potential and post-liquefaction behavior, analysis of reinforced soil systems and deep braced excavations, mitigation of membrane compliance effects in undrained testing of coarse granular soils, effects of site conditions on seismic site response, finite element analysis of soil-structure interaction, stability and performance evaluation for hazardous waste fills, risk assessment for levees and flood control systems, and others. He has also served as an advisor to local, state and national governmental agencies and professional organizations on the development of policies and design codes for practice in the fields of geotechnical and earthquake engineering.

Among the professional honors accorded him, he has received the Thomas A. Middlebrooks Award (1987), the Edmund Friedman Young Engineer Award for Professional Achievement (1989), the Arthur Casagrande Award (1989), and the Huber Research Prize (1996) from the American Society of Civil Engineers (ASCE), the Prakash Award for international contributions to Seismic Geotechnics (1997), the Presidential Young Investigator Award (1985) from the U.S. National Science Foundation, a Special Resolution from the California Geology Board recognizing contributions to State seismic safety (2001), and a formal citation of appreciation for consulting services from the Egyptian Government's High and Aswan Dam Authority. He was selected as the 2003 Queen Mary Lecturer (ASCE), and the 2006 George W. Sowers State of Practice Lecturer (ASCE). Professor Seed has also received a number of awards and honors recognizing his contributions as an educator, including the 1989 University of California Distinguished Teaching Award (the University's highest teaching award), the New Engineering Educator Excellence Award (1988) from the American Society for Engineering Education, and several other teaching awards from the Department of Civil Engineering at U.C. Berkeley.

Curriculum Vitae: RAYMOND BOLTON SEED

Title:	Professor of Civil and Environmental Engineering
Office Address:	423 Davis Hall Department of Civil and Environmental Engineering University of California Berkeley, CA 94720-1710
Office Phone:	(510) 643-8438 E-mail: Rmseed6@aol.com
Cell Phone:	(925) 930-8692

EDUCATION:

University of California, Berkeley: Ph.D. - Geotechnical Engineering, December, 1983.

University of California, Berkeley: M.S. - Geotechnical Engineering, June, 1981.

University of California, Berkeley: B.S. - Civil Engineering, June, 1980.

AWARDS AND HONORS:

University of California Outstanding Freshman Award, 1975

Member of Dean's Honor Roll, 1975-1980

Graduated with Highest Honors, 1980

Regents Fellow, University of California, 1980-81

Converse Award for Most Outstanding Graduate Student in Geotechnical Engineering, 1981

Member, Chi Epsilon Civil Engineering Honor Society, 1981

Member, Tau Beta Pi Engineering Honor Society, 1981

Exxon Teaching Fellow, 1982-1983

Presidential Young Investigator Award, U.S. National Science Foundation, 1985

Certificate of Appreciation: Woodward-Clyde Consultants and the Egyptian Government High and Aswan Dam Authority, 1985

Member, Sigma Xi Scientific and Engineering Honor Society, 1986

Thomas A. Middlebrooks Award, American Society of Civil Engineers, 1987

Award for Outstanding Service, American Society of Civil Engineers, 1988

New Engineering Educator Excellence Award, American Society for Engineering Education, 1988

Best Professor Award, Student Chapter of the American Society of Civil Engineers, University of California at Berkeley, 1988

Edmund Friedman Young Engineer Award for Professional Achievement, American Society of Civil Engineers, 1989

Best Professor Award, Student Chapter of the American Society of Civil Engineers, University of California at Berkeley, 1989

University Distinguished Teaching Award, University of California at Berkeley, 1989

Arthur Casagrande Award, American Society of Civil Engineers, 1989

Walter L. Huber Civil Engineering Research Prize, American Society of Civil Engineers, 1996

Shamsher Prakash Award for International Contributions to Geotechnical Earthquake Engineering, 1998

Special Resolution in recognition of contributions to State seismic safety, California State Board of Mines and Geology, 2001

2003 Queen Mary Lecturer; 25th Annual Spring Seminar, American Society of Civil Engineers, GeoInstitute, Los Angeles Section, on board HMS Queen Mary, Long Beach, California, April 30.

2006 George W. Sowers State of Practice Lecturer; American Society of Civil Engineers, GeoInstitute, Southeast Section, Atlanta, Georgia, May 12.

PROFESSIONAL AFFILIATIONS:

Member, International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE)

Member, American Society for Engineering Education (ASEE)

Member, Earthquake Engineering Research Institute (EERI)

Member, Earthquake Engineering Research Center, University of California at Berkeley (EERC)

Individual Member, California Universities for Research in Earthquake Engineering (CUREe)

PROFESSIONAL SERVICE:

Member, Organizing Committee, XIth International Conference on Soil Mechanics and Foundation Engineering, San Francisco, 1985.

Chairman, U.S. National Society Publications Committee, XIIth International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, Brazil, 1989.

Member, Structural Engineers Association of Northern California (SEAONC), Committee (S4) on Geotechnical Issues for the SEAOC and NEHRP Seismic Codes, 1990 - 1997.

Chairman, SEAONC Committee S4 Sub-Committee on SEAOC Seismic Code Issues Related to Liquefaction and Ground Failure, 1992 - 1995.

Member, CDMG Working Group for Implementation of the 1990 Seismic Hazards Act, California Division of Mines and Geology, 1991-present.

Member, Publications Committee, Geotechnical Division, American Society of Civil Engineers, 1987 -1992.

Associate Editor, Journal of Geotechnical Engineering, American Society of Civil Engineers, 1992 - 1993.

Member, Editorial Board: Computers and Geotechnics, 1986 - 1991.

Member, Board of Editors, Taiwan Journal of Geotechnical Engineering, Taiwan Geotechnical Society, 2005 – present.

Member, Committee on Embankment Dams and Slopes, American Society of Civil Engineers, 1989 – 1996, and 2005 – present.

Member, TRB Committee on Subsurface Soil-Structure Interaction, National Research Council, 1985-1993.

Co-Chairman, Organizing Committee, ASCE Specialty Conference on "Stability and Performance of Slopes and Embankments - II (A 25-Year Perspective)", Berkeley, June, 1992; also Proceedings editor.

Member, Board of Directors, American Society for Engineering Education, Pacific Southwest Section, 1988 - 1991.

Chairman, Committee on Younger Members, Pacific Southwest Section, American Society for Engineering Education, 1988 - 1991.

Vice Chairman, Membership, Pacific Southwest Section, American Society for Engineering

Education, 1989 - 1991.

Chairman, Organizing Committee, Annual Conference of the Pacific Southwest Section, American Society for Engineering Education, Berkeley, California, October 1991.

Member, Ad-hoc Committee on Younger Members, Earthquake Engineering Research Institute, 1987 –1992.

Member, Organizing Committee for the Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Rolla, Missouri, May 1991.

Co-Chairman and Site Host, 3rd International Conference on Earthquake Geotechnical Engineering and 12th International Conference on Soil Dynamics and Earthquake Engineering (3rd ICEGE/12th ICSDEE), Berkeley, California, January 7-9, 2004.

Member, U.S. NSF Post-Earthquake Investigation Teams:
- 1989 Loma Prieta Earthquake, California.
- 1994 Northridge Earthquake, California.
- 1995 Hyogoken-Nanbu (Kobe) Earthquake, Japan.
- 1999 Kocaeli Earthquake, Turkey.
- 1999 Chi-Chi Earthquake, Taiwan.
- 1999 Central Mexico (Tehuacan) Earthquakes of June 15 and June 19
- 2001 Bhuj Earthquake, India.

Leader, NSF-Sponsored Independent Investigation of the performance of the New Orleans Flood Protection Systems During Hurricane Katrina, 2005-2006.

Participating Instructor: Five-day short course on "Seismic Stability Analyses of Earth and Rockfill Dams" for the U.S. Federal Energy Regulatory Commission, San Francisco, CA, Sept. 9-13, 1985.

Participating Instructor: Four-day short course on "Microcomputers in Geotechnical Engineering Practice," Madison, WI, June 3-6, 1986.

Participating Instructor: Five-day short courses on "Seismic Analysis, Design and Evaluation of Tunnels and Dams," for the U.S. Federal Energy Regulatory Commission (FERC), Berkeley, CA, June 18-22, 1990, and August 19-23, 1991.

Participating Instructor: Two-day short course/seminar on "Seismic Re-Evaluation and Retrofit of Bridges", University of California at Berkeley, June 8-9, 1992.

Participating Instructor: Five-day short course on "Geotechnical Earthquake Engineering for Practicing Engineers", University of California at Berkeley, August 20-25, 1994

Participating Instructor: One-day short courses on "Seismic Analysis and Design of Waste Landfills"; Berkeley, California, June 4, 1994, and March 10, 1995; Los Angeles, California, Jan. 21, 1995; and Washington, D.C., July 21, 1995.

Lead Organizer and Participating Instructor: Three-day CDMG-sponsored short courses for regulatory officials and practicing design engineers on "Evaluation and Mitigation of Seismic Hazards" addressing the Soil Liquefaction and Seismic Slope Deformation elements of the 1990 Seismic Hazards Act; January 22-24, 1998, Los Angeles; July 30-August 1, 1998, Los Angeles; August 20-22, 1998, Berkeley; August 2-4, 2001, Los Angeles; August 8-10, 2002, Berkeley, California; April 7-9, 2005, San Diego, California; August 25-27, 2005, Berkeley, California.

Instructor: Four-day short course on Recent Advances in Seismic Geotechnics, Guayaquil, Ecuador, July 12-15, 2004.

Faculty participant, three-day invitational workshop to examine problems and solutions associated with providing new engineering faculty for the future, co-sponsored by NSF and the American Society for Engineering Education, Washington, D.C., January 12-14, 1989.

Invited participant, Workshop on "Methods for Seismic Hazards Zonation", jointly sponsored by California SMGB, CDMG, California SSC, and USGS; Tomales Bay, Calif., February 19-21, 1991.

Invited participant, Workshop for planning of western U.S. strong motion and other seismic site instrumentation programs, U.S. Geological Survey, Asilomar, California, March 3-5, 1991.

Invited participant, NSF Workshop for development of research plans and priorities in the areas of geotechnical earthquake engineering and soil dynamics, Sacramento, California, February 4-6, 1992.

Invited Participant, NSF-sponsored workshop on Resolution of Seismic Response Issues from the Northridge Earthquake (ROSRINE), Los Angeles, California, December 18-19, 1998.

Member, NSF Proposal Review Panel, Geotechnical Earthquake Engineering Program: 1992, 1994, 1999, 2003.

Member, Extramural Proposal Review Panel, U.S. Geological Survey; 1988, 1989, 1990.

Member, Research Review Panel for Proposals for Research Involving the October 17, 1989 Loma Prieta Earthquake, U.S. Geological Survey, 1989.

Journal Reviews:

- Journal of the Geotechnical Engineering Division, A.S.C.E.
- Soils and Foundations, JSSMFE.
- Geotechnique.
- Transportation Research Record, National Research Council
- International Journal of Soil Dynamics and Earthquake Engineering
- Geotechnical Testing Journal, A.S.T.M.
- Canadian Geotechnical Journal, National Research Council, Canada
- International Journal for Numerical and Analytical Methods in Geomechanics
- Computers and Geotechnics
- ASME Transactions, American Society of Mechanical Engineers
- Bulletin of the Seismological Society of America
- Earthquake Spectra, the professional journal of E.E.R.I.
- Earthquake Engineering and Structural Dynamics.
- Marine Geotechnology.
- Journal of Engineering Sciences, Saudi Arabia.

EMPLOYMENT RECORD:

Professor of Civil and Environmental Engineering: University of California, Berkeley, July 1991 - present.

Associate Professor of Civil Engineering: University of California, Berkeley, July 1989 - June 1991.

Assistant Professor of Civil Engineering: University of California, Berkeley, Jan. 1987 -Feb. 1989.

Assistant Professor of Civil Engineering: Stanford University, August 1983 - December 1986 (and Part-Time Visiting Professor, January 1987-December 1990).

Teaching Assistant and Graduate Research Assistant: University of California, Berkeley, September 1981 - June 1983.

Lead Engineer: Converse Consultants, San Francisco, California, June 1981 - September 1981
Dynamic soil-structure interaction analyses, liquefaction analyses, statistical risk analyses. Project director for a major aqueduct lifeline hazard analysis study.

Staff Engineer: Woodward-Clyde Consultants, San Francisco, California, June 1980 - September 1980. Developed laboratory and field testing programs for the National Nuclear Waste Repository Study; Basalt Borehole Plugging Program.

Staff Engineer: Dames and Moore, Honolulu, Hawaii, June 1979 - January 1980
Pile load tests, pile driving inspection, excavation and fill inspection, borehole and test pit logging, settlement and slope stability analyses, design of retaining walls, report and proposal preparation.

Engineer: EDS Nuclear, San Francisco, California, June 1978 - January 1979
Computer modeling and three-dimensional finite element analyses of nuclear reactor piping with respect to gravity, thermal, hydraulic, and seismic loadings.

Field Engineer: East Bay Municipal Utility District, Oakland, California, June 1977 - September 1977
Fill inspector, Upper San Leandro Dam earth fill.

CONSULTING EXPERIENCE:

Since 1982, consultant to:

Governmental Port Authorities, Nice, France: Study of the 1979 slope failure and tidal wave at the New Port of Nice, 1982-84.

Converse Consultants: Seismic risk studies of the Mokelumne Aqueduct System in the Sacramento - San Joaquin River Delta Region, California, 1982.

Kaiser Aluminum Corporation: Soil-structure interaction aspects of flexible culvert design for large-span culvert structures; design, analysis, laboratory and field testing of new aluminum culvert types and new types of spiral pipe; field problems associated with construction and backfill placement operations; finite element analyses; forensic studies; expert testimony; consultation regarding individual culvert installations across the continental United States, 1982-88.

Nikken Sekkei, Ltd.: Soil-structure interaction effects and seismic earth pressure evaluation for large oil storage tank foundations in Japan, 1983.

H. Bolton Seed, Inc.: Generation of modified acceleration time histories and response spectra for seismic analyses, 1984.

U.S. Army Corps of Engineers: Finite element analyses of Barkley Dam for liquefaction studies, 1983; development and implementation of methods for mitigation of membrane compliance effects in undrained testing of gravelly soils, 1985-86; Post-liquefaction seismic slope stability studies of Lower San Fernando Dam in the 1971 San Fernando Earthquake, 1985-88; Review of seismicity, soil liquefaction, and seismic stability and performance studies of Tuttle Creek Dam, Kansas, 1991; Member of working group for development of seismic design manuals for the U.S. Navy dealing with evaluation and mitigation of soil liquefaction hazard, design of walls, locks and other retaining structures, and evaluation of liquefaction-related settlements, 1991; Consultation regarding development of national criteria for seismic safety evaluation of Federal dams and levee systems, 1996-1997, Consultation and review of seismic stability studies for Chessman Dam, Missouri, 2005.

Woodward-Clyde Consultants: Laboratory cyclic triaxial and index testing for seismic stability studies of the Aswan Dam, 1984-85; laboratory cyclic triaxial and steady-state residual strength testing for seismic stability studies of Lake Madigan Dam, Solano County, California, 1988; Consultation and review of seismicity and seismic stability studies of Big Dalton, Little Dalton, Santa Anita and Sawpit debris dams, studies performed for the Los Angeles County Department of Public Works, 1990-91; Consultation regarding seismic stability, soil liquefaction, and flow deformation studies for a tailings impoundment in the mid-western U.S., 1998.

Bechtel Civil and Minerals: Finite element analyses of Mount Tabor Reservoir embankment dam for seismic liquefaction studies, 1985.

Lockwood, Singh and Associates: Consultation and review of finite element and conventional stability analyses of the Big Rock-Mesa landslide, Los Angeles, California, 1985-86.

City of Benicia: Review of geotechnical investigations, static and seismic stability analyses for the Panoche Repository Class I hazardous waste landfill in Solano County, California, 1987-88; Review of preliminary closure plans for the Panoche Repository, 1988.

Engineering Science: Consultation and review of finite element analyses for a proposed extension of Ramona Dam in San Diego County, California, 1987.

San Lorenzo Valley Water District: Consultation and review of static and seismic slope stability studies and seismic slope displacement studies for Big-Con Dam and Reservoir in Santa Cruz County, California, 1987-88.

Peter Kaldveer and Associates, Inc.: Probabilistic seismicity evaluation and seismic site response analyses for a bayshore development in Emeryville, California, 1987-88; Similar studies, as well as consultation and review of dynamic pile response analyses for Pier 39 in San Francisco, California, 1988.

Northern Engineering and Testing, Inc.: Seismic slope displacement and post-liquefaction stability studies for the proposed seismic rehabilitation of Chessman Dam, Montana, 1987-88.

Gator Culvert, Inc., Florida: Finite element analyses of soil-structure interaction effects of multi-axle vehicle loads over long-span culverts at shallow cover depths and development of design procedures for such vehicle load conditions, 1988.

Rosenberg & Reisman: Finite element analyses, forensic post-failure investigation and expert testimony regarding the failure of a long-span culvert overpass structure in Cooper City, Florida, 1988.

Chemical Waste Management, Inc.: Studies of the slope stability failure of March 19, 1988 at the Kettleman Hills Hazardous Waste Management Facility, California, 1988; Review of slope stability studies for the Arlington Facility hazardous waste repository, Arlington, Oregon, 1988; Consultation and review of final cause of failure studies for Landfill Unit B-19, Phase I-A, Kettleman Hills Hazardous Waste Management Facility, California, 1990-91.

Haro, Kasunich & Associates, Inc.: Consultation and review of seismic site response analyses for a proposed structure in Santa Cruz, Calif., 1989.

Canonie Environmental Services Corp.: Evaluation of liner system interface shear strengths for multi-layered liner systems for three proposed hazardous waste landfills in Southern California, 1988-89.

Contech Construction Products, Inc.: Finite element analyses and studies of structural stability of in-service, deformed, corrugated aluminum box culverts, 1988.

CH2M Hill: Evaluation of liner system interface shear strengths for two lined waste repository basins in King County, Washington, 1989; Consultation and review of site characterization studies, preliminary design and static and seismic stability analyses for a proposed waste landfill in central California, 1989-1992; Consultation and review of stability analyses and closure plans for a second waste landfill in central California, 1989.

Williams, Kelly, Polverari & Skelton: Review and comment on geotechnical studies for a coastal site in Seal Cove, California distressed due to slope stability failures and coastal erosion, 1989.

U.S. Bureau of Reclamation: Large-scale (12-in. dia.) monotonic and cyclic triaxial testing of gravelly soils for the shells of the proposed Jordanelle Dam in northern Utah, 1989; Consultation and review of seismicity and seismic stability studies and remediation works for Bradbury Dam, Santa Barbara Co., California, 1994-96; Review of BuRec policies and procedures for seismic evaluation of dams potentially subject to soil liquefaction, 2004.

California Department of Transportation (CALTRANS): Review of seismic design spectra for bayshore sites in the San Francisco Bay Area, 1989-1992.

Nelson & Leighton: Development of seismic design spectra, evaluation of seismic slope stability, and general geotechnical consultation for a San Francisco bayshore residential development in Marin County, California, 1990.

Browning-Ferris Industries: Consultation regarding evaluation of static and seismic stability and performance of a lined municipal waste fill in Los Angeles County, California, 1990.

Leighton and Associates, Inc.: Review of studies pertaining to liquefaction hazard for a proposed development in Los Angeles County, California, 1990.

California Department of Water Resources (DWR): Consultation and review of remedial works to prevent failure of levees on Sherman Island, Sacramento County, California, 1991; Consultation regarding studies of seismic response and performance of levees and related systems in the Sacramento - San Joaquin Delta region, 1991 – present; Member, Delta Seismic Board, 1992-present; Member, CALFED Delta Levees Working Group, 1994-2000; Review Panel, proposed "In-Delta" storage program, 2001-present; Consultation and review of seismic stability studies for Paris Dam, 2003-present, Consultation and review of probabilistic hazard evaluations related to potential seismically-induced levee failures in the Sacramento-San Joaquin Delta and their likely consequences with regard to water conveyance and delivery as well as environmental ramifications, 2003-present.

Emcon Associates, Inc.: Consultation regarding seismic stability and performance of the Palo Alto Sanitary Landfill, San Mateo County, California, 1991; Consultation regarding studies of seismic stability and performance of Richmond Sanitary Services Class II Waste Landfill, Contra Costa

County, California, 1991.

The Mark Group: Consultation regarding seismic site response studies and pile foundation analyses for the Contra Costa County Water District's proposed Old River Pumping Facility, Los Vaqueros Dam Project, Contra Costa County, California, 1992.

Pacific Gas and Electric Company: Consultation and review of seismicity, seismic stability and performance studies of Lake Almador Dam, Plumas County, California, 1992; Consultation and review of similar studies for Butte Valley Reservoir Dam, Plumas County, California, 1992.

LAW Engineering: Undrained cyclic triaxial testing, and related index testing, for the Savannah River Tritium Replacement Facility, Georgia, 1993-2001.

Harza Kaldveer: Consultation regarding seismic response analyses, soil-structure interaction and foundation element stability studies for the Corte Madera Creek Bridges, Marin County, California, 1993.

CDM Federal Programs Corp.: Consultation and review of seismicity, static and seismic stability and deformation and cover design studies for the OII Landfill, Los Angeles, California, 1993 - 1999.

B.C. Hydro: Consultation and review of liquefaction and seismic stability studies for Keenleyside Dam, British Columbia, Canada, 1993-99.

Santa Cruz County Planning Department: Consultation and review of seismic stability studies of Soda Lake Dam, Santa Cruz County, California, 1993.

AGS Consultants: Consultation and review of seismicity, site response and liquefaction studies, and deep foundation design studies, for proposed BART station and parking garages at San Francisco International Airport, 1996; consultation and review of seismic hazard evaluation and engineered design mitigation for proposed MUNI Metro light rail servicing yards, San Francisco, 1996-1999.

Coffey Partners Intl. Pty. Ltd.: Consultation and review of seismicity, site response and soil liquefaction hazard evaluations on behalf of the Regional Government, MFP project area, Adelaide, Australia, 1996.

Tech Ion Industrial Brazil S.A.: Consultation and review of seismicity studies, site response analyses, liquefaction studies, slope stability studies, and foundation design for a proposed nuclear facility in Manaus, Brazil, 1997; Similar studies for a second site in Belem, Brazil, 1997-1998.

Berloger Geotechnical Consultants: Consultation and review of liquefaction hazard evaluation and remediation studies for a proposed residential development in Alameda, California, 1997-1998.

Olivia Chen Consultants: Consultation and review of liquefaction and seismic stability studies for Calaveras Dam, California, 2000-2003.

Ove Arup, Ltd.: Consultation regarding seismic soil liquefaction issues for a proposed underwater rail transit tube across the Marmary/Bosphorus Straight, Istanbul, Turkey, 2003; consultation regarding seismic stability and liquefaction issues for the proposed Messina Straights Bridge, Italy, 2004.

Bechtel/BART Consortium: Consultation and review of seismic vulnerability and remediation design studies for the Bay Area Rapid Transit (BART) trans-bay crossing, 2003-present.

Geomatrix Consultants: Consultation and review of seismic stability studies of San Pablo Dam, California, 2003-present.

URS Consultants: Consultation and review of seismic studies for the proposed runway expansion and associated fill for the San Francisco International Airport, 2005 – present.

INVITED LECTURE PRESENTATIONS: (Excluding Conference Papers)

1. "Coastal Liquefaction Slide as a Result of Tidal Drawdown," United States Geological Survey, Menlo Park, Calif. July 12, 1984.
2. "The Failure of the New Port at Nice, France," Virginia Polytechnic Institute and State University, September 14, 1984.
3. "Finite Element Analyses of Compaction-Induced Stresses and Deformations," 64th Annual Meeting of the Transportation Research Board, Washington, D.C., January 15, 1985.
4. "Soil Liquefaction Under Monotonic Loading: The Nice Failure," University of California at Davis, February 6, 1985.
5. "Application of Finite Element Methods to the Solution of Insoluble Problems," Seminar on Application of Finite Element Methods in Geotechnical Engineering, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, May 16, 1985.
6. "Cyclic Pore Pressure Generation Behavior of Gravelly Soils," XIth International Conference on Soil Mechanics and Foundation Engineering, Session 7A, August 15, 1985.
7. "Current Stanford University Research on Penetration Testing," The First U.S.-Japan Workshop on In-Situ Testing Methods for Evaluation of Soil Liquefaction Susceptibility, San Francisco, August 17-18, 1985.
8. "Static Finite Element Analysis of Earth Dams and Embankments," a two lecture series for the Federal Energy Regulatory Commission, San Francisco, September 11-12, 1985.
9. "Analysis of Compaction-Induced Soil Stresses," University of California at Berkeley, March 26, 1986.
10. "Seismic Site Response Analysis," Professional Seminar on Microcomputers in Civil Engineering Practice, University of Wisconsin, Madison, June 5, 1986.
11. "Mitigation of Membrane Penetration Effects in Undrained Triaxial Testing," U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, November 7, 1986.
12. "The Failure of the New Port at Nice, France," University of Santa Clara, San Jose, California, November 11, 1986.
13. "The Mokelumne Aqueduct Seismic Risk Analysis Studies," special SEMM Seminar, Department of Civil Engineering, University of California, Berkeley, March 30, 1987.
14. "The Failure of the New Port at Nice, France," meeting of the San Diego Section of the American Society of Civil Engineers, Geotechnical Division, San Diego, November 10, 1987.
15. "Analysis, Design and Testing of Smooth-Walled Box Structures," meeting of Committee A2KO4 on Subsurface Soil-Structure Interaction, 66th Annual Meeting of the Transportation Research Board, Washington D.C., January 13, 1988.
16. "Compaction-Induced Earth Pressures," meeting of the Los Angeles Section of the American Society of Civil Engineers, Geotechnical Division, Los Angeles, January 20, 1988.
17. "Mokelumne Aqueduct Security Studies," Joint Meeting of the San Francisco Bay Area Section and the Golden Gate Section of the American Society of Civil Engineers, Geotechnical Division, San Francisco, May 17, 1988.
18. "The Mokelumne Aqueduct Seismic Risk Analysis Studies," professional training seminar for engineers and planners of the East Bay Municipal Utility District, Oakland, California, June 7, 1988.
19. "Dynamic Slope Stability and Slope Deformation Analysis", a one-day professional training seminar for engineers and management officers of EMCON Associates, San Jose, November 12, 1988.
20. "The Kettleman Hills Waste Repository Stability Failure", Virginia Polytechnic Institute and State University, Blacksburg, Virginia, January 20, 1989.
21. "Case Study: Coastal Landslide at Nice", invited lecture at the 1989 Annual Geotechnical Conference sponsored jointly by the University of Kansas and local sections of the American Society

of Civil Engineers and the Association of Engineering Geologists, Lawrence, Kansas, March 3, 1989.

22. "The Kettleman Hills Waste Repository Stability Failure," joint meeting of the Golden Gate Section and the U.C. Berkeley Student Chapter of the American Society of Civil Engineers, March 16, 1989.
23. "The Kettleman Hills Waste Repository Stability Failure," meeting of the San Diego Section of the American Society of Civil Engineers, San Diego, April 19, 1989.
24. "Seismic Response of the Puddingstone and Cogswell Dams in the 1987 Whittier Narrows Earthquake", special seminar sponsored by the California Strong Motion Instrumentation Program, Sacramento, May 9, 1989.
25. "The Failure of the New Port at Nice, France", professional seminar for Woodward-Clyde Consultants, Oakland, May 22, 1989.
26. "Lessons Learned from the Failure of the Kettleman Hills Waste Repository", theme lecture for annual national professional development seminar, CH2M Hill, Inc., Denver, Colorado, September 16, 1989.
27. "The Failure of the New Port at Nice, France", evening lecture for annual professional development seminar, CH2M Hill, Inc., Denver, Colorado, September 16, 1989.
28. "Preliminary Geotechnical Observations: The Loma Prieta (Santa Cruz) Earthquake of October 17, 1989", Special public seminar, Wheeler Auditorium, University of California, Berkeley, October 25, 1989.
29. "Briefings for the U.S. Senate and the U.S. House of Representatives on Seismological and Geotechnical Aspects of the Loma Prieta (Santa Cruz) Earthquake of October 17, 1989", Capitol Hill, Washington, D.C., November 7 and 8, 1989.
30. "A Preliminary Geotechnical Overview of the Loma Prieta (Santa Cruz) Earthquake of October 17, 1989", NSF/EPRI Workshop on Soil Dynamics, Palo Alto, California, November 9, 1989.
31. "A Preliminary Geotechnical Overview of the Loma Prieta (Santa Cruz) Earthquake of October 17, 1989", Organizational meeting of Project VELACS, a coordinated national program for geotechnical dynamic centrifuge studies, Davis, California, November 20, 1989.
32. "The Kettleman Hills Waste Repository Stability Failure", University of Washington, Seattle, Washington, November 30, 1989.
33. "The Failure of the New Port of Nice", meeting of the Washington Section of the American Society of Civil Engineers, Geotechnical Division, Seattle, Washington, November 30, 1989.
34. "Post-Earthquake Briefing; Geotechnical Aspects, Loma Prieta Earthquake of October 17, 1989", Earthquake Engineering Research Institute Northern California post-earthquake briefing, Berkeley, California, December 2, 1989.
35. "Post-Earthquake Briefing; Geotechnical Aspects, Loma Prieta Earthquake of October 17, 1989", Earthquake Engineering Research Institute Northern California post-earthquake briefing, Stanford, California, December 2, 1989.
36. "Soil-Structure Interaction: Local Site Effects on Seismic Exposure", annual meeting of U.S. National Federation of Municipal Analysts, Los Angeles, October 19, 1989.
37. "Geological and Geotechnical Factors Controlling Damage Patterns in the Loma Prieta Earthquake: Important Lessons Re-Learned", annual meeting of the American Association for Advancement of Science, New Orleans, Louisiana, February 19, 1990.
38. "Geological and Geotechnical Factors Controlling Damage Patterns in the Loma Prieta Earthquake: Important Lessons Re-Learned", Rossmoor Engineer's Club, Rossmoor, California, February 27, 1989.
39. "Soil Liquefaction During the Loma Prieta Earthquake of October 17, 1989", Special University/Industry ILP Symposium, University of California at Berkeley, March 13, 1990.
40. "The Kettleman Hills Waste Repository Stability Failure", ASCE Geotechnical Seminar on Geotechnics of Waste Fills, Denver, Colorado, March 22, 1990.

41. "The Failure of the New Port at Nice, France", Public Works Research Institute, Tsukuba, Japan, June 8, 1990.

42. "The Failure of the New Port at Nice, France", University of Tokyo, June 9, 1990.

43. "The Failure of the New Port at Nice, France", Kyoto University, Japan, June 10, 1990.

44. "Overview of Geotechnical Features of the 1989 Loma Prieta Earthquake", Okayama University, Okayama, Japan, June 11, 1990.

45. "Geological and Geotechnical Factors Controlling Damage Patterns in the Loma Prieta Earthquake of October 17, 1989", annual meeting of the Japanese Society of Soil Mechanics and Foundation Engineering, Okayama, Japan, June 13, 1990.

46. "Recent Advances in Seismic Stability and Deformation Evaluation for Dams and Embankments", a series of lectures as part of a 5-day short course on "Seismic Design of Tunnels and Dams" for FERC, University of California at Berkeley, June 19 & 20, 1990.

47. "Lessons Learned from the Loma Prieta Earthquake Regarding the Influence of Geotechnical Factors on Seismic Risk and Vulnerability", Stanford University, August 15, 1990.

48. "The Kettleman Hills Waste Repository Stability Failure", meeting of the Los Angeles Section of the American Society of Civil Engineers, Los Angeles, November 12, 1990.

49. "Geotechnical Lessons from the 1989 Loma Prieta Earthquake," presentation at Woodward Clyde Consultants professional development seminar, San Francisco, November 30, 1990.

50. "Recent developments in Seismic Stability Assessment for Earth and Rockfill Dams", three-hour seminar for CH2M Hill, Inc., San Francisco, January 8, 1991.

51. "The Kettleman Hills Waste Repository Stability Failure of March 19, 1989", Stanford University, January 30, 1991.

52. "The Failure of the New Port at Nice, France", professional seminar for Woodward-Clyde Consultants, Santa Ana, California, January 31, 1991.

53. "Issues and Future Research Directions in the Application of the Earth Sciences to Seismic Zonation", 4th International Conference on Seismic Zonation, Stanford University, Stanford, California, August 26, 1991.

54. "Seismic Response of Soft and Deep Cohesive Sites", Los Angeles Section of the American Society of Civil Engineers, Los Angeles, California, January 15, 1992.

55. "Seismic Response of Soft and Deep Cohesive Sites", Woodward-Clyde Consultants, Oakland, California, January 22, 1992.

56. "Analysis and Prediction of Seismic Response of Cohesive Soil Sites", Joint Workshop on Geotechnical Seismic Building Code Issues; National Bureau of Standards and NSF, Gaithersberg, Maryland, January 27, 1992.

57. "An Overview of Particularly Important and/or Urgent Problem Areas in Practice", NSF Workshop on Geotechnical Research Needs for the Assessment and Mitigation of Infrasturcture Deterioration in Response to Earthquake Hazards, Sacramento, California, February 4-5, 1992.

58. "Seismic Response Characteristics and Foundation Problems for Soft Clay Sites", 14th Annual Conference, Industrial Liaison Program, University of California at Berkeley, March 11, 1992.

59. "Seismic Response of Soft and Deep Cohesive Sites", joint lecture session for the Portland Sections of the Association of Engineering Geologists and the American Society of Civil Engineers Geotechnical Division, Portland, Oregon, March 20, 1992.

60. "Recent Lessons Regarding the Significance and Accurate Prediction of the Influence of Local Site Conditions on Strong Shaking", a special seminar for CALTRANS Structural and Geotechnical Divisions, Sacramento, California, May 4, 1992.

61. "Analysis of the Seismic Response of Soft and Deep Cohesive Sites", a special seminar for CALTRANS Geotechnical Division, Sacramento, California, May 4, 1992.

62. "Major Changes in Recommended Procedures for Evaluation of the Seismic Response of Soft Clay Sites", Workshop on Geotechnical Issues Affecting the SEAOC and UBC Seismic Building Codes, San Francisco, California, May 18, 1992.
63. "Recent Significant Advances in Evaluation of Site Effects on Strong Shaking and Soil Liquefaction", lecture presented as part of a two-day seminar on "Seismic Analysis and Retrofit of Bridges", University of California at Berkeley, June 9-10, 1992.
64. "Observations Regarding Seismic Response Analyses for Soft and Deep Clay Sites", meeting of the Committee on Foundations and Earthquake Engineering, International Society of Soil Mechanics and Foundation Engineering, Mexico City, August 20, 1992.
65. "Recent Advances in Analysis of Site-Dependent Seismic Site Response", a special seminar for CALTRANS' Geotechnical Division, Sacramento, California, October 19, 1992.
66. "Recent Lessons Regarding Site-Dependent Seismic Site Response", a special seminar for CALTRANS' Structural Design Division, Sacramento, California, December 7, 1992.
67. "Seismic Response of Soft and Deep Clay Sites", NSF Workshop on Earthquake Site Response and NEHRP Seismic Code Provisions, Los Angeles, California, December 10, 1992.
68. "Site-Dependent Seismic Site Response", Stanford University, Stanford, Calif., March 3, 1993.
69. "Recent Advances in Evaluation of Site Effects on Site Response", Industrial Liaison Program Symposium, University of California at Berkeley, March 10, 1993.
70. "Recent Advances, Current Trends, and Future Research Needs with Respect to Site-Specific Seismic Response Evaluation for Structural Design", Second Annual CALTRANS Seismic Research Seminar, Sacramento, Calif., March 16, 1993.
71. "Research Needs and Priorities: Geotechnical Earthquake Engineering", One-Day Meeting and Workshop on Seismic Vulnerability of San Francisco Bayshore Margins, co-sponsored by USGS and USGS and CONCERT, June 1, 1993.
72. "Geotechnical Engineering Lessons from the 1995 Kobe Earthquake", Omaha Geotechnical Section, ASCE, March 16, 1995.
73. "Lessons from the Kettleman Hills Waste Landfill Stability Failure", One-day regional seminar on Analysis, Design and Performance of Waste Landfills, Omaha, Nebraska, March 17, 1995.
74. "Evaluation of Seismic Stability and Performance for Embankment Dams," U. S. Army Corps of Engineers, Washington, D. C., October 11, 1996.
75. "Recent Advances in Evaluation and Mitigation of Soil Liquefaction Hazard," ASCE Regional Seminar, Portland, Oregon, November 7, 1996.
76. "Recent Advances in Evaluation and Mitigation of Soil Liquefaction Hazard," U.S. Bureau of the Reclamation, Denver, Colorado, January 23, 1997.
77. "Engineering Evaluation of Post-Liquefaction Residual Strength," Third Bay Area Workshop/Short-Course on Soil Liquefaction, San Francisco, California, November 5, 1997.
78. "Development of Probabilistic Tools for Evaluation of Soil Liquefaction and Lateral Spreading Hazard," PG&E/PEER Research Workshop, San Francisco, California, November 5, 1997.
79. "Soil Liquefaction in a Rapidly Changing World," Meeting of the San Francisco Section of the American Society of Civil Engineers, Geotechnical Division, Oakland, California, January 15, 1998.
80. "Soil Liquefaction Engineering in a Rapidly Changing World," Joint Meeting of the Association of Engineering Geologists and the American Society of Civil Engineers, Los Angeles, California, March 16, 1998.
81. "Introduction to Seismic Site Response Issues", PEER Earthquake Engineering Center Scholar's Course, Berkeley, California, October 6, 2000.
82. "Liquefaction Engineering: Soil Liquefaction and Deformation Potential," PEER Earthquake Engineering Center, October 7, 2000.

83. "Seismic Design Codes & Policy: A Geotechnical Perspective," PEER Earthquake Engineering Center, October 7, 2000.
84. "Observations and Overview of Performance of Dams in the 2001 Bhuj Earthquake," Gujarat Ministry of Dams, Ahmedabad, India, February 21, 2001.
85. "Geotechnical Aspects of the 2001 Bhuj Earthquake: Liquefaction and Ground Failure," Special EERI Earthquake Reconnaissance Seminar, San Francisco, California, April 21, 2001.
86. "Seismic Performance of Earth Dams in the 2001 Bhuj Earthquake," Special EERC/PEER Seminar, University of California at Berkeley, May 16, 2001.
87. "Characterization and Treatment of Seismic Slope Site Response," Seminar on Geotechnical Earthquake Engineering and Microzonation, Istanbul, Turkey, August 24, 2001.
88. "Recent Advances in Liquefaction Hazard Assessment," International Satellite Conference on Lessons from Recent Earthquakes, organized by Committee TC-4, ISSMGE, Istanbul, Turkey, August 25, 2001.
89. "Recent and Ongoing Advances in Seismic Soil Liquefaction Engineering," URS Consultants Oakland, California, May 18, 2002.
90. "Soil Liquefaction Engineering: A Consistent Framework," 25th Annual Spring Seminar, Los Angeles Section, GeoInstitute of the American Society of Civil Engineers, HMS Queen Mary, Long Beach, California, April 30, 2003.
91. "Probabilistic Evaluation of Liquefaction-Induced Lateral ground Displacements", PEER Lifelines Engineering research Program, quarterly meeting, University of California at Berkeley, October 15, 2004.
92. "Recent Advances in Soil Liquefaction Engineering", Bay Area Section of the GeoInstitute, American Society of Civil Engineers, Oakland, California, February 15, 2005.
93. "New Orleans Levee Failures and California's own Levee Risks", Townhall Meeting, Center for Catastrophic Risk Mitigation (CCRM), University of California, Berkeley, September 8, 2005.
94. "New Orleans in Hurricane Katrina: Why Did the Levees Fail?", Senate testimony, U.S. Senate Committee on Homeland Security and Governmental Oversight, Washington, D.C., November 2, 2005.
95. "Preliminary Report on the Performance of the new Orleans Flood protection System During Hurricane Katrina", Special Lecture program, center for Catastrophic Risk Mitigation (CCRM), University of California, Berkeley, November 22, 2005.
96. "Preliminary Report on the Performance of the New Orleans Flood Protection System During Hurricane Katrina, and the State of Levee Risk in California", Southern California Section of the American Public Works association (APWA), Los Angeles, California, January 12, 2006.
97. "Performance of the New Orleans Flood Protection System During Hurricane Katrina, and the State of Levee Risk in California", One-Day "Charette" (problem solving workshop seminar), Boalt Law School, University of California, Berkeley, January 19, 2006.
98. "Performance of the New Orleans Flood Protection System During Hurricane Katrina, and the State of Levee Risk in California", Banquet lecture, California Council on Science and Technology (CCST), Sacramento, California, January 31, 2006.

RESEARCH GRANTS:

1. Development of Analytical and Behavioral Models for Evaluation of Compaction-Induced Stresses and Deformations (National Science Foundation; 1/85 - 12/86; $62,000; Principal Investigator).
2. Effects of Borehole Fluid and Seismic History on Penetration and Liquefaction Resistance Evaluations (U.S. Bureau of Standards; 5/85 - 4/86; $29,000; Principal Investigator).
3. Laboratory Evaluation of Undrained Cyclic and Residual Strengths of Lower San Fernando Dam Sands (subcontract, U.S. Army Corps of Engineers; 6/85 - 3/86; $44,000; Principal Investigator).
4. Presidential Young Investigator Award (National Science Foundation; 6/85 - 5/91; $256,000; Principal Investigator).
5. Grant in Aid (Kaiser Aluminum and Chemical Corporation; for support of research on soil-structure interaction; 1985-1986; $17,000; Grantee).
6. Development of a Laboratory Technique for Correcting Results of Undrained Triaxial Test Results on Soils Containing Coarse Particles for Effects of Membrane Compliance (Battelle Columbus Laboratories; 5/86 - 10/86; $18,000; Principal Investigator).
7. Evaluation and Mitigation of Membrane Compliance Effects in Soil Liquefaction Testing (National Science Foundation; 5/87 - 4/89; $132,000; Principal Investigator).
8. Finite Element Evaluation of Reinforced Soil Systems (STS Consultants, Ltd.; 10/87 - 6/88; $28,000; Principal Investigator).
9. Dynamic Response Analyses of the Puddingstone and Cogswell Reservoir Dams in the 1987 Whittier Earthquake (California State Division of Mines and Geology; 7/88-6/89; $25,000, Principal Investigator.)
10. Grant in Aid (ARCO Foundation; for support of research on stability evaluation for hazardous waste repositories; 1989; $7,000; Grantee).
11. Grant to Support Research Involving Large-Scale Triaxial Testing of Gravelly Soils and Rockfill (U.S. Bureau of Reclamation; 1989; $4,300; Grantee).
12. Investigation of Effects of Pore Pressure Redistribution on Residual Strengths of Sand After Earthquake Shaking (National Science Foundation; 1/90-12/92; $88,000; Principal Investigator).
13. Investigation of Soil Liquefaction at Critical East San Francisco Bay Area Sites in the 1989 Loma Prieta Earthquake (U.S. Geological Survey; 1/90-12/90; $50,000; Principal Investigator).
14. Grant in Aid (Shimizu Corporation; for support of investigations of geotechnical aspects of the Loma Prieta Earthquake of October 17, 1989; 1990; $70,000; Co-Principal Investigator).
15. Seismic Response of Deep Soil Sites in the San Francisco Bay Area (California Department of Transportation - CALTRANS; 8/90-1/92; $315,000; Co-Principal Investigator).
16. Coordinated Geotechnical an Earthquake Engineering Research Program at the University of California at Berkeley (California Department of Transportation - CALTRANS; 6/95 - 12/98; $1,490,000; Principal Investigator).
17. An Empirical Evaluation of Soil-Structure Interaction Effects on Seismic Loading of Structures (U.S. Geological Survey, 7/97-1/99; $89,000; Principal Investigator).
18. Development of Tools/Methodologies for Probabilistic Evaluation of Liquefaction and Lateral Spreading Hazard (PG&E, 7/97-12/98; $90,000; Principal Investigator).
19. Evaluation of Cyclic Liquefaction Resistance and Post-Liquefaction Deformation Potential, (PEER Core Program, U.S. National Science Foundation; 7/97-6/98; $65,000; Principal Investigator).
20. SPT-Based Probabilistic Evaluation on Seismic Soil Liquefaction Triggering Hazard (PEER Lifelines Program, 1/99-6/00, $120,000; Principal Investigator).
21. CPT-Based Probabilistic Evaluation of Seismic Soil Liquefaction Hazard (PEER Lifelines Program, 1/00-6/03, $146,000; Principal Investigator).
22. Development of Improved Probabilistic Tools for Assessment of Liquefaction-Induced Lateral

Spreading Hazard (PEER Lifelines Program, 7/03-6/04, $76,000; Principal Investigator).

23. Triggering of Submarine Slides Under Multidirectional Loading (U.S. National Science Foundation, 6/03-7/05, $176,000; Co-Principal Investigator).
24. Investigation of the Performance of the New Orleans Levees During Hurricane Katrina (U.S. National Science Foundation, 10/05-9/06, $29,000; Principal Investigator).
25. Independent Investigation of the Performance of the New Orleans Flood Protection Systems During Hurricane Katrina (U.S. National Science Foundation, 1/06-12/06, $199,000; Principal Investigator, final approval pending).

POST-M.S. RESEARCH SUPERVISION:

I. Completed Dissertations:

(a) Master of Engineering Dissertations:

1. "Field Measurements and Finite Element Analyses of Compaction-Induced Deformations of a Long-Span Flexible Metal Culvert," Mr. Chang-Yu Ou, Engineer's Degree dissertation, Stanford University, April 1986.
2. "A Survey of Pile Driving Analysis Methods in Japan," Mr. Fuminao Okumura, Master of Engineering report, University of California, Berkeley, December 1987.
3. "The Residual Strength Characteristics of a Weathered Residual Clay Soil", Mr. George Lightwood, Master of Engineering report, University of California, Berkeley, co-supervised with Prof. N. Sitar, December 1988.
4. "Investigation of Soil Liquefaction at the Port of Richmond During the 1989 Loma Prieta Earthquake", Mr. Raymond P. Shilling, Master of Engineering report, University of California, Berkeley, May 1990.

(b) Doctoral Dissertations:

1. "Finite Element Analysis of Compaction-Induced Stresses and Deformations," Ph.D. dissertation, Dr. Chang-Yu Ou, Stanford University, November 1987.
2. "A Critical Investigation of Post-Liquefaction Strength and Steady-State Flow Behavior of Saturated Soils," Ph.D. dissertation, Dr. Hsing-Lian Jong, Stanford University, March 1988.
3. "Nonlinear Elastoplastic Finite Element Analysis of Braced Excavations in Clay," Ph.D. dissertation, Dr. Seung-Rae Lee, co-supervised with Prof. R.I. Borja, Stanford University, April 1989.
4. "Evaluation and Mitigation of Membrane Compliance Effects in Undrained Testing of Saturated Soils," Ph.D. dissertation, Dr. Hossain Anwar, Stanford University, December 1989.
5. "The Effects of Tectonic Movements on Stresses and Deformations in Earth Embankments," Ph.D. dissertation, Dr. Jonathan Bray, University of California at Berkeley, January 1990.
6. "Measurement and Elimination of Membrane Compliance Effects in Undrained Testing of Coarse Gravelly Soils," Ph.D. dissertation, Dr. Peter Nicholson, Stanford University, May 1990.
7. "Liquefaction Behavior of Saturated Cohesionless Soils Subjected to Uni-Directional and Bi-Directional Static and Cyclic Simple Shear Stresses," Ph.D. dissertation, Dr. Ross W. Boulanger, University of California at Berkeley, November 1990.
8. "Slope Stability Analysis of Lined Waste Landfills," Ph.D. dissertation, Dr. Mu-Hsiung Chang, University of California at Berkeley, co-supervised with Dr. J. K. Mitchell., May 1992.
9. "The Effects of Testing Conditions on the Constitutive Behavior of Loose, Saturated Sands Under Monotonic Loading," Ph.D. dissertation, Dr. Michael F. Reimer, University of California at Berkeley, November 1992.
10. "Dynamic Response of Soft and Deep Cohesive Soils During the Loma Prieta Earthquake of October 17, 1989," Ph.D. dissertation, Dr. Stephen E. Dickenson, University of California at Berkeley, June

1994.

11. "Accelerogram-Energy Approach for Prediction of Earthquake - Induced Ground Liquefaction", Ph.D. dissertation, Dr. Robert E. Kayen, co-supervised with Dr. J. K. Mitchell, University of California at Berkeley, December, 1994.
12. "An Empirical Assessment of Soil-Structure Interaction Effects on the Seismic Response of Structures", Dr. Jonathan P. Stewart, University of California at Berkeley, December, 1996, co-supervised with Professor G. Fenves.
13. "Shaking Table Scale Model Tests of Nonlinear Soil-Pile-Superstructure Interaction in Soft Clay", Dr. Phillip J. Meymand, University of California at Berkeley, December 1998, co-supervised with Professor J. M. Pestana.
14. "Numerical Modelling of Seismic Soil-Pile-Superstructure Interaction in Soft Clay", Ph.D. dissertation, Dr. Man Hoi Lok, University of California at Berkeley, December, 1999, co-supervised with Professor J. M. Pestana.
15. "Physical Model Studies of Seismically Induced Deformations in Slopes", Ph.D. dissertation, Dr. Joseph Wartman, University of California at Berkeley, December 1999, co-supervised with Professor J. D. Bray.
16. "Reliability-Based Assessment of Seismic Soil Liquefaction Initiation Hazard", Ph.D. dissertation, Dr. K. Onder Cetin, University of California at Berkeley, June 2000.
17. "Two-Directional Effects in Seismic Soil-Pile-Superstructure Interaction in Soft Clays", Ph.D. dissertation, Dr. Juan M. Mayoral, June 2002, co-supervised with Prof. J. M. Pestana.
18. "Undrained Response of Monterey 0/30 Sand Under Multidirectional Cyclic Simple Shear Loading Conditions", Ph.D. dissertation, Dr. Ann M. Kammerer, University of California at Berkeley, July 2002, co-supervised with Professor J. M. Pestana.
19. "Cyclic Simple Shear Testing and Assessment of Post-Liquefaction Deformation Potential of Monterey 0/30 Sand," Ph.D. dissertation, Dr. Jiaer Wu, University of California at Berkeley, December 2002.
20. "CPT-Based Probabilistic Assessment of Seismic Soil Liquefaction Initiation", Ph.D. dissertation, Dr. Robb E. S. Moss, June 2003.
21. "Assessment of Liquefaction-Induced Lateral Spreading and Displacement", Ph.D. dissertation, Dr. Allison Faris, June 2004, co-supervised with Dr. R. E. Kayen.
22. "1-G Physical Modelling and Analysis of Seismically-Induced Slope Displacements and Deformations", Ph.D. dissertation, Dr. Wei-Yu Chen, co-supervised with Prof. J.D. Bray.

II. Ongoing Research Supervision:

1. "Engineering Assessment of Post-Liquefaction Strength", Ms. Adda Athanasopoulos.
2. "Investigation of the Performance of the New Orleans Flood Protection Systems During Hurricane Katrina", Mr. Diego Cobos.
3. "Investigation of the Performance of the New Orleans Flood Protection Systems During Hurricane Katrina", Ms. Carmen Cheung.

UNIVERSITY COURSES TAUGHT:

(a) University of California at Berkeley:

C.E. 175 - "Soil and Foundation Engineering" (3 semester units)
C.E. 176 - "Soil Mechanics and Foundation Design" (2 semester units)
C.E. 177 - "Soil Properties and Their Engineering Application" (2 semester units)
C.E. 177 - "Introduction to Foundation Engineering: (3 semester units)
C.E. 270A - "Advanced Soil Mechanics" (3 semester units)
C.E. 270B - "Advanced Foundation Engineering" (3 semester units)
C.E. 270L - "Advanced Soil Mechanics Laboratory" (3 semester units)
C.E. 275 - "Soil Dynamics and Earthquake Engineering (3 semester units)
C.E. 276 - "Earth Dams" (3 semester units)
C.E. 290 - "Earth Structures (Graduate Seminar: 1 semester unit)

Also, contributing instructor/guest lecturer for the courses:

Engin. 36 - "Statics" (2 semester units)
C.E. 60 - "Structures and Properties of Civil Engineering Materials" (3 semester units)
C.E. 90 - "Introduction to Civil Engineering (1 semester unit)
C.E. 227 - "Earthquake Resistant Design - Structures" (3 semester units)
C.E. 267A - "Advanced Foundation and Mass Concrete Construction" (3 semester units)

(b) Stanford University (1983-1987):

C.E. 190 - "Introduction to Geotechnical Engineering" (4 units)
C.E. 291 - "Foundation Engineering" (4 units)
C.E. 292 - "Earth Structures" (4 units)
C.E. 293 - "Experimental Soil Mechanics" (4 units)
C.E. 295 - "Advanced Geotechnical Analysis" (2 units)
C.E. 294 - "Soil and Site Improvement" (4 units)
C.E. 298 - "Structural and Geotechnical Seminar" (1 unit)
C.E. 299 - "Geotechnical Finite Element Analyses" (2 units)

Also, contributing instructor/guest lecturer for the courses:

C.E. 125 - "Computers in Civil Engineering" (4 units)
Eng. 6 - "Engineering at Stanford" (1 unit)

UNIVERSITY SERVICE:

(a) University of California at Berkeley:

- Undergraduate Advisor, 1987-1992, 1995-998, 2002-present
- Graduate Advisor, 1992-1994, 1998-2002
- Member, Civil Engineering Undergraduate Studies Committee, 1987-989, 2002-present.
- Member, Ad Hoc Committee to Revise Civil Engineering Brochure, 1987-1988
- Faculty Advisor, Student Chapter of the American Society of Civil Engineers, 1988-1990
- Member, Civil Engineering Department, Computer Coordination Committee, 1988-89
- Member, Civil Engineering Department, Strategic Long Range Planning Committee, 1989-1991
- Member, School of Engineering, Faculty Advisory Committee to the Engineering Cooperative Study Program, 1990-1996
- Member, Seismic Safety Review Advisory Committee, University of California at Berkeley, 1991-96
- Member or Chair, Departmental and/or School of Engineering Ad Hoc Committees to hire new faculty or to prepare and/or review tenure and promotion cases; 1991-1993, 1994, 1996, 1999, 2001, 2003.
- Group Head, GeoEngineering Program, 1998-2002.

- Member, Civil and Environmental Engineering Department, Executive Committee, 1998-2002.
- Member, Civil and Environmental Engineering Department, Development Committee, 2000-2002.
- Acting Director, U.C. Berkeley Earthquake Engineering Research Center (EERC), 2002.

(b) Stanford University (1983-1987):

- Author of successful proposal "Innovative Applications for Networked Microcomputer Workstations in Civil Engineering Instruction and Research," resulting in donation by IBM Corp. of $450,000 (in microcomputer hardware and software) to the Department of Civil Engineering at Stanford University, November, 1984.
- Member, Civil Engineering Admissions Committee, 1984-86.
- Member, Civil Engineering Machine Shop Committee, 1984-86.
- Member, Faculty Search Committee, 1984-86.
- Director, Geotechnical Laboratory, 1984-87.
- Member, Civil Engineering Computing Facilities Committee, 1984-86.
- Undergraduate and Graduate Advisor, 1983-87.

PUBLICATIONS

1. R. B. Seed, "Soil Structure Interaction Effects of Compaction-Induced Stresses and Deflections," Ph.D. Thesis, University of California, Berkeley, December 1983.
2. R. B. Seed and J. M. Duncan, "Soil-Structure Interaction Effects of Compaction-Induced Stresses and Deflections," Geotechnical Engineering Research Report No. UCB/GT/83-06, University of California, Berkeley, December 1983, 447 pp.
3. R. B. Seed and J. M. Duncan, "SSCOMP: A Finite Element Analysis Program for Evaluation of Soil-Structure Interaction and COMPaction Effects," Geotechnical Engineering Research Report No. UCB/GT/84-02, University of California, Berkeley, February 1984, 127 pp.
4. J. M. Duncan, R. B. Seed, and R. H. Drawsky, "Design of Corrugated Metal Box Culverts," Geotechnical Engineering Research Report No. UCB/GT/84-09, University of California, Berkeley, June 1984, 39 pp.
5. J. M. Duncan, R. B. Seed, K. S. Wong, and Y. Ozawa, "FEADAM84: A Computer Program for Finite Element Analysis of Dams," Geotechnical Engineering Research Report No. SU/GT/84-03, Stanford University, November 1984, 78 pp.
6. R. B. Seed and J. M. Duncan, "Earth Pressure and Surface Load Effects on Buried Pipelines," Proceedings of the Second International Conference on Advances in Pipeline Engineering, Madison, Wisconsin, pp. 320-330, August 1985.
7. J. M. Duncan, R. B. Seed and R. H. Drawsky, "Design of Corrugated Metal Box Culverts," Transportation Research Record, No. 1008, pp. 33-41, September, 1985.
8. H. B. Seed, R. B. Seed, S. S. Lai and B. Khamenehpour, "Seismic Design of Concrete Faced Rockfill Dams," Proceedings, ASCE Symposium on Concrete Faced Rockfill Dams, Detroit, pp. 459-478, October 1985.
9. C. Y. Ou and R. B. Seed, "The Promontory Long-Span Culvert Overpass Structure: Field Measurements and Finite Element Analyses," Geotechnical Research Report No. SU/GT/85-01, Stanford University, November 1985, 56 pp.
10. J. M. Duncan and R. B. Seed, "Compaction-Induced Earth Pressures Under K_0-Conditions," Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 112, No. 1, pp. 1-22, January 1986.
11. R. B. Seed and J. M. Duncan, "FE Analyses: Compaction-Induced Stresses and Deformations," Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 112, No. 1, pp. 23-43, January 1986.
12. R. B. Seed, J. G. Collin and J. K. Mitchell, "FEM Analyses of Compacted Reinforced-Soil Walls," Proceedings of the Second International Conference on Numerical Methods in Geomechanics, Belgium, March 31-April 4, 1986, pp. 553-562.
13. R. B. Seed and J. M. Duncan, "Analysis of Compaction-Induced Stresses and Deformations," Proceedings of the Second International Conference on Numerical Methods in Geomechanics, Belgium, March 31-April 4, 1986, pp. 439-450.
14. R. B. Seed, S. R. Lee, H. L. Jong and L. F. Harder, "Effects of Borehole Fluid and Seismic History on Penetration and Liquefaction Resistance Evaluations," report prepared for the U.S. National Bureau of Standards, Geotechnical Research Report No. SU/GT/86-01, Stanford University, July 1986, 64 pp.
15. C. A. Human, R. B. Seed, J. K. Mitchell and R. I. Borja, "Predicted Behavior of the Stanstead Abbotts Trial Embankment," invited prediction, Proceedings of the Reinforced Earth Prediction Symposium, King's College, London, England, September 17-18, 1986.
16. R. B. Seed and N. Dean Marachi, "Lifeline Risk Analysis: The Mokelumne Aqueduct Study," Proceedings of the Specialty Session on Seismic Evaluation of Lifeline Systems, ASCE Fall Conference, Boston, October 27-31, 1986, pp. 28-43.
17. R. B. Seed and H. Anwar, "Development of a Laboratory Technique for Correcting Results of Undrained Triaxial Shear Tests on Soils Containing Coarse Particles for Effects of Membrane

Compliance," report prepared for the U.S. Army Corps of Engineers, Geotechnical Research Report No. SU/GT/86-03, December 1986, 94 pp.

18. R. B. Seed and C. Y. Ou, "Measurement and Analysis of Compaction Effects on a Long-Span Culvert," Transportation Research Record, No. 1087, pp. 37-45, January, 1987.

19. H. L. Jong, P. G. Nicholson and R. B. Seed, "Laboratory Evaluation of Undrained Cyclic and Residual Strengths of Lower San Fernando Dam Soils," Geotechnical Research Report No. SU/GT/87-01, Stanford University, June 1987, 168 pp.

20. J. R. Raines, R. I. Borja, H. Anwar and R. B. Seed, "Numerical Analysis of Membrane Penetration Effects on Undrained Triaxial Tests," Proceedings of the 3rd International Conference on Soil Dynamics and Earthquake Engineering, Princeton, New Jersey, June 22-24, 1987, Elsevier Press series "Advances in Geotechnical Engineering", Vol. 42, pp. 353-364.

21. R. B. Seed and N. D. Marachi, "Seismic Risk Assessment for a Lifeline Aqueduct System," Proceedings of the 3rd International Conference on Soil Dynamics and Earthquake Engineering, Princeton, New Jersey, June 22-24, 1987, Elsevier Press series "Advances in Geotechnical Engineering", Vol. 45, pp. 415-426.

22. R. B. Seed and H. L. Jong, "Factors Affecting Post-Liquefaction Strength Assessment," Proceedings of the 5th Canadian Conference on Earthquake Engineering, Ottawa, Canada, July 6-8, 1987, pp. 483-492.

23. R. B. Seed, J. R. Koseff and J. R. Raines, "Scale Model Hydraulic Flow Tests of Corrugated Box Culverts and Smooth-Walled Flexible Box Structures," Geotechnical Research Report No. SU/GT/87-02, Stanford University, July 1987, 28 pp.

24. P. De Alba, H. B. Seed, E. Retamal and R. B. Seed, "Residual Strength of Sand from Dam Failures in the Chilean Earthquake of March 3, 1985", Report No. EERC 87-11, Earthquake Engineering Research Center, University of California, Berkeley, September 1987, 38 pp.

25. C. Y. Ou and R. B. Seed, "Finite Element Analysis of Compaction-Induced Stresses and Deformations," Geotechnical Research Report No. SU/GT/87-03, Stanford University, November 1987, 415 pp.

26. F. H. Siddiqi, R. B. Seed, C. K. Chan, R. Pyke and H. B. Seed, "Strength Evaluation of Coarse-Grained Soils," Report No. EERC 87-22, Earthquake Engineering Research Center, University of California, Berkeley, December 1987, 53 pp.

27. H. L. Jong and R. B. Seed, "A Critical Investigation of Factors Affecting Seismic Pore Pressure Generation and Post-Liquefaction Flow Behavior of Saturated Soils," Geotechnical Research Report No. SU/GT/88-01, Stanford University, April 1988, 407 pp.

28. R. B. Seed and C. Y. Ou, "Compaction-Induced Distress of a Long-Span Culvert Overpass Structure," Proceedings of the Second International Conference on Case Histories in Geotechnical Engineering, St. Louis, June 1-5, 1988, pp. 1183-1190.

29. H. B. Seed, R. B. Seed, L. F. Harder and H. L. Jong, "Re-Evaluation of the Slide in the Lower San Fernando Dam in the 1971 San Fernando Earthquake," Report No. UCB/EERC-88/04, Earthquake Engineering Research Center, University of California, Berkeley, April 1988, 118 pp.

30. R. B. Seed, S. R. Lee and H. L. Jong, "Penetration and Liquefaction Resistances: Seismic History Effects," Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 114, No. 6, June 1988, pp. 691-697.

31. H. B. Seed, R. B. Seed, F. Schlosser, F. Blondeau and I. Juran, "The Landslide at the Port of Nice on October 16, 1979", Report No. UCB/EERC-88/10, Earthquake Engineering Research Center, University of California, Berkeley, June, 1988, 68 pp.

32. R. B. Seed, J. K. Mitchell and H. B. Seed, "Slope Stability Failure Investigation: Kettleman Hills Repository Landfill Unit B-19, Phase I-A", Geotechnical Research Report No. UCB/GT/88-01, University of California, Berkeley, July 1988, 96 pp.

33. R. B. Seed, L. F. Harder, T. L. Youd and M. Bennet, "Effects of Borehole Fluid on Standard Penetration Test Results," Geotechnical Testing Journal, American Society for Testing and Materials, Vol. 11, No. 4, December 1988, pp. 248-256.

34. P. De Alba, H. B. Seed, E. Retamal and R. B. Seed, "Analyses of Dam Failures in the 1985 Chilean Earthquake," Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 114, No. 12, December 1988, pp. 1414-1434.

35. R. B. Seed and J. R. Raines, "Failure of Flexible Long-Span Culverts Under Exceptional Live Loads," Transportation Research Record, No. 1191, pp. 22-29, December, 1988.

36. S. R. Lee, R. I. Borja and R. B. Seed, "Nonlinear Elastoplastic Finite Element Analysis of Braced Excavations", Research Report No. SU/GT/88-02, Stanford University, March, 1989, 163 pp.

37. R. B. Seed, J. D. Bray, R. W. Boulanger and H. B. Seed, "Seismic Response of the Puddingstone and Cogswell Dams in the 1987 Whittier Narrows Earthquake," CSMIP89 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data, Sacramento, Calif., pp. 7-1 through 7-10, May 9, 1989.

38. R. I. Borja, S. R. Lee and R. B. Seed, "Excavation in Cohesive Soils: Modelling the Effects of Creep on Long-Term Performance," Proceedings of the Third International Conference on Numerical Models in Geomechanics, Niagara Falls, Canada, May 8-11, 1989, pp. 585-592.

39. R. I. Borja, S. R. Lee and R. B. Seed, "Numerical Simulation of Excavation in Elastoplastic Soils," International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 13, pp. 231-249, June, 1989.

40. H. B. Seed, R. B. Seed, L. F. Harder and H. L. Jong, "Re-Evaluation of the Lower San Fernando Dam; Report 2: Examination of the Post-Earthquake Slide of February 9, 1971," Report No. GL-89-2, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, July, 1989, 265 pp.

41. R. B. Seed, H. Anwar and P. G. Nicholson, "Elimination of Membrane Compliance Effects in Undrained Testing," Proceedings of the XIIth International Conference on Soil Mechanics and Foundation Engineering, Rio De Janeiro, August 13-18, 1989, pp. 111-114.

42. J. D. Bray, R. B. Seed and H. B. Seed, "The Effects of Tectonic Movements on Stresses and Deformation in Earth Embankments," Report No. UCB/EERC-90/13, Earthquake Engineering Research Center, University of California, Berkeley, September, 1989, 414 pp.

43. K. Arulanandan, H. B. Seed, R. B. Seed, C. Yogachandran and K. Muraleetharan, "Centrifuge Model Tests to Study the Effects of Volume Change Characteristics on the Dynamic Stability of Heterogeneous Earth Dams", Geotechnical Research Report, University of California at Davis, September, 1989.

44. A. Astaneh, V. V. Bertero, B. A. Bolt, S. A. Mahin, J. P. Moehle, and R. B. Seed, "Preliminary Report on the Seismological and Engineering Aspects of the October 17, 1989 Santa Cruz (Loma Prieta) Earthquake", Report No. UCB/EERC-89-14, Earthquake Engineering Research Center, University of California, Berkeley, October 1989, 51 pp.

45. J. K. Mitchell, N. Sitar and R. B. Seed, "Waste Geotechnics at the University of California at Berkeley", Geotechnical News, Vol. 7, No. 4, December, pp. 28-31, 1989.

46. R. B. Seed, J. D. Bray and D. Thomas, "Analysis, Design and Prototype Testing of a Smooth-Walled Box Culvert System," Transportation Research Record, No. 1231, National Research Council, pp. 1-13, December 1989.

47. R. Boulanger, R. B. Seed and J. C. Schluter, "Measurements and Analyses of Deformed Flexible Box Culverts," Transportation Research Record, No. 1231, National Research Council, pp. 25-35, December 1989.

48. R. B. Seed, H. Anwar and P. G. Nicholson, "Measurement and Elimination of Membrane Compliance Effects in Undrained Triaxial Testing", Research Report No. SU/GT/89-01, Stanford University, December, 1989, 172 pp.

49. P. G. Nicholson, R. B. Seed and H. Anwar, "Measurement and Elimination of Membrane Compliance Effects in Undrained Triaxial Testing", Report No. UCB/EERC-89/10, Earthquake Engineering Research Center, University of California at Berkeley, December, 1989, 267 pp.

50. M. Riemer, R. B. Seed and P. G. Nicholson, "Steady-State Testing of Loose Sands: Limiting Density", Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 116, No.

2, pp. 332-337, February, 1990.

51. R. B. Seed, S. E. Dickenson, M. F. Riemer, J. D. Bray, N. Sitar, J. K. Mitchell, I. M. Idriss, R. E. Kayen, A. J. Kropp, L. F. Harder, Jr. and M. S. Power, "Preliminary Report on the Principal Geotechnical Aspects of the October 17, 1989 Loma Prieta Earthquake", Report No. UCB/EERC-90/05, Earthquake Engineering Research Center, University of California, Berkeley, April, 1990, 137 pp.

52. J. K. Mitchell, R. B. Seed and H. B. Seed, "The Kettleman Hills Waste Landfill Slope Failure - I: Liner Interface Properties", Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 116, No. 4, pp. 647-668, April 1990.

53. R. B. Seed, J. K. Mitchell and H. B. Seed, "The Kettleman Hills Waste Landfill Slope Failure - II: Stability Analyses", Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 116, No. 4, pp. 669-690, April, 1990.

54. R. B. Seed and L. F. Harder, "SPT-Based Analysis of Cyclic Pore Pressure Generation and Undrained Residual Strength", Proceedings of the H. Bolton Seed Memorial Symposium, University of California, Berkeley, May 10-11, 1990, pp. 351-376.

55. J. K. Mitchell, T. Masood, R. E. Kayen and R. B. Seed, "Soil Conditions and Earthquake Hazard Mitigation in the Marina District of San Francisco", Report prepared for the Mayor of San Francisco, Report No. UCB/EERC-90/08, Earthquake Engineering Research Center, University of California at Berkeley, May 1990, 59 pp.

56. J. D. Bray, R. B. Seed and H. B. Seed, "Modelling and Analysis of Base Rock Fault Rupture Propagation Through Overlying Cohesive Soils", Proceedings of the Fourth U.S. National Conference on Earthquake Engineering, Palm Springs, California, pp. 713-722, May 20-24, 1990.

57. J. D. Bray, R. B. Seed and R. W. Boulanger, "Investigation of the Response of Puddingstone and Cogswell Dams in the Whittier Narrows Earthquake of October 1, 1987. Volume I: Puddingstone Dam", Report No. UCB/GT/90-01, Department of Civil Engineering, University of California, Berkeley, June, 1990, 60 pp.

58. R. W. Boulanger, R. B. Seed and J. D. Bray, "Investigation of the Response of Puddingstone and Cogswell Dams in the Whittier Narrows Earthquake of October 1, 1987. Volume II: Cogswell Dam", Report No. UCB/GT/90-02, Department of Civil Engineering, University of California, Berkeley, June, 1990, 53 pp.

59. R. B. Seed, I. M. Idriss and S. E. Dickenson, "Geotechnical Factors Controlling Damage Patterns in the Loma Prieta Earthquake of October 17, 1989", Proc., Specialty Session on the Loma Prieta Earthquake, Annual Meeting of the Japanese Society of Soil Mechanics and Foundation Engineering, Okayama, Japan, June 12-14, 1990, pp. 1-36.

60. R. B. Seed, J. K. Mitchell and H. B. Seed, "Stability Considerations in the Design and Construction of Lined Waste Repositories", Proceedings of the Symposium on Geotechnics of Waste Fills - Theory and Practice, ASTM, Proc. Volume STP 1070, San Francisco, June 1990, pp. 207-224.

61. J. M. Duncan, G. W. Williams and R. B. Seed, "User's Guide for EPCOMP2 and NCOMP3", Geotechnical Division, Department of Civil Engineering, Virginia Polytechnic Institute and State University, August, 1990, 13 pp.

62. J. D. Bray, R. B. Seed and H. B. Seed, "The Effects of Tectonic Movements on Stresses and Deformations in Earth Embankments", Report No. UCB/EERC-90/13, Earthquake Engineering Research Center, University of California, Berkeley, September, 1990, 414 pp.

63. R. B. Seed, "Soil Liquefaction During the 1989 Loma Prieta Earthquake," Proceedings, "Putting the Pieces Together", a one-year anniversary conference sponsored by FEMA and the Bay Area Regional Earthquake Preparedness Project (BAREP), San Francisco, California, October 15-18, 1990, pp. 34-44.

64. R. B. Seed, S. E. Dickenson and M. F. Reimer, "Soil Liquefaction During the Loma Prieta Earthquake of October 17, 1989", invited theme paper, Proc., Second International Conference on Soil Dynamics and Earthquake Engineering, St. Louis, Missouri, March 11-15, 1991, Vol. II, pp. 1575-1586.

65. R. B. Seed, S. E. Dickenson and I. M. Idriss, "Principal Geotechnical Aspects of the 1989 Loma Prieta Earthquake", Soils and Foundations, JSSMFE, Vol. 31, No. 1. pp. 475-500, March, 1991.

66. R. B. Seed, "Engineering Hazards Associated with San Francisco Bay Sediments and Bayshore Fills," GSA Abstract, Proceedings, Cordilleran Section Meeting, San Francisco, March 27, 1991.

67. R. B. Seed and R. W. Boulanger, "Smooth HDPE/Clay Liner Interface Shear Strengths: Compaction Effects", Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 117, No. 4, pp. 686-693, April, 1991.

68. R. W. Boulanger, J. D. Bray, S. H. Chew, R. B. Seed, J. K. Mitchell and j. M. Duncan, "SSCOMP-PC: A Finite Element Analysis Program for Evaluation of Soil-Structure Interaction and COMPaction Effects", Research Report no. UCB/GT/91-02, Department of Civil Engineering, University of California at Berkeley, April, 1991, 210 pp.

69. R. W. Boulanger, R. B. Seed, C. K. Chan, H. B. Seed, and J. Sousa, "Liquefaction Behavior of Saturated Sands Under Uni-Directional and Bi-Directional Monotonic and Cyclic Simple Shear Loading", Report No. UCB/GT/91-08, University of California, Berkeley, 521 pp., August, 1991.

70. J. M. Duncan, G. W. Williams, A. L. Sehn and R. B. Seed, "Estimating Earth Pressures Due to Compaction", Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 117, No. 12, December, 1991, pp. 1833-1847.

71. R. B. Seed, J. M. Duncan and C. Y. Ou, "Finite Element Analysis of Compaction Problems," Chapter 2 of the text Advanced Geotechnical Analyses, the fourth volume of the text series, "Developments in Soil Mechanics and Foundation Engineering" (P. K. Banerjee and R. Butterfield, Eds.), Elsevier Publ., Inc., London, 1991, pp. 47-94.

72. S. E. Dickenson, R. B. Seed, J. Lysmer and C. M. Mok, "Response of Soft Soils During the 1989 Loma Prieta Earthquake and Implications for Seismic Design Criteria", Proceedings, Pacific Conference on Earthquake Engineering, November 20-23, 1991, Auckland, New Zealand.

73. R. B. Seed, S. E. Dickenson and C. M. Mok, "Seismic Response Analyses of Soft and Deep Cohesive Sites: A Brief Summary of Recent Lessons", Proceedings, CALTRANS First Annual Seismic Research Workshop, Sacramento, California, December 3-4, 1991.

74. R. B. Seed, S. E. Dickenson and C. M. Mok, "Seismic Response of Soft Clay Sites: Recent Lessons", Proceedings, Annual Meeting of EERI, San Francisco, California, February 6-8, 1992.

75. G. Castro, R. B. Seed and H. B. Seed, "Steady State Strength Analysis of the Lower San Fernando Dam Slide", Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 118, No. 3, March, 1992, pp. 406-427.

76. M. F. Riemer and R. B. Seed, "Observed Effects of Testing Conditions on the Residual Strength of Loose, Saturated Sands", Proceedings, Fourth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Honolulu, Hawaii, May 27-29, 1992.

77. R. E. Kayen, J. K. Mitchell, A. L. Lodge, R. B. Seed, S. Y. Nishio and R. Q. Countinho, "Evaluation of SPT-, CPT-, and Shear Wave-Based Liquefaction Potential Assessment Methods Using Loma Prieta Earthquake Data", Proceedings, Fourth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Honolulu, Hawaii, pp. 179-204, May 27-29, 1992.

78. R. B. Seed, S. E. Dickenson and C. M. Mok, "Recent Lessons Regarding Seismic Response Analysis of Soft Clay Sites", Proceedings, Fourth Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Honolulu, Hawaii, May 27-29, 1992.

79. M.D. Evans, R.B. Seed and H.B. Seed, "Membrane Compliance and Liquefaction of Sluiced Gravel Specimens," Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 118, No. 6, pp. 856-872, June, 1992.

80. Bray, J. D., Boulanger, R. W., Chew, S. H., and Seed, R. B., "Finite Element Analysis in Geotechnical Engineering", Proceedings, ASCE 8th Computing in Civil Engineering Conference, Dallas, Texas, June 7-9, 1992.

81. P. G. Nicholson, H. A. Anwar and R. B. Seed, "An Injection - Correction System to Mitigate Membrane Compliance", Geotechnical Testing Journal, ASTM, June, 1992.

82. R. B. Seed and R. Bonaparte, "Seismic Analysis and Design of Lined Waste Fills: Current Practice, Proceedings, Specialty Conference on Stability of Slopes and Embankments-II, American Society of Civil Engineers, Berkeley, California, June 28-July 1, 1992.

83. J. D. Bray, R. B. Seed and H. B. Seed, "On the Response of Earth Dams Subjected to Earthquake Fault Rupture", Proceedings, Specialty Conference on Stability of Slopes and Embankments-II, American Society of Civil Engineers, Berkeley, California, June 28-July 1, 1992.

84. R. B. Seed, S. E. Dickenson, G. A. Rau, R. K. White, and C. M. Mok, "Observations Regarding Seismic Response Analyses for Soft and Deep Clay Sites", Proc., Meeting and Symposium sponsored by the Soil Dynamics/Foundations Committee, International Society of Soil Mechanics and Foundation Engineering, Mexico City, August 20, 1992.

85. P. G. Nicholson and R. B. Seed, "A Laboratory Correction Method for Undrained Testing of Coarse Gravelly Soils", Proc., 45th Canadian Geotechnical Conf., Toronto, Ontario, Canada, October 26-29, 1992.

86. R. E. Kayen, R. B. Seed, J. K. Mitchell, A. Lodge, C. Human, L. Scheibel, S. Nishio and R. Coutinho, P. G. Nicholson and R. B. Seed, "Soil Liquefaction in the East Bay Area During the 1989 Loma Prieta Earthquake", Proc., 45th Canadian Geotechnical Conf., Toronto, Ontario, Canada, October 26-29, 1992.

87. R. E. Kayen, R. B. Seed, J. K. Mitchell, A. Lodge, C. Human, L. Scheibel, S. Nishio and R. Coutinho, "Soil Liquefaction along the Eastern Shoreline of San Francisco Bay During the Loma Prieta Earthquake, 17 October, 1989 " Geotechnical Engineering Report No. UCB/GT/92-2, January 1992.

88. R. E. Kayen, R. B. Seed, J. K. Mitchell, A. Lodge, C. Human, L. Scheibel, S. Nishio and R. Coutinho, "Soil Liquefaction along the East Side of San Francisco Bay During the Loma Prieta Earthquake 17 October, 1989, " NEHRP 14-08-00001-G1855, 44p., 26 figures, January 1992.

89. R. W. Boulanger, C. K. Chan, H. B. Seed, R. B. Seed, and J. Souza, "A Low-Compliance Bi-Directional Cyclic Simple Shear Apparatus", Geotechnical Testing Journal, ASTM, pp. 36-45, March, 1993.

90. R. B. Seed and S. E. Dickenson, "Site-Dependent Seismic Site Response", Proc., Second Annual CALTRANS Seismic Research Workshop, Sacramento, Calif., March 16-18, 1993.

91. M. F. Riemer, R. B. Seed and S. Sadek, "The SRS/RTF Soil Evaluation Testing Program", Geotechnical Research Report No. UCB/GT-93/01, University of California at Berkeley, March, 1993, 132 pp.

92. J. D. Bray, R. B. Seed and H. B. Seed, "1g Small-Scale Modelling of Fault Rupture Propagation Through Saturated Cohesive Soils", Geotechnical Testing Journal, American Society for Testing and Materials, Volume 16, Number 1, pp. 46-53, March, 1993.

93. R. W. Boulanger, J. D. Bray and R. B. Seed, "Response of Two Dams in the 1987 Whittier Narrows Earthquake", Proceedings of the Third International Conference on Case Histories in Geotechnical Engineering, Vol. I, pp. 635-642, June 1-6, 1993.

94. J. K. Mitchell, M. Chang and R. B. Seed, "The Kettleman Hills Landfill Failure: A Retrospective View of the Failure Investigations and Lessons Learned", Proc., 3rd International Conference on Case Histories in Geotechnical Engineering, St. Louis, Mo., Vol. II, pp 1379-1392, June 1-6, 1993.

95. P. G. Nicholson, R. B. Seed and H. A. Anwar, "Elimination of Membrane Compliance in Undrained Triaxial Testing, Part I: Measurement and Evaluation", Canadian Geotechnical Journal, Vol. 30, No. 5, pp. 727-738, October, 1993.

96. P. G. Nicholson, R. B. Seed and H. A. Anwar, "Elimination of Membrane Compliance in Undrained Triaxial Testing , Part II: Mitigation by Injection Compensation", Canadian Geotechnical Journal, Vol. 30, No. 5, pp. 739-746, October , 1993.

97. K. Arulanandan, H. B. Seed, C. Yogachandron, K. K. Muraleetharan, R. B. Seed and K. Kabilamany, "Centrifuge Study on Volume Changes and Dynamic Stability of Earth Dams", Journal of Geotechnical Engineering, ASCE, Vol. 119, No. 11, pp. 1717 - 1731, November, 1993.

98. S. Chang, G. Santana, J. D. Bray and R. B. Seed, "Strong Ground Motion", Chapter 3 in the "Preliminary Report on the Seismological and Engineering Aspects of the January 17, 1994 Northridge Earthquake", Earthquake Engineering Research Center, Report No. UCB/EERC-94/01, University of California, Berkeley, pp. 3-1 to 3-11, January 24, 1994.

99. J. D. Bray, M. Riemer, R. B. Seed, N. Sitar and J. Stewart, "Geotechnical Considerations", Chapter 4 in the "Preliminary Report on the Seismological and Engineering Aspects of the Janauary 17, 1994 Northridge Earthquake", Earthquake Engineering Research Center, Report No. UBC/EERC-94/01, University of California, Berkeley, pp. 4-1 to 4-19, January 24, 1994.

100. M. F. Riemer and R. B. Seed, "Dynamic Testing of Soils from the SRS/ITP Facility," Report. No. UCB/GT-94/02, Department of Civil and Environmental Engineering, University of California at Berkeley, February, 1994.

101. Geotechnical Engineering Group, Department of Civil Engineering, University of California at Berkeley, "Preliminary Report of the Geotechnical Aspects of the January 17, 1994 Northridge Earthquake" in Geotechnical News, Vol. 12, No. 1, pp. 27-29, March, 1994.

102. J. D. Bray, R. B. Seed, L. S. Cluff and H. B. Seed, "Earthquake Fault Rupture Propagation Through Soil", Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 120, No. 3, pp. 543-561, March, 1994.

103. J. D. Bray, R. B. Seed and H. B. Seed, "Analysis of Earthquake Fault Rupture Propagation through Soil", Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 120, No. 3, pp. 562-580, March, 1994.

104. S. W. Chang, J. D. Bray and R. B. Seed, "Ground Motions and Damage Patterns; The Northridge Earthquake of Jan. 17, 1994" in Geotechnical News, Vol. 12, No. 2, pp. 49-52, June 1994.

105. J. Stewart, P. Thomas, R. B. Seed and J. D. Bray, "Soil Liquefaction and Dynamic Ground Compaction; The Northridge Earthquake of Jan. 17, 1994" in Geotechnical News, Vol. 12, No. 2, pp. 53-56, June 1994.

106. J. Stewart, R. B. Seed, M. F. Riemer and J. Zornberg, "Geotechnical Aspects of the Northridge Earthquake of January 17, 1994: Geotechnical Structures," Geotechnical News, Vol. 12, No. 2, pp.56-62, June 1994.

107. A. J. Augello, J. D. Bray and R. B. Seed, "Solid Waste Landfill Performance: The Northridge Earthquake of Jan. 17, 1994," Geotechnical Nes, Vol. 12, No. 2, pp. 63-65, June 1994.

108. J. K. Mitchell, A. L. Lodge, R. Q. Coutinho, R. E. Kayen, R. B Seed, S. Nishio, and K. H. Stokoe, "Insitu Test Results from Four Loma Prieta Earthquake Liquefaction Sites: SPT, CPT, DMT and Shear Wave Velocity," Earthquake Engineering Research Center, Report No. UCB/EERC-94/04, p. 179, 1994.

109. J. P. Stewart, J. D. Bray, R. B. Seed and N. Sitar, eds., "Preliminary Report on the Principal Geotechnical Aspects of the January 17, 1994 Northridge Earthquake", Earthquake Engineering Research Center, Report No. UCB/EERC-94/08, University of California, Berkeley, 238 pp., June, 1994.

110. P. G. Nicholson and R. B. Seed, "Injection- Correction for Compliance in Liquefaction Testing of Gravelly Soils", ASTM Special Technical Publication No. 1213; Dynamic Geotechnical Testing II, San Francisco, Calif., August, 1994.

111. K. Arulanandan, R. Dobry, A. Elgamel, J.Y. Ko, B. Kutter, M. F. Riemer, A. Schofield, R. Scott, R. Seed, and X. Zeng, "Interlaboratory Studies to Evaluate the Dependability of Dynamic Centrifuge Model Tests," Dynamic Geotechnical Testing, Vol. II, ASTM STP 113; Ebelhar, Drnevich and Kutter, eds., 1994.

112. M. F. Riemer, R. B. Seed, "Dynamic Testing of Soils from the Barney Reservoir Expansion Project," Rept. No. UCB/GT-94/06, Department of Civil and Environmental Engineering, University of California at Berkeley, October, 1994.

113. A. J. Augello, J. D. Bray, N. Matasovic, E. Kavazanjian, and R. B. Seed, "Solid Waste Landfill Performance During the 1994 Northridge Earthquake," Third International Conference on Recent Advances in Geotechnical Engineering and Soil Dynamics, St. Louis, MO, Vol. III, pp. 163-169, April 2-7, 1995.

114. S. W. Chang, J. D. Bray, and R. B. Seed, "Ground Motions From the Northridge Earthquake," Third International Conference on Recent Advances in Geotechnical Engineering and Soil Dynamics,

St. Louis, MO, Vol. III, pp. 205-213, April 2-7, 1995.

115. E. Kavazanjian, N. Matasovic, J. Bray, A. Augello and R. B. Seed, "Damage to Landfills from the Northridge Earthquake," U.S. National Science Foundation Natural Hazard Mitigation Grantees Workshop, Session III, Paper No. 3, Lake Tahoe, Nevada, April 27-28, 1995.

116. J. Stewart, S. Chang, J. D. Bray, R. B. Seed, N. Sitar and M. F. Riemer, "A Report on Geotechnical Aspects of the January 17, 1994 Northridge Earthquake," Seismological Research Letters, Vol. 66, No. 3, pp. 7-19, June, 1995.

117. K. Akai, J. D. Bray, R. W. Boulanger, J. T. Christian, W. D. L. Finn, L. F. Harder, I. M. Idriss, K. Ishihara, Y. T. Iwasaki, J. K. Mitchell, Y. Moriwake, K. Nakagawa, T. D. O'Rourke, R. B. Seed, N. Sitar, K. Soga, P. Somerville, I. Towhata and T. L. Youd, "Geotechnical Reconaissance of the Effects of the January 17, 1995, Hyogoken-Nanbu Earthquake, Japan", Rept. No. UCB/EERC - 95/01, Earthquake Engineering Research Center, U.C. Berkeley, July 1995.

118. A. J. Augello, N. Matasovic, J. D. Bray, E. Kavazanjian and R. B. Seed, "Evaluation of Solid Waste Landfill Performance During the Northridge Earthquake," Earthquake Design and Performance of Solid Waste Landfills, ASCE Geotechnical Section Special Publication No. 54; Yegian and Finn, eds.; and Proc. ASCE Annual Convention, San Diego, Calif., pp. 17-50, 1995.

119. R. W. Boulanger and R. B. Seed, "Liquefaction of Sand Under Bidirectional Monotonic and Cyclic Loading," Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 121, No. 12, pp. 870-878, December, 1995.

120. J. D. Bray, R. B. Seed, L. S. Cluff and H. B. Seed, "Closure to Earthquake Fault Rupture Propagation Through Soil," Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 122, No. 1, pp. 82-83, January, 1996.

121. S. W. Chang, J. D. Bray, and R. B Seed, "Engineering Implications of Ground Motions from the Northridge Earthquake," Bulletin of the Seismological Society of America, Vol. 86, No.1B, pp.S270-S288, February, 1996.

122. J. P. Stewart, R. B. Seed and J. D. Bray, "Incidents of Ground Failure from the 1994 Northridge Earthquake," Bulletin of the Seismological Society of America, Vol. 86, No. 1B, pp. S300-S318, February, 1996.

123. R. B. Seed, "Recent Advances in Evaluation and Mitigation of Liquefaction Hazard," Proc., Ground Stabilization and Seismic Mitigation; Regional Conf. Sponsored by the Oregon Section of the American Society of Civil Engineers, Portland, Oregon, November 6-7, 1996.

124. M. F. Riemer and R. B. Seed, "Factors Affecting the Apparent Position of the Steady State Line," Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers, Vol. 123, No. 3, pp. 281-288, March, 1997.

125. J. M. Pestana, T. Lok, P. Meymand, M. Riemer and R. B. Seed, "Modelling of Soil-Pile Interaction in Clay Deposits," Proc., Seminario Internacional de Ingenieria Sismica Caracas, Venezuela, July 21-22, 1997.

126. A. J. Augello, J. D. Bray, R. B. Seed, N. Matasovic and E. Kavazanjian, "Performance of Solid Waste Landfills During the 1994 Northridge Earthquake," Proc., NSF-USGS Northridge Earthquake Research Conference, Los Angeles, California, pp. II-71 through II-80, August 20-23, 1997.

127. R. B. Seed, S. W. Chang, S. E. Dickenson and J. D. Bray, "Site-Dependent Seismic Response Including Recent Strong Motion Data," Proc., XIV International Conference on Soil Mechanics and Foundation Engineering, Hamburg, Germany, pp. 125-134, September 6-12, 1997.

128. A. J. Augello, J. D. Bray, N. A. Abrahamson and R. B. Seed, "Dynamic Properties of Solid Waste Based on Back-Analysis of the OII Landfill," Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers, Vol. 24, No. 3, pp.211-222, March 1998.

129. P. Meymand, M. Riemer, T. Lok, J. Pestana and R. B. Seed, "Shaking Table Model Tests of Nonlinear Soil-Pile-Superstructure Interaction in Soft Clay," Proc., 5th CALTRANS Seismic Research Workshop, Sacramento, California, Paper No. 3-1, June 16-18, 1998.

130. T. Lok, J. M. Pestana, P. Meymand, M. F. Riemer and R. B. Seed, "Numerical Modelling and Simulation of Soil-Pile-Superstructure Interaction Experiments," Proc., 5th CALTRANS Seismic Workshop, Sacramento, California, Paper No. 3-2, June 16-18, 1998.

131. J. Wartman, E. Rathje, J. D. Bray, M. F. Riemer and R. B. Seed, "Shaking Table Based Evaluation of the Newmark procedure for Estimating Seismically Induced Slope Deformations", Proc., 5th CALTRANS Seismic Workshop, Sacramento, California, June 16-18, 1988.

132. J. P. Stewart, R. B. Seed and G. L. Fenves, "Empirical Evaluation of Inertial Soil-Structure Interaction Effects", Pacific Earthquake Engineering Research Center, Report No. PEER-98/07, University of California at Berkeley, 205 pp., 1998.

133. J. Wartman, M. F. Riemer, and J. D. Bray and R. B. Seed, "Newmark Analyses of a Shaking Table Slope Stability Experiment," Proceedings, ASCE Specialty Conference on Geotechnical Earthquake Engineering and Soil Dynamics Conference, Seattle, Washington, ASCE Geotechnical Special Publication No. 75, pp.778-789, August, 1998.

134. T. M. Lok, J. M. Pestana and R. B. Seed, "Numerical Modelling and Simulation of Coupled Soil-Pile-Structure Interaction," Proceedings, ASCE Geotechnical Earthquake Engineering and Soil Dynamics Conference, Seattle, Washington, ASCE Geotechnical Special Publication No. 75, pp.1211-1222, August, 1998.

135. M. H. Chang, J. K. Mitchell and R. B. Seed, "Model Studies of the 1988 Kettleman Hills Landfill Slope Failure," Geotechnical Testing Journal, ASTM, Vol. 22, No. 3, pp. 61-66, 1998.

136. A. J. Augello, J.D. Bray, R. B. Seed, N. Matasovic, and E. Kavazanjian, Jr., "Performance of Solid-Waste Landfills During the Northridge Earthquake, " Proc., NEHRP Conference and Workshop on the Northridge, California Earthquake of January 17, 1994, California Universities for Research in Earthquake Engineering, Los Angeles, CA, pp.II-79 through II-80, June 16-18, 1998.

137. T.M. Lok, J.M. Pestana and R.B. Seed, "Effect of Soil Nonlinearity on the Prediction of Dynamic Interaction," Proc., Twelfth Structural Congress, American Society of Civil Engineers, San Francisco, California, July, 1998.

138. J. P. Stewart, G. L. Fenves and R. B. Seed, "Seismic Soil-Structure Interaction in Buildings. I: Analytical Methods," Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers, Vol. 125, No. 1, pp. 26-37, January 1999.

139. J. P. Stewart, G. L. Fenves and R. B. Seed, "Seismic Soil-Structure Interaction in Buildings. II: Empirical Findings," Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers, Vol. 125, No. 1, pp. 38-48, January 1999.

140. P.J. Meymand, M.F. Riemer and R.B. Seed, "Caltrans Seismic Soil-Pile-Superstructure Interaction Research project, Shaking Table Test Series 1.2", Geotechnical Engineering Research Report No. UCB/GT/99-04, January, 1999.

141. P.J. Meymand, M.F. Riemer and R.B. Seed, "Caltrans Seismic Soil-Pile-Superstructure Interaction Research project, Shaking Table Test Series 1.3", Geotechnical Engineering Research Report No. UCB/GT/99-05, January, 1999.

142. P.J. Meymand, M.F. Riemer and R.B. Seed, "Caltrans Seismic Soil-Pile-Superstructure Interaction Research project, Shaking Table Test Series 1.4", Geotechnical Engineering Research Report No. UCB/GT/99-06, January, 1999.

143. P.J. Meymand, M.F. Riemer and R.B. Seed, "Caltrans Seismic Soil-Pile-Superstructure Interaction Research project, Shaking Table Test Series 1.5", Geotechnical Engineering Research report No. UCB/GT/99-07, January, 1999.

144. P.J. Meymand, M.F. Riemer and R.B. Seed, "Caltrans Seismic Soil-Pile-Superstructure Interaction Research project, Shaking Table Test Series 2.1", Geotechnical Engineering Research Report No. UCB/GT/99-08, January, 1999.

145. P.J. Meymand, M.F. Riemer and R.B. Seed, "Caltrans Seismic Soil-Pile-Superstructure Interaction Research project, Shaking Table Test Series 2.2", Geotechnical Engineering Research Report No. UCB/GT/99-09, January, 1999.

146 P.J. Meymand, M.F. Riemer and R.B. Seed, "Caltrans Seismic Soil-Pile-Superstructure Interaction Research project, Shaking Table Test Series 2.3", Geotechnical Engineering Research Report No. UCB/GT/99-10, January, 1999.

147. P.J. Meymand, M.F. Riemer and R.B. Seed, "Caltrans Seismic Soil-Pile-Superstructure Interaction Research Project, Shaking Table Test Series 2.4", Geotechnical Engineering Research Report No. UCB/GT/99-11, January, 1999.

148. P.J. Meymand, M.F. Riemer and R.B. Seed, "Caltrans Seismic Soil-Pile-Superstructure Interaction Research project, Shaking Table Test Series 2.5", Geotechnical Engineering Research Report No. UCB/GT/99-12, January, 1999.

149. R.B. Seed, "Engineering Evaluation of Post-Liquefaction Residual Shear Strengths", Proc., Workshop on New Approaches to Liquefaction Analysis, Annual Meeting of the Transportation Research Board (TRB), Washington, D.C., January 10, 1999.

150. P. Meymand, T.M. Lok, J.M. Pestana, M.F. Riemer and R.B. Seed, "Large-Scale Shaking Table Model Tests and Analyses of Seismic Soil/Pile/Superstructure Interaction," Proc., Second International Conference on Earthquake Geotechnical Engineering, Lisbon, Portugal, pp.341-346, June 21-25, 1999.

151. J. Wartman, R.B. Seed, J.D. Bray, M.F. Riemer and E. Rathje, "Laboratory Evaluation of the Newmark Procedure for Assessing Seismically-Induced Slope Displacements and Deformations," Proc., Second International Conference on Earthquake Geotechnical Engineering, Lisbon, Portugal, Vol.2, pp.673-678, June 21-25, 1999.

152. R. B. Seed, "Site Response, Soil Liquefaction and Seismic Slope Instability Engineering: Rapid Evolution of Practice in California," Proc., Second International Conference on Earthquake Geotechnical Engineering, Lisbon, Portugal, June 21-25, 1999.

153. R. B. Seed and R. E. S. Moss, "Recent Advances in U.S. Codes and Policy with Regard to Seismic Geotechnics", Proc., Second International Conference on Earthquake Geotechnical Engineering, Lisbon, Portugal, Vol. 3, pp.111-1116, June 21-25, 1999.

154. J. M. Pestana, M. J. Mendoza, J. M. Mayoral, R. E. S. Moss, R. B. Sancio, R. B. Seed, J. D. Bray and M. P. Romo, "Preliminary Report on the Geotechnical Engineering Aspects of the June 15 and June 21, 1999, Mexico Earthquakes," Geotechnical Engineering Research Report No. UCB/GT/99-17, University of California, Berkeley, 25 pp., July, 1999.

155. A. Kammerer, J. Wu, J. M. Pestana, M. F. Riemer and R. B. Seed, "Cyclic Simple Shear Testing of Nevada Sand for PEER Center Project 20519999," Geotechnical Engineering Research Report No. UCB/GT/00-01, University of California, Berkeley, January, 2000.

156. A. Kammerer, J. Wu, J. M. Pestana, M. F. Riemer.and R. B. Seed, "Cyclic Simple Shear Testing of Nevada Sand for PEER Center Project 20519999: Electronic Data Files (CD)," Geotechnical Engineering Research Report No. UCB/GT/00-02, University of California, Berkeley, January, 2000.

157. J. P. Bardet and R. B. Seed (Coordinators and Principal Contributors); K. O. Cetin, W. Lettis, E. Rathje, G. Rau and D. Ural (Principal Contributors); M. B. Baturay, R. W. Boulanger, J. D. Bray, D. Erten, D. Frost, A. Kaya, B. Sozer, J. P. Stewart, B. Sunman and T. Yilmaz (Contributors), "Soil Liquefaction, Landslides, and Subsidence," Chapter 7 of the Kocaeli, Turkey Earthquake of August 17, 1999, Reconnaissance Report, in Earthquake Spectra Journal, Suppl. A to Vol.16, EERI, pp.141-162, 2000.

158. A. Kammerer, J. Wu, J. Pestana, M. F. Riemer and R. B. Seed, "Use of Cyclic Simple Shear Testing In Evaluation of the Deformation Potential of Liquefiable Soils", Fourth International Conference and Symposium on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Paper 1.20, San Diego, California, March 26-28, 2001.

159. R. B. Seed, K. O. Cetin, R. E. S. Moss, A. Kammerer, J. Wu, J. M. Pestana and M. F. Riemer, "Recent Advances in Soil Liquefaction Engineering and Seismic Site Response Evaluation", Fourth International Conference and Symposium on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Paper SPL-2, San Diego, California, March 26-28, 2001.

160. C. E. Hunt, J. M. Pestana, J. D. Bray, M. F. Riemer and R. B. Seed, "Geotechical Field Measurements After Pile Installation in a Soft Clay Deposit, " Geotechnical Engineering Report No. UCB/GT/2000-15, University of California, Berkeley, March 2000, 99 pp.

161. M-H. Lok, J. M. Pestana and R. B. Seed, "Numerical Modeling of Seismic Soil-Pile-Superstructure Interaction, " Proc., 12th World Conference on Earthquake Engineering, Paper 914, Auckland, New Zealand, 2000.

162. R. Dobry, R. D. Borcherdt, C.B. Crouse, I. M. Idriss, W. B. Joyner, G. R. Martin, M. S. Power, E. E. Rinne and R. B Seed, "New Site Coefficients and Site Classification Systems Used in Recent

Code Provisions (1994/1997 NEHRP and 1997 UBC)," Spectra, the professional journal of the Earthquake Engineering Research Institute, 2000.

163. R. A. Torres, N. A. Abrahamson , F. N. Brovold, G. Cosiom M. w. Driller, L. F. Harder, Fr., N. D. Marachi, C. H. Nendeck, L. M. O'Leary, M. Ramsbotham, and R. B. Seed, "Seismic Vulnerability of the Sacramento-San Joaquin Delta Levees, " a report prepared as part of the CALFED Bay-Delta Program, April 2000.

164. R.B. Seed, J. Stewart, R. E. S. Moss and O. Cetin, "Lessons and Opportunities Regarding Liquefaction Presented by the 921 Earthquake", First Anniversary Workshop for the 921 (Chi-Chi, Taiwan) Earthquake, October 15-16, Taipei, Taiwan, 2000.

165. J. P. Stewart, D. B. Chu, R. B. Seed, J. W. Ju, W. J. Perkins, R. W. Boulanger, Y. C. Chen, C. Y. Ou, J. Sun and C. Yu, "Incidents of Soil liquefaction from the 921 Chi Chi (Taiwan) Earthquake", First Anniversary Workshop for the 921 (Chi-Chi, Taiwan) Earthquake, October 15-16, Taipei, Taiwan, 2000.

166. J. Wartman, R. B. Seed and J. D. Bray, "Physical Model Studies of Seismically Induced Deformations in Slopes", GeoEngineering Research Report No. UCB/GT/01-01, Department of Civil and Environmental Engineering, University of California, Berkeley, January 2001.

167. J. Wartman, R. B. Seed and J. D. Bray, "Experimental Data for Physical Model Studies of Seismically Induced Deformations in Slopes, "GeoEngineering Research Report No. UCB/GT/01-02, Department of Civil and Environmental Engineering, Unversity of California, Berkeley, January 2001.

168. J. D. Bray, R. B. Sancio, L. F. Youd, C. Christensen, O. Cetin, A. Onalp, T. Durgunoglu, J. P. Stewart, R. B. Seed, M. B. Baturaym, T. Karadayilar and C. Oge, "Documenting Incidents of Ground Failure Resulting from the August 17, 1999 Kocaeli, Turkey Earthquake," Pacific Earthquake Engineering Research Center website: http://www.eerc.berkeley.edu/turkey/adapazari/, February, 2001.

169. R. B. Sancio, J. M. Pestana, J.M. Mayoral, R. B. Seed and J. D. Bray, "Attenuation of Peak Ground Acceleration with Distance of the June 15, 1999 Tehuacan, Mexico Earthquake, " Proc., Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, California, March 26-31, 2001.

170. J. Wartman, J. D. Bray and R. B. Seed, "Shaking Table Experiment of a Model Slope Subjected to Two Ground Motions," Proc., Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, California, March 26-31, 2001.

171. J. P. Stewart, D. B. Chu, R. B. Seed, J. W. Ju, W. J. Perkins, R. W. Bouoanger, Y. C. Chen, C. Y. Ou, J. Sun and M. S. Yu, "Chapter 4: Soil Liquefaction. Chi-Chi, Taiwan Earthquake of September 21, 1999 Reconaissance Report", Earthquake Spectra, the professional journal of the Earthquake Engineering research Institute, Vol. 17, Supplement A, pp 37-60, April, 2001.

172. Travasarou, T., Bray, J. D. Bray, Wartman, J., Seed, R. B., and Riemer, M. F., "Evaluation of Seismic Slope Displacement Procedures through Back-Analysis of Physical Model Tests", Geotechnical Engineering Report No. UCB/GT/01-04, University of California, Berkeley, June, 2001, 107 pp.

173. J. D. Bray, R. B. Sancio, H. T. Durgunolgu, A. Onalp, R. B. Seed, J. P. Stewart, T. L. Youd, M. B. Baturay, K. O. Cetin, C. Christensen, T. Karadayilar and C. Emrem, "Ground Failure in Adapazari, Turkey," Proc., Earthquake Geotechncal Engineering Satellite Conference on Soil Mechanics & Geotechnical Engineering, Istanbul, Turkey, August 24-25, 2001.

174. A. Kammerer, J. Wu, M. Riemer, J. Pestana and R. Seed, "Deformations of Dense Sand Under Cyclic Loading", extended abstract, Tenth International Conference and Symposium on Soil Dynamics and Earthquake Engineering, October 7-10, 2001.

175. T.L. Youd, I.M. Idriss, R.D. Andrus, I. Arango, G. Castro, J.T. Christian, R. Dobry, W.D.L. Finn, L.F. Harder, Jr., M.E. Hynes, K. Ishihara, J.P. Koester, S.C. Liao, W.F. Marcuson, G.R. Martin, J.K. Mitchell, Y. Moriwaki, M.S. Power, P.K. Robertson, R.B. Seed and K.H. Stokoe, "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils", Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers, Vol. 127, No.10, pp.817-833, October, 2001.

176. J. M. Pestana, R. B. Sancio, J. D. Bray, M. P. Romo, M. J. Mendoza,R. E. S. Moss, J. Mayoral, and R. B. Seed, "Geotechnical Engineering Aspects of the June 1999 Central Mexico Earthquakes", Earthquake Spectra, the professional journal of he Earthquake Engineering Research Institute, Vol. 18, No. 3, pp. 481-500, August, 2002.

177. A. Kammerer, J. M. Pestana and R. B. Seed, "Undrained Response of Monterey 0/30 Sand Under Multidirectional Cyclic Simple Shear Loading Conditions," GeoEngineering Research Report No. UCB/GE/02-01, University of California, Berkeley, 2002.

178. A. Kammerer, J. Wu, J. M. Pestana, M. F. Riemer and R. B.Seed, "Undrained Response of Monterey 0/30 Sand Under Multidirectional Cyclic Simple Shear Loading Conditions: Electronic Data Files (CD)", GeoEngineering Research Report No. UCB/GE/02-02, University of California, Berkeley, 2002.

179. J. M. Mayoral, J. M. Pestana and R. B. Seed, "Determination of Multidirectional p-y Curves for Soft Clays, " GeoEngineering Reserch Report No. UCB/GE/2002-05, Department of Civil and Environmental Engineering, University of California, Berkeley, 2002.

180. J. M. Mayoral, J. M. Pestana and R. B. Seed, "Multidirectional p-y Behavior of Model Clay," GeoEngineering Research Report No. UCB/GE/2002-07, Department of Civil and Environmental Engineering, University of California, Berkeley, 2002.

181. J. M. Mayoral, J. M. Pestana and R. B. Seed, "A Simplified Model of Clay-Pile Interface Behavior Under Multidirectional Loading," GeoEngineering Research Report No. UCB/GE/2002-08, Department of Civil and Environmental Engineering, University of California, Berkeley, 2002.

182. R.B. Seed (Principal Author), U. Dayal, P.L. Narula, R.E.S. Moss, L.F. Harder, Jr., U. Patil, J.P. Bardet, E.M. Rathje, J.P. Stewart, J.P. Singh, S.K. Chaubey and S. Sinha (Contributing Authors), "Ground Failure and Geotechnical Effects: Dams", Chapter 9 of the Report on the January 26, 2001 Bhuj (India) Earthquake, Spectra, the professional journal of the Earthquake Engineering Research Institute, Vol. 18, Supplement A, pp. 131-146, July, 2002.

183. K. O. Cetin, T. L. Youd, R. B. Seed, J. D. Bray, R. Sancio, W. Lettis, M. T. Yilmaz, and T. Durgunoglu, "Liquefaction-Induced Ground Deformations at Hotel Sapanca During Kocaeli (Izmit), Turkey Earthquake", International Journal of Soil Dynamics and Earthquake Engineering, Vol. 22, pp. 1083-1092, December, 2002.

184. R. Sancio, J. D. Bray, J. P. Stewart, T. L. Youd, H. T. Durgunoglu, A. Onalp, R. B. Seed, C. Christensen, M.B. Baturay and T. Karadaylar, "Correlation Between Ground failure and Soil Conditions in Adapazari, Turkey " International Journal of Soil Dynamics and Earthquake Engineering, Vol. 22, pp. 1093-1102, December, 2002.

185. K.O. Cetin, A. Der Kiureghian and R. B. Seed, "Probabilistic Models for the Initiation of Seismic Soil Liquefaction," Structural Safety Journal, Elsevier Pubs., Vol. 24, pp. 67-82, December, 2002.

186. R. E. S. Moss and R. B. Seed, "Probabilistic Evaluation of Seismic Soil Liquefaction Potential Using CPT," Proc., 8th U. S./Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Liquefaction, " Tokyo, Japan, Paper IX-5, December 16-18, 2002.

187. R. E. S. Moss, K. O. Cetin, and R. B. Seed, "Seismic Liquefaction Triggering Correlations Within a Bayesian Framework," Proc., 9th International Conference on Applications of Statistics and Probability in Civil Engineering, San Francisco, CA, July 6-9, 2003.

188. R. B. Seed, K. O. Cetin, R. E. S. Moss, A. Kammerer, J. Wu, J. M. Pestana, M. F. Riemer, R. B. Sancio, J. D. Bray, R. E. Kayen and A. Faris, "Recent Advances in Soil Liquefaction Engineering: A Unified and Consistent Framework", Keynote Address, 26th Annual Geotechnical Spring Seminar, Los Angeles Section of the GeoInstitute, American Society of Civil Engineers, H.M.S. Queen Mary, Long Beach, California, April 30, 2003.

189. J. Wartman, J. D. Bray and R. B. Seed, "Inclined Plane Studies of the Newmark Sliding Block Procedure", Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers, Vol. 129, No. 8, pp. 673-684, August, 2003.

190. J. P. Stewart, D. B. Chu, S. Lee, J. S. Tsai, P. S. Lin, B. L. Chu, R. E. S. Moss, R. B. Seed, S. C. Hsu, M. S. Yu and M.C.H. Wang, "Liquefaction and Nonliquefaction from the 1999 Chi-Chi, Taiwan Earthquake", in Advancing Mitigation Technologies and Disaster Response for Lifeline Systems, Technical Council on Lifeline Earthquake Engineering, Monograph No. 25, J. E. Beavers (ed.), pp. 1021-1030, 2003.

191. M. Suziki, K. Tokimatsu, R. E. S. Moss, R. B. Seed and R. E. Kayen, "CPT-Based Liquefaction Field Case Histories from the 1995 Hyogoken-Nanbu (Kobe) Earthquake (Japan)", GeoEngineering Research Report No. UCB/GE-2003/03, University of California at Berkeley, 2003.

192. R. E. S. Moss, R. B. Seed, R. E. Kayen, J. P. Stewart, T. L. Youd and K. Tokimatsu, "Field Case Histories for CPT-Based Liquefaction Potential Evaluation", GeoEngineering Research Report No. UCB/GE-2003/04, University of California at Berkeley, 2003.

193. A. M. Kammerer, J. M. Pestana and R. B. Seed, "Sand Response Under Undrained Multidirectional Loading Conditions: Insights for Constitutive Model Development", 1st Japan-U.S. Workshop on Testing, Modeling and Simulation in Geomechanics, Invited Paper, Massachusetts Institute of Technology, Boston, June, 2003.

194. R. E. S. Moss and R. B. Seed, "Probabilistic Assessment of Seismic Soil Liquefaction Using the CPT", accepted for publication in the Proceedings, 11th International Conference on Soil Dynamics and Earthquake Engineering and the 3rd International Conference on Earthquake Geotechnical Engineering (a jointly convened conference pairing), University of California at Berkeley, January 7-9, 2004.

195. K. L. Knudsen, A. Rosinski and R. B. Seed, "Production of Regional Liquefaction-Induced Deformation Maps", accepted for publication in the Proceedings, 11th International Conference on Soil Dynamics and Earthquake Engineering and the 3rd International Conference on Earthquake Geotechnical Engineering (a jointly convened conference pairing), University of California at Berkeley, January 7-9, 2004.

196. R. B. Seed, K. O. Cetin, A. Der Kiureghian, K. Tokimatsu, L. F. Harder, R. E. Kayen, and R. E. S. Moss, "SPT-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential, " accepted for publication in the Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers.

197. J. M. Mayoral, J. M. Pestana and R. B. Seed, "Determination of Multi-Directional p-y Curves for Soft Clays," accepted for publication in the Geotechnical Testing Journal, ASTM, in press.

198. K. O. Cetin and R. B. Seed, "Nonlinear Shear Mass Participation Factor (r_d) for Cyclic Shear Stress Ratio Evaluation," accepted for publication in the International Journal of Soil Dynamics and Earthquake Engineering.

199. J. Wu and R. B. Seed, "Estimation of Liquefaction-Induced Ground Settlement (Case Studies)", submitted to the 5th International Conference on Case Histories in Geotechnical Engineering, New York, April 13-17, 2004.

200. R. Kayen, R. B. Seed, R. E. S. Moss, O. C. Cetin, Y. Tanaka and K. Tokimatsu, "Global Shear Wave Velocity Database for Probabilistic Assessment of the Initiation of Seismic Soil Liquefaction, submitted to the 11th International Conference on Soil Dynamics and Earthquake Engineering, University of California at Berkeley, January 7-9, 2004.

201. A. M. Kammerer, R. B. Seed, J. M. Pestana-Nascimento amd M. F. Riemer, "Results From Undrained Multidirectional Cyclic Simple Shear Testing on Sand: Lessons for Constitutive Model Development", Report No. PEER-2003/xx, Pacific Earthquake Engineering Research Center, University of California at Berkeley, in review.

202. R. E. S. Moss, R. B. Seed, R. B. Kayen, J. P. Stewart, T. L. Youd and K. Tokimatsu, "CPT-Based Probabilistic Assessment of Seismic Soil Liquefaction Initiation", Report No. PEER-2003/xx, Pacific Earthquake Engineering Research Center, University of California at Berkeley, in review.

203. R. E. S. Moss and R. B. Seed, "Thin Layer Correction for the CPT," submitted to the Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers.

204. K. O. Cetin, T. L. Youd, R. B. Seed, J. D. Bray, E. Rathje, H. T. Durgunoglu, W. Lettis, R. Sancio, and M. T. Yilmaz, "Liquefaction-Induced Lateral Spreading at Izmit Bay During the 1999 Kocaeli (Izmit), Turkey Earthquake," submitted to the Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers.

205. J. D. Bray, R. Sancio, T. Durgunoglu, A. Aonalp, T. L. Youd, J. P. Stewart, R. B. Seed, K. O. Cetin, E. Bol, M. B. Baturay, C. Christensen, and Karadayilar, "Subsurface Characterization at Ground Failure Sites in Adapazari, Turkey," submitted to the Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers.

206. M.-H. Chang, J. K. Mitchell and R. B. Seed, "Reanalysis of the 1988 Kettleman Hills Landfill Failure Based on Observed 3-Dimensional Mechanism", submitted to the Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers.

• • •

XXX. Seed, R.B., Nicholson, P.G., Dalrymple, R.A., Battjes, J., Bea, R.G., Boutwell, G., Bray,. J.D., Collins, B.D., Harder, L.F., Headland, J.R., Inamine, M., Kayen, R.E., Kuhr, R., Pestana, J.M., Silva-Tulla, F., Storesund, R., Tanaka, S., Wartman, J., Wolff, T.F., Wooten, L. and Zimmie, T. (2005) "Preliminary Report on the Performance of the New Orleans Levee Systems in Hurricane Katrina on August 29, 2005", Report No. UCB/CITRIS – 05/01, CITRIS Center, University of California, Berkeley, November 16.

Post-Hearing Questions for the Record
Submitted to Peter Nicholson, Ph.D.
From Senator Susan M. Collins

"Hurricane Katrina: Why Did the Levees Fail?"

November 2, 2005

1. One question that has not been answered is whether and when the Army Corps of Engineers should have known that the soil beneath the flood walls in New Orleans was weak and left the city more vulnerable to storms than had been believed.

One possible indication that the Army Corps should have known of the weakness earlier is a 1997 lawsuit between Pittman Construction, a building contractor, and the Army Corps. In the suit, Pittman contended, and I quote from the opinion in that case, that, together with another factor, the "relative weakness of the soils permitted the concrete to shift during construction, resulting in monoliths that were not in alignment as required by the contract."

It would seem logical that the weaknesses identified in this 1997 lawsuit should have tipped off the Army Corps that the flood walls were more vulnerable than believed. However, a recent New Orleans Times-Picayune article quotes Pittman's expert witness, Herbert Roussel, as stating that the soil weaknesses, "in no way jeopardizes the integrity of the wall as far as flood protection is concerned."

Can you shed light on whether the soil weaknesses that caused flood walls to fail – particularly on the 17th Street and London Avenue levees – should have been known about and addressed perhaps years earlier?

I do not know what the U.S. Army Corps of Engineers knew or should have known about the soil conditions under the New Orleans levee system at the time Hurricane Katrina struck. ASCE believes Congress must enact a comprehensive national levee safety program modeled on the National Dam Safety program established in 1974. The levee safety program should include mandatory inspections of the levees nationally by the federal or state agencies responsible for their construction and maintenance. Such a program may have revealed structural problems with the New Orleans levee system before August 29.

Post-Hearing Questions for the Record
Submitted to Peter Nicholson, Ph.D.
From Senator Pete V. Domenici

"Hurricane Katrina: Why Did the Levees Fail?"

November 2, 2005

1. Are you a civil or mechanical engineer?

I am a civil (geotechnical) engineer.

2. Can you please give us details on your education, background, and experience as it relates to engineering matters?

I received a bachelor's degree in Geology & Geophysics from Yale University followed by a master's degree and a Ph.D. in Civil/Geotechnical Engineering from Stanford University. I am a Licensed Professional Engineer with more than 20 years' experience working and consulting in geotechnical engineering including foundations, slope stability, retaining walls, dams and embankments.

3. When did you begin your investigation of the breached levees in New Orleans?

Our investigation began September 29 with the first members of our assessment team in the field.

4. Where are you at in the process of that investigation?

The investigation authorized for the ASCE Assessment Team was for field reconnaissance, observations, and data collection to be incorporated into the Preliminary Report. No further ASCE investigation is planned after the release of the Preliminary Repor on November 2, 2005..

5. How long do you believe your investigation will take?

There are currently no plans for continuation of the investigation by the ASCE team at this time.

6. Might other data, information, or issues come to light that could change your current assessment?

As investigations continue, and evidence and pertinent data is released, preliminary assessments may be appended and revised. Assessments made in the Preliminary Report were based solely on data and observations made during our field reconnaissance in September and October 2005.

7. Are any opinions you make today based only on your preliminary findings?

The opinions made were based solely on preliminary findings which include data and models obtained up to the release of the Preliminary Report.

RAYMOND B. SEED, Ph.D.
1530 Whitecliff Way
Walnut Creek, CA 94596
Ph: (925) 930-8692
E-mail: Rmseed6@aol.com

October 11, 2005

TO: Donald L. Basham
David A. Pezza
Dr. Paul F. Mlakar
Dr. W. F. Marcuson, III

**RE: Observations and Urgent Recommendations,
New Orleans Flood Control System,
On-Site Data Gathering and Investigation**

Gentlemen,

These are complicated and trying times, and we are all very busy. I feel obligated, however, to pass along to you a number of observations and recommendations from our recent (and ongoing) multi-team independent site data gathering visit. There are some issues of which you will need to be aware, and some of these carry potential urgency as they pertain to ongoing potential risk associated with some of the temporary emergency repairs.

The comments herein are mine alone, and should not be construed as coming from the full assembled COPRI, G-I and NSF teams. They are, however, also observations and views that were well-discussed among the combined members of these teams last week. There was a large degree of unanimity on most issues. Some of the team members feel even more strongly than I will present here, and I have promised to pass these observations along to you. Some of the members of both teams were reluctant to leave the region last weekend without some assurance that these would be passed along, and without some assurance from the local USACE New Orleans District that further and more effective action would be taken immediately. We received that assurance from the District at our meeting/outbriefing last Friday, but it was not clear that our concerns were locally fully understood and thus that the situations of immediate concern would be fully addressed.

These comments deal with issues pointedly not addressed at last Friday afternoon's press briefing. These issues were, however, directly addressed at last Friday morning's exit meeting/debriefing with the USACE.

17th Street Canal Breach Section:

The breach at the 17th Street Canal was clearly the result of a largely translational failure of the soil embankment. A large and relatively intact section of the embankment remains clearly visible along the northern third of the failed section, and our measurements indicated that it it is displaced approximately 35 feet laterally from its initial position (as can clearly be established based on the intact fence line on the embankment fragment.) There is no sign of even splash-over induced scour behind the floodwalls at adjacent sections along the levees lining both sides of the canal, and we have identified 3 water level marks judged by the COPRI experts as being "highly reliable" at the nearby London avenue canal that clearly indicate that the high water level in that canal was at least 70 cm below overtopping the floodwalls at those locations. The actual mechanism that induced the embankment instability failure, and the soil strata involved, remain to be investigated in detail (CPT probes, borings and sampling, lab testing and analyses, etc.), so there is certainly more investigative work to be done here.

Our more immediate concern is in regard to the temporary/emergency closure embankment section, and how it was constructed.

When we first arrived at the site (Monday, October 3rd), the emergency closure section had a crest about 3 feet above canal water level, and the crest and inboard and outboard faces consisted of a gap-graded sandy gravel fill with some silt fines. This material is locally known to be hydraulically unstable with regard to its inability to maintain internal filtering stability. It has been explained to us that this material covers a core section of the large sand bags and large stones which were initially used to plug the flowing breach (this is a common procedure, and we do the same out here.)

Unfortunately, we also observed four sinkholes at the outboard lip of the crest of the emergency embankment. Three of these sinkholes could be hand traced as arcing back towards to central core, and all extended farther into the core than our longest pole could "poke". Despite the ambient noise, including construction equipment about 150 yards away, we could clearly hear water flowing in one of these sinkholes.

Our opinion is that the central core section is likely porous, with considerable void space available, and that materials from the crest and outboard face sections are actively eroding into the core section. There was no indication (yet) that material was being actively eroded from the inboard side, as exiting water at the inboard toe appeared clear and no accumulation of soil was evident at the inboard toe where water was flowing out. (There is an excellent location, at a storm drain inlet that is currently collecting most of the flow, where a sandbag weir could easily be constructed to permit monitoring of the flow to ensure that it is not progressing.)

We were immediately concerned, and formally notified Dr. Paul Mlakar that we felt that the situation warranted an urgent response. He agreed to pass along that recommendation.

We re-visited the site on Wednesday (Oct. 5th) and there had been a response. A row of large sand bags had been placed, much like flower pots, along the front (outboard) lip of the temporary crest section directly on top of where we had observed the sinkholes. These did not block the likely points of water ingress that would have caused the sinkholes, as those would have been below canal water level, but they did successfully cover the resulting overlying surficial sinkholes so that their progress could no longer be observed nor further monitored.

In addition to the large sand bags, a three foot thick layer of coarse, open stone (apparently 6-inch to 24-inch stone with no sand or fines) had been placed atop the crest, behind the line of large sand bags, obstructing potential inspection of the rest of the crest. We again formally expressed concern, as none of this would be effective in mitigating the potential internal erosion of the underlying embankment section, and it would obstruct timely inspection and monitoring. The large stones would also preclude safe placement of additional overlying fill, as that fill would be underlain by an open seepage zone of coarse stone without filtration between the two strata. The open stones would also likely preclude the driving of a sheet pile wall along the crest of the emergency embankment section. Dr. Mlakar agreed again to pass along our concerns.

When we again re-visited the site on Thursday, there had been further progress. At that time we observed a five foot thick single lift of better graded silty, gravelly sand fill being end-pushed over the crest and inboard and outboard faces of the entire emergency embankment section. An additional lift of this material was subsequently added, and the slope faces have been well dressed with a blade. This succeeded in hiding any and all evidence of the evolving underlying erosive distress, and in obstructing any hope of monitoring internal erosive distress until it develops considerably further.

It had become apparent by this stage, based on the local District's responses to our formal notifications, that the urgency of the emergency response operations may have precluded application of the level of geotechnical oversight that would otherwise have been ideal. We felt that the current embankment section was poorly configured with regard to ongoing risk of failure. Moreover, the recent work did not appear to have improved the situation. Indeed, it had likely made it more dangerous, because:

1. The covering of the new embankment was deceptively attractive and hid an underlying dangerously unfiltered and clearly erodable interior, but yet gave the potential impression that all was well and that the situation was resolved.
2. The coarse rock layer represented a dangerous potential flow path, so that the embankment would be poorly suited to withstand another rise in water levels in the canal. (Water can reportedly rise several feet in this canal over just a few hours from simple passage of weather fronts far less dramatic than tropical storms.)
3. The coarse rock layer represented an unfiltered erosive contact with the otherwise likely more competent crest fill section, and erosion at this interface would be a clear hazard in the event of an additional high water event.
4. The massive weight of the temporary embankment section greatly exceeds the previous loading imposed by the original embankment topped by the nearly weightless floodwall. As the embankment has already clearly failed once due to inadequate shear strength of the soils at this location, only the hope that resultant scour had succeeded in fully removing potentially weak foundation soils would provide any level of assurance that the new (massive) embankment load would not induce slope instability. In my experience with levee failures, scour is usually far more pronounced inboard of the original embankment centerline than outboard. If weak soils left in place at the outboard toe yield and cause a sudden outboard stability failure, the resulting hydraulic connection (through the apparently porous central sand bag and stone core) would then cause the soil fill "skin" on the inboard face to rapidly become the only significant impediment to break-through of the flow. As this skin appears to be thin, rapid erosion and blowout would become likely in this case.
5. Ongoing internal erosion had already been observed to be actively occurring, and it could no longer be monitored given the covering fill sections.

We thus sought additional assurances at the outbriefing/meeting with the USACE on Friday morning (October 7th) that suitable geotechnical expertise, and further remedial actions, would be applied to this section. We were told that an outsourced geotechnical A&E would be contracted to study and design a longer-term fix, and that this would likely include driving a sheetpile curtain at the outboard toe of the current embankment.

The USACE will take some time to complete this process if the geotechnical work needs to be outsourced. This cannot wait.

The Corps would not likely be forgiven if New Orleans floods a third time, especially in the absence of another hurricane. The daily likelihood of a failure is low, but it is not zero. A non-zero risk is unacceptable in light of recent events.

The engineers assembled last week felt that the USACE should immediately take further action. Recommendations varied a bit, but were essentially congruent. As I am writing this as a lone individual, I will summarize my own view of these. The USACE should immediately do the following:

1. A highly qualified geotechnical engineer from within the USACE, with good levee experience, should immediately be put in charge of this section, and should be given the authority and resources necessary to safely resolve it. The USACE is stretched right now, and has its hands full, but there cannot possibly be a more urgent task than keeping this from failing again. The USACE has been required to reduce its geotechnical expertise in recent years, but surely the necessary resources can be made immediately available. Several members of the USACE investigation team from ERDC might be good choices here. Involving them in getting this fixed would not appear likely to compromise their investigative objectivity, they have the necessary background and understanding, and some of them have local district experience that might be valuable in collaborating with local USACE in this trying situation. In the alternative, Dave Pezza could come in and directly handle this himself, or someone else could be sent. As the next sections of this memorandum will point out dauntingly similar apparent shortcomings in four other emergency closure sections at the four other major central New Orleans breaches, a high level of involvement and responsibility would not be inappropriate here.

2. This site should be competently monitored around the clock until it is rendered fully safe. Backfill materials could be stockpiled at the site, and a loader, a blade, and several dump trucks could be parked local to the site in case urgent actions become necessary. A weir should be set up to monitor outflows to ensure that no rapid change or progression occurs.

3. A sheetpile curtain is a good idea. The outboard toe is now probably the best available location, but this now juts well out into the canal and would appear likely to impede pumping flows. An alternative would be to remove the 3-foot layer of coarse stone, and the overlying crest fill, drive the sheetpiles through the interim crest, and then re-place the crest section without the open stone layer.

4. While figuring what further steps to take, a relatively simple interim step would be to place a stabilizing berm on the inboard side of the emergency closure section. This would promote soil stability on the inboard side, and the soil used should be selected to be competent to prevent inboard migration of fines from the fills occurring to the waterside.

Cost should not be allowed to be a controlling issue here in light of recent events. Red tape should be cut through, and effective action taken. It might be necessary to acquire the land inboard of the current emergency closure section, as the right of way may already be fully occupied by the emergency embankment which is considerably wider than the previous embankment topped by the floodwall. Again, this should not delay taking action as what is potentially at stake outweighs these considerations.

London Avenue Canal, North Breach:

The breach on the west side at the northern breach section of the London Avenue canal is also clearly related to instability and movement of the underlying embankment section. It is less clear at this site whether these movements were primarily lateral translation or largely rotational in nature, and there are a number of potential mechanisms and soil units that might account for the observations made to date. Here, again, there is considerable scope for additional field and laboratory investigations, and engineering analyses, to track down these details. We were able to locate three high water marks considered by the COPRI team's experts to be of high reliability in close proximity to the breach section, and these indicate that high water was at least 70 cm below the top of the floodwalls at this breach site. There is also no evidence of scour from overtopping at adjacent, unbreached levee sections.

The floodwall directly across the canal is shown to have similar (very poor) foundation soil conditions, with considerable peat, in the subsurface cross-sections that we have acquired to date, and this floodwall was considerably distressed. It was pushed at least 12 to 19 inches laterally inboard along a considerable length, opening a gap of this width between the concrete and sheetpile floodwall and the adjacent (outboard side) embankment fill. The embankment crest on the inboard side of the floodwall showed four sinkholes, and there was an apparent pipe exit boil at the inboard toe of the embankment with eroded ejecta. In addition, there was evidence that the inboard embankment section has translated laterally inboard, probably on the order of about 0.5 to 1.5 feet, as evinced by pushing of fences and a clear overthrust of the embankment toe relative to the inboard "level" ground at one location at the toe.

This is a distressed section, with at least one evident pipe, and it may be that the failure of the fully breached section directly across the canal drew the water down and reduced hydraulic loading at this section in time to prevent a more serious incident. **This "distressed" section on the east side needs to be remediated if it is to again serve as useful flood protection in a high water situation.** So far, all attention and remedial activity appears to have been focused on the breach across the canal, on the west side.

In addition, we have painfully watched as the emergency breach closure section at this site followed essentially the same progression as described previously for the 17th Street Canal breach closure. The initial sand bag and stone water flow barrier which now forms the core of this embankment section was covered with gap graded sandy gravel. An open, coarse fill layer was placed atop this, and then the whole section was topped by an apparently competent silty gravelly sand fill. This is, again, an unfiltered section, and there is considerable flow currently passing through and/or beneath this section. Clear evidence of erosion and partially developed piping at the section directly across the canal only serves to further highlight the potential dangers here.

Recommendations for addressing this would be largely the same as those previously enunciated for the 17th Street breach section. Several members of our combined teams felt that this section represents an even higher level of hazard than the 17th Street section, but I personally see little basis for preference of one site relative to the other in terms of apparent risk of a potential "sunny day" failure.

Again, urgent and resolute action is warranted here.

London Avenue Canal, South Breach:

The breach section on the west side of the southern portion of the London canal was much more severely eroded than the two breached sections described thus far, and the resulting large scour hole required placement of larger volumes of fill for the emergency closure. As a result, little remained to be seen during our site study, and no firm conclusions can be drawn directly from our site study regarding likely failure mechanisms at this location. We have, however, also acquired photos of the initial conditions not long after the breach (prior to burial by the closure section fill), and these suggest that embankment stability failure may have occurred at this site as well. We will pass copies of these on to the USACE levee investigation team. The high water marks farther north along the canal, and local absence of scour at the inboard toes of adjacent floodwall sections, indicate that no overtopping occurred at this location.

Once again, the emergency embankment closure section appears to have gone through essentially the same evolution as the two breach sections previously described. We did not directly witness the emplacement of a layer of open stone, but large stones are intermittently visible on both the inboard and outboard faces of the emergency closure fill section. The rate of flow inboard through this section appears to be larger than at either of the two sections discussed previously. **It should be determined if the emergency closure fill section is unfiltered. If so, this would represent a potential hazard. Again, urgent and resolute further action would then appear to be warranted here.**

Two Breaches on the East Side of the Industrial Canal at the Ninth Ward:

Two major breaches occurred at this location. The southernmost breach is a considerably longer feature than the one to its north, and the now infamous large barge passed through this breach and now rests on the inboard side.

Both breaches appear to be associated with overtopping-induced scour at the inboard toes of the concrete floodwalls, and significant such scour (to variable depths) is clearly evinced at adjacent, unbreached sections. The scour reduces lateral support of the concrete floodwalls (I-walls) and their contiguous sheetpiles, and it appears likely that this led to both breaches. The sheetpiles are not very deeply imbedded here, and it appears likely that they were pushed over as a relatively rigid toppling failure, and then were simply overwhelmed by the ensuing water forces and severe scour that followed.

We spent some fair energy figuring out that the barge did not cause the southernmost breach, but instead arrived later and was drawn in through the breach by the inrushing water. The breach was well developed by the time the barge arrived, as it was supported by a fair depth of already ponded water on the inboard side and it thus passed cleanly over a chain link fence, a mailbox, and two small trees (which likely bent to let it by.) It also passed over or around a small yellow school bus, then settled down to crush the front end of the bus. The barge would have been traveling south in the canal, driven by wind and waves, and it apparently struck the concrete floodwall at the extreme southern end of the southernmost breach section as it was drawn in through this breach. The effects of this single impact are clearly evinced both on the concrete floodwall and on the barge itself.

After we had flexed our forensic muscles to figure this out, Tom Wolf arrived with the second week's team and brought with him a photo showing the southernmost breach at an early stage of its development. The feature is only about 100 feet long at the time of this photo (less than one fifth of its eventual length), and water is rushing in, scouring and widening the feature. The yellow school bus is present in the foreground of the photo, but the large barge has not yet made its appearance. Good confirmation of our hypothetical model. (Paul: We're setting up a website at our end, with a secure section, so that your team can download this and other photos and documents, etc.)

Once again, the emergency closure embankments need to be evaluated to determine if they are internally stable with regard to erosion as seepage is passing through both sections. If they cannot be demonstrated, beyond doubt, to be adequately filtered then these sections should also be subject to urgent further work. The Ninth Ward has been flooded twice, and even a small likelihood of a third flooding is too high.

Other Observations:

We made numerous additional observations, many of which will likely be useful when reconstructing elements of the New Orleans flood control system. No doubt many others will also offer suggestions, etc. As busy as you are, there is no urgency in these.

The five major breach sections discussed above, however, do warrant urgent attention. Even if the likelihood of progressive erosional degradation and eventual failure of each of these sections is small in the short-term, any such non-zero risk should be addressed rapidly and by highly expert USACE geotechnical experts with significant levee expertise and experience. The "level of safety that preceded Katrina" cannot be re-established simply by getting the crests of the closure section embankments up to an elevation equal to the tops of the pre-breach floodwalls. It can only be re-established by getting competent, stable closure sections up to that level. The need for stability, both internally with respect to erosion and globally with regard to slope stability and bearing capacity, are difficult issues that require expertise in geotechnics not typically available in emergency task teams.

Given the stakes involved, I recommend that you immediately put several of your top geotech's in charge of these sections, and give them an essentially blank check in terms of equipment, funds, and personnel, etc. until this is safely resolved. It does not appear prudent to wait for outsourced geotechnical A & E's to get up to speed and then wend their way through the contracting process to effect further repairs. Once USACE geotechnical levee experts (who are directly held responsible for each of the interim breach closure sections) are satisfied with their stability, outsourced geotech's could then study and design longer-term repairs.

I apologize for the length of this memo, as I know how busy everyone is. It is important that the situation be fully understood, and in detail, as you consider all of this.

We were very grateful for the excellent cooperation, open exchanges of data, and also logistical assistance provided by Dr. Paul Mlakar and his USACE/ERDC levee investigation team, and also for the opportunity to get our teams in to examine the levees in the midst of the still ongoing emergency repair efforts. At a number of sites we were able to capture key observations and data that will be vital to discerning what happened, and within days (and in some cases hours) this data was then buried or scooped up as repair efforts continued. The opportunity to get our teams in on a timely basis was invaluable.

If you have any questions, or wish to discuss this further, I can best be reached by return E-mail, on my cell phone at 925-899-6101, or at my home/office phone at 925-930-8692.

cc: Dr. Peter Nicholson
Dr. Tony Dalrymple
Dr. Francisco Silva
Dr. Joseph Wartman
Dr. Lee Wooten
Dr. Bob Bea
Dr. Jon Bray
Dr. John Headland
Dr. Gordon Boutwell
Rune Storesund
Dr. Jurjen Battjes
Dr. Shigenobu Tanaka

From: RMSeed6@aol.com

Sent: Tuesday, October 18, 2005 12:32 AM

To: Donald.L.Basham@hq02.usace.army.mil; David.A.Pezza@hq02.usace.army.mil; Paul.F.Mlakar@erdc.usace.army.mil; William.F.Marcuson@erdc.usace.army.mil; James.R.Rowan.COL@erdc.usace.army.mil

Cc: Peter193@aol.com; boutwell@steofla.com; bray@ce.berkeley.edu; harder@water.ca.gov; jw64@drexel.edu; lwooten@geiconsultants.com; silva@alum.mit.edu; bea@ce.berkeley.edu; rstoresund@earthlink.net; stanaka@pwri.go.jp; j.battjes@ct.tudelft.nl; rad@jhu.edu; inamine@water.ca.gov; george.l.sills@erdc.usace.army.mil; jheadland@moffatnichol.com; zimmit@rpi.edu; pestana@ce.berkeley.edu; michael.d.ramsbotham@usace.army.mil; wolff@egr.msu.edu; lroth@asce.org; jdurrant@asce.org

Subject: Re: New Orleans Levees: Thanks, Debreifing Notes, and Potential Current Concerns

Ladies and Gentlemen,

I am writing this memorandum to formally thank everyone for their assistance in successfully consummating the initial two weeks of field studies for the NSF and ASCE levee investigation field teams. The collaboration and support provided by Dr. Paul Mlakar and his ERDC team was first rate, and we are all deeply grateful.

The attachment is a set of notes prepared by Dr. Les Harder summarizing the debriefing from the NSF and ASCE team members to the USACE near the end of the second week (on Thursday, October 13.) There are a number of excellent observations and also some recommendations with regard to moving forward with repair and rehabilitation of the damaged flood control system. These were prepared by the outgoing "Week 2" team. I have been through them, and they are very good ideas.

We were grateful for the explanation of the plans for going forward with the repairs to the 17th Street and London Canal breach sections. The Corps should be commended for their rapid responses at these sites, and the situations at each site appear to be improving.

Since our first week's team departed, additional buttressing fill has been placed at the inboard side of the emergency embankment section at the 17th Street breach, resulting in an inboard face with a series of benches at roughly 6-foot vertical intervals. Following this work, minor longitudinal cracking was noted along the crest on Thursday, October 13th. This cracking may well have been the result of differential settlement of the berm fill, which was a recent load and which extends well inboard of the original levee toe (and so represents new loading.) In this case it may have been relatively benign. There was no vertical offset across the cracks, only purely tensile opening, in both the initial crest crack and the narrower crack that appeared near the top of the inboard face the next day. While the cracking quite likely was related to differential settlement of the new fill, landside sliding towards the scour area could not be ruled out. As a result, the NSF/ASCE teams recommended that the landside scour area be immediately filled in.

The Corps apparently took this recommendation very seriously and responded immediately by filling in most of the deep scour area and constructing a landside buttress over the scour pit. The new buttress was approximately 100 feet by 100 feet. This buttressing was accomplished by the end of the day on Friday, less than 24 hours after the teams' recommendation was given, and thus should be regarded as extremely responsive and commendable. The cracking observed may also, however, exacerbate internal seepage issues and so should be further remediated as discussed in the next paragraph.

We understand that the next stage plans for the section include a row of sheetpiles on the waterside, and a 4:1 fill on the inboard face. Our team(s) recommend placement of the remaining inboard fill ASAP, as this will further enhance stability of the section. Clearing of slide debris, tree stumps, and old building foundations so that the inboard berming can be extended along the full length of the breach repair section, and the placement of this additional berm fill, should also be done as quickly as practicable.

The cover fill of cohesive material placed (mainly on the waterside) since our initial (Week #1) team's departure at the North and South London Avenue Canal breach sections looks like an improvement. I understand that flow has been significantly reduced at the 17th Street and London North breach repairs, but that significant flow (on the order of about 10 to 15 cfs) continues at the London South breach repair section.

When sheetpiles are next installed along these sections, it is important that they overlap the existing sheetpile/floodwall sections sufficiently to mitigate flow through the ends of the repair sections. It is also important that the new sheetpiles extend more deeply into the foundation soils than the original piles so as to more effectively cut off flow through pervious soils beneath these sections. That appears to be especially important at the two London Avenue Canal sites, where pervious sands appear to occur in the foundation with a relatively thin overlying cap of peaty and/or organic soils.

Our Week #2 team(s) did not have an opportunity to spend much time at the two large breaches at the west side of the Ninth Ward (at the Industrial Canal), but as the outboard water levels are currently relatively low at these two locations there is less to be observed here.

Potentially Urgent Issues:

1. With the season's next named storm (Wilma) now forming, it is prudent to look at the ability of the major breach repair sections to withstand high-water conditions. The three canal breach repair sections (17th Street, London North, and London South) are all more stable than last week, but with the open-graded stone layers occurring only a few feet above mean canal levels they would be potentially hydraulically fragile if water within the canals was to rise significantly due to storm surge. Continued use of the sheetpile cutoffs at the north ends of the canals as "gates" to retard storm surges would be adviseable.
2. The "distressed" section on the east side of the London Avenue Canal North breach has not yet been remediated. This section shows clear evidence of piping erosion, as well as some evidence of lateral softening and/or minor lateral movement. Immediately buttressing this section, both at the inboard face of the levee and at the inboard side of the toe of the concrete floodwall, would be a relatively quick and inexpensive action that would enhance short-term stability until more extensive repairs can be made.
3. The two large breach repairs at the west edges of the Ninth Ward (on the Industrial Canal) both appear to have unfiltered, open-graded sections within the closure embankment sections. Unlike the Canal breaches, there is no possibility of controlling storm surge rises at these sections, so further action may be urgently warranted here. Additional berming of the inboard sides can only help these sections, and any such activity would further enhance their stability. Wilma is currently projected to hook north towards western Florida, but it is early yet and forecasts of this sort can change. There is still time to further improve these two important closure sections, and taking fullest possible advantage of that opportunity is recommended.
4. We understand that bid documents for the next phases of work on the 5 major closure sections discussed above have been issued, and that these include plan and section drawings as well as

available local boring logs. We have seen a set of these for the 17th Street Canal closure, but do not yet have copies of our own. Can Paul's group, or someone, please send us a full set of these drawings and logs for the five large closure sections at 17th Street, London Avenue North, London Avenue South, and the 2 Ninth Ward breaches on the Industrial Canal?

It would be adviseable to pass along these observations to the geotechnical firms now being retained to oversee further repairs at these sites. It might also be a good idea to ask them to contact us if they have any questions. We would also like to contact them, so that we can follow further progress at these sites.

Finally, in looking through all the observations and recommendations summarized in Dr. Harder's excellent debriefing summary, Les and I picked the following several as worthy of a bit of extra emphasis:

- The sheetpiles proposed for the emergency closure sections should overlap the ends of the intact sections considerably, have connection/treatment details to prevent lateral seepage around the ends, and should extend much deeper than the original sheetpiles to more effectively cut off underflow.
- Corps or contracted inspectors should be employed for construction and performance monitoring of interim repairs. Significant variations in levels of performance of both earthwork and site preparation were observed by our people in the field, and inspection was not present at all sites.
- Monitoring of breach closure movements and seepage at critical sites should be a high priority, along with proper construction/fill placement.
- The Corps routinely employs independent Boards of Consultants when dealing with issues associated with safety of large dams. The flood control system of the greater New Orleans area protects at least as many lives, and as much property, as most large dams, and it would seem appropriate to retain a Board of Consultants (or similar) to assist in oversight of the repair and rebuilding efforts.

It has been a busy couple of weeks, and I'm sure we're all a bit overwhelmed with all that we've observed, measured and recorded. It will take us a while to get our hands around all of this, even in a preliminary way, and it is likely that more insight will evolve as we progress. We will also continue to study this, and will be grateful for the background documents, etc. that we have discussed with Dr. Mlakar and his team, as well as the results of ongoing field and lab programs, etc. as these become available.

We hope our teams were also a bit helpful as your own team's investigations now move forward, and we deeply appreciate the opportunity to have been onsite with such excellent colleagues.

We will stay in touch, as all teams will continue to have much data, etc. to cross-transfer as everyone moves forward. I am impressed by the open sharing of data achieved to date, and hope that we can keep this up. In the meantime, if anyone has any questions, please feel free to let me know at any time. I can be reached by return E-mail at Rmseed6@aol.com, on my cell phone at (925)899-6101, or on my home/office phone at (925)930-8692.

Best regards to all,

Ray Seed

Summary of Preliminary Comments, Findings, and Recommendations Regarding Levee Performance Following Hurricane Katrina

Presented Jointly by the Second Groups of the National Science Foundation and the American Society of Engineers Teams Formed to Investigate the Levee Performance Following Hurricane Katrina

October 13, 2005

The following is a summary of preliminary comments, findings, and recommendations regarding levee performance that was presented jointly by the second groups of the NSF and ASCE Teams to members of the team from the United States Army Engineer Research and Development Center, headed by Dr. Paul Mlakar. The summary was part of a team debriefing held in the Hotel Le Pavillon at 6 p.m. on October 13, 2005. The following points were discussed:

1. The NSF and ASCE teams want to express their deepest thanks and appreciation to the ERDC team, and to the Corps of Engineers in general, for providing assistance, tours, explanations, and written information. This greatly assisted team members in inspecting various levees and in understanding their performance. ERDC team members were extremely diligent in making the Corps operations as transparent as possible, and we believe that no information was being held back. The NSF and ASCE teams very much appreciate the long hours that various ERDC/Corps personnel put in to assist us.

2. The second groups of the NSF and ASCE teams were able to examine literally dozens of levee breaks and reaches of levee distress:

    - Most of the levee breaks and levee distress appeared to be related to water levels higher than the I-walls or embankments, and thus may be related to loadings above what these structures were designed for. Levee failures and/or distress in this category would include the following:

        - Significant overtopping of I-walls leading to landside toe scour that resulted in passive pressure failure, piping, or a combination of these two mechanisms.

        - Piping beneath I-walls without landside toe scour.

        - Significant overtopping of earth embankments, notably sandy embankments, resulting in significant scour and erosion, particularly at transitions between embankments and I-walls.

- Three levee failures appear to be not related to overtopping or landside toe scour: 17th Street Canal, London Canal North, and London Canal South. There are no landside toe scour trenches and water levels in these two canals apparently never reached the tops of the I-walls. The failure mechanisms at these three sites appear to be related to:

  - Slope instability caused by sliding on weak peaty organic soils or clays within the marsh foundation. This mechanism seems to be plausible for the 17th Street Canal levee failure.

  - Piping and/or passive pressure failure caused by high pore pressures in foundation sand layers with relatively thin surface caps of marsh soil. This mechanism seems to be plausible for the London Canal North and London Canal South sites.

3. In hindsight, there seemed to be several lessons learned:

   - When storm/flood loadings exceeding the capacities of the I-walls, brittle failures resulted. If scour protection for overtopping had been provided at the base of the landside toes of the walls (e.g. concrete slab, riprap, articulated blocks), many of the levee failures might have been prevented. This would probably have added only a few percent to the overall original cost of the project, but would have resulted in significant benefits.

   - There were several cases of inconsistent elevations of I-walls and embankments at transitions. If all of the flood protection was at the same level, some of the levee failures or distress might have been avoided.

   - It is clear that right-of-way limitations constrained many of the design options.

4. The following recommendations for levee repairs were suggested:

   - It is understood that new sheetpile walls are planned to cutoff seepage at the various levee repair sites. The sheetpiles must be deep enough to cut off seepage through both the original pervious material, but also through the pervious sand and rock materials placed in the scour holes.

   - The sheetpile cutoffs must also extend significantly beyond the ends of each breach section in order to lengthen the seepage path around the sheetpile where it overlaps the original, shorter length piles beneath the I-walls. Additional seepage protection at the overlaps should also be considered.

- Settlement and monitoring of cracking, where present, should also be made at the breach closures.

- Breach closures where there is significant seepage (e.g. London Canal North, London Canal South, 17th Street Canal) should have weirs or other measuring devices installed to collect and monitor seepage. The amounts of seepage should be plotted against canal water elevation to help determine if things are getting better or worse, particularly before and after new fill or sheetpiles are added.

- There are particular concerns involving the breach closure at the 17th Street Canal levee failure. Earlier on Thursday, October 13th, team members observed a small, longitudinal tension crack near the crest at the south end of the breach. This crack was approximately an eighth to a quarter of an inch wide and ran approximately 100 feet. While it might be related to differential settlement of the new fill, it might also be related to potential sliding movement of the new fill. Since there are indications that sliding on soft soil was responsible for the failure at this location, this can't be ruled out. In addition, portions of the scour hole landward of the new fill remain. Accordingly, it is recommended that the scour pond be immediately filled in. According to ERDC team members, the interim/final repair calls for filling in this hole, so the sooner it is done, the better.

- For the present time, we recommend that the emergency fills placed for the more critical breach closures be inspected on a 24-hour basis until additional repairs and/or performance information are evaluated.

- An emergency response plan should be developed to address potential distress of the breach closures. Such a plan should include phone trees, pre-positioned stockpiles of earth and rock, as well as equipment to move them quickly.

- For some of the canal breach repairs, plans call for building out into the canal. Hydraulic analyses should be conducted to evaluate if this significantly affects the conveyance capacity of the canal, or if this could result in any scour of the canal slopes in these locations.

- There is an overwhelming amount of construction work being initiated to fill in levee breaches in many areas throughout the flood control system. In some areas, the work appears to be done mainly by equipment operators without contractor foremen or Corps inspectors being present. We believe that Corps inspectors should be at all levee repair sites to provide adequate quality control and quality assurance.

  In some levee breach areas, it appears that equipment operators have bulldozed soil back into scour holes without first removing debris, removing loose material washed in, appropriately cutting back loose material on the breach_abutments, or providing appropriate compaction of the new fill. In these areas, choices need to be made as to ripping out this new fill and replacing it with appropriately constructed material, or compensating by making the section much wider or driving sheetpiles to length the seepage path.

- There are many miles where the I-walls were overtopped and scour trenches were eroded out at the landside toe. These trenches need to be cleared of debris and loose material and replaced with compacted soil. Consideration should be given to armoring the landside toe with concrete slabs, articulated concrete blocks, or riprap.

- There needs to be an overall examination of the levee system on a system-wide basis. This will require assembling a tremendous amount of information and looking for weaknesses of the system (e.g. inconsistent I-wall/levee elevations, transitions, etc.).

- Consideration should be given to retaining at least some of the sheetpiles placed against bridges across London and 17th Street Canals near Lake Pontchartrain. These sheetpiles were placed to help reduce/prevent surges from coming down the canals. Until the levees in these canals are repaired and/or more permanent check structures are placed, having the ability to rapidly prevent storm surges down the canals is still needed.

- The Corps of Engineers, like other public agencies, commonly uses Independent Boards of Consultants to review the adequacy of the design and construction of major dams. The levee system in New Orleans actually protects more life and property than almost any other major dam in the United States. Accordingly, we believe that the Corps should retain an Independent Board of Consultants to review the adequacy of the interim and permanent levee repairs being carried out in the aftermath of Katrina.

5. There were some significant successes in the levee system that are worth noting:

   - Clay levees covered with grass successfully withstood significant overtopping.

   - The rubber waterstop within the joints of the concrete I-wall sections appeared to be well-constructed and still quite flexible after several decades.

   - The hot-rolled sheetpile interlocks performed very well – even in the failed sections along the Industrial Canal where the sheetpiles were tossed around like bands of ribbons in the water flow. Even in these areas, the interlocks held together very well.

6. It is unclear what methods, criteria, and factors of safety were used to design the I-walls. The design methodology and criteria should be produced and then evaluated to determine if a system-wide review is needed.

Second Group of NSF and ASCE Teams:

Gordon Boutwell	ASCE
Thomas Wolff	ASCE
Les Harder	NSF
Mike Inamine	NSF
Juan Pestana	NSF
Rebecca Kuhr	NSF
Thomas Zimmie	NSF

ERDC Team Members Present:

Paul Mlakar
George Sills
Donald Yule
Joe Dunbar
Robert Ebeling
Kevin Abraham
Reed Masher

Also Present:

Ken Klaus COE-MVD

Preliminary Report on the Performance of the New Orleans Levee Systems in Hurricane Katrina on August 29, 2005

by

R.B. Seed, P.G. Nicholson, R.A. Dalrymple, J.A. Battjes, R.G. Bea, G.P. Boutwell, J.D. Bray, B.D. Collins, L.F. Harder, J.R. Headland, M.S. Inamine, R.E. Kayen, R.A. Kuhr, J. M. Pestana, F. Silva-Tulla, R. Storesund, S. Tanaka, J. Wartman, T.F. Wolff, R.L. Wooten and T.F. Zimmie

Preliminary findings from field investigations and associated studies performed by teams from the University of California at Berkeley and the American Society of Civil Engineers, as well as a number of cooperating engineers and scientists, shortly after the hurricane.

Report No. UCB/CITRIS – 05/01
November 17, 2005

NSF Berkeley Engineering ASCE GEO INSTITUTE

This project was supported, in part, by the National Science Foundation under Grant No. CMS-0413327.
Any opinions, findings, and conclusions or recommendations expressed in this report are those of the author(s) and do not necessarily reflect the views of the Foundation.

This report contains the observations and findings of a joint investigation between independent teams of professional engineers with a wide array of expertise. The materials contained herein are the observations and professional opinions of these individuals, and does not necessarily reflect the opinions or endorsement of ASCE or any other group or agency.

Ver. 1.2

This report has been slightly modified from its original version, which was issued on November 2, 2005 in response to a deadline for testimony before the U.S. Senate Committee on Homeland Security and Government Oversight. The minor revisions are not substantive in nature, and serve principally to improve the accuracy of the language and the clarity of some of the statements. No significant changes in the technical content or findings have been made in this second iteration.

List of Authors

Jurjen A. Battjes, Ph.D., Emeritus Professor in Fluid Mechanics, Delft University of Technology, Delft, The Netherlands

Robert G. Bea, Ph.D., P.E., G.E., S.E., Professor, Civil & Environmental Engineering, University of California, Berkeley, CA

Gordon P. Boutwell, Ph.D.,P.E., President, Soil Testing Engineers, Inc., Baton Rouge & New Orleans, LA

Jonathan D. Bray, Ph.D., P.E., Professor, Civil & Environmental Engineering, University of California, Berkeley, CA

Brian D. Collins, Ph.D., P.E., Research Civil Engineer, United States Geological Survey, Menlo Park, CA

Robert A. Dalrymple, Ph.D., P.E., Professor, Civil Engineering, Johns Hopkins University, Baltimore, MA

Leslie F. Harder. Jr., Ph.D., Acting Deputy Director for Public Safety, California Department of Water Resources, Sacramento, CA

John R. Headland, P.E., Senior Vice President, Moffatt & Nichol Engineers

Michael S. Inamine, P.E., Construction Office Chief, Division of Engineering, California Department of Water Resources, Sacramento, CA

Robert E. Kayen, Ph.D., P.E., Research Civil Engineer, United States Geological Survey, Menlo Park, CA

Rebecca A. Kuhr, P.E., P.G., Senior Project Manager, Water Resources Engineering, HNTB Corporation, Kansas City, MO

Peter G. Nicholson, Ph.D., P.E., Associate Professor & Graduate Chair, Civil & Environmental Engineering, University of Hawaii, Manoa, HI

Juan M. Pestana, Ph.D., P.E., Associate Professor, Civil & Environmental Engineering, University of California, Berkeley, CA

Raymond B. Seed, Ph.D., Professor, Civil & Environmental Engineering, University of California, Berkeley, CA

Francisco Silva-Tulla, Sc.D., P.E., Consulting Civil Engineer, GeoEngineering and Environment, Lexington, MA

List of Authors (Continued)

Rune Storesund, P.E., Consulting Engineer, Storesund Consulting, Albany, CA

Shigenobu Tanaka, Principal Research Engineer, Secretariat for Preparatory Activities of the UNESCO-PWRI Centre, Japan

Joseph Wartman, Ph.D., P.E., Assistant Professor, Civil, Architectural & Environmental Engineering,
Drexel University, Philadelphia, PA

Thomas F. Wolff, Ph.D., P.E., Associate Dean for Undergraduate Studies, College of Engineering,
Michigan State University, East Lansing, MI

R. Lee Wooten, P.E., Vice President, GEI Consultants, Inc., Winchester, MA

Thomas F. Zimmie, Ph.D., P.E., Professor, Civil, Environmental & Geotechnical Engineering, Rensselaer Polytechnic Institute, Troy, NY

Table of Contents

Cover Image from http://www.noaanews.noaa.gov/stories2005/s2506.htm

EXECUTIVE SUMMARY

This report presents the results of field investigations performed by several teams of engineers and scientists in the wake of the passage of Hurricane Katrina to study the performance of the regional flood protection systems in the New Orleans area. The principal focus of these efforts was to capture perishable data and observations related to the performance of flood control systems.

The initial field investigations occurred over a span of approximately two and a half weeks, from September 28 through October 15, 2005. The starting date for these field investigations was determined by balancing the need to gather vital perishable data before it was damaged or obscured by emergency repair operations versus the need to avoid interference with such emergency operations, and issues associated with safe access, logistics, etc. There were numerous occasions when team units arrived and investigated sites only days, or even hours, prior to the covering of vital information by ongoing emergency repair activities.

The storm surges produced by Hurricane Katrina resulted in numerous breaches and consequent flooding of approximately 75% of the metropolitan areas of New Orleans. Most of the levee and floodwall failures were caused by overtopping, as the storm surge rose over the tops of the levees and/or their floodwalls and produced erosion/scour that subsequently led to failures and breaches.

Overtopping was most severe on the east side of the flood protection system, as the waters of Lake Borgne were driven west towards New Orleans, and also farther to the south, along the lower reaches of the Mississippi River. Significant overtopping and erosion produced numerous breaches in these areas. The magnitude of overtopping was less severe along the Inner Harbor Navigation Canal (IHNC) and along the western portion of the Mississippi River Gulf Outlet (MRGO) channel, but this overtopping again produced erosion and caused additional levee failures.

Field observations suggest that little or no overtopping occurred along most of the levees fronting Lake Pontchartrain, but evidence of minor overtopping and/or wave splashover was observed at a number of locations. There was a breach in the levee system at the northwest corner of the New Orleans East protected area, near the Lakeside Airport.

Farther to the west, in the Orleans East Bank Canal District, three levee failures occurred along the banks of the 17th Street and London Avenue Canals. Evidence that we observed indicates that these failures occurred when water levels were below the tops of the floodwalls lining these canals. Based on our observations, we believe that these three levee failures were likely caused by failures in the foundation soils underlying the levees. In addition, we observed lateral displacements, sinkholes, and sand boils indicative of an incipient breach at a fourth distressed levee/floodwall segment on the London Avenue Canal.

This report presents an overview of initial observations and findings regarding the performance of the New Orleans flood protection system, including observations regarding preliminary assessments of likely causes of failures and/or significant damage to levees and floodwalls at many sites. Although most of the failures/breaches that occurred were primarily due to overtopping and subsequent erosion, three major and costly breaches appear to have been the result of stability failures of the foundation soils and/or the earthen levee embankments themselves. In addition, it appears that many of the levees and floodwalls that failed due to overtopping might have performed better if conceptually simple details had been added and/or altered during their original design and construction.

Major repair and rehabilitation efforts are now underway to prepare the New Orleans flood protection system for future high water events. The next hurricane season will begin in June of 2006. Based on our observations, a number of initial comments are warranted concerning the rebuilding and rehabilitation of the levee system, and this preliminary report makes a number of observations and recommendations regarding ongoing flood system repair efforts. Preparing the levees for the next hurricane season should also include a review of how the system performed during Hurricane Katrina, so that key lessons can be learned and then used to improve the performance of the system.

There are ongoing studies of the performance of the flood protection system in this catastrophic event, as well as efforts to improve the levels of reliability and safety of these types of defenses for the future. We hope that the results of these studies will lead to a clear appreciation of what happened in Katrina, and that the lessons learned from this event will lead to improved protection in the future, not just in the New Orleans area, but throughout the nation and around the world.

Chapter One: Introduction and Overview

1.1 Introduction

This report presents the results of field investigations performed by collaborating teams of scientists and engineers in the wake of the passage of Hurricane Katrina to study performance of the regional flood protection systems and the resulting flooding that occurred in the New Orleans area. The principal focus of these efforts was to capture perishable data and observations related to the performance of flood control systems before they were lost to ongoing emergency response and repair operations.

Several independent investigation teams jointly pooled their efforts in order to capture as much data as possible in the precious timeframe available. The participating teams were an NSF-sponsored team led by the University of California at Berkeley, a team from the American Society of Civil Engineers (ASCE) organized by its Geo-Institute and its Coasts, Oceans, Ports, and Rivers Institute. A team from Louisiana State University's Hurricane Research Center (LSU/HRC) also accompanied the field investigation teams during their first week of investigations. These teams were accompanied and assisted in the field by members of the U.S. Army Corps of Engineers (USACE) levee investigation team from the Engineering Research and Development Center (ERDC). All of these investigative teams shared data and findings freely and openly, and the mutual pooling of talents and expertise greatly benefited all as it enabled the field teams to gather more data in the critical days available.

The initial field investigations occurred over a span of approximately two and a half weeks time. Initial scouts from the USACE/ERDC team and the ASCE G-I team arrived onsite on September 26 and 28, respectively. Four members each from the NSF-sponsored, ASCE G-I and ASCE COPRI teams then worked as a combined 12-person team from October 1 - 8, 2005, and a second group consisting of two more ASCE G-I team members and five more NSF-sponsored team members worked the next week from October 8 - 15, 2005. The NSF and ASCE teams were accompanied in the field, and supported logistically, by members of the USACE/ERDC investigation team. Members of the LSU/HRC team also accompanied the main field teams and provided important insights regarding water levels, storm surge projections, etc.

The starting date for these field investigations was determined by balancing the need to gather vital ephemeral data before it was lost or obscured due to emergency repair and response operations versus the need to avoid interference with such emergency operations and issues associated with safe access, logistics, etc. It was fortunate that the main teams arrived when they did, as there were numerous occasions when team units arrived and investigated sites only days, or even hours, prior to the covering of vital information by ongoing emergency repair activities. At a number of sites, observations made were sufficient to make preliminary determinations of mechanisms of failure, while only a day later the burial of key evidence at these same sites would have rendered even eventual identification of the potential causes of failure highly unlikely. The field investigation teams are very grateful for the unusual opportunity to have been granted free and unobstructed access to all sites in spite of ongoing emergency reconstruction and repair activities.

1.2 Hurricane Katrina

The path of Hurricane Katrina's eye is shown in Figures 1.1 and 1.2. Hurricane Katrina crossed the Florida peninsula on August 25, 2005 as a Category 1 hurricane. It then entered the Gulf of Mexico, where it gathered energy from the warm Gulf waters, producing a hurricane that eventually reached Category 5 status on Sunday, August 28, shortly before making its second mainland landfall just to the east of New Orleans on Monday, August 29, as shown in Figure 1.2. The Hurricane had weakened to a Category 4 level prior to landfall on the morning of August 29.

Because the eye of this hurricane passed just slightly to the east of New Orleans, the hurricane imposed unusually severe wind loads and storm surges (and waves) on the New Orleans region and its flood protection systems.

1.3 Overview of the New Orleans Flood Protection Systems

Figure 1.3 shows the general study region. The City of New Orleans is largely situated between the Mississippi River, which passes along the southern edge of the main portion of the city, and Lake Pontchartrain, which fronts the city to the north. Lake Borgne lies to the east, separated from developed areas by open swampland. "Lake" Borgne is directly connected to the waters of the Gulf of Mexico. To the southeast of the city, the Mississippi River bends to the south and flows out through its delta into the Gulf of Mexico.

The flood protection system that protects the New Orleans region is organized as a series of protected basins or "polders", each protected by its own perimeter levee system, and these are dewatered by pumps. Polder is the Dutch word for a contiguous land unit protected by a perimeter levee system, and it is an appropriate term here.

As shown in Figures 1.4 and 1.5, there are four main polders, or protected areas, that comprise the New Orleans flood protection system. A number of smaller levee-protected units also exist in this area, but the focus of these current studies is the four main protected areas which were largely constructed under the supervision of the U.S. Army Corps of Engineers. Figures 1.4 and 1.5 show the locations of most of the levee breaches and severely distressed (but non-breached) levee sections covered by these studies. Levee breaches are shown with solid blue stars, and distressed sections as well as minor or partial breaches are indicated by red stars. The original base maps, and many of the stars, were graciously provided by the USACE (2005), and additional stars have been added to the map in Figure 1.4 as a result of the field studies reported herein. We understand that the yellow stars correspond to deliberate breaches made to facilitate draining the flooded areas after the storm.

As shown in Figure 1.4, the Orleans East Bank section is one polder. This protected unit contains the downtown district, the French Quarter, and the Garden District. The northern edge of this polder is fronted by Lake Pontchartrain on the north, and the Mississippi River passes along its southern edge. The Inner Harbor Navigation Canal (also locally known as "the Industrial Canal") passes along the east flank of this polder, separating the Orleans East Bank polder from New Orleans East (to the northeast) and from the Ninth Ward and St. Bernard Parish (directly to the east.) Three large drainage canals extend into the Orleans East Bank polder from Lake Pontchartrain to the north, for the purpose of conveying water pumped north into the lake by large pump stations within the city. These canals, from west to east, are the 17th Street Canal, the Orleans Canal, and the London Avenue Canal.

A second polder surrounds and protects New Orleans East, as shown in Figure 1.4. This polder fronts Lake Pontchartrain along its north edge, and the Inner Harbor Navigation Canal along its west flank. The southern edge is fronted by the Mississippi River Gulf Outlet channel (MRGO) which co-exists with the Gulf Intracoastal Waterway (IWW) along this stretch. The eastern portion of this polder is currently largely undeveloped swampland, contained within the protective levee ring. The east flank of this polder is fronted by additional swampland, and Lake Borgne is located slightly to the southeast.

The third main polder contains both the Ninth Ward and St. Bernard Parish, as shown in Figure 1.4. This polder is also fronted by the Inner Harbor Navigational Canal on its west flank, and has the MRGO/IWW channel along its northern edge. At the northeastern corner, the MRGO bends to the south (away from the GIWW channel) and forms the boundary at the northeastern edge. Open swampland occurs to the south and southeast. Lake Borgne occurs to the east, separated from this polder by the MRGO channel and a narrow strip of undeveloped marshland. The main urban areas occur within the southern and western portions of this polder. The fairly densely populated Ninth Ward is located at the west end, and St. Bernard Parish along approximately the southern half of this polder. The northeastern portion of this polder is undeveloped marshy wetland, contained within the protected polder in anticipation of future development. A secondary levee, operated and maintained by local levee boards, separates the undeveloped marshlands of the northeastern portions of this polder from the Ninth Ward and St. Bernard Parish metropolitan areas.

The fourth main polder is a narrow, protected strip along the Mississippi River heading south from St. Bernard Parish to the mouth of the river at the Gulf of Mexico, as shown in Figure 1.5. This protected strip, with levees fronting the Mississippi River and a second side of levees facing away from the river forming a protected strip less than a mile wide, serves to protect a number of small communities as well as utilities and pipelines. This protected corridor also provides protected access for workers and supplies servicing the large offshore oil fields out in the Gulf. This levee-protected corridor will be referred to in this report as "the Plaquemines Parish" protected zone, or polder.

The current perimeter levee and floodwall defense systems for these four polders were largely designed and constructed under the supervision of the U.S. Army Corps of Engineers in the wake of the catastrophic flooding caused by Hurricane Betsy of 1965. The flood protection improvements typically involved raising existing levee defenses and adding new floodwalls.

1.4 Flood Protection System Performance During Hurricane Katrina

The regional flood protection system had been designed to safely withstand the storm surges and waves associated with the Standard Project Hurricane, which is intended to represent a scenario roughly "typical" of a rapidly moving Category 3 hurricane passing close to the New Orleans region. There is, however, no "typical" hurricane, nor associated storm surge, and the actual wind, wave and storm surge loadings imposed at any location within the overall flood protection system are a function of location relative to the storm, wind speed and direction, orientation of levees, local bodies of water, channel configurations, offshore contours, vegetative cover, etc. These loadings vary over time, as the storm moves through the region.

Figure 1.6 shows a plot of peak storm surge levels predicted by the LSU Hurricane Research Center on August 28, 2005, just a day before the arrival of Katrina. The water levels shown in Figure 1.6 were predicted using a numerical model for a point in time when the eye of the hurricane would pass slightly to the east of New Orleans. Predicted and actual storm surge heights varied over time, at different locations, and the water levels shown in Figure 1.6 do not represent predictions of the peak storm surges noted at all locations. Instead, this image shows predicted conditions at a point in time when a large surge was being driven west from Lake Borgne. These types of storm surge modeling calculations are being calibrated and updated based on actual field measurements of high water marks, etc.

It should be noted that a number of different datums have been used as elevation references throughout the historic development of the New Orleans regional levee systems, and this situation is further complicated by ongoing subsidence in the region. This investigation has not yet had time to adequately resolve differences between different datums, so all elevations stated in this preliminary report should be regarded as somewhat approximate, and should be taken as referring approximately to elevation with respect to NAVD 88 or "mean sea level" in the region.

Hurricane Katrina, as expected, produced a large onshore storm surge from the Gulf of Mexico. This produced significant overtopping of levees along the lower Mississippi reaches in the Plaquemines Parish area, and numerous levee breaches occurred in this area, as shown in Figure 1.5. It also raised water levels within Lake Borgne (which is directly connected to the Gulf.)

As the hurricane passed northwards to the east of New Orleans, the counterclockwise direction of the storm winds also produced a well-predicted storm surge southwards towards the south shore of Lake Pontchartrain. The lake level rose, but stayed below the crests of most of the lakefront levees. The lake rose approximately to the tops of the lakefront levees at a number of locations, especially along the shoreline of New Orleans East, and there was moderate overtopping (or at least storm wave splash-over) and some resulting erosion on the crests and inboard faces of some lakefront levee sections in this area. One lakefront levee breach occurred, near the west end of New Orleans east.

The largest storm surge, however, was produced by waters from Lake Borgne which had been raised by the onshore storm surge from the Gulf. As the storm passed to the west of New Orleans, the lake waters were driven west by the passing storm onto the east flank of the

New Orleans regional flood protection system (as shown in Figure 1.6.) This produced a storm surge estimated at approximately 18 to 25 feet, which rolled by about 5 to 10 feet over the levee protection system along the northeastern edge of the protected basin containing St. Bernard Parish and the Ninth Ward. Studies of timelines for both flooding and water levels are ongoing, and a number of investigating field groups are working at the time of this writing to better define peak water levels and storm surge timings. There is strong evidence for the massive overtopping of the levees along the northeast edge of the St. Bernard Parish/Ninth Ward polder, however, as a gate tender responsible for a lock gate along this frontage remained at his station throughout the storm. He retreated to his crow's nest lookout tower, and debris from the storm surge was recovered from well up this tower. The storm surge at his location rose at least 5 to 10 feet above the top of the levee system, matching well with current numerical modeling of storm surge at this location performed by several modeling groups.

The levees in this area, which were largely earthen levees constructed of relatively poor materials, were simply overwhelmed and were massively eroded. The floodwaters from this severe overtopping then flowed across the open, undeveloped swampland to the southwest and overtopped a lower set of levees separating the developed areas of this Polder from the largely undeveloped wetlands, producing a number of additional erosive breaches on this secondary levee system, as shown in Figure 1.4.

The combined storm surges from several directions produced storm surges along the Inner Harbor Navigation Canal (IHNC) and the MRGO channel, and these storm surges were sufficient to produce overtopping at a number of locations along both of these channels. This overtopping was less severe, however, than that which occurred along the east flank of the St. Bernard Parish polder, and many sections of the levee protection system that were overtopped along the IHNC and the MRGO channel survived without breaching. A number of breaches did occur along both the IHNC and the MRGO channel, however, and large areas of both New Orleans East and the Ninth Ward/St. Bernard Parish polder basins were flooded.

Farther to the west, the storm surge along the Pontchartrain lakefront did not produce water levels sufficiently high as to overtop the crests of the concrete floodwalls atop the earthen levees lining the three drainage canals that extend from north of downtown to Lake Pontchartrain; the 17th Street Canal, the Orleans Canal, and the London Avenue Canal. Three major breaches occurred along these canals, however, and these produced significant flooding of large areas within the Orleans East Bank polder (as shown in Figure 1.4)

The consequences of the flooding of major portions of all four levee-protected polders were catastrophic. Figure 1.7 shows inundation of the Ninth Ward adjacent to one of the major breaches in the levee along the IHNC. Numerous areas of greater New Orleans were similarly flooded, as shown in Figures 1.4 and 1.5. Large developed areas within all of the main polders were flooded, and they remained inundated for several weeks before levee breaches could be repaired and the waters pumped out.

Neighborhoods that were inundated exhibit stark evidence of this catastrophic flooding. Water marks, resembling oversized bathtub rings, line the sides of buildings and cars in these stricken neighborhoods, as shown in Figure 1.8. Household and commercial chemicals and solvents, as well as gasoline, mixed with the salty floodwaters in many neighborhoods, and at the time of this investigation's first field visits the paint on cars below the watermarks on adjacent buildings had been severely damaged, and bushes and shrubs were browned below the watermarks, but often starkly green above. Driving through neighborhoods that had been flooded, there was often the impression that one was viewing a television screen where the color of the picture was somehow distorted or altered below a horizontal line; the level at which the floodwaters had been ponded. The devastation in these neighborhoods, and its lateral extent across many miles of developed neighborhoods, was stunning even to the many experienced members of our forensic teams that had seen numerous devastating earthquakes, tidal waves, and other major disasters.

Close to major breaches, the hydraulic forces of the inflowing floodwaters often had devastating effect on the communities. Figure 1.9 shows the devastation immediately inboard from the large breach at the same Ninth Ward site shown previously in Figure 1.7, but in this case after the area had been unwatered. Note the numerous empty slabs where homes had been stripped away and scattered, mostly in pieces, across a large area.

Figure 1.10 shows another aspect of the flooding. This photograph shows a region within St. Bernard Parish in which numerous homes were floated and transported from their original locations by the floodwaters, and then deposited in new locations. Figure 1.11 shows a number of homes in the Plaquemines Parish polder that were carried across the narrow polder (from left to right in this photograph) as the west side (left side of photo) "hurricane levee" or back levee was breached, and were then nearly floated over the crest of the Mississippi River levee. The water side slope face of the Mississippi River levee is clearly shown in this photograph, as evinced by the concrete slope face protection on the outboard side of the riverfront levee in the right foreground of the figure.

Figures 1.12 and 1.13 show typical devastation within the stricken flooded areas. The spray painted markings on the sides of the buildings in these areas are left by search and rescue teams, and they denote a number of important findings within each dwelling, including toxic contamination, etc. The most important numbers are those centered at the base of the large "X", as this denoted the number of dead bodies found within the building. In most cases, as shown previously in Figure 1.8, this number was "0", but this was not always the case. Figure 1.14 shows the outside of a dwelling in the Ninth Ward with a "3" beneath the X, indicating three deaths within. This was a housing unit, and the wheelchair ramp from the front door is askew at the bottom of the photograph. Figure 1.15 shows the muddy devastation, and a wheelchair, within this flooded structure.

At the time of the writing of this preliminary report, the death toll has risen just past 1,000, with more than 700 of these deaths occurring in the State of Louisiana. Loss projections continue to evolve, but estimates of overall losses have now climbed to the $100 to $ 200 billion range.

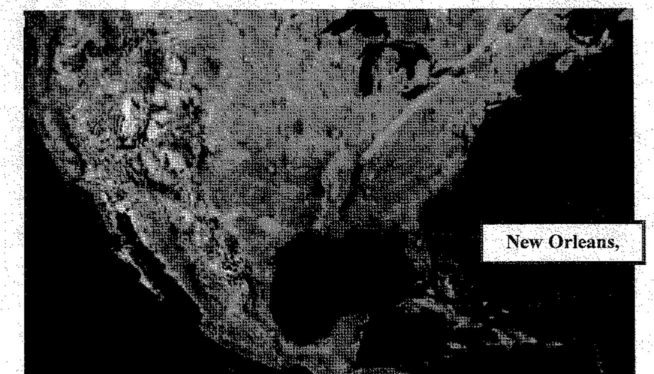
1.5 Organization of this Interim Report

The purpose of this interim report is to disseminate as much of the data and observations made during our initial site investigations as possible, for the mutual benefit of all research and investigation teams attempting to further study the performance of flood control systems in this event, and for the benefit of efforts to repair and rebuild the levee protective systems in preparation for the next hurricane season (which will begin in June of 2006.)

Considerable further studies are planned, and all observations reported should be considered as preliminary in nature, as further field studies, including borings and sampling, CPT probes, etc, as well as laboratory testing are anticipated in the months ahead. Considerable additional field work is also planned to further define high water levels to refine and field-calibrate numerical models of storm surges vs. time throughout the flood protection system. Background documentation, including site investigations, design calculations and design memoranda, as-built drawings, etc. have been requested at many sites of interest, and the U.S. Army Corps of Engineers (USACE) has agreed to provide all of these as quickly as time, and the still ongoing emergency repair operations, permit. As of the issuance of this report, the USACE had initiated posting of data online.

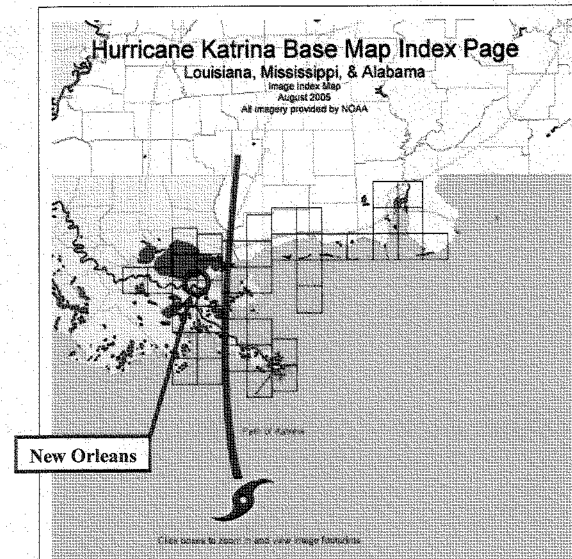
In addition, significant additional site investigations (including CPT probes, borings and sampling, etc.), as well as laboratory testing are already underway under the auspices of the USACE, and the USACE have agreed to openly share all resulting data with the various levee investigation teams currently studying this event.

Chapters 2 through 5 of this report present a summary of observations and preliminary findings to date associated with protective levee system performance in the (2) Orleans East Bank, (3) Ninth Ward/St. Bernard Parish, (4) New Orleans East, and (5) Plaquemines Parish protected areas, respectively. Chapter 6 briefly addresses observations regarding pumping and dewatering systems, and other aspects of the overall regional flood protection system. Chapter 7 describes LIDAR imagery data sets taken to capture three-dimensional representations of detailed ground surface conditions and configurations at a number of key sites. Finally, Chapter 8 summarizes a number of preliminary overall observations and recommendations.



Source: http://flhurricane.com/googlemap

Figure 1.1: Location of New Orleans, and map of the path of the eye of Hurricane Katrina.



Source: http://ngs.woc.noaa.gov/katrina/KATRINA0000.HTM

Figure 1.2: Traced path of the eye of Hurricane Katrina at landfall in the New Orleans area.

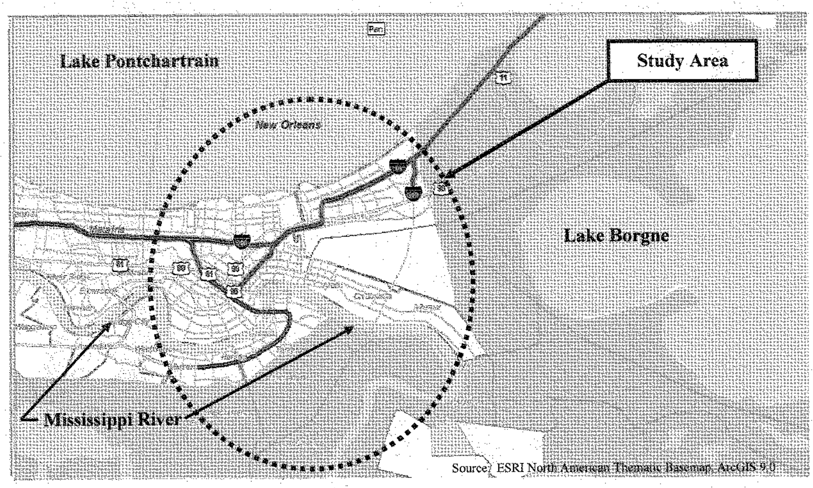


Figure 1.3: The Greater New Orleans Region Levee Performance Study Area.

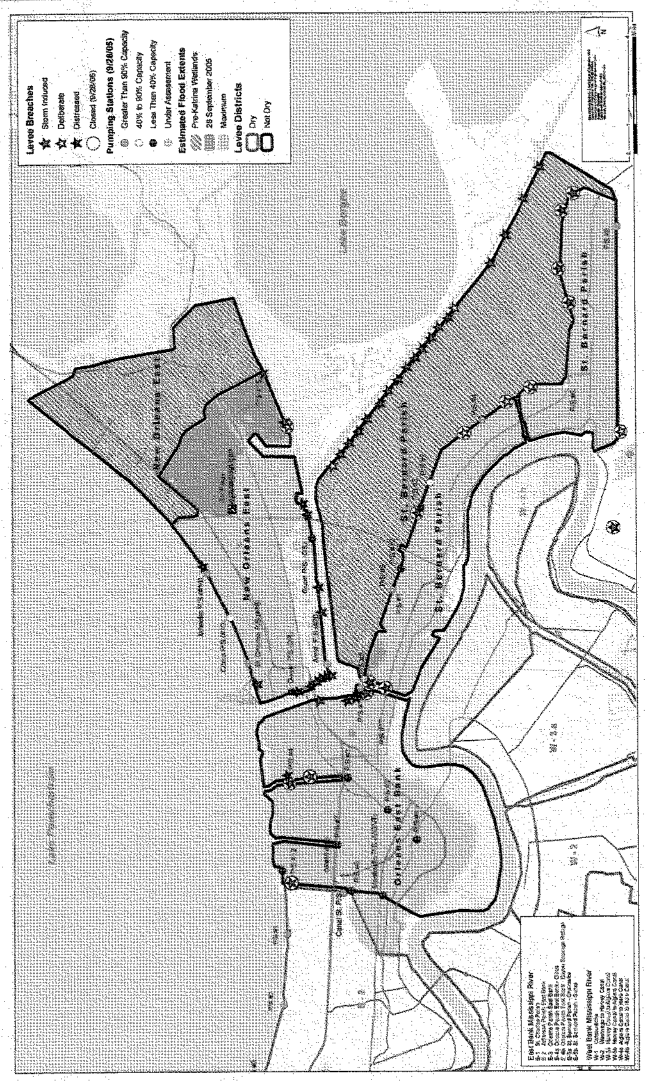


Figure 1.4: Map showing principal features of the main flood protection rings or "polders" in the New Orleans area. [Modified after USACE, 2005]

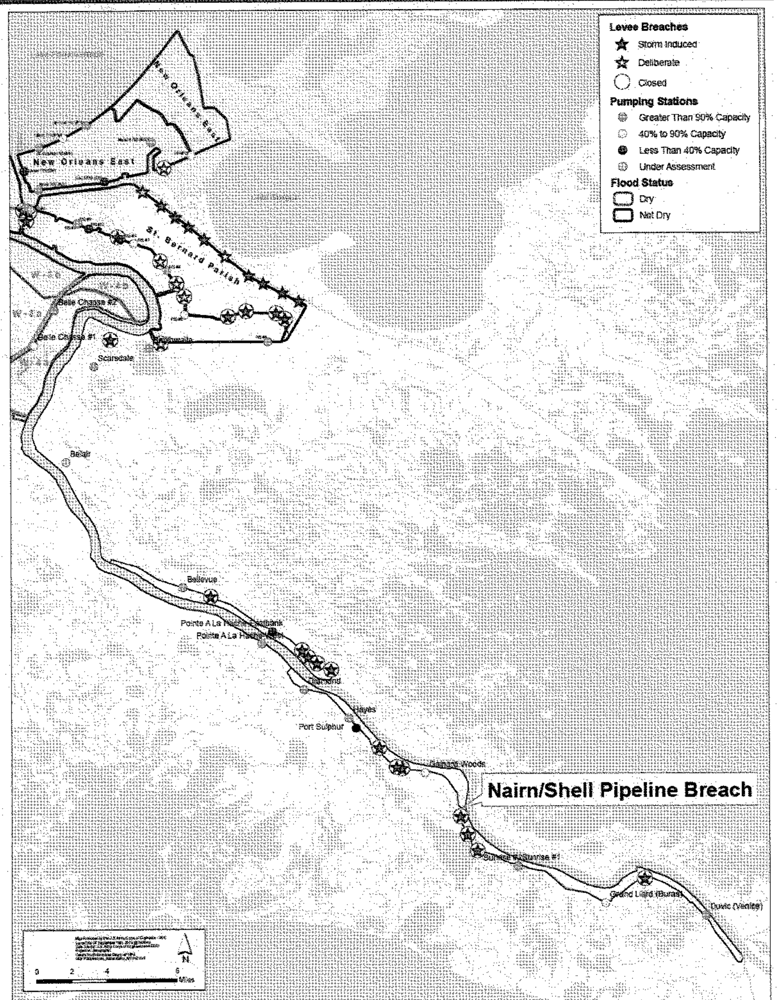
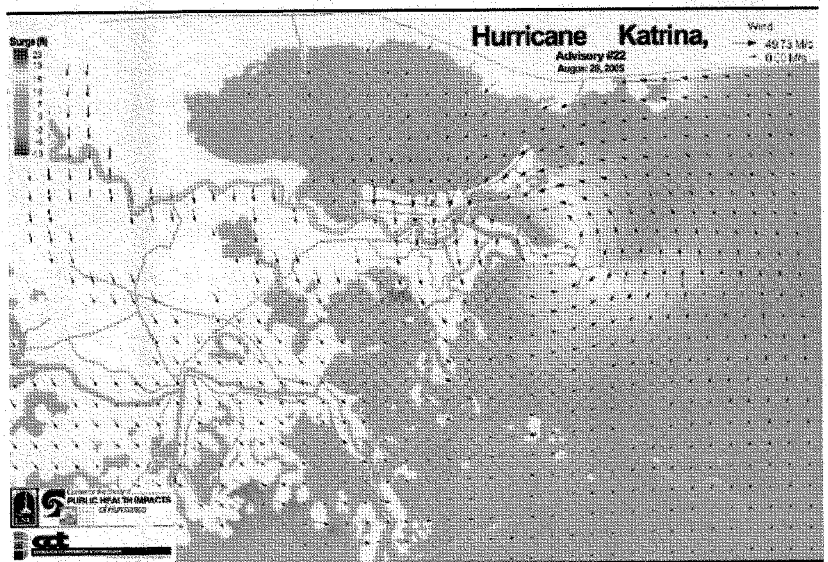


Figure 1.5: Map showing the levee protected areas along the lower reaches of the Mississippi River (in the Plaquemines Parish Area) [USACE, 2005]



Source: http://hurricane.lsu.edu/floodprediction/

Figure 1.6: Map of calculated storm surge levels, at time when the eye of the storm passed close to the east of New Orleans. [LSU Hurricane Research Center, 2005]

Figure 1.7: Flooding at the west end of the Ninth Ward, and outflow through levee breach as initial storm surge subsides.

Photograph by Rune Storesund

Figure 1.8: High water marks remain on structures after temporary levee repairs have been completed and flood waters have been pumped out.

Photograph by Les Harder [oct.14, 2005]

Figure 1.9: Oblique view of the (south) levee break at the Inner Harbor Navigation Canal into the lower Ninth Ward.

Photograph by Les Harder

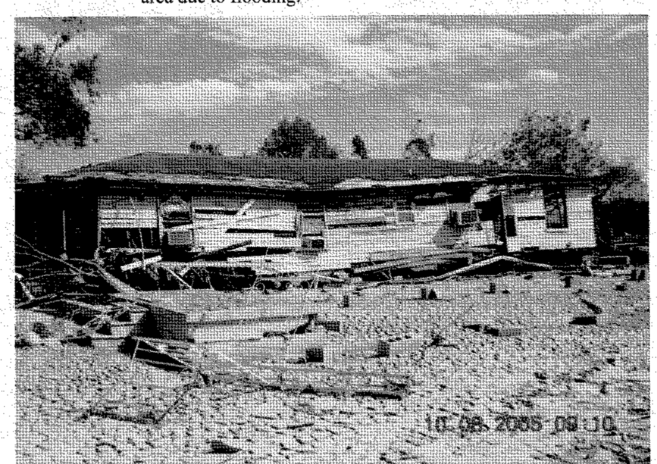
Figure 1.10: Flooded neighborhood in St. Bernard Parish, showing homes floated off their foundations and transported by floodwaters.

Photograph by Les Harder

Figure 1.11: Homes in Plaquemines Parish carried from left to right in photo and strewn across the crown of the Mississippi Riverfront levee.

Photograph by Rune Storesund

Figure 1.12: Damage to a residential neighborhood in the 17th Street Canal area due to flooding.



Photograph by Rune Storesund

Figure 1.13: Another view of flooding damage, this time in the lower Ninth Ward.

Photograph by Les Harder [Oct 10, 2005]

Figure 1.14: Search and rescue team markings on a building in the Ninth Ward where three inhabitants died.

Photograph by Les Harder [Oct. 10, 2005]

Figure 1.15: View inside structure shown previously in Figure 1.14.

Chapter Two: The Orleans East Bank (Downtown) Protected Area

2.1 Overview

The location of the Orleans East Bank protected section, or polder, was shown previously in Figure 1.4. This encompasses the main downtown area of New Orleans, as well as a number of famous historic districts including the French Quarter and the Garden District.

Figure 2.1(a) shows an enlarged view of the principal levees protecting the northern portion of this polder, in the "Canal" district. The small numbers in Figure 2.1(a) indicate the approximate elevations of the tops of the levees along the lakefront, and the tops of the floodwalls at the crests of the earthen levees along the three main drainage canals. As shown in this figure, the tops of the lakefront levees were generally on the order of elevation +17.5 to +18 feet, while the tops of the floodwalls along the sides of the three drainage canals were typically at elevations of about +13 to +15 feet.

The storm surge towards the south from Lake Pontchartrain drove both lake waters and waves against the lakefront levees. Best available field data, and numerical calculations of storm surge, at the time of this writing suggest that the lakefront storm surge in this area rose to about 11 feet, well below the crests of the lakefront levees in this area. No significant sustained overtopping occurred (only wave splashover at a few locations).

These levees were well-constructed earthen embankments, constructed using apparently cohesive soils, and they generally had good erosion protection on their outboard faces (generally consisting of large stone rip-rap.) These lakefront levees performed well, and despite some evidence of minor wave overtopping at a few locations, these lakefront levees safely withstood the storm with only minor evidence of any erosion at the crests and back faces evident after the storm had passed.

The three drainage canals traverse the canal district from south to north, as shown in Figures 1.4 and 2.1. These drainage canals serve as open channels to carry flow from large pumping stations at their southern ends northwards into Lake Pontchartrain. They are used to unwater the southern end of this protected polder. The three drainage canals have a slightly S-shaped entrance configuration at the lake end, so that wind driven waves at the Lake Pontchartrain lakefront will not be fully transmitted southwards into the canals. Accordingly, they also have slightly lower crest heights (at the tops of their floodwalls) than the Pontchartrain lakefront levees.

The levees along all three drainage canals consist of earthen embankments, topped by concrete floodwalls. The concrete floodwalls are mainly "I-walls", with the concrete wall section being cast atop a row of sheetpiles driven through the crest of the earthen embankment, as shown in Figure 2.2(a). These concrete walls get their stability by cantilever action as they and their sheetpiles are supported by the embankment soils. Some of the floodwalls along these canals appeared to be "T-walls", as shown in Figure 2.2(b). These wall sections also cap a sheetpile curtain, but they get additional rotational and lateral stability by nature of their broad concrete base (which forms an inverted "T".) They may also be founded on battered (inclined, reinforced concrete) bearing piles, which can provide significant additional rotational stability.

The three canals did not appear to have equally well-constructed and maintained levee and floodwall protection. The central canal, the Orleans Avenue Canal, generally had visibly wider soil embankment sections, and was also generally better maintained with regard to preventing growth of brush and trees on the land side slope faces.

The other two canals, the 17th Street Canal and the London Avenue Canal, generally had narrower embankments. Brush growth, and even trees, were noted at a number of locations on the land side faces of the levees along both of these canals.

A major breach occurred at the east bank of the 17th Street Canal, near the north end, as shown in Figure 1.4. This produced flooding over a significant area between the 17th Street and Orleans Avenue Canals.

Two additional major breaches occurred on the London Avenue Canal. As shown in Figure 2.1, one of these occurred near the north end of the London Avenue Canal, at the west bank levee, and this breach flooded a significant area between the London Avenue Canal and the Orleans Canal. In addition, significant "distress" occurred directly across the canal from this breach, along the eastern levee embankment and floodwall.

A second major breach occurred farther south along the east bank of the London Avenue Canal, as shown in Figure 1.4. This breach flooded a significant area east of the London Avenue Canal.

2.2 The 17th Street Canal Breach

Figure 2.3(a) shows the major breach at the east side of the 17th Street Canal as it is being "plugged" with large sandbags being delivered by military helicopters in the wake of Hurricane Katrina. This photo is taken looking to the northeast. Figure 2.3(b) shows the same figure, but this time highlighting key features for discussion. The line of grassy soil units in the center of the photo are the inboard half of the southern end of the original levee embankment, and the chain link fence is remnants of the fence that passed along the inboard lip of the crest road, separating the crest from adjacent homeowner's back yards. The southern end of the embankment has translated to the east, traveling laterally up to about 45 feet away from its original position. The northern end of the breached embankment section was largely eroded by scour after the breach opened.

Figure 2.4 shows a second view of some of the details at this site. The relatively intact southern embankment sections translated laterally approximately 45 feet, and without significant rotation, as the trees and chain link fence remained vertical throughout this displacement. The laterally translating wedge of embankment (and possibly also some foundation) soil "plowed" into soft soils at the inboard toe, causing them to bulge upwards, heaving the largely collapsed shed and pushing it into the house.

Figure 2.5 shows a view looking east across the zone through which the principal floodwaters flowed. Clearly evident in this photo are large blocks of peat scoured from the eroding foundation by the floodwaters.

Figure 2.6 shows an approximate plan view of this site, highlighting key locations and objects of interest. The overall breach was 465 feet in width at the end of the flooding and scour, and the intact embankments and floodwalls immediately to the north and south of the breached section were largely undamaged.

Figure 2.7 shows a simplified schematic cross-section through the site, roughly along Section A-A′ in Figure 2.6. This shows the lateral translation of the inboard portion of the embankment, and the compression and heaving produced at the inboard toe by these movements.

Foundation soils at this site were known to consist of a layer of organic, peaty material. The peats were interbedded with occasional thin, soft clayey layers, probably periodic overbank flood deposits, and one such clay layer within the peat unit was exposed at the southern end of the breach opening, as shown in Figures 2.8 and 2.9. A torvane performed in the field during our visit indicated an undrained shear strength of approximately 200 lb/ft^2 for this weak material, which varied in thickness from about 1 to 4 inches over several feet laterally at this location.

Figure 2.10 shows the approximate configuration of the levee, and its sheetpile curtain and concrete floodwall. As shown in Figure 2.10, the sheetpiles do not penetrate very deeply into the poor foundation soils, and they do not provide a full cut-off for underseepage through the pervious foundation soils.

Maximum storm surge water levels within the canal during the Hurricane are not yet known with certainty. There are, however, well-determined water level measurements available from the nearby London Avenue Canal (see Section 2.2), and these match well with current numerical modeling of water levels in this vicinity. These same calculations show peak water levels in the 17th Street Canal to be about 3 to 5 feet below the tops of the floodwalls at this site. In addition, there was no evidence of overtopping-induced scour along unbreached sections of the 17th Street Canal, as shown for example in Figure 2.11, which was taken immediately south of the breach. The bridge crossing the 17th Street Canal at Robert E. Lee bridge, just to the north of the breach site, had not yet had its side walls raised to elevation +14 feet (such raising of these walls had been planned, but not yet implemented), and this bridge thus represented a "low spot" along a canal whose other floodwalls were generally at elevation +13 to + 15 feet. Most of the other bridges along all three canals had already had their side walls raised. There was evidence of minor scour from overtopping at the east end of the bridge, suggesting that minor overtopping occurred at this location, which would have placed water levels at this location at an elevation just a bit above elevation +10 feet. Best available evidence to date thus indicates that the 17th Street Canal levee embankment floodwalls did not overtop during the storm, but instead had a maximum storm surge that caused the canal waters to rise to within about 3 to 5 feet from the tops of the concrete floodwalls.

The mechanism of failure at this site appears to have been a stability failure of the foundation soils beneath the earthen embankment. The embankment was pushed sideways, by about 45 feet, by storm surge induced water pressures acting against the front face of the sheetpile/I-wall vertical barrier. The actual depth at which foundation soil shear failure occurred is not yet known, and this remains to be investigated. Also still to be determined is the actual soil unit or strata that provided the weak sliding plane, and the precise mechanism of weakness that was most critical.

Additional soil borings and sampling are currently being performed at this site, under the supervision of the USACE, and additional CPT probes are planned as well. The USACE is also planning additional laboratory testing of the samples obtained. The USACE has agreed to share all results of these additional field and laboratory studies with the various investigation teams involved.

These investigations will provide a basis for better evaluating the subsurface conditions at this site, and for better evaluation of soil shear strength and underseepage flow characteristics at this site. Additional analyses will, of course, follow once this new data becomes available.

At the time of our field teams' initial visit (October 3, 2005) an embankment fill had been placed over the core of large sandbags and large stone used to effect the initial closure. Additional gravelly fill had been placed at the inboard toe to provide a working mat. The conditions at this time are shown in Figure 2.12. The fill used as a covering veneer was a gap graded sandy gravel known locally to be internally unstable with regard to erosion, and our site team noted four sinkholes at the outboard lip of the crest of the temporary levee section, as shown in Figure 2.13. Three of these could be observed to be curving inward toward the center of the embankment section, and running water could be clearly heard in one of these.

The USACE was notified of the apparently unstable condition, with evidence of ongoing internal erosion of the fill, and the section was covered the next day, initially with a three foot thick layer of open graded stone (6-inch to 24-inch stone), which was then covered at the crest by a five to seven foot (uncompacted) lift of better graded silty sand, as shown in Figure 2.14. Both the open-graded stone, and the covering veneer silty sand fill can be clearly seen in this photo. The silty sand was also pushed down the inboard and outboard faces of the embankment providing a covering veneer of several feet on both sides of the emergency embankment section. The USACE was again notified that this did not appear to represent a hydraulically stable (or well filtered) embankment configuration; and the rapid placement of additional competent fill as an inboard berm, to be quickly followed by installation of a sheetpile cut-off wall, was recommended.

An inboard side toe berm was placed on October 11, 2005. On the morning of October 13, 2005 a longitudinal crack approximately 1/8 inch wide opened along the crest of the embankment. The crack widened slightly the next day, and a second, narrower crack opened along the upper inboard face of the embankment. Additional berming on the inboard side was recommended and immediately implemented, and operations are now underway to install a sheetpile cut-off curtain on the outboard side of the emergency closure section.

2.3 The London Avenue Canal Breaches and Distressed Section

2.3.1 The North Breach and Distressed Sections at Robert E. Lee Blvd.

A major breach occurred on the west bank of the London Avenue Canal, near the north end of the canal, as shown previously in Figure 1.4. In addition, the levee embankment and floodwall section on the east bank, directly across the canal, suffered major distress and is compromised with regard to its ability to safely retain high water levels in future events.

Figure 2.15 shows the breach at the west side of the canal. The scour patterns inboard (to the west) suggest that the embankment may have initially moved laterally to the west, pulling apart at the transitions between the translating central embankment section and the two intact ends to the north and south, and emitting the strongest scouring water forces at the northern end, with a secondary scour stream near the southern end. There is some evidence of possible vertical uplift at the toe, as the playhouse in Figure 2.16 was originally at the level of the ground at the inboard toe and was elevated to its current position as the embankment movements occurred, but this may also have been the result of "heaving" of the soils at the inboard toe as they were "plowed" or compressed by the lateral embankment movements.

Figures 2.15 and 2.17 show how the sheetpile/concrete floodwalls were pushed back by the elevated canal waters on the outboard sides, and by the reduction of earth pressure support on their inboard sides. Figure 2.17 is taken from the south end of the breach, and the gapping between the floodwalls and the soil of the outboard portion of the earthen levee embankment is clearly evident. According to design documents available to date, the sheetpiles were relatively short at this breach site (a design tip elevation of -16 feet), and the floodwalls appear to have toppled backwards away from the canal in a rigid manner ("post-hole toppling failure".)

Significant deposits of sediment occurred inboard of this breach, and these appeared to represent a mix of soils scoured out from the breached embankment section and its foundation soils, as well as sediments from the canal outboard of the failed section (see Figure 2.18.)

Three high water marks, determined to be of high reliability, were found in close proximity to the breach section at this canal by members of our team from COPRI, and these indicate that the maximum water levels at this portion of the canal were at approximately Elev. +11 to +12 feet, or approximately 2 to 3 feet below the tops of the floodwalls at this section. In addition, there was no evidence of overtopping producing erosion at the inboard sides of intact levee floodwalls anywhere along this canal. The sidewalls of the Robert E. Lee bridge had not yet been raised to the elevation of the adjacent I-walls, so the bridge represented a low spot in the system. There was evidence of minor overtopping at one end of the bridge, but this was slight. As the bridge walls were approximately 4 feet lower than the adjacent I-walls, this would further confirm that the maximum water level at this location in the canal was about 3 feet (or so) below the tops of the I-walls. Best available evidence, and current field-calibrated numerical analyses of storm surge levels, thus indicate that the floodwalls along the London Avenue Canal were not overtopped.

Evidence at this site strongly suggests that the breach occurred as a result of the sheetpile/floodwall being pushed backwards by the elevated water pressures on the outboard side, and that support on the inboard side of the sheetpile/floodwall was reduced as a result of soil failure at or beneath the base of the earthen levee embankment. The severe distress of the similar levee and floodwall directly across the canal (on the east bank), and its similar foundation conditions, provide additional evidence here.

Figure 2.19 shows the floodwall of the "distressed" section directly across the canal, on the east bank. This photo shows the outboard side of the floodwall, which has been pushed laterally, opening an extensional crack as wide as approximately 18 to 28 inches at its original outboard side base contact with soil at the levee embankment crest.

Figure 2.20 shows conditions on the inboard side of the east bank distressed section, directly on the other side of the wall shown in Figure 2.19. The wall has been pushed towards the inboard side, and now leans inwards (to the right) by about 5° off vertical in this photo. Figure 2.21 shows a closeup view of part of a line of sinkholes noted at the inboard toe of the wall, along the section shown in Figure 2.20. These appear to have been related to underseepage and resulting erosion and piping. Figure 2.23 shows the "boil" outlet of one erosional "pipe" at the inboard toe of the embankment at this location.

This does not mean that erosion and piping caused the distress at this levee/floodwall section, nor the failure at the breached section across the canal. Instead, the underseepage and erosion appear to be indicative of massive underseepage flows during the period when the water levels in the canal were elevated by the storm surge. The "distressed" embankment section on the east bank translated slightly inboard, as evinced by a partially eroded overthrust feature that occurred at the inboard toe along a short distance just to the south of the swimming pool shown in Figure 2.22, as well as by lateral bulging (and resultant vertical humping) of the ground and the lateral deflection of backyard chain link fences in this same inboard toe area.

The evidence at the "distressed" east bank section, and at the breached west bank section, would both be consistent with similar failure and "distress" mechanisms. Indeed, the east bank section appears to have been in an incipient failure condition, and failure at the east bank may have been prevented by the drawdown of water levels produced by the failure at the west bank, and also by the failure at the second breached section along the canal further to the south.

The foundation soils at these two sites (the east and west banks) consist of a relatively thick deposit of sands, overlain by a relatively thin top layer of marsh and peat deposits. These marsh and peat deposits vary in thickness between 10 to 15 feet. Based on the available data, the poorly graded Holocene beach sands extend to an elevation of approximately -40 to -50 feet. These sands were underlain by less pervious soils.

Evidence at both sites suggests that massive underseepage passed beneath the relatively short sheetpiles, and this may have weakened the foundation soils beneath the inboard sides of the earthen levee embankments. At the same time, elevated water levels in the canal pushed strongly against the outboard sides of the sheetpile/floodwalls. Soil failure appears to have occurred at or below the base of the inboard half of the earthen levee embankment on the west bank, and evidence suggests that an incipient failure of similar nature nearly occurred on the other side of the canal. It is also possible that straightforward erosion and piping led to one or both of these situations.

Significant further investigation is needed to better define the actual failure and "distress" mechanisms here. The actual depth at which foundation soil shear failure occurred is not yet known, and this remains to be investigated. Also still to be determined are the actual soil units or strata that provided the weak sliding planes, and the precise mechanism of weakness that was most critical.

Additional soil borings and sampling are currently being performed at this site, under the supervision of the USACE, and additional CPT probes are planned as well. The USACE is also planning additional laboratory testing of the samples obtained. Most importantly, the USACE has agreed to share all results of these additional field and laboratory studies with the various investigation teams involved.

These investigations will provide a basis for better evaluating the subsurface conditions at this site, and for better evaluation of soil shear strength and underseepage flow characteristics at this site. Additional analyses will, of course, follow once this new data becomes available.

Figure 2.23 shows placement of fill during construction of the emergency repair embankment section at the east-side breach section of the London Avenue Canal (North) site. The progressive evolution of the embankment section at this site closely paralleled that described previously in Section 2.2 at the 17th Street Canal breach site, except that no sinkholes were noted in the temporary embankment section at the time of our teams' site visits. The core of the embankment is, again, large sandbags and stones used to effect the initial emergency closure. Clearly visible in Figure 2.23 are the gap graded sandy gravel fill that covered this irregular core, and the layer of open graded stone that was placed atop the interim crest of the sandy gravel fill. At time of the photo in Figure 2.23, better-graded silty sand fill was being end-pushed without compaction to form the final crest and also to provide a covering veneer on both the inboard and outboard faces of the embankment section. Our field investigation teams formally advised the USACE that this did not represent an internally stable embankment section with regard to internal erosion, and a clayey cap was placed over the silty sand fill and additional inboard side berm fills were rapidly added. In addition, plans are now underway to install a sheetpile cutoff that will extend to a much greater depth (the new sheetpiles design tip elevations are Elevation – 65 feet) than the original sheetpiles of the breached section. The new sheetpiles will have significant lateral overlap with the remaining intact sheetpile curtains at the north and south ends of the repair section.

2.3.2 The South Breach at Mirabeau Avenue

A second major breach occurred further to the south, on the east bank of the London Avenue Canal at Mirabeau Avenue, as shown in Figure 1.4. Figure 2.24 shows an oblique aerial view of this breach site as it appeared during the construction of the temporary repair berm.

Figure 2.25 shows a view looking to the northeast across at the water side of the breached section, after initial closure and interim repair. The sheetpile/I-walls had again toppled inwards towards the land side. Scour was very extensive at this breach, and the scour hole that had to be filled to effect the emergency closure was very large. Much of the breached embankment was eroded away by the scour, and much of what remained was buried by the large closure section required. Significant deposits of soils from the embankment, the foundation, and the canal sediments from just outboard of the breach were deposited in the neighborhood on the land side, as shown in Figure 2.26.

At the time of our field investigations, relatively little remained to be observed at this site, due to the massive scouring erosion produced by the breach, and the massive quantities of fill required in the initial emergency repairs. Accordingly, it is not yet possible to state with certainty the cause of this breach.

Foundation soil conditions at this site were relatively similar to those at the breach site to the north that was described previously in Section 2.3.1. Cross sections of soil conditions along this section show approximately 5 to 10 feet of artificial fill (embankment material). This artificial fill is underlain by 10 to 13 feet of fat clay marsh deposit. These marsh deposits are underlain by a Holocene poorly graded sand beach deposit. As with the breach section farther to the north, the sheetpiles supporting the floodwall did not extend to great depth, and design drawings available to date indicate that the piles had tip elevations at -26 feet. This would not have provided a full cutoff for underseepage through the pervious sands. Photographic evidence immediately after the failure suggests that lateral movements of the levee embankment may have occurred at this site as well, but significant further studies will be required to develop a firm theory as to the cause of failure at this site.

Additional soil borings and sampling are currently being performed at this site, under the supervision of the USACE, and additional CPT probes are planned as well. The USACE is also planning additional laboratory testing on the samples obtained. Our investigation teams have made a number of recommendations and requests regarding some of the details of these ongoing field and laboratory investigations, including investigations of site conditions immediately to the north and south of the heavily scoured breach section, and also across the canal on the west bank side. Most importantly, the USACE has agreed to share all results of these additional field and laboratory studies with the various investigation teams involved.

These investigations will provide a basis for better evaluating the subsurface conditions at this site, and for better evaluation of soil shear strength and underseepage flow characteristics at this site. Additional analyses will, of course, follow once this new data becomes available.

The construction of the emergency closure embankment and the subsequent temporary closure embankment sections at this site largely paralleled those described previously in Sections 2.2 and 2.3.1 for the 17th Street Canal and London Avenue Canal (North) breach sites. Inboard berms are currently in place, and plans are underway for more permanent closure construction, including a sheetpile cutoff that will, again, extend to significantly greater depth than the original (breached) design section. Considerable water flow is still occurring at the inboard toe of this temporary closure section, but some significant portion of that flow has recently been traced to a broken and flowing water line.

2.4 Performance of the Flood Protection System Along the West Bank of the IHNC

In addition to the three major breaches along the 17th Street and London Avenue Canals, the eastern portion of the Orleans East Bank polder was also subjected to floodwaters as a result of a number of smaller failures along the frontage of the INHC, as shown in Figure 1.4.

The IHNC frontage includes the main Port of New Orleans. Two sets of levees and floodwalls occurred along much of the Port frontage on the west bank of the IHNC, and both were overtopped by storm surges at a number of locations. Multiple failures (breaches) occurred along this frontage, and these will be briefly described in this Section. Best available evidence suggests that storm surges overtopped numerous stretches of levees along this Canal frontage.

Figure 1.4 shows the locations of breaches and major "distressed" sections (or partial breaches) along this west bank of the IHNC. Several different types of distress and/or failure were observed along this section of the flood protection system.

Figure 2.27 shows a breached section of concrete floodwall immediately inboard of the main Port, at Location "A" in Figure 2.1(a). Figure 2.28 shows deep erosion at the inboard toe of the floodwall section immediately (adjacent) to the north of the section shown in Figure 2.27. Our site investigation teams arrived at this site just in time to observe the infilling and then burial of deeply eroded trenches at the inboard toes of the floodwalls adjacent (to the north and south) of this breached floodwall sections. It was apparent that overtopping flows had deeply, and variably, eroded the soils at the inboard sides of the sheetpile/concrete "I-walls", reducing their inboard lateral support and thus also their ability to safely withstand outboard side water pressures associated with the elevated (overtopping) water levels.

The fill being placed to infill the eroded inboard floodwall toes, and then the overlying fill being placed to buttress the inboard sides of the non-breached floodwalls, at the adjacent floodwall sections immediately to the north and south of the breached section were being placed without engineering supervision, and without suitable compaction. Our investigation teams notified the USACE that these fills appeared to be not competent for their apparent intended purpose, and that they should be removed and replaced with a properly engineered fill.

Figure 2.29 shows the results of overtopping erosion at a "transition" from an earthen embankment levee to a concrete "T-wall" just to the south, at Location "B" in Figure 2.1(a). At this location, preferential erosion at the concrete/earthen embankment transition led to a full breach. This represents an example of a common problem noted at numerous locations throughout the regional flood protection system; failure at a "transition" between a structural (concrete) section and an earthen (levee) section. The concrete wall section at this location carried a steel floodgate to permit through passage of traffic from the Port, but which could be closed during periods of high water in the IHNC, as shown in Figure 2.30. The embedment (or overlap) at the transition section (from concrete wall to earthen levee) at the end of the concrete wall was insufficient, and this was exacerbated by the fact that the concrete wall and adjacent earthen levee section had different crest heights. It was common practice in the New Orleans area to build in "structural superiority" wherein structural walls (e.g.: the concrete T-wall and gate structure) had higher crowns than the crests of adjacent earthen levees. This caused overtopping to occur at the earthen levee sections, and produced especially severe overtopping erosion at the "transitions" between the concrete gate wall and earthen levees at each end.

The embankment material at this site was a sandy "shell" fill; a mix of sand and shells widely available in this region. This material, shown in close-up in Figure 2.31, appears to be highly erodeable, and was noted at a number of failed (breached) sections throughout the New Orleans flood protection system.

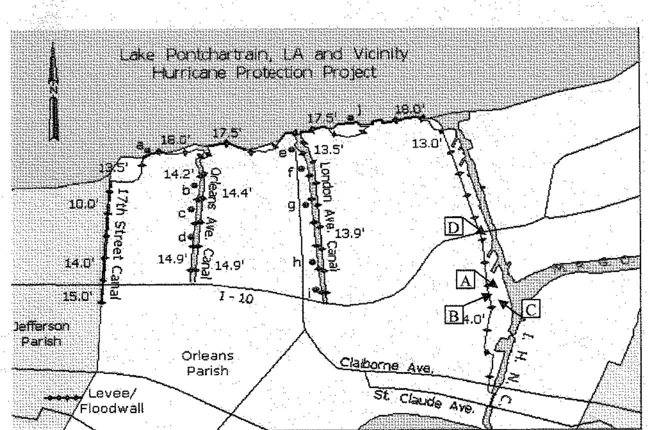
Figure 2.32 shows an additional example of this type of "transition" deficiency between a structural (concrete) wall and adjacent earthen levees, just a bit farther to the east at Location "C" in Figure 2.1(a).

Figure 2.33 shows a view looking to the southwest from the breach at Location "C" in Figure 2.32. Another breach, just 20 yards to the east of the breach section shown on Figure 2.29 also overtopped and eroded and breached. Figure 2.33 shows the inboard side results; massive flooding damage and considerable sediment deposits, including "shells" from the embankment fill.

There was an outboard protective wall and levee in the Port area, and this too was apparently overtopped and breached before the waters then overtopped the inboard levees and walls as discussed above. Our field investigation teams did not have the time to fully investigate all sections of the outboard walls and levees along this section, but there were some important observations and findings in the sections that were examined.

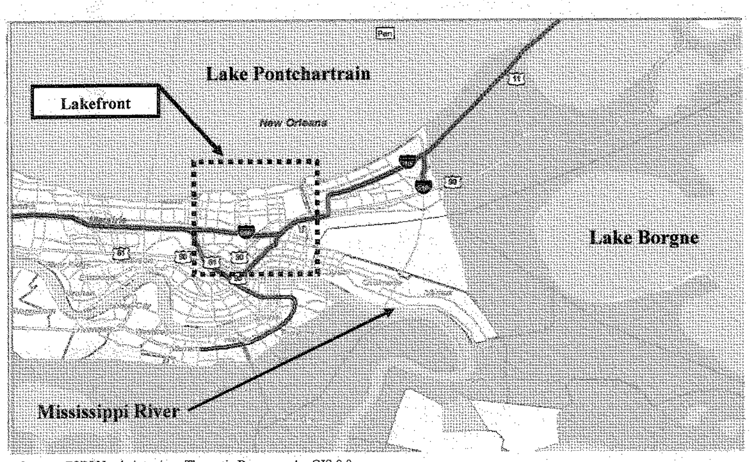
Figure 2.34 shows a complex "transition" at the northern end of the Port region along the west bank of the IHNC, immediately to the south of the Highway I-10 bridge, at Location "D" in Figure 2.1(a). At this location, outboard side levees and floodwalls associated with the Port and industrial operations conjoin with inboard side levees and floodwalls constructed by the USACE. In addition, a roadway embankment crosses through the levees, and a second gap in the "line of protection" for a railway line (crossing the adjacent IHNC) crosses through at this location. This represents a very complex "transition" section, with overlapping users and overlapping authorities and responsible entities. The gate of the railway's floodgate wall had been knocked off by a train derailment several months prior to Hurricane Katrina, and the railway was to have closed the resultant opening with a sandbag levee section within the gated opening. Our understanding is that this sandbag closure was inspected by the Orleans Levee Board. This emergency closure appears to have been unsuccessful, as floodwaters appear to have passed through this opening, and then to have eroded and breached the earthen roadway embankment adjacent and behind this section. Our field investigation teams were unable to track the direct consequences of this, as additional breaches along this same frontage section, as well as the major breach at the east bank of the nearby London Avenue Canal, all apparently contributed to flooding of the neighborhoods immediately inboard of this site.

Overall, multiple breaches and sections of significant distress were noted along the west bank of the IHNC, both along the levees and floodwalls outboard of the Port and industrial facilities, and also along the main USACE-designed levees and floodwalls on the inboard side of these Port and industrial facilities. All of these appeared to be the result of overtopping, and resultant erosion. Some were simply erosional failures of earthen embankments, or of preferential erosion at "transitions" between earthen embankment sections and adjacent structural wall sections. The significant breach at Location "A" appears to have been due to overtopping of the concrete floodwall (the sheetpile/I-wall section), and resultant erosion of soils at the inboard toe of the floodwall which reduced the ability of the sheetpile/floodwall to withstand the lateral water pressures exerted by the elevated water levels on the outboard side.



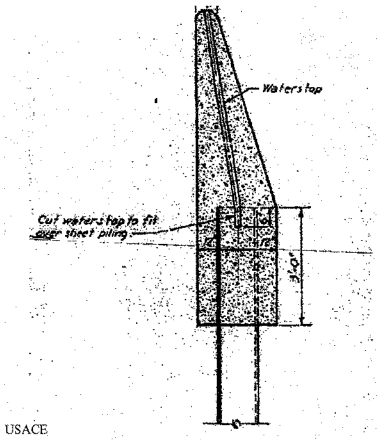
Source: http://www.mvn.usace.army.mil/pao/response/amaps.asp updated July 2003

Figure 2.1(a): Orleans Parish and eastern Jefferson Parish, in the Canal district.



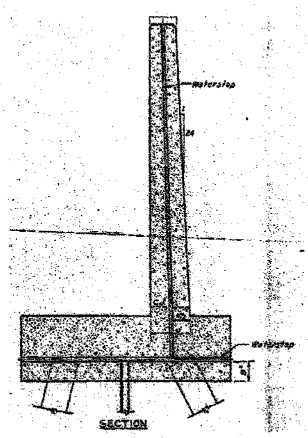
Source: ESRI North American Thematic Basemap, ArcGIS 9.0

Figure 2.1(b): Map showing location of the Downtown protected section, and location of enlarged section shown above in Figure 2.1(a).



Source: USACE

Figure 2.2(a): Typical I-wall section in the New Orleans region.

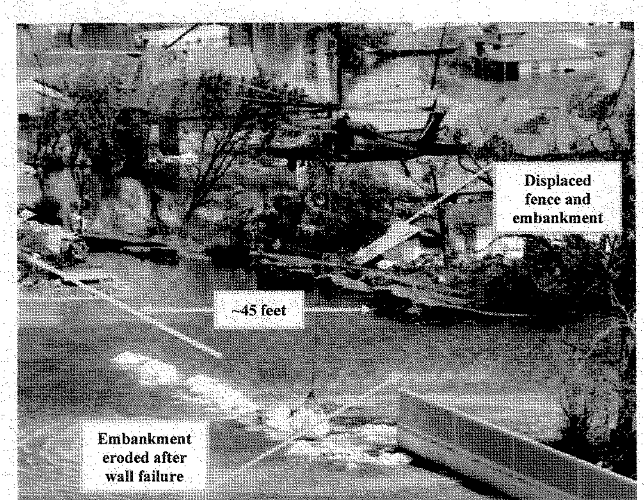


Source: USACE

Figure 2.2(b): Typical T-wall section in the New Orleans region.

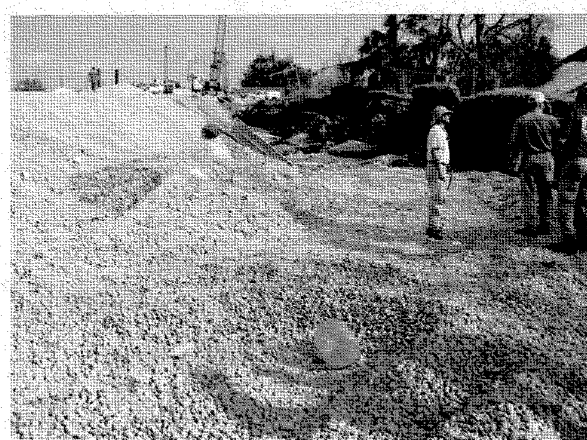
Source: http://www.usace.army.mil/katrina-images/NO-A-09-04-05_0072.jpg

Figure 2.3(a): The 17th Street Canal breach during initial breach closure.



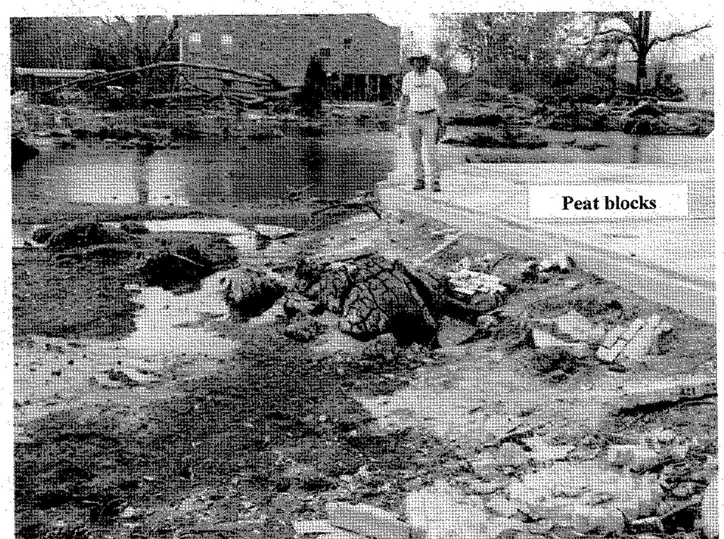
Source: http://www.usace.army.mil/katrina-images/NO-A-09-04-05_0072.jpg

Figure 2.3(b): The 17th Street breach, highlighting key points for discussion



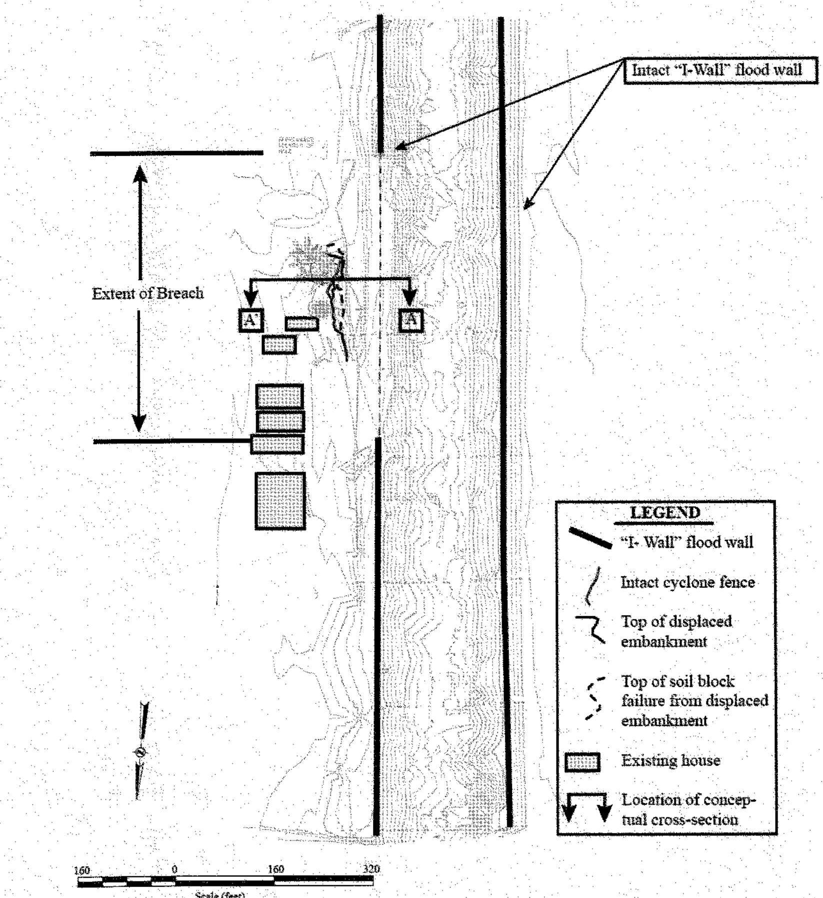
Photograph by Jonathan Bray

Figure 2.4: View of the 17th Street breach section from the south.



Photograph by Jonathan Bray

Figure 2.5: View from crest of emergency embankment closure section at the 17th Street Canal breach, looking south across the floodwater scoured zone.



Source: Plans prepared by Linfield, Hunter & Junius Inc., titled "Lake Pontchartrain and vicinity, 17th Street Canal Floodwall Breach, New Orleans, Louisiana, SURVEY," dated October 6, 2005.

Figure 2.6: Schematic plan view of the 17th Street Canal breach site. Results of LIDAR scan superimposed on base survey.

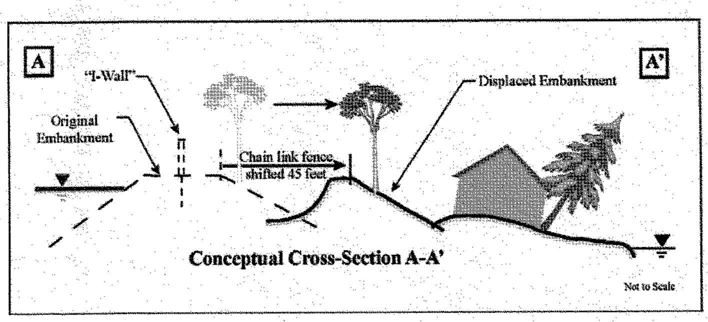
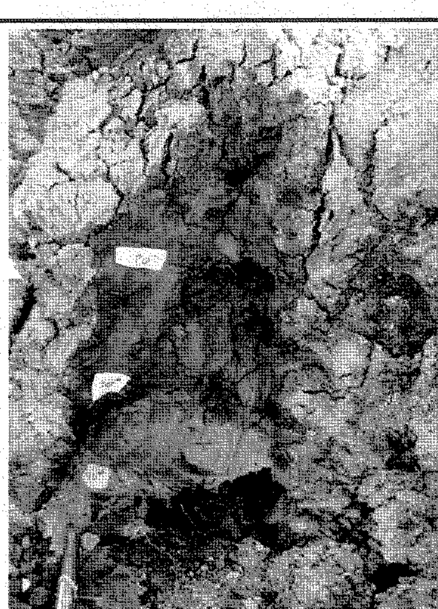


Figure 2.7: Schematic cross section at the 17th Street breach section.

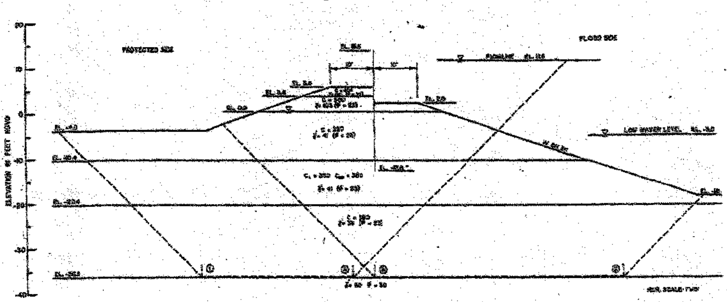
Photograph by Jonathan Bray

Figure 2.8: Location at which clay seam interbedded within the peat at the toe of the translated levee embankment was sampled.



Photograph by Jonathan Bray

Figure 2.9: Clay seam (light gray layer) underlain by darker lean clay, and overlain by fibrous peat.



Source: Eustis Engineering, "Geotechnical Analyses, Metairie Relief Canal (17th Street Canal), OLB Project No. 2043-0222, New Orleans, Louisiana, 31 August, 1988.

Figure 2.10: Design cross-section at the 17[th] Street breach.

Photograph by Jonathan Bray

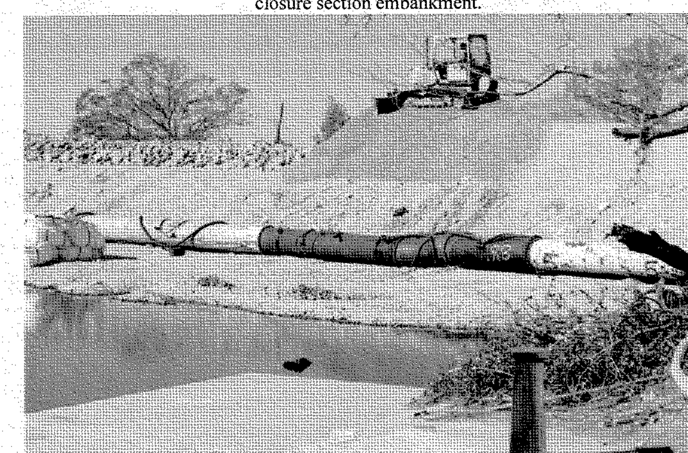
Figure 2.11: Typical conditions at the inboard side of floodwalls along the 17th Street Canal showing no scour of soil at the toe of the wall.

Photograph by Rune Storesund

Figure 2.12: Temporary closure section embankment on October 3rd, 2005.

Photograph by Jonathan Bray

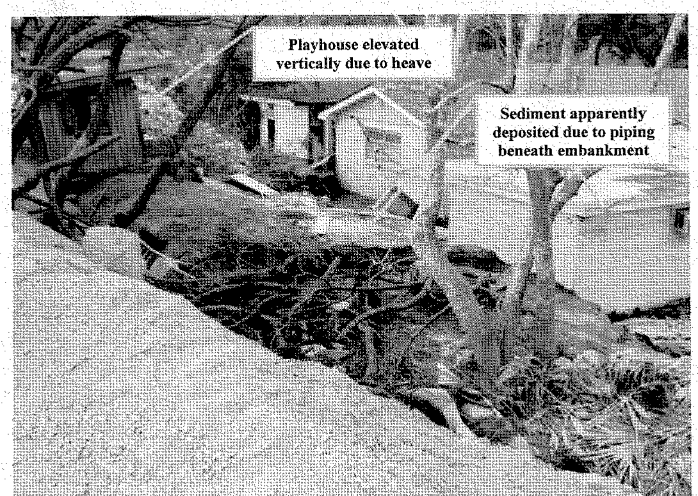
Figure 2.13: One of four sinkholes noted at the front lip of the crest of the temporary closure section embankment.



Photograph by Jonathan Bray

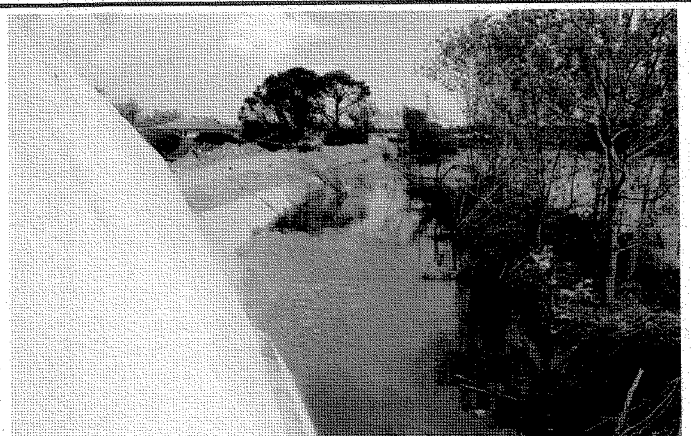
Figure 2.14: Placement of silty sand fill at the crest and on both the inboard and outboard faces of the temporary embankment closure section on October 6, 2005.

Figure 2.15: The breach section at the west side of the London Avenue Canal (North).



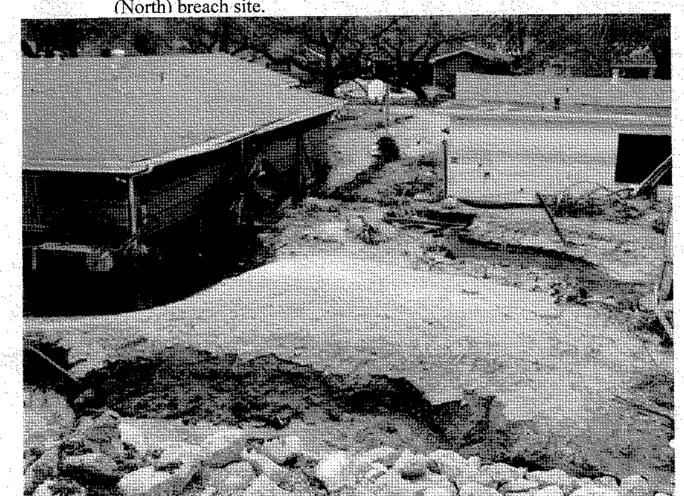
Photograph by Jonathan Bray

Figure 2.16: Conditions at the inboard toe of the London Avenue Canal (North) breach section.



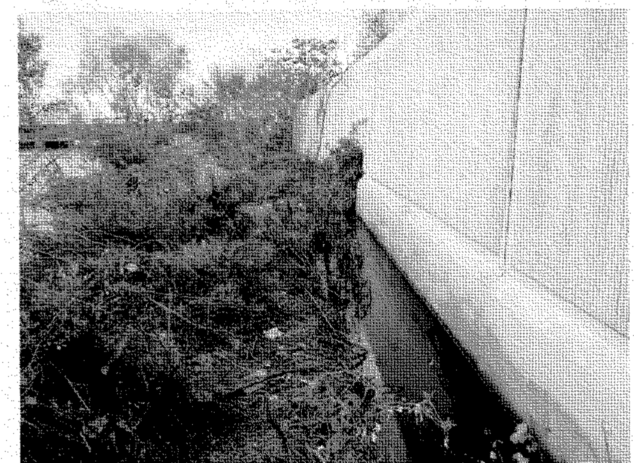
Photograph by Jonathan Bray

Figure 2.17: The toppled floodwall/sheetpile walls at the London Avenue Canal (North) breach site.



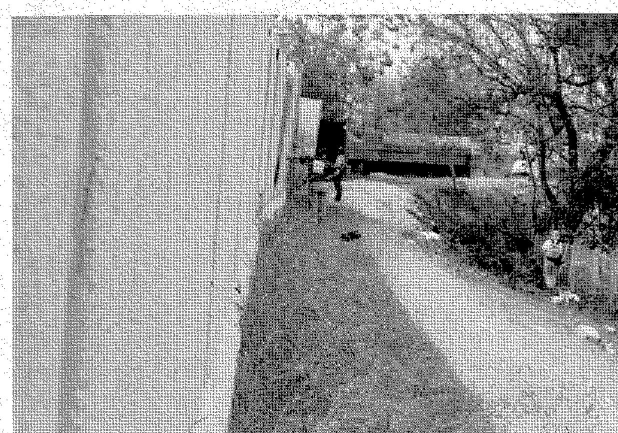
Photograph by Jonathan Bray

Figure 2.18: Sediment from the London Avenue Canal was deposited inboard of the levee break. High water marks (from long-term ponding) are visible on the exteriors of the residential homes.



Photograph by Jonathan Bray

Figure 2.19: Gap at the base of the floodwall on the canal side of the East Bank "distressed" section.

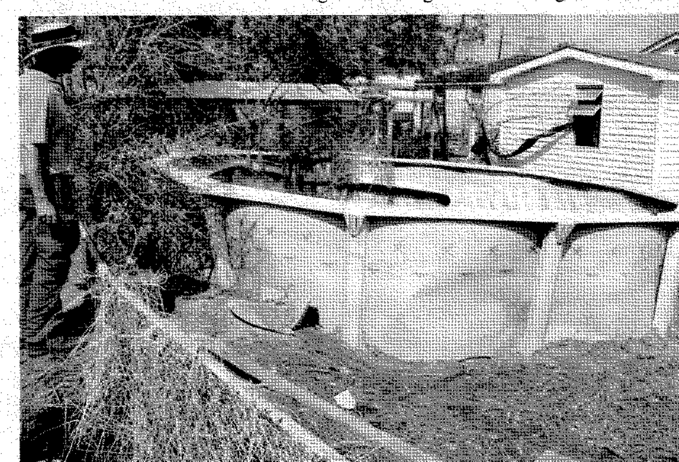


Photograph by Jonathan Bray

Figure 2.20: View of the inboard side of the floodwall and earthen levee embankment.

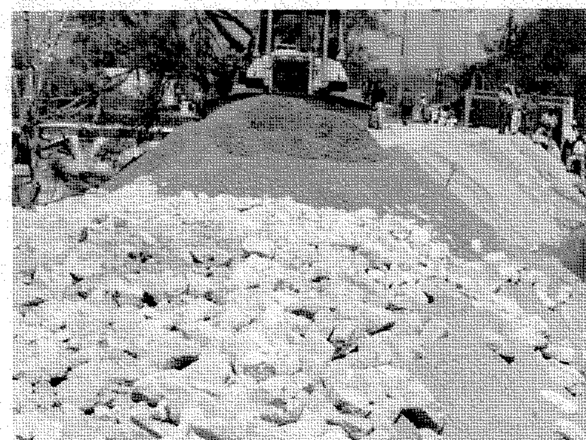
Photograph by Jonathan Bray

Figure 2.21: Closeup view of sinkholes at the inboard toe of the floodwall, at the location of the engineer wearing a red shirt in Figure 2.20.



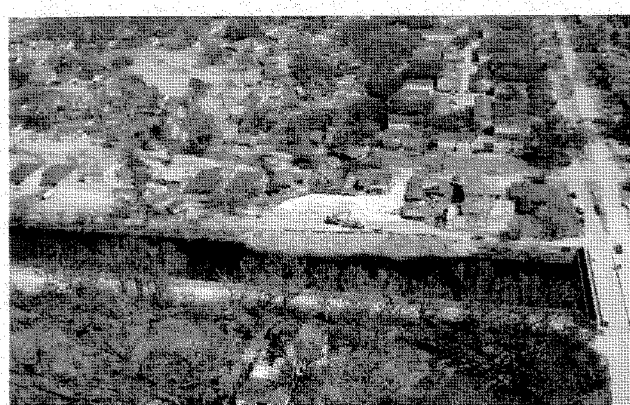
Photograph by Jonathan Bray

Figure 2.22: View of conditions at the inboard toe, immediately inboard of the locations shown previously in Figures 2.21 and 2.22. Note the bulged and hummocky ground, the laterally displaced chain link fence, and the piping boil ejecta.



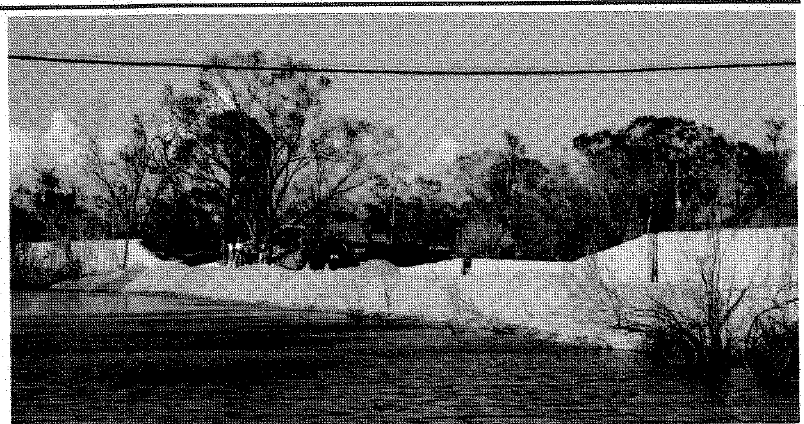
Photograph by Jonathan Bray

Figure 2.23: Photo during construction of the emergency breach repair embankment at the London Avenue Canal (North) breach site.



Photograph by Les Harder

Figure 2.24: Aerial view of the breach section at London Avenue Canal (South).



Photograph by Francisco Silva

Figure 2.25: View of the crest of the temporary embankment closure section at the London Avenue Canal (South) breach.

Photograph by Rune Storesund

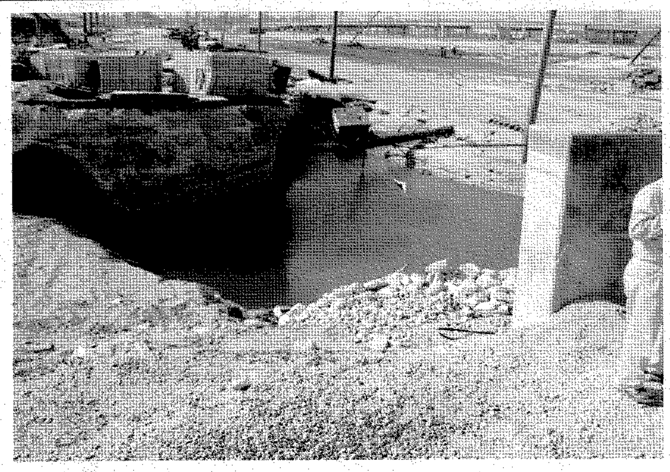
Figure 2.26: Significant quantities of sediment were deposited in the residential neighborhoods on the east side of the London Avenue Canal. More than five feet of sediment was deposited around this home.

Photograph by Rune Storesund

Figure 2.27: Breached levee floodwall section at Location "A" along the west side of the INHC.

Photograph by Rune Storesund

Figure 2.28: Erosion at the inboard toe of concrete floodwalls at Location "A" along the west side of the INHC, adjacent to the breached section shown previously in Figure 2.27.



Photograph by Jonathan Bray

Figure 2.29: Erosion at a "transition" between a concrete floodgate wall and the adjacent earthen embankment section.

Photograph by Jonathan Bray

Figure 2.30: View of the structural wall and floodgate structure from Figure 2.29.

Photograph by Rune Storesund

Figure 2.31: Close-up view of sandy "shell" fill at the scoured edge of the breach shown previously in Figure 2.29.

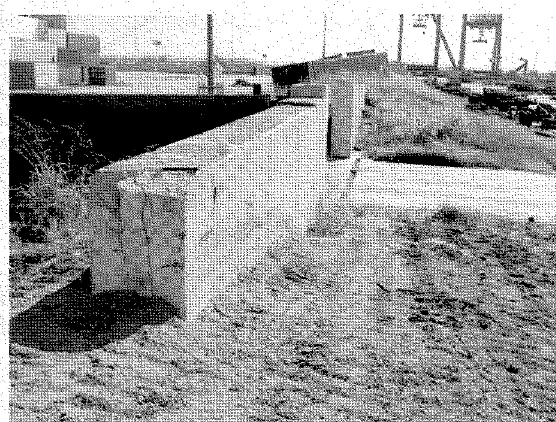


Figure 2.32: Common structural wall (with flood gate) and earthen levee transition problem with erosion at the contact between the earth and concrete sections.

Photograph by Rune Storesund

Figure 2.33: Scour hole and deposits of sediment and shells, inboard of the breach shown previously in Figure 2.32.

Photograph by Rune Storesund

Figure 2.34: A complex "transition" involving several overlapping operations and penetrations through the flood protection levees immediately south of the I-10 bridge across the IHNC.

Photograph by Joe Wartman

Figure 2.35: Rail line crossing through floodgate structure at the west side of the INHC at the complex transition shown in Figure 2.34.

Chapter Three: New Orleans East Protected Area

3.1 Overview

The region known as New Orleans East is bordered by distinctively different hydraulic boundaries: Lake Pontchartrain borders it to the north and east; the Inner Harbor Navigational Canal (IHNC), locally also known as the Industrial Canal, borders it to the west; to the south and southeast is the Intracoastal Waterway (IWW)/Mississippi River Gulf Outlet (MRGO) and Lake Borgne, respectively. The principal flood control for the New Orleans East polder is illustrated with flood elevation protection levels in Figure 3.1

This area was exposed to conditions that exceeded those for which the levee system was designed. Overtopping of the flood control levees and floodwalls was observed to have occurred on most sides of the New Orleans East polder. Overtopping evidence included significant landside scour and debris on the tops of walls and levees. On the north side fronting Lake Pontchartrain, the available field data and numerical calculations of storm surge, at the time of this writing, suggest that the lakefront storm surge in this area stayed below the crests of the lakefront levees except in the area near the Lakefront Airport. No significant sustained overtopping, only "splash over" due to waves generated in the lake, occurred at certain locations along the lakefront. Breaches of the levee system occurred at various other locations with the notable exception of the eastern earthen levee. This levee is fronted by large extents of wetlands between the levee and the actual shoreline, in this case, the easternmost end of Lake Pontchartrain to the northeast. Storm surge water levels along the IWW/MRGO channel were relatively high and significantly exceeded design conditions. This storm surge then propagated westward into the IWW/MRGO channel. Researchers at the LSU hurricane center have postulated that the IWW/MRGO channel area acts as a funnel that causes storm surges as it propagates to the west.

Most of the flood protection fronted by Lake Pontchartrain performed well despite some wave overtopping with a few notable exceptions. Many of the breaches of the levee system in this region could be attributed to one or more "transition" problems characterized by different wall types, material types or adjacent levee crest elevations, or combinations of the above. Transitional issues also occurred where levees crossed from one jurisdiction to another. Each of these transitional issues will be discussed in more detail later. Other sections of the flood control system, particularly along the IWW/MRGO, where storm surge heights were greatest, were overwhelmed by severe overtopping that caused scour on the landsides of floodwalls and earthen levees. These sections will also be discussed.

3.2 Lakefront Airport

The Lakefront Airport is located at the northwest corner of the New Orleans East polder on Lake Pontchartrain near the entrance to the IHNC. Evidence of surge/wave overtopping was observed here along with a breach at a complex transition that combined levee sections of varying floodwall/levee heights and materials. Figure 3.2 shows a panorama of this distressed transitional area. The problems observed here were: 1) a concrete floodwall higher than adjacent roadway over an earthen material adjacent to; 2) railroad tracks laid over highly pervious ballast, with tracks at approximately the same elevation as the top of the floodwall, adjacent to; 3) an earthen embankment levee. The breach that occurred at this location was, in fact, two breaches. One was a scour of the roadway section next to the higher concrete wall, while the other occurred through the embankment levee immediately south of the railroad embankment. It is difficult to assess the role the pervious ballast beneath the tracks played, if any, to the problems observed at this site.

I-wall sections on the lakefront side appeared to have been overtopped, or to have at least experienced significant splash over, as evidenced by scour on the protected side of the walls and debris both on and behind the walls. Inspection of these wall sections showed little to no distress despite the significant scouring at places (Figure 3.3). This was in contrast to many other I-wall sections that had either been severely distressed or failed. It appeared that the construction of the I-wall sections in this area were significantly more robust than those other sections with damage. The walls appeared to be newer than most of the other I-wall observed in New Orleans East, with uniformly thicker and taller concrete sections. The section of floodwall that paralleled the shoreline was exposed to waves generated in Lake Pontchartrain. The scour trenches behind the walls parallel to the shorefront were relatively wide and deep. Interestingly, the scour behind wall sections perpendicular to the shorefront were smaller, an apparent result of the absence of waves reaching those sections.

3.3 Lakefront East from the Airport

Proceeding along the shoreline of Lake Pontchartrain in a northeastward direction beyond the Lakefront Airport we observed earthen levees with and without concrete floodwalls that largely withstood the storm surge and waves. Figure 3.4 shows the beginning stages of scouring along the landside toe of a concrete floodwall most likely due to wave overtopping. Figure 3.5 illustrates both the value of armoring the floodwall toe against scour and the difficulties encountered at the transition points between the armored and non-armored sections. Figure 3.6 shows an apparent low point along the lakefront levee with evidence of erosion from wave overtopping.

Further to the east, beyond Paris Road, the lakefront community of Little Woods located lakeside of the levee was almost completely demolished by the wind and storm waters (Figure 3.7). Figure 3.8 shows debris from the demolished structures left very near the levee crest, indicating a high water level consistent with other water lines we observed in the lakefront area. Debris from the houses was also strewn on the landside of the levee in a pattern that suggested wind transport. Figure 3.9 shows the only surviving structure at Little Woods, which was noticeably elevated on piles. It appears intact except for the absence of stairs to reach the elevated balcony, suggesting that the building industry can construct structures that resist storm forces like the ones experienced during Hurricane Katrina at Little Woods.

3.4 I-wall Failures - Intracoastal Waterway and MRGO

Some sections of the I-walls along the southern boundary of New Orleans East, on the IWW/MRGO, were observed to have failed while others remained standing either in good working order or in various states of distress. Virtually all of the I-walls had been overtopped, and the soil behind them significantly scoured (Figure 3.10). The various states of distress (and failures) appeared to be for the most part related to the loss of passive resistance resulting from the scour (Figure 3.11). Those that were in distress but not failed also showed gapping between the wall and the soil foundation on the waterside (Figure 3.12). This waterside gap would also assist in destabilizing the walls by reducing support of the sheet piles beneath the concrete wall sections. Where there were T-walls we observed no significant distress to the walls. In general, the T-wall sections appeared to be used only adjacent to gate structures and pumping facilities. Figure 3.10 also shows an example of a T-wall adjacent to an I-wall on the IWW/MRGO. The T-wall showed no apparent distress.

There was a failure of embedded sheetpile without concrete caps along the IWW. This case occurred where the top of the sheetpile wall was at a lower elevation than an adjacent concrete wall, thereby drawing the floodwaters over the more vulnerable sheetpile section first (Figure 3.13). Figure 3.14 is an aerial view of the same site portrayed in Figure 3.13 showing the magnitude of scour at the breach.

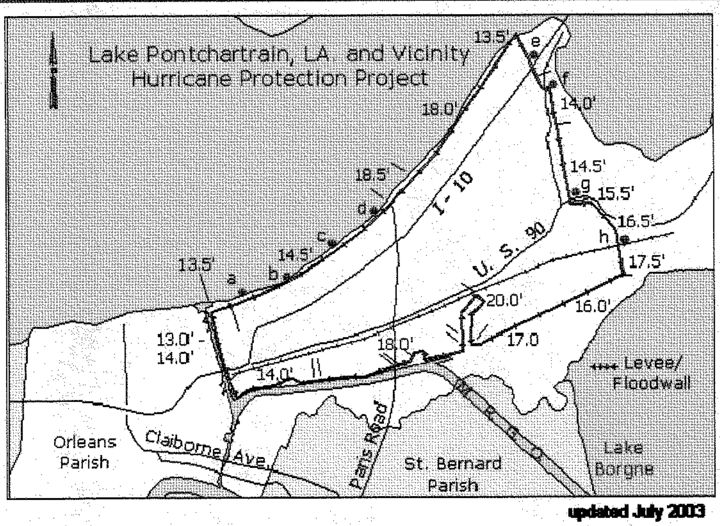
3.5 Earth Embankments – East and South

Many of the earthen embankment levees providing flood protection for New Orleans East performed well. While many of the embankments on the east and south sides of the protected area were overtopped, most of these survived well. At least one embankment section was reported by the USACE to have breached on the southeastern border along the IWW while others only showed signs of erosion and scour (Figures 3.15). Still others came through virtually unscathed (Figure 3.16). The performance of these earthen embankment sections with little to minor damage may be in part due to their construction and the materials of which they were made. This is in stark contrast to some of the numerous breaches of overtopped embankment sections that we observed in other locations, such as along the south eastern side of the MRGO, where easily eroded materials along with higher levels of storm surge and waves, likely led to their poor performance. A significant attribute noted for the performance of both the earthen embankments and I-wall sections was the relationship between orientation of the flood barriers and the assumed direction of the storm surge and associated waves.

The earth levee along the north bank of the Intracoastal Waterway under the Route 47 Bridge stands as an example of satisfactory performance despite hydraulic conditions that far exceeded the design criteria. Figure 3.17 shows the erosion damage on the landside slope of the levee due to the overtopping. Figure 3.18, taken from the Entergy Michoud Generating Plant, shows the area in Figure 3.17 under storm conditions. Given the ferocity of the storm as evidenced in Figure 3.18, the relatively modest damage to the earth levee represents satisfactory performance.

3.6 Additional Transition Problems - IHNC

Aside from the failure of some significant sections of I-walls and sheet pile walls, many portions of the flood control system surrounding New Orleans East performed well under greater than design conditions. The common failures occurred where transitions between differing materials or varying flood protection heights (or both) occurred. A detailed explanation was provided in Section 3.2 of a breach at a complex transition near the Lakeview Airport. This problem was especially prevalent on the western boundary of New Orleans East along the IHNC. A significant number of levee washouts were observed where the weaker of two adjacent materials was at a lower elevation. In this situation, the floodwaters would initially be concentrated or channelized to flow over the weaker material. Water flow and stress concentrations at transitions were likely causes of a number of failures where sheetpile walls transitioned to concrete walls (Figure 3.19). Another common transition problem was observed where differing wall heights, especially between dissimilar materials, were found adjacent to each other. Along the western border of the protected area, the earthen levee was regularly interrupted by a concrete structure supporting a flood control gate for vehicle and rail access to the shipping facilities. At nearly every one of these transitions, the earth had been scoured at each transition around the concrete. Many of these scours had already been filled when the team made its observations so that the extent of the scour holes could not be assessed.



Source: http://www.mvn.usace.army.mil/pao/response/amaps.asp

Figure 3.1 New Orleans East Protected Area

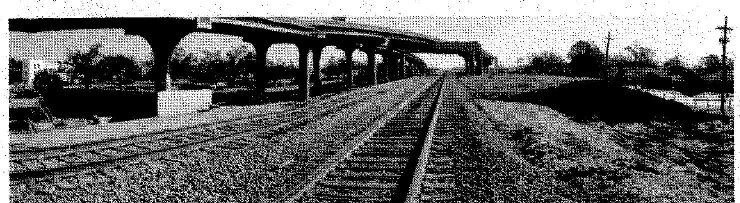


Photo by Lee Wooten

Figure 3.2: Complex transition near Lakefront Airport consisting of various flood protection heights, differing materials and junctures between various jurisdictional organizations. These types of complex transitions were found to be associated with several of the levee flood protection problems.

Photo by Peter Nicholson

Figure 3.3: I-wall adjacent to the Lakefront Airport showing deep back-scour but no evidence of distress to the wall.

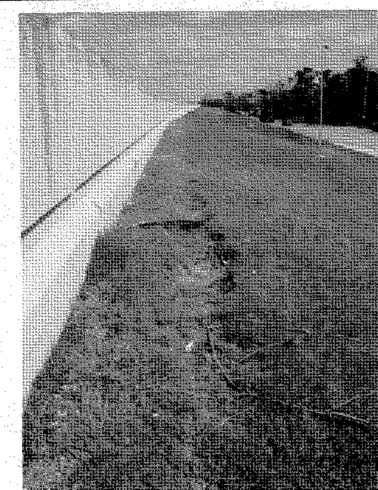


Photo by Francisco Silva

Figure 3.4: Beginning of overtopping scour along lakefront flood wall suggests moderate overtopping at this location.

Photo by Francisco Silva

Figure 3.5: Concentrated scour due to presence of concrete apron. Area in the background is a good example of the benefits of armoring the base of the flood walls.

Photo by Francisco Silva

Figure 3.6: Wave overtopping of lakefront earthen levee at low spot in structure did not cause serious damage (N 30° 03' 47.8", W 89° 58' 13.1)

Photo by Francisco Silva

Figure 3.7: The lakefront community of Little Woods destroyed by wind and water (N 30° 04' 70.5", W 89° 56' 44.0")

Photo by Francisco Silva

Figure 3.8: Debris from the Little Woods houses accumulated near the crest of the earth levee indicates the level of the lake waters during the storm. (N 30° 04' 70.5", W 89°, 56' 44.0")

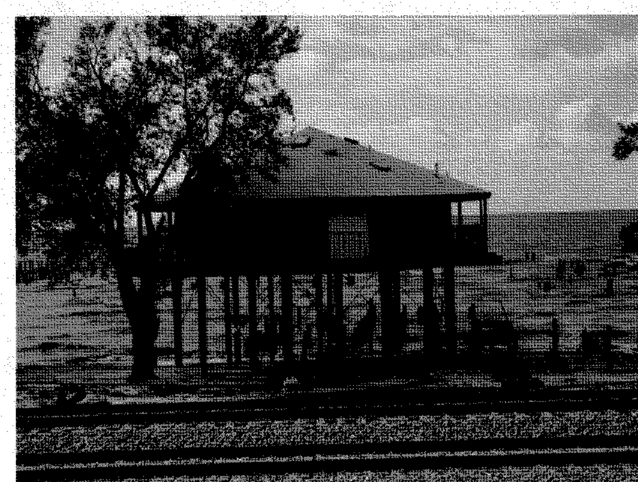


Photo by Francisco Silva

Figure 3.9: The lone surviving structure at Little Woods appears unscathed, except for the lack of stairs.

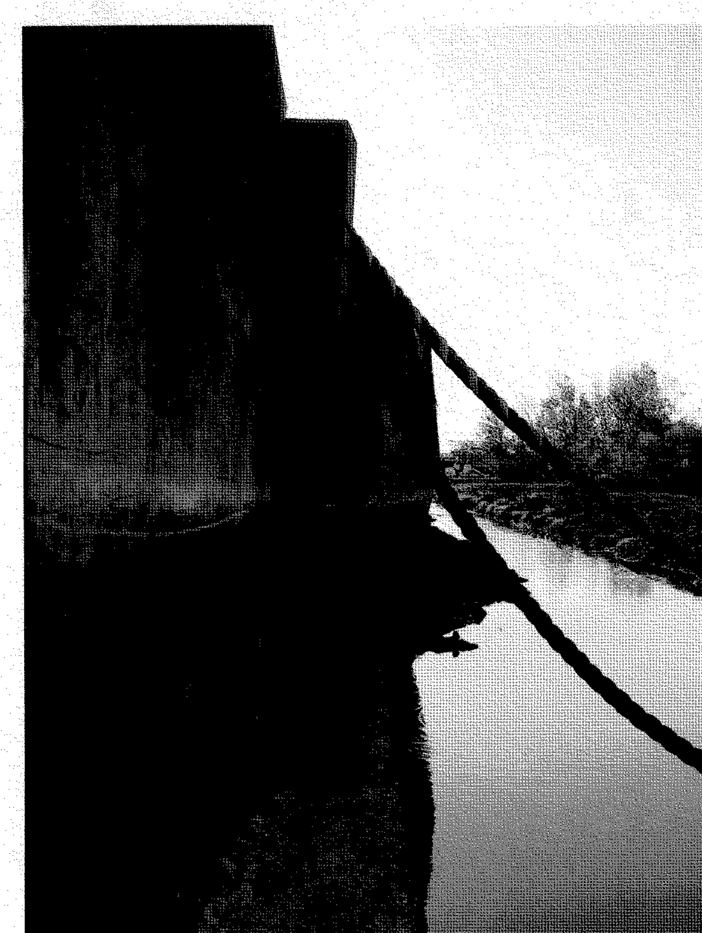


Photo by Jonathan Bray

Figure 3.10: Undamaged T-wall in foreground and damaged I-wall in background along the IWW/MRGO. Severe scour on the landside and distress of the I-wall (N30.00030 W89.99459).

Photo by Lee Wooten

Figure 3.11: Severely distressed I-wall after overtopping from the water side along the IWW/MRGO.

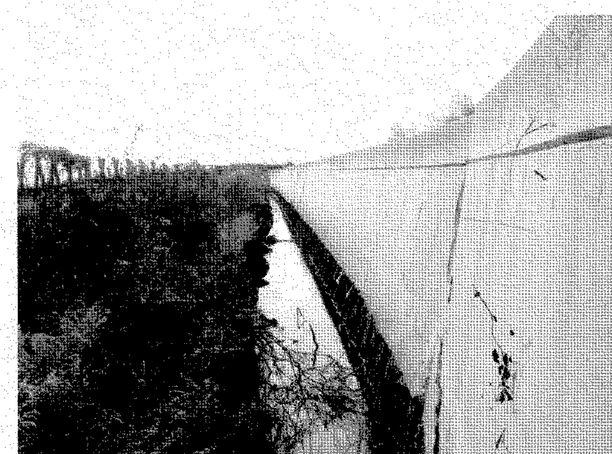


Photo by Lee Wooten

Figure 3.12: "Gapping" between soil and wall as distressed wall was displaced landward from the IWW/MRGO.

Photo by Peter Nicholson

Figure 3.13 Failure of sheetpile wall adjacent to higher and stronger concrete topped I –wall on the north side of the IWW.

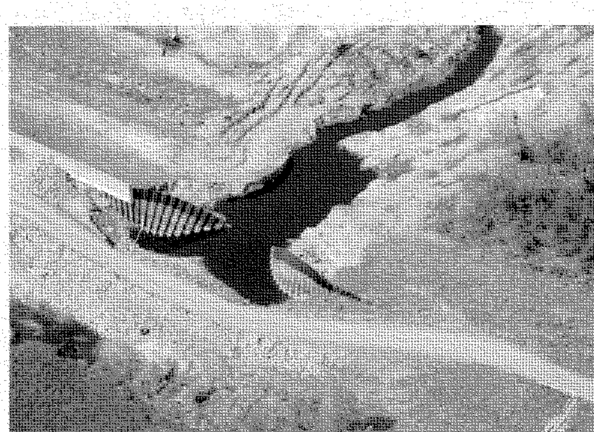


Photo by Les Harder

Figure 3.14: Aerial view of the failed wall section shown in Figure 3.14

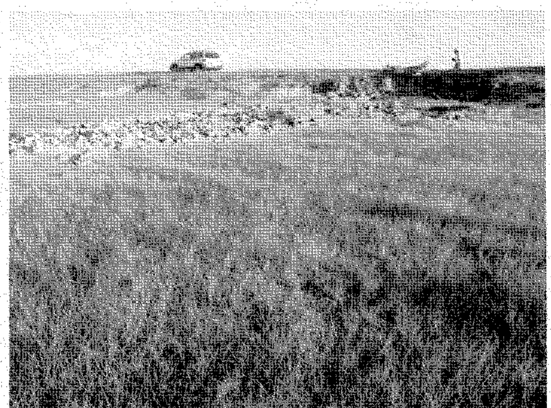
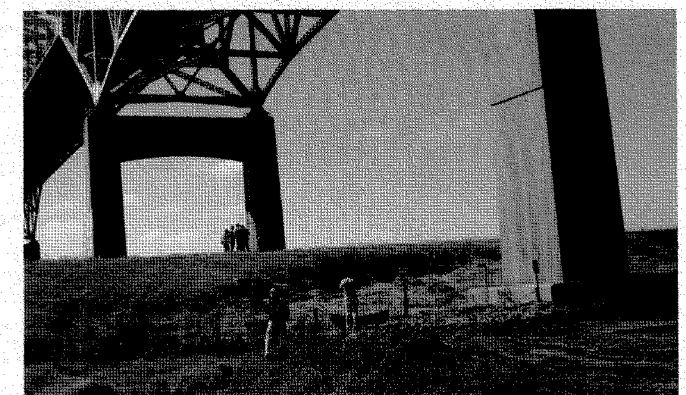


Photo by Jonathan Bray

Figure 3.15: Embankment along the IWW/MRGO that survived although somewhat scoured.

Photograph by Jonathan Bray

Figure 3.16: Virtually unscathed earth embankment levee on the eastern edge of the protected area of New Orleans East



Photograph by Francisco Silva

Figure 3.17: Earth levee beneath the north abutment of the Route 47 Bridge over the IWW/MRGO, next to the Entergy Michoud Generating Plant, looking south. Despite considerable damage, the levee performed satisfactorily during and after overtopping.

Photograph courtesy of Entergy Corporation

Figure 3.18: Same view of the overtopped earth embankment as seen in Figure 3.18 taken during the storm surge.

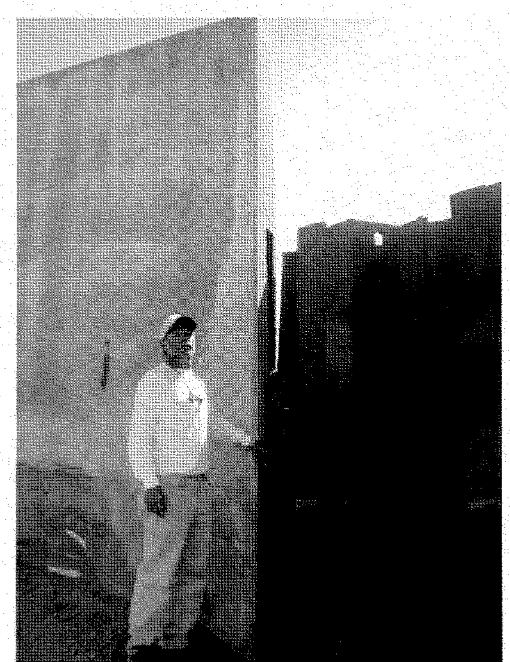


Photo by Lee Wooten

Figure 3.19: Transition between concrete and sheetpile walls at uneven wall height elevations

Chapter Four: Lower Ninth Ward and Adjacent St. Bernard Parish Protected Area

4.1 Overview

The Lower Ninth Ward of New Orleans and the neighboring portion of St. Bernard Parish were some of the hardest hit communities in the New Orleans metropolitan region. These communities had a combined pre-Katrina population of approximately 87,000 people and jointly include a residential area that extends over approximately 27 square miles. The structures in the region consist largely of wood frame or masonry residential units interspersed with larger commercial buildings along major roadways. The Lower Ninth Ward is a historic neighborhood where many of the homes date to the early twentieth century. St. Bernard Parish is a newer, more suburban community that grew significantly in the 1950's and 1960's. Hurricane-related flooding is not unknown in these communities; for example, in 1965, Hurricane Betsy left parts of the Lower Ninth Ward and the nearby town of Chalmette, St. Bernard Parish under as much as 8 feet of water. Parts of the Lower Ninth Ward were also flooded during Hurricane Flossie in 1956.

The Lower Ninth Ward of New Orleans and neighboring St. Bernard Parish together form an 81 square mile polder located across the Inner Harbor Navigational Canal (IHNC) and locally referred to as the Industrial Canal from central New Orleans (see Figure 1.4). Elevations within the polder range from approximately -4 feet to 12 feet, with the higher elevation reaches situated near its southern edge, which is bordered by the Mississippi River. The Gulf Intracoastal Waterway (IWW) and Mississippi River Gulf Outlet Canal (MRGO) are located north of the polder. Figure 4.1 shows the primary levee system surrounding the polder. The primary levee system, which includes earthen levees, I-wall, T-wall, and sheet pile sections, was designed and constructed by the U. S. Army Corps of Engineers (USACE). The polder also includes a secondary or local levee shown in Figure 1.4 that separates the developed portions of the region from the wetlands to the north. The local levee serves two purposes: (1) it acts as a hydraulic boundary for nearby pump stations, which discharge water into the marshlands, and (2) it forms a temporary holding basin that protects the residential areas from flooding in the event of limited overtopping of the primary levees along the north edge of the polder. The Lake Borgne Levee District operates and maintains the local levee system. The performance of the local levee system was not assessed in this study.

While the levee system along the Mississippi River performed well in the region, many portions of the primary levee system located along the western and northern edges of the polder sustained significant damage from the storm surge (Table 4.1). Two of the most significant breaches occurred along the western edge of the polder bordering the IHNC in the Lower Ninth Ward. Widespread damage to the levee system along MRGO was so severe that the local levees presently provide the only flood protection in this area. Portions of the primary levees protecting the area to the northeast, i.e. those along the southeastern banks of the MRGO, are exposed to the water levels in the Gulf of Mexico, via Lake Borgne. These water levels reached significantly higher elevations than those in Lake Pontchartrain and in the outfall canals. This area appears to also be exposed to waves generated in Lake Borgne.

4.2 IHNC, East Side, South Breach, (Lower Ninth Ward)

The flood protection system located north of the Claiborne Avenue Bridge in the Lower Ninth Ward consists of I-walls embedded in the earthen levees. The I-walls at this location consist of approximately 20 feet of sheet pile topped by an 8 foot high concrete floodwall section. The sheet pile extends about 5 feet into the floodwall with a concrete sheet-pile connection. Subsurface conditions in the vicinity generally consist of approximately 10 feet of very soft clays over 5 feet of soft peats underlain by about 25 feet of soft clay. Dense sands are encountered at a depth of approximately 40 feet.

Figures 4.2 and 4.3 show aerial views of an approximately 900 feet long levee breach located 850 feet north of the Claiborne Avenue Bridge. The breach initially resulted from the Hurricane Katrina storm surge in the IHNC. An emergency repair was made shortly after the breach occurred. This repaired portion of the breach was later re-breached on September 24 by a storm surge caused by Hurricane Rita, which flooded the Lower Ninth Ward for a second time. This second flooding incident was reportedly much less severe than that caused by Hurricane Katrina (floodwaters reached a depth of about 3 feet), and as such, it is likely that it caused relatively little, if any, additional damage to the levee system at this location.

In this area, the earthen portion of the levee was almost completely destroyed and the I-wall was overturned toward the landside and dragged inland by as much as 190 feet. As shown in Figure 4.2, the displaced I-wall assumed a sinuous shape that reached its maximum distance along the northern extent of the breach. It is worth noting that the sheet pile remained interlocked, hence the displacement resulted from elongation of the sheet pile portion of the I-wall structure. The unbreached portions of the I-wall system located immediately north and south of the failure were tilted landward, reaching their maximum inclination of approximately 3 degrees near the breach and gradually tapered to close to vertical at further distances from the breach. Scour trenches at the landside toe of the floodwall (protected side) were found along the entire length of the intact I-wall section. The scour trenches were typically about 5 feet wide at the top and extended to depths of approximately 4 feet. The scour trenches were generally wide and U-shaped near the breach and gradually became narrower, V-shaped and incised with at further distances from the breach (Figure 4.4).

Figure 4.5 shows a unique feature of the failure site: a large barge that was drawn through the breach and came to rest on the landside of the levee as floodwaters receded. The barge was reportedly docked in the IHNC and became unmoored during Hurricane Katrina. Note the crushed school bus under the right side of the barge. Review of press photographs indicate that the barge initially came to rest further inland as floodwaters from Hurricane Katrina receded. The barge was later refloated as the Ninth Ward flooded a second time during Hurricane Rita. The barge drifted back toward the breach and came to rest upon the school bus as the Lower Ninth Ward was later unwatered.

It is likely that the breach resulted from overtopping of the levee system along the IHNC, leading to scour and subsequent loss of passive resistance at the base of the wall, which then overturned in response to the high water levels in the canal. This hypothesis is supported by the extensive scour found at the base of the protected side of the levee. As the breach opened, the rushing waters may have eroded what remained of the earthen portion of the levee while carrying the I-wall sections landward. Though it is thought that overtopping may be the principal cause of the levee failure, it is not yet known why the failure occurred at this exact location along the IHNC levee system.

Figure 4.6 shows the emergency repair of the breach, which consists of a core of large sandbags overlain by embankment fill. Additional gravelly fill had been placed along the top of the embankment to serve as a working mat. The sandbags were airlifted into place, while the stone was placed from land. There was no significant seepage noted at the time of site visits on October 4 and during the week of October 9.

4.3 IHNC, East Side, North Breach, (Lower Ninth Ward)

The flood protection system in the vicinity of Florida and Surekote Avenues near the northwest corner of the Lower Ninth Ward consists of I-walls/earthen levees that transition to T-wall sections near an adjacent flood gate (Figure 4.7). The I-walls at this location are the same as those found at the south breach location. Figure 4.8 shows a T-wall levee system at the site. The T-wall system at the site is generally similar to that discussed earlier in Section 2.4. Subsurface conditions at the site are similar to those found at the south breach site, with very soft clays overlying soft peats at shallow depths.

Figure 4.9 shows an aerial view of a 210 foot long levee breach located approximately 500 feet south of Florida Avenue. The breach initially resulted from the Hurricane Katrina storm surge in the IHNC. An emergency repair was made soon after. It is reported that unlike the south breach location, the north breach emergency repair was not overtopped in Hurricane Rita The earthen portion of the I-wall levee system was almost completely destroyed and the I-wall was overturned and dragged inland by as much as 70 feet while remaining fully interlocked. In the most extreme case, the I-wall came to rest upside down, with the concrete portion at the bottom, and the toe of the sheeting pointing upward (Figure 4.10). The sheet pile separated from the concrete wall at the north end of the site by splitting the webbed section rather than tearing the interlock.

The unbreached portions of the I-wall system located immediately south of the failure were tilted inward (landward). The tilted I-walls reached their maximum inclination of approximately 3 degrees near the breach and gradually tapered to close to vertical at further distances to the south. Scour trenches at the landside toe of the floodwall (protected side) were found along the entire length of the intact I-wall section. The scour trenches were typically about 5 feet wide at the top and extended to depths of approximately 3 to 4 feet. As with the south breach, the scour trenches were wide and u-shaped near the breached area and gradually became narrower, v-shaped and incised at greater distances. Scour was also noted along the landside of the T-wall levee sections (Figure 4.8).

It is likely that the breach occurred in a manner similar to that described for the south breach location (i.e. overtopping of the levee, leading to scour and loss of passive resistance at the base of the wall, resulting in overturning). The scour-related failure hypothesis is again supported by extensive erosion found at the base of the protected side of the levee. While it is thought that overtopping may be the principal cause of the levee failure, it is not yet known why the failure occurred at this location along the IHNC levee system.

Figures 4.9 and 4.11 show the emergency repair, consisting of a core of large sandbags overlain by embankment fill. The sandbags were airlifted into place, while the stone was placed from land. Owing to the presence of standing water on the landside during a visit on October 4, it was not possible to determine if seepage was occurring through the repaired section.

4.4 IWW/MRGO Bayou Bienvenue Gate and West

The flood protection system at the Bayou Bienvenue gate site is a complex levee-gate transition involving several different levee sections located as shown in Figure 4.12. These include (from northwest to southeast) an earthen levee, transitioning to an I-wall, transitioning to a gate structure, transition to a sheet pile section, which finally transitions again to an earthen levee along the MRGO.

Figure 4.13 shows an approximately 80 feet long levee breach in the sheet pile section located immediately southeast of the gate structure. The earthen portion of the levee was completely obliterated and the sheet pile wall appears to have been torn from its connection southeast to the Bayou Bienvenue gate structure, and overturned. Representatives of the Orleans Levee District indicated that the gates were closed during Hurricane Katrina, and later reopened manually, due to the lack of electric power, after the storm had passed. Many of the sheet pile breach features were obscured by water at the site, and hence it was not apparent if the breach occurred due to a structural failure at the sheet pile gate connection, a result of overtopping, leading to scour and subsequent loss of passive resistance, or some combination of these factors. At the time of the last visit to the site on October 5, no repairs had been made to the breach.

Visible in Figure 4.12 is a large barge that struck and then overran the I-wall section northwest of the gate. The barge eventually came to rest directly upon the I-wall, which was locally damaged by the impact of the barge. Scour was found immediately adjacent to the I-wall damage as a result of concentrated water flow at this location (Figure 4.14). Despite the combined effects of the scour, impact damage, and the vertical load imposed by the barge, the I-wall at this location survived relatively intact and performed remarkably well. As shown in Figure 4.15, minor scour was also noted at the transition between the earthen levee and I-wall section located northwest of the barge.

Figure 4.16 shows the levee and floodwall along the south bank of the IWW, looking west from the Highway 47 Bridge. The concrete floodwall survived with only minor damage despite the impact of several barges shown in the photograph grounded against the levee. Also evident in Figure 4.16 is the characteristic scouring from floodwall overtopping. The levee did experience a breach at the transition between the concrete gate structure and the earth embankment. Flood-transported debris partially plugged the breach.

Crest road erosion damage was also noted at several locations along the earthen levee between the Bayou Bienvenue Gate and the northwest corner of the Lower Ninth Ward. This suggests that the earthen levees were overtopped at these locations; nevertheless, no breaches were found and the overall performance of the levee system was very good at these locations. These earth levees (west of Bayou Bienvenue) show a clear debris line at the crest level as shown in Figure 4.17. The result of the overtopping appears to have been limited to occasional moderate erosion of surface soils. Figure 4.18 shows one of the various types of barges that made contact with the earth embankment without any significant consequences.

4.5 MRGO, Bayou Dupree and Northeast St. Bernard Parish

Figure 4.19 presents a plan view of MRGO and indicates the numerous breaches caused by Hurricane Katrina along the southwest bank of the waterway. This section covers the levee sections located southeast of Bayou Bienvenue. The field evidence, including numerous sections of earth levees obliterated by the storm waters, indicates that the flood protection barriers were overtopped along the MRGO.

The map in Figure 4.19 shows that the storm barriers along the MRGO suffered damage at many locations. Figures 4.20 and 4.21 capture the failure of earth levees with steel pile sheeting between Bayou Bienvenue and Bayou Dupree. At some locations, the canal side of the earth embankment was completely eroded away and the erosion from overtopping left only remnants of the landside portion of the levee. The section where pipelines cross the steel sheeting (Figure 4.21) show scour on both sides of the sheets and deflections in both directions possibly as result of wave action and outflows.

Figures 4.22 and 4.23 show that the gate structure at Bayou Dupree suffered a failure similar to the one observed at Bayou Bienvenue. While the concrete structures remain largely intact, except for a section of concrete sheet piles to the right of those shown in the figures, the soils at the transition section were eroded by the storm waters resulting in a breached barrier.

Figures 4.24 and 4.25 show that overtopping obliterated the earth levees along the southwestern bank of MRGO near Bayou Dupree. Not only were the sandy soils in the embankment material completely removed in some sections (e.g. Figure 4.25), but the more cohesive soils at the foundation level suffered deep scouring. The only erosion protection on soil embankment levees that was visible for much of this area was grass. Figure 4.26 shows an aerial view of a section of these levees that survived the storm, albeit with erosion damage.

Members of the team observed a breach repair immediately north of Bayou Dupree on 12 October 2005. It is not known if this was a temporary or permanent repair. Saturated soils in scour areas were being filled over with local materials; new embankment was tied into existing embankment without shaping or removal of loose, disturbed fill; and compaction was accomplished by tracking fill with a small dozer. These repairs, if permanent, will likely be more vulnerable to problems than adjacent levees that survived Katrina intact. Construction supervision was not observed onsite. However, the team only observed a brief snapshot of construction activity, and we were later informed by the USACE Public Information Officer that a request had gone out to recruit over 100 additional personnel, apparently for purposes of inspection and contract administration.

The performance of much of the storm barrier along the section of the MRGO in St. Bernard Parish appears to have been influenced by the following factors:

- Severe overtopping of the storm barrier;
- Use of unarmored highly erodable sandy soils for construction of the earth portions of the levees which could not resist the effects of overtopping;
- Accelerated erosion of soils at the transition between soil and concrete structures; and
- Lack of capping on sheet piles.

The storm surge levels in this area were on the order of 18 to 25 feet, which significantly exceeded original design conditions and the +17.5 feet levee crest elevation. It is no surprise, therefore, that the levees were damaged as much as was observed. Large segments of the levees along the St. Bernard Parish bank of the MRGO were completely destroyed by the storm. Studies at Louisiana State University (LSU) suggest that the MRGO and East New Orleans levees form a funnel-like structure which intensifies a wave sent into the funnel. During hurricane Katrina, the St. Bernard Parish levees bore the brunt of the storm surge. Advanced Circulation (Model ADCIRC) analyses examined by coastal engineers from the NSF/ASCE team suggest that the higher surge along the MRGO levees was due in part to the northeasterly winds as the hurricane approached and the long straight section of levees perpendicular to the wind direction, rather than a funneling effect. This storm surge was then transmitted into the MRGO and the IWW.

Table 4.1: Summary of Damage to Primary Levee System in the Lower Ninth Ward/St. Bernard Parish Polder

Location [Figure 4.1 Designation]	*Levee Type*	*Damage Summary*	*Length of Breach or Damaged Section*	*Notes*
IHNC, East Side, South Breach, (Lower Ninth Ward) [1]	I-wall	Breach	930 ft	Significant scour found at the toe of adjacent levee sections Emergency repair was overtopped in Hurricane Rita
IHNC, East Side, North Breach, (Lower Ninth Ward) [2]	I-wall	Breach	210 ft	Significant scour found at the toe of adjacent levee sections
Intracoastal Waterway/ MRGO, Bayou Bienvenue Gate Site [3]	Sheet Pile	Breach	~ 80 ft	Located at transition to concrete gate structure Earthen levee located west of site was overtopped; however, no significant damage occurred.
MRGO, Southwest Bank [4]	Earthen and Sheet Pile Sections	Multiple Breaches		Extensive damage to wide stretches of levee
Bayou Dupree Gate Site [5]	Earthen and concrete sheet pile sections	Multiple breaches		Complete washouts of earthen and concrete sheet pile sections

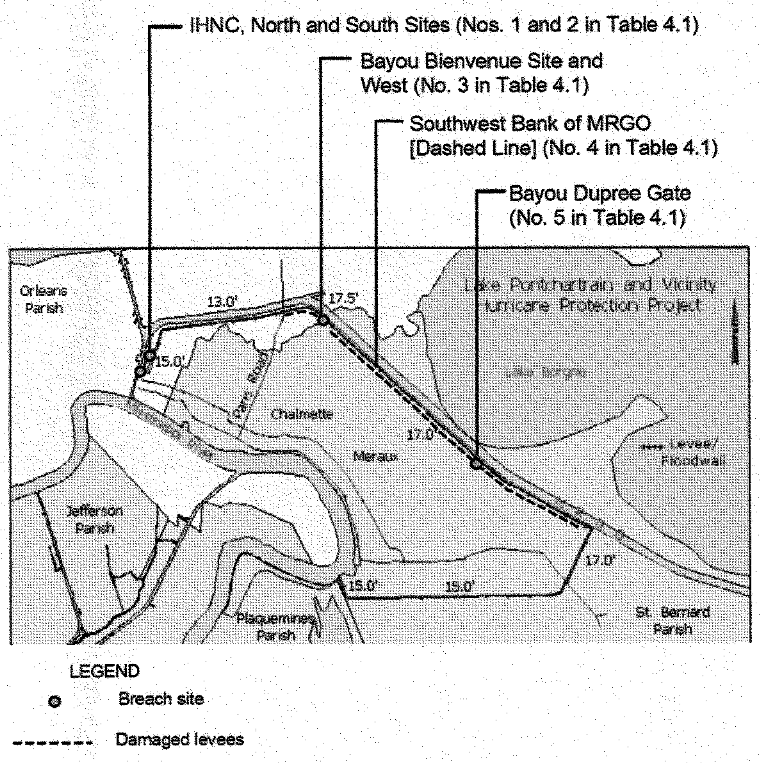


Figure 4.1: Overview map of the Lower Ninth Ward/St. Bernard Parish Polder showing the locations of damage to the primary levee system. Sites nos. 1 through 4 are summarized in Table 4.1. The elevations shown correspond to the top of the levee system at each location (after USACE).

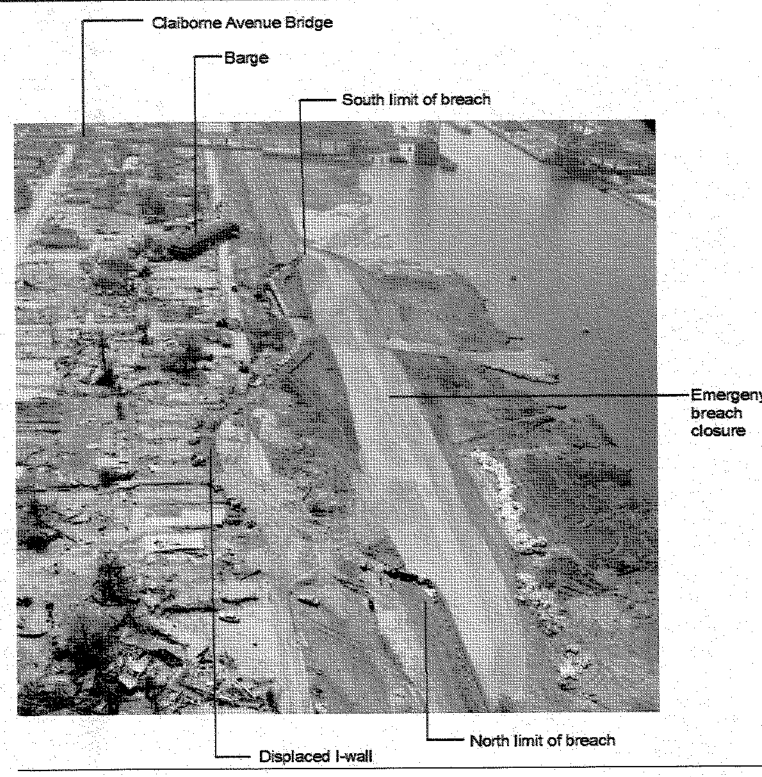


Figure 4.2: Aerial view of the south breach at the Lower Ninth Ward (L. Harder, October 14, 2005).

Figure 4.3: Airborne digital imagery of the south breach at the Lower Ninth Ward. Water is shown flowing back into the IHNC (courtesy NOAA, August 31, 2005).

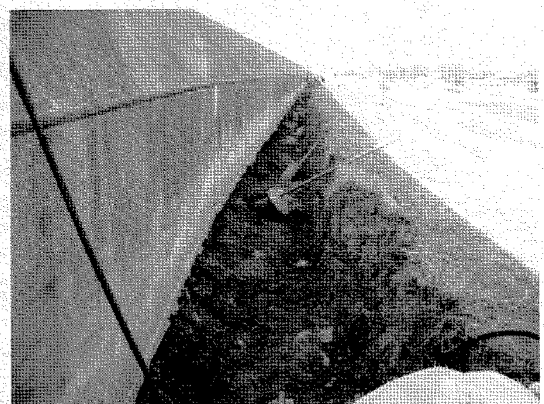


Figure 4.4: North view from the end of the south breach of Lower Ninth Ward. Note how the scour trench becomes progressively wider as it approaches the breach (J. Wartman, October 4, 2005).

Figure 4.5: A barge was drawn through the south breach of the Lower Ninth Ward (J. Wartman, October 4, 2005).

Figure 4.6: South view of the south breach repair at the Lower Ninth Ward (J. Wartman, October 4, 2005).

Figure 4.7: Airborne digital imagery of the north breach at the Lower Ninth Ward. Water is shown flowing back into the IHNC (courtesy NOAA, August 31, 2005).

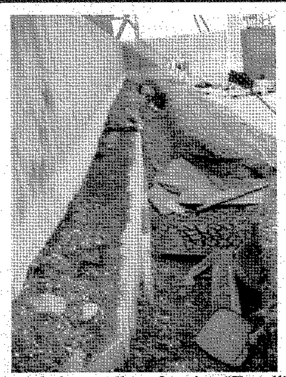


Figure 4.8: A scoured, but nevertheless well-performing "T-wall" levee section located near the north breach of the Lower Ninth Ward (J. Wartman, October 4, 2005).

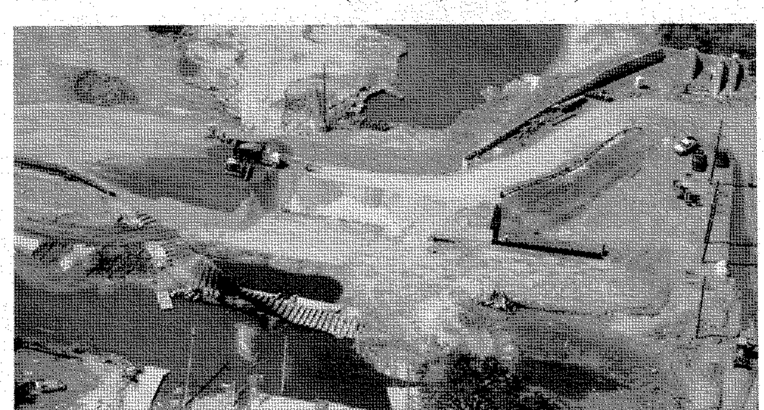


Figure 4.9: Aerial view of the north breach of the Lower Ninth Ward (L. Harder, October 14, 2005).

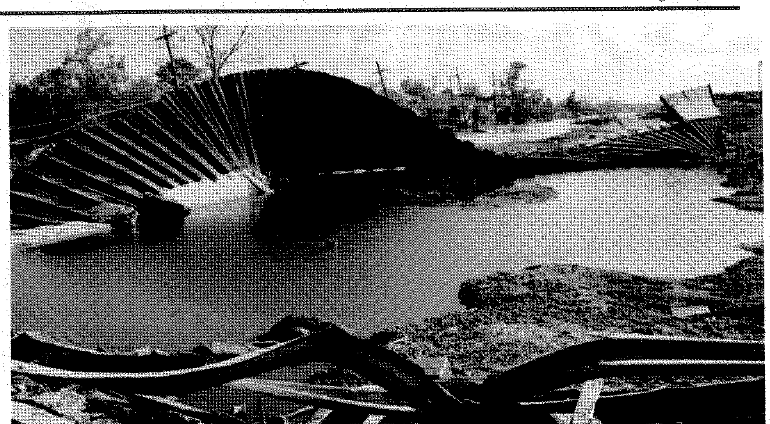


Figure 4.10: Overturned I-wall system at north breach of Lower Ninth Ward (J. Wartman, October 4, 2005).

Figure 4.11: Looking south along the north breach repair at the Lower Ninth Ward (J. Wartman, October 4, 2005).

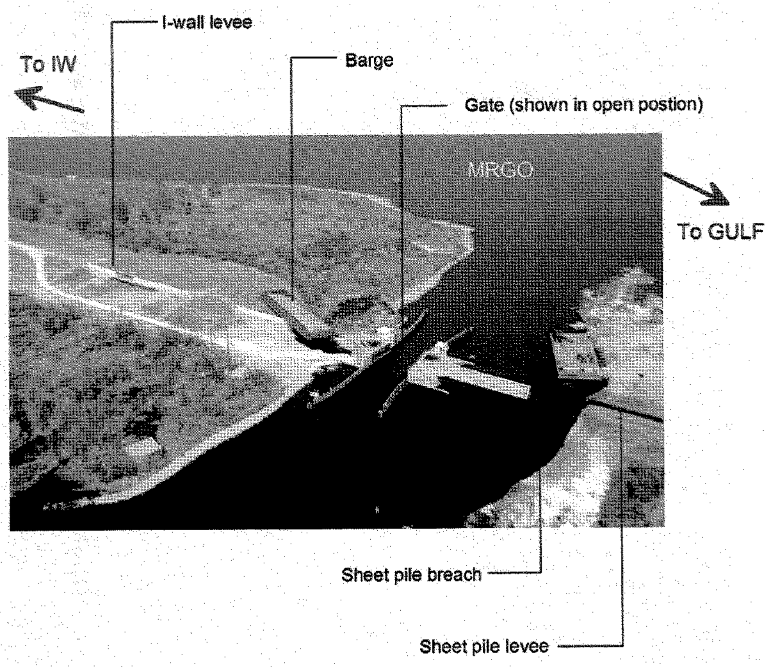


Figure 4.12: Northwest facing aerial view of the Bayou Bienvenue Gate structure (L. Harder, October 14, 2005).

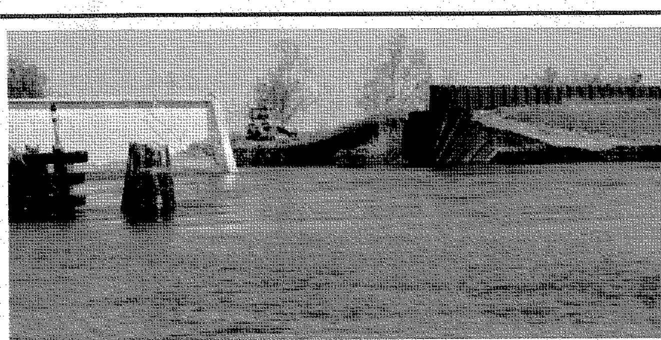


Figure 4.13: Sheet pile breach at the Bayou Bienvenue Gate (J. Wartman, October 5, 2005).

Figure 4.14: Scour near barge damage at the Bayou Bienvenue Gate site (J. Wartman, October 5, 2005).

Figure 4.15: Scour near Bayou Bienvenue Gate site (L. Wooten, October 5, 2005).

Figure 4.16: View of levee along the south bank of the Intracoastal Waterway from the Rt. 47 Bridge (Lee Wooten, October 6, 2005).

Figure 4.17: Debris line near levee crest just west of the Rt. 47 Bridge south abutment (L. Wooten, October 5, 2005).

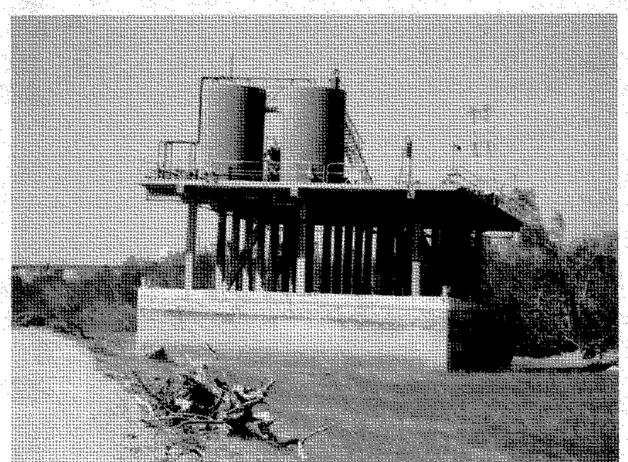


Figure 4.18: Various barges and other floating structures made contact with the earth levees without causing significant damage. Photo shows a gas processing barge (F. Silva, October 1, 2005).

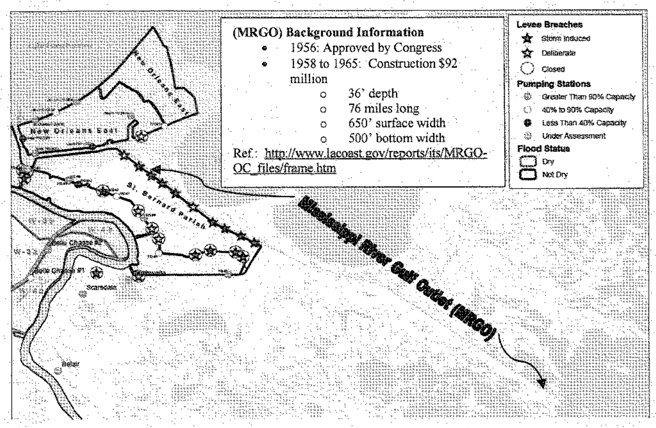


Figure 4.19: Mississippi River Gulf Outlet [MRGO] (USACE). The two yellow stars (i.e., deliberate breaches) along MRGO seem to correspond to locations of gate structures where storm-induced breaches occurred. These yellow stars markers are likely errors in the original map that should have been designated using blue star markers.

Figure 4.20: Failure of earth levee with steel sheetpile barrier on the southeast bank of the MRGO. Note severe erosion and scour (L. Wooten, October 6, 2005).

Figure 4.21: Levee failure on southwestern bank of MRGO between Bayou Bienvenue (where barge is aground on I-wall) and Bayou Dupree. Note severe erosion and scouring (L. Harder, October 14, 2005).

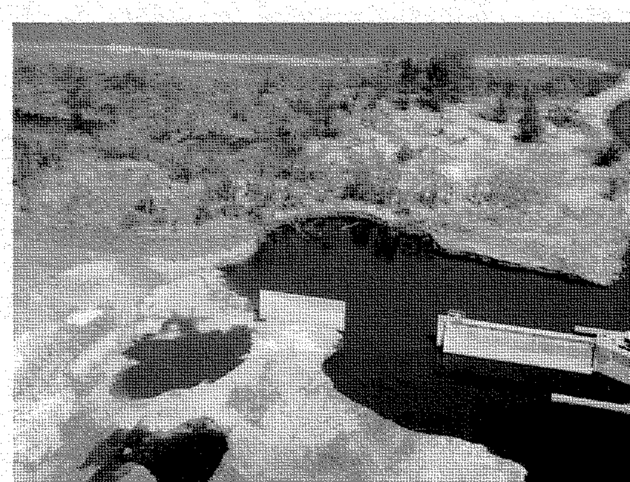


Figure 4.22: Levee failure on southwestern bank of MRGO at Bayou Dupree. Note concrete sheetpile and levee transition washouts (L. Harder, October 14, 2005).

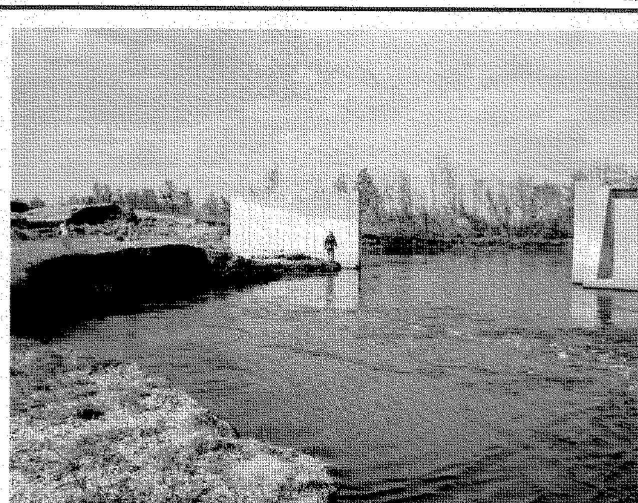


Figure 4.23: Ground perspective of Bayou Dupree gate abutment failure (L. Wooten, October 6, 2005).

Figure 4.24: Failure of earth levee on southwest bank of MRGO adjacent to the Bayou Dupree gate (L. Wooten, October 6, 2005).

Figure 4.25: Overtopping obliterated earth levee along southwestern bank of MRGO, within two miles southeast of Bayou Dupree. Note deep scour at the levee foundation level (L. Harder, October 14, 2005).

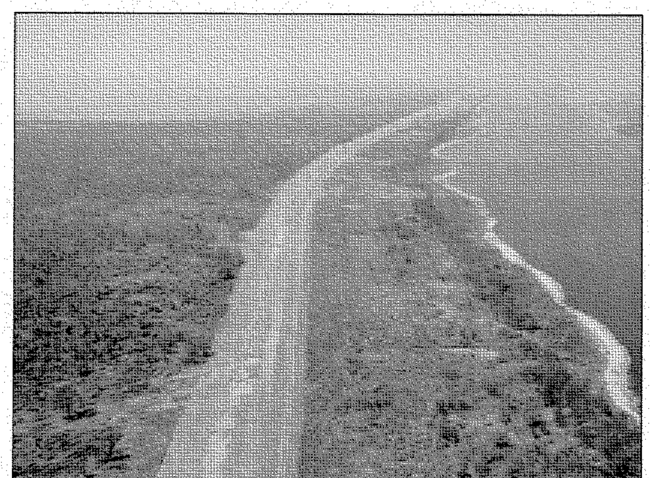


Figure 4.26: Aerial view of MRGO looking towards the city of New Orleans (L. Harder, October 14, 2005).

Chapter Five: Plaquemines Parish

5.1 Overview

Plaquemines Parish is the area where the last portion of the Mississippi River flows into the Gulf of Mexico (see Figure 1.5). Extending southeast from New Orleans, Plaquemines Parish straddles the banks of the Mississippi River for about 70 miles out to the river's mouth in the Gulf. It is an area that is sparsely populated, with only about 27,000 people in the entire parish (see Plaquemines Parish Government Website: http://www.plaqueminesparish.com/). Most of the residents live in small, unincorporated towns and villages along the river. Not only are these communities subject to potential flooding from the Mississippi River, but they are also vulnerable to flooding from hurricane surges because the parish extends so far out into the Gulf from the mainland. For flood protection from the Mississippi River, large federal project levees were constructed along both sides of the river. For many of the communities lying along the Mississippi River levees, hurricane or back levees were also constructed behind them to protect them from hurricane surges coming from the Gulf. Thus, many of the homes in these areas are sandwiched between two sets of levees: one along the river and the other behind the towns.

Hurricanes Katrina and Rita devastated many of the Plaquemines Parish communities. Hurricane Katrina was reported to have induced storm surges up to 20 feet in this region, which overtopped and damaged many portions of the hurricane levees. Both the United States Army Corps of Engineers (see Figure 1.5) and the Plaquemines Parish Government website report numerous breaches of the hurricane levees and widespread deep flooding and destruction (see Figures 5.1 through 5.3).

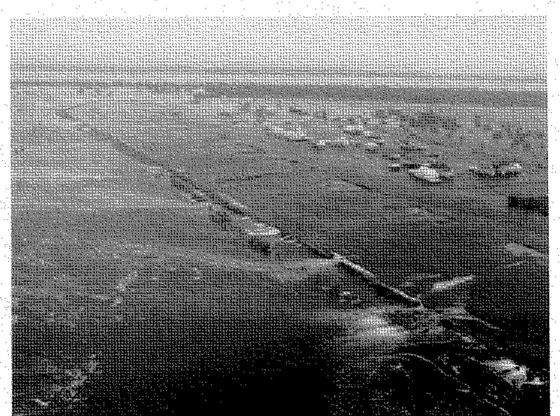
5.2 Pointe a la Hache

Pointe a la Hache is the parish seat for Plaquemines Parish and is located along the east side of the Mississippi River. Storm surges from the east largely overwhelmed the back levee, breached it in several places, and inflicted deep flooding and widespread destruction in this town. Figure 5.4 presents an aerial photograph of one such breach taken on September 25, 2005 (from Plaquemines Parish Government Website). Shown in this photograph is a temporary road constructed across the breach to facilitate access and repairs.

Figure 5.5 shows this same levee breach a few weeks later during the installation of a sheetpile cutoff that was undoubtedly intended to be part of an interim, and perhaps permanent repair. The team members viewing the installation believed that the sheetpile wall was a good concept to effect a positive cutoff of seepage through the deeply scoured breach and loose debris. However, during the installation, team members noted that the contractor was having difficulty advancing the southern portion of the sheetpiles very far into the ground with the equipment in use at the time of the team's visit. It is not known how the contractor resolved this situation.

Residences in Pointe a la Hache were commonly inundated to depths of 12 to 15 feet (see Figure 5.6). Flooding was so great that water flowed across the community from the east towards the Mississippi River, and even overtopped the Mississippi River levee by several feet. Based on debris found on tractor equipment left on the levee crown along the Mississippi River, overflows of up to 4 feet were estimated. For the areas visited by the teams, no significant damage was observed on the Mississippi River levee, possibly because the river sides of the levees viewed by the team were paved with concrete slope protection (see Figure 1.11).

Like many New Orleans residences, the small wooden homes in Pointe a la Hache were commonly founded on cinderblock piers. As a result of the deep flooding and the flow towards the Mississippi River, homes in Pointe a la Hache were commonly picked up and floated away from their foundations. Many ended up being deposited on or across the Mississippi River Levee as a result of flood waters flowing into the Mississippi River (see Figures 5.7 through 5.9).

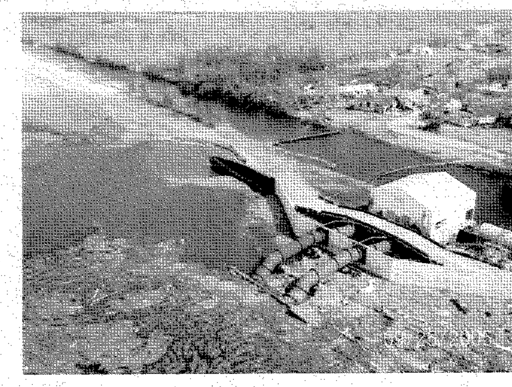


Source: http://www.plaqueminesparish.com/

Figure 5.1: Aerial photograph of inundated portion of Myrtle Grove along western side of the Mississippi River (September 25, 2005)

Source: http://www.plaqueminesparish.com/

Figure 5.2: Aerial photograph of levee breach of hurricane (back) levee along western side of the Mississippi River near the community of Sunrise (September 25, 2005)



Source: http://www.plaqueminesparish.com/

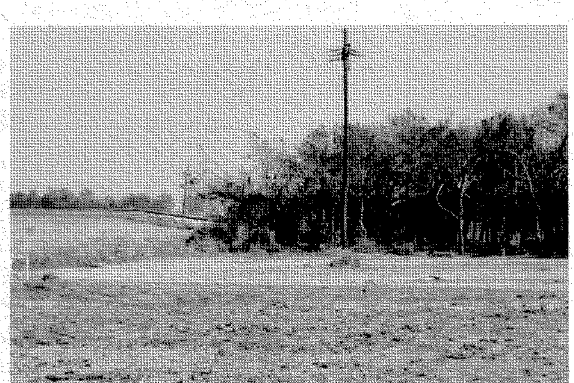
Figure 5.3: Aerial photograph of levee breach of hurricane (back) levee at levee transition near Hayes Pump Station (September 25, 2005)

Source: http://www.plaqueminesparish.com/

Figure 5.4: Aerial photograph of levee breach of hurricane (back) levee east of Pointe a la Hache (September 25, 2005)

Photograph by Les Harder

Figure 5.5: Photograph of sheetpile cutoff being placed into levee breach of hurricane (back) levee east of Pointe a la Hache (October 12, 2005)



Photograph by Les Harder

Figure 5.6: Photograph of flood elevation on trees landward of hurricane levee east of Pointe a la Hache – illustrating that flood water remained to large depths for extended periods (October 12, 2005)

Photograph by Les Harder

Figure 5.7: Photograph of Pointe a la Hache home deposited on Mississippi River levee crown after storm surges overtopped this levee from the east (left) towards the river – which is to the right in this photograph (October 12, 2005)

Photograph by Les Harder

Figure 5.8: Photograph of Pointe a la Hache homes deposited on Mississippi River levee after storm surges overtopped the levee from the east (left) towards the river (right) (October 12, 2005)

Photograph by Les Harder

Figure 5.9: Photograph of Pointe a la Hache home site where wooden home was floated off of its cinderblock piers – note concrete stairs and black plastic sheet in tree illustrating the depth of flooding (October 12, 2005)

Chapter 6 – The New Orleans Flood Defense System

The physical components of the New Orleans Flood Defense System (NOFDS) include levees and flood walls, flood gates and adjacent structures, canals, and pump stations.

During this initial phase of field work, primary attention was focused on the levees and flood walls. As the work proceeded, it became apparent that the other elements that comprise the NOFDS play equally important roles in defending the city against potential flooding. In addition, it was readily apparent that the organizational components of the NOFDS played roles that had very important effects on the performance of the NOFDS during hurricanes Katrina and Rita.

The USACE has been primarily responsible for overseeing the design and construction of many of the elements in the NOFDS. After commissioning of the completed flood protection elements, they are transferred to other organizations to be operated and maintained. These other organizations include not only local public agencies (e.g.: the New Orleans Levee Board, and the New Orleans Sewage and Water Board) but also private agencies and in some cases private property owners. (e.g.: Department of Transportation roadways and highways, railways, private shipping companies, etc.). The USACE does not maintain direct control and supervision of the flood protection elements over the life of the elements.

In our surveys of the NOFDS it was not always clear which agency had responsibilities for what part or parts of the system. In many instances, it was clear that flooding and breaching of the NOFDS had developed because of breakdowns within the multiplicity of organizations or at their interfaces.

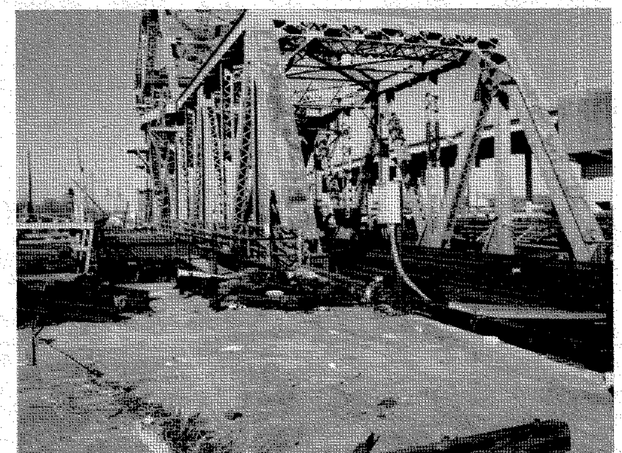
An example of system vulnerabilities associated with the multiplicity of organizations was found on the east side of the IHNC at the lake front adjacent to the railroad bridge that crosses this canal near the Lakefront Airport (Figure 6.1). Inspections of this area clearly indicated that large amounts of water had entered through a railway opening in the adjacent concrete flood wall and soil levee (Figure 6.2). The inspection did not disclose the presence of a flood gate that had closed the railway opening, even though immediately adjacent to this opening was a securely closed flood gate and concrete flood control structure maintained by the USACE (this gate and the adjacent flood control structure had not been breached and showed no signs of overtopping). The low spot in this complex interchange was the base of the railroad ballast, and it was here that the water had flowed through. Attempts had been made to place sandbags prior to the arrival of hurricane Katrina; the attempts had not been successful and water had poured through the opening flooding the areas immediately south and west of the opening.

Another example of system vulnerabilities associated with the multiplicity of organizations occurred in the same area, near the lake front airport (Figure 6.3). The earth levee that paralleled the lake front defending the neighborhood to the south of the Lakefront airport had experienced some overtopping, but water had breached a section between the adjacent flood control structure (concrete, flood gate closed) and the earth levee (Figure 6.4). The earth levee was at an elevation that was lower than the flood control structure. Massive scour had developed in the earth levee due to the surge waters. This water was then conducted into the adjacent neighborhood through the road underpass. There were no flood defenses provided for the road underpass.

We visited one of the key pumping stations that are responsible for pumping water collected from within the city into the drainage canals, and thence into Lake Pontchartrain (Figure 6.5). These pump stations were put in service in the early 1900's, and many of the electrically driven pumps bore manufacturing identification plates that bore testimony to their age (Figure 6.6). The pumps were very old, and were obviously kept in service by tender loving care. While we were there, work was underway to dry out the pumps and associated electrical control equipment that had been submerged during the flooding - including the banks of stand-by batteries that are shown in Figure 6.7. Discussions with the pump station operators that had been present at the time of the hurricane disclosed how, as the water rose in the pump station, a decision was made to shut-down the pumps and evacuate the operating personnel by walking out on the adjacent 'elevated' railway. At this point in the storm, there was no hope of being able to pump water from the rapidly flooding city.

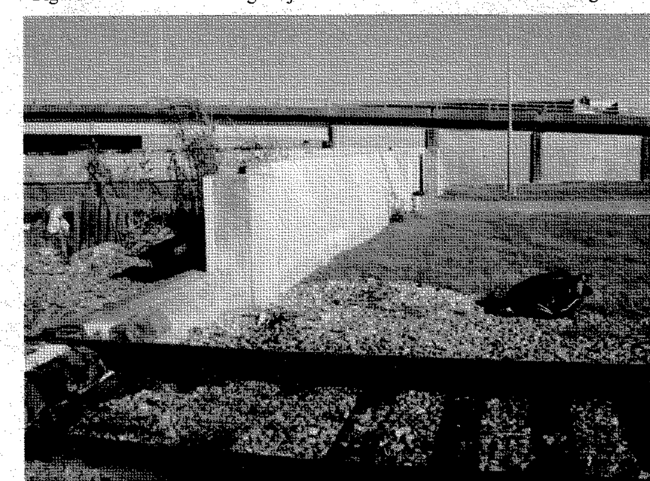
After touring the pump station, we surveyed the area immediately outside of the pump station to determine how the flood walls and other parts of the levee system had performed. We found that it had performed very well, with little signs of overtopping. However, as we toured the area we found that there were 5 different elevations of different parts of the levee system in a small area (Figure 6.8). A significant example of this occurs on the east bank where the floodwall on the earthen levee abruptly ends at a considerable distance (some 300 feet) before the levee reaches the pumping station, leaving a long, low gap where there should have been a contiguous, closed perimeter flood defense. A similar situation occurs on the west side where the floodwall transitions into a short stretch of sheet pile with a considerably lower elevation. Note that these gaps provide access of floodwater into the surrounding residential areas at a water level well below the flood protection system design level. Some overtopping had in fact occurred in both places, as reported by the pump station operator, who was onsite during Hurricane Katrina. Other variations in the elevations of the flood defense elements were correlated with the agencies that had responsibilities for various parts of this part of the system, (e.g. highway department determining the heights under the road overpass immediately adjacent and upstream of the pump station, Figure 6.9)).

At the end of this data and information gathering process, it was apparent that vulnerabilities had been embedded in the physical aspects of this system. These vulnerabilities were often found at transitions between flood protection elements and/or where other infrastructure was involved. In many cases, multiple organizations were involved, and the system was such that any imperfections in the merging of the different elements resulted in vulnerabilities in the overall system. These weak links needed much more coordination, review, and oversight to prevent the failures that occurred, and which could occur again if not remediated.



Photograph by Robert Bea

Figure 6.1: A railroad bridge adjacent to the Lake Pontchartrain frontage road.



Photograph by Robert Bea

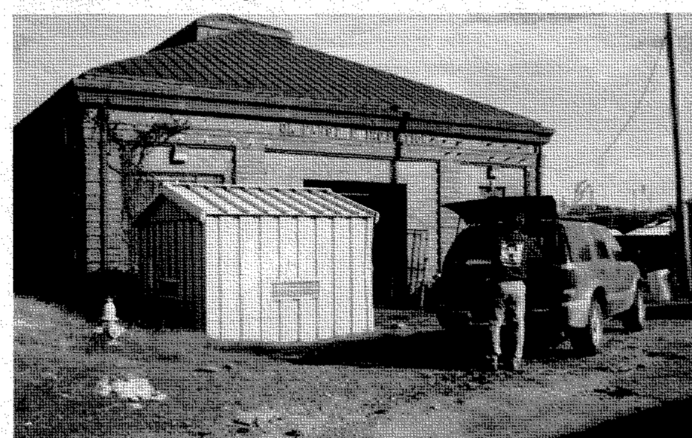
Figure 6.2: Lack of a floodgate at the railroad line crossing resulted in scour around the railroad tracks. No overtopping was observed the floodgate across the adjacent roadway.

Photograph by Rune Storesund

Figure 6.3: Lack of a flood gate beneath the railroad over-crossing facilitated the flooding of residential neighborhoods.

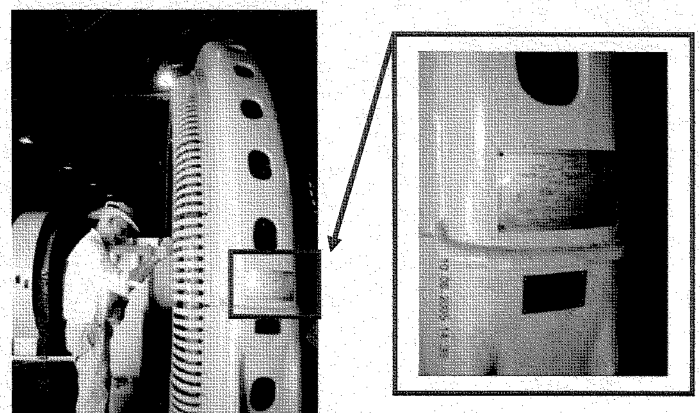
Photograph by Rune Storesund

Figure 6.4: This flood protection levee was overtopped and scoured, resulting in flooding of this lakefront residential area.



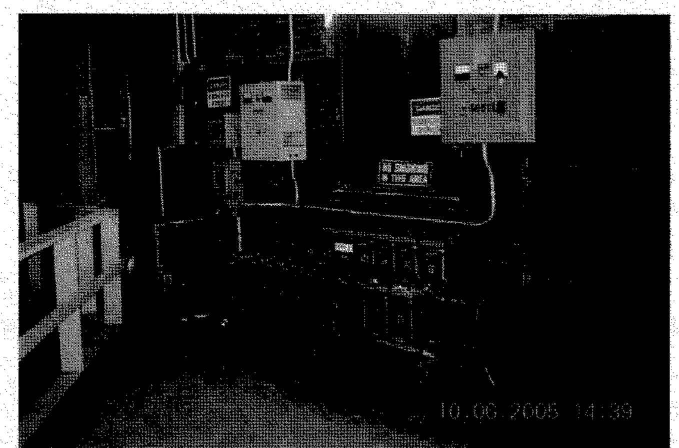
Photograph by Rune Storesund

Figure 6.5: Side view of the Orleans Canal pumping station.



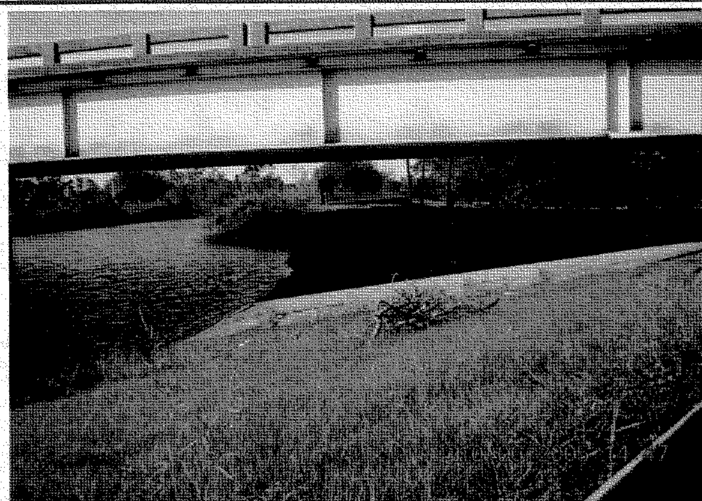
Photograph by Rune Storesund

Figure 6.6: Original pump equipment at the Orleans Pumping Station from the early 1900s.



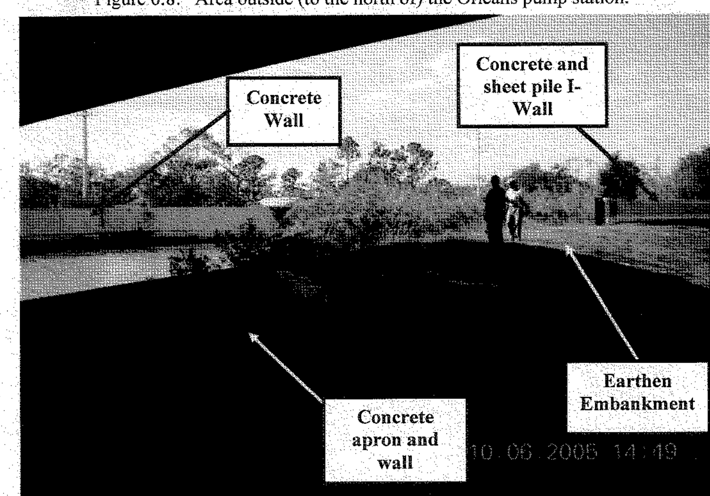
Photograph by Rune Storesund

Figure 6.7: A battery bank in the pump station used for "emergency" power.



Photograph by Rune Storesund

Figure 6.8: Area outside (to the north of) the Orleans pump station.



Photograph by Rune Storesund

Figure 6.9: At the Orleans Canal pump station, the flood protection system consisted of different components, each with a different "top of wall" elevation.

Chapter Seven: Terrestrial LIDAR Imagery of New Orleans Levees Affected by Hurricane Katrina

7.1 Introduction

Preservation of information regarding the magnitude and geometry of structural and geotechnical deformations is paramount for the analysis of levee failure modes. This chapter describes the areas of focus and methodology used in laser mapping of surface evidence of levee deformation and distress at ten areas within the greater New Orleans area. The area of focus extends from the 17th Street Canal in the Orleans East Bank area, to the Entergy power plant in the New Orleans East area. The NSF-sponsored investigation team included two researchers from the United States Geological Survey (USGS) who brought to the field area a terrestrial laser mapping tool to perform laser scanning or LIDAR (LIght Detection And Ranging) data collection. The laser mapping effort was conducted over 5 days from October 9-14, 2005. The objective of the laser scanning effort was to obtain precise measurements of the ground surface to map soil displacements at each levee site, the non-uniformity of levee height freeboard, depth of erosion where scour occurred, and distress in structures at incipient failure. Toward that end, ten sites were visited for LIDAR scanning (Figure 7.1). The sites, along with their global position coordinates (WGS84 Datum) and the number of individual scans collected at each site are outlined in Table 7.1. Because several of the sites are less than one kilometer apart (i.e. Sites 2 & 3, Sites 4 & 5, and Sites 6 & 7), individual scans from each of these site pairs were collected and developed as a single LIDAR model and are listed jointly.

7.2 Methodology

The terrestrial LIDAR method, a 3D laser scanning technique, consists of sending and collecting laser pulses from surface objects to build a point file of three-dimensional coordinates. The time of travel for a single pulse return from a surface is measured along a known trajectory such that the distance from the laser and consequently the exact location can be computed. In addition, visual data on points located within and outside of the laser range can be obtained through the use of a CCD color sensor. A unique aspect of the LIDAR method is the rapid rate of data collection. The USGS laser scanning system can measure the location of up to 8,000 surface points in one second. Thus within a few minutes, an entire surface, be it a structure or levee, can be imaged efficiently with a point file that contains several million position points. The point files from collected scans are typically transformed into three-dimensional surfaces so that cross-sections can be generated and volumetric calculations can be performed between consecutively scanned surfaces.

The LIDAR technique has been successfully utilized by members of the reconnaissance team in a wide range of environments, most recently, for studies involving coastal bluff change along the California coast (Collins and Sitar, 2004, 2005), and in earthquake reconnaissance studies (Kayen et al., 2004, Kayen et al., in press). Complete details of the laser scanning process can be found in these references.

In the study of damage to the levee systems protecting the New Orleans area, the USGS scanning laser, a Riegl Z210 scanner (Riegl, 2005), was utilized as a tripod mounted survey instrument (Figure 7.2). To improve the imagery and increase the efficient transportation of the sensor between scans, the tripod was elevated to a fixed platform on the roof of the field vehicle. Elevating the scanner to approximately 4 meters above the ground reduced shadow zones and extended coverage of each scan. The laser was set up over existing survey benchmarks where available, to tie the data into georeferenced coordinates. However, for the most part, a separate, local coordinate system was utilized for each site. Each laser scan collected approximately 2.3 million data points, scanning an azimuthal range up to 336 degrees and an elevation range of positive 40 degrees to negative 40 degrees measured from the horizontal.

Multiple scans were collected to fill in "shadow zones" of locations not directly in the line of sight of the laser and to expand the range and density of the point data. Processing of the data was performed using the I-SiTE software program (I-SiTE, 2005) specifically designed to handle laser data. Specific details of the processing procedures used at each site are provided with each location's summary.

The range of radial target distances for natural targets is approximately 2 m - 400 m and at these distances the point measurement accuracy is 0.8-2.5 cm, depending on specific laser settings. Time required for scanning at fine-scale density of points (e.g., 2.3 million targeted points) is 4 minutes. In New Orleans, the fine-scale resolution was used to scan the levee sections in most cases. At the highest resolution, the angular separation of the vertical line scans is 0.01°. Thus, the near-field point separation is less than 1 mm and the separation of the farthest data at 400 m can be about 7 cm.

The angular position of the laser-pulse leaving the scanner is controlled by precise stepper-motors within the unit. The scanner makes millions of individual x, y, z position measurements that together form a "point cloud" data set of information about the solid objects that return reflected pulses. The USGS scanner has an optical sensor that records reflective color and intensity. With the addition of a color channel, the natural appearance of the surface can be draped on to the three dimensional surface model. Several useful applications of the color and intensity channels are to (1) extract non-topographic textural information about the target; (2) identify color-based lithologic changes in the target; and (3) enhance and identify georeference reflectors that send back the strongest reflected signal. On some occasions (less than 10 scans) during the team's reconnaissance mission, schedules necessitated night-time data collection such that real-color scans were not collected. This only affected the color imagery of the data, not the positional accuracy or resolution of the point files.

In most cases, after arriving at a site, the scanner was mounted on a tripod on the roof of the field vehicle. In other configurations, the laser was placed on a tripod on the ground, or on its side, for example on the top of an I-wall section to scan downwards into toe scour (Figure 7.3). Typically, the scanner is set upright and leveled, with the unit rotating horizontally.

3-D laser scanners cannot see behind objects, therefore the first surface encountered casts a shadow over areas blocked from the view of the scanner. For example, it can be seen in a scan of the levee at the east side, north breach of the Inner Harbor Navigational Canal (IHNC), locally referred to as the Industrial Canal (Figure 7.4) that shadows are cast by near-field objects like the exhumed sheet pile foundation over the debris behind it. As the incident-angle of the laser point decreases, proportionally larger shadows are cast on the ground behind the target. Therefore, to minimize shadow zones and get full coverage of the target surface using terrestrial LIDAR, the scanner is moved to a number of locations surrounding the target zone (Figure 7.5). The levee scans involved 13 to 29 scanner set-ups to cover the entire feature and surrounding area and to minimize the number of shadow areas. Using multiple setups provided both a convenient way to limit the number of shadow zones while also increasing the resolution of the data collected and the boundaries of the scanned area.

7.3 Data Coverage: LIDAR scan sites at Levee Breaks within the New Orleans Area

Figures 7.6 through 7.12 define the approximate bounds of highly detailed continuous LIDAR data. Considerable data exist outside of these bounds, though they are not continuous and may have shadow effects. In general, point to point spacing of individual LIDAR data points within the outlined areas is on the order of 25 mm providing an extremely dense coverage of all objects within each site. However, typical surfaces generated from the data are typically filtered to a minimum point separation of 10 to 50 cm when greater accuracy is not required.

7.4 Processing of LIDAR Imagery

At each levee site, the topographical surroundings were imaged on thirteen or more individual scans, together consisting of many millions of data points. The investigation team utilized the I-SiTE surface modeling software package, to both collect the scan point-cloud data and allow for post processing of multiple scans into geo-referenced solid surfaces.

After data are acquired, there is a suite of standard processing steps needed to produce a surface model. First, the multiple scans are either locally or absolutely geo-referenced to one-another. A least squares "best-fit" match is made between scans, augmented by precise survey measurements made with a total station or differential global positioning satellite (e.g., real time kinematic RTK-GPS, or Omnistar HP-differential GPS). Filters are then used to eliminate unwanted data. For example, typically filters are applied to remove vegetation-related data points so as to observe the "bare" earth. Finally, the filtered data serves as the working digital terrain model (DTM) that is used to render a solid surface of the object (ground). Again, different surface modeling schemes can be used to fuse and render a surface from multiple scans. The surface model represents a highly accurate virtual representation of the ground that can be used for documentation and change detection of volumes, areas, and distances.

7.5 Analysis Examples of Levee Deformation Using LIDAR Data

Laser mapping allows for highly accurate computation of rotation, length, area, and volume. Rotational displacement was common at areas of levee I-wall distress. For example, the east side of the London Canal immediately south of Robert E. Lee Boulevard suffered distress and lateral deformation associated with incipient failure of the levee. This movement is along a section of wall diagonally northeast of the west side breach across the canal. In Figure 7.13, an oblique image of the distressed wall can be seen from the south. The wall, preserved in incipient failure, leans toward the levee maintenance road and landside portion of the levee. In the right-hand background, is the bridge abutment on Robert E. Lee Blvd for reference.

Considerable vegetation grows along the banks of the canal side of the levee that are less maintained for growth than the landside neighborhood-side of the levee wall. Thin slices of the point-cloud data orthogonal to the alignment of the levee wall (Figure 7.14) display highly accurate cross sections of the distressed I-wall at London Canal. Segment (a) is toward the south (left) of Figure 7.13 and has a modest 1.9 degree rotational deformation. Near a position of maximum distress, the I-wall has 5.0 degrees of rotational deformation toward the landside of the levee.

The London Canal levee failure (west side) and distressed wall (east side) are both immediately south of the bridge crossing at Robert E. Lee Boulevard. A significant gap in height between the lower un-walled bridge abutment and I-wall prevents water from overtopping these levees. The height gap differs slightly between the walls located north and south of the bridge, due either to differing design heights or differential settlement following construction. At the distressed I-wall section on the southeast corner of the bridge, LIDAR surveys and visual inspection indicated the gap at this location was approximately 1.7 meters (5.6 feet). Therefore, water rising in the canal would overtop the bridge abutment and begin to flood the surrounding community when the water level was 1.7 meters (5.6 feet) below the top of the I-wall. Figure 7.15 shows this considerable wall gap, as well as moderate scour at the southeast edge of the bridge abutment (Figure 7.15a). On the northeast corner of the bridge abutment near the north levee wall, LIDAR surveys indicate the gap at this location to be approximately 1.51 meters (5.0 feet). Figure 7.16 and 7.17 show this gap, as well as a scour trench at the base of the northeast abutment (Figure 7.17a).

There was no evidence of overtopping of the levee walls or erosion scour anywhere along this section of the canal except at the gap at the bridge. The LIDAR and scour evidence therefore indicate that the floodwalls along the London Canal section, south of the Robert E. Lee Boulevard Bridge were not overtopped prior to failure of the levee wall.

Measurement of displacement along the 17th Street Canal breach can be made by identifying the blocks of ground formerly within the intact levee that slid eastward toward the landside of the levee. Figure 7.18 is an overview image of a portion of the 17th Street point cloud data set consisting of 11 individual scans. In this image, the bridge crossing over the canal at Robert E. Lee Blvd. (also called the Hammond Highway.) is toward the upper left (north). A dense cluster of points is visible at the levee breach in the center of the image as are the houses in the affected area. Close in to the levee breach in Figure 7.19, the remaining I-wall can be seen in alignment with the crest of the replacement structure. Here, a total breach repair width of 142 meters (466 feet) as measured between intact I-wall sections has been calculated directly from the LIDAR data set. A cross section taken through this area is shown in Figure 7.20. A multi-section view is shown, consisting of a section of the intact southern I-wall overlain over the failed section of the levee. The geometry of the emergency repair embankment is clearly visible. The sections also show the magnitude of the displacement of several earth blocks that moved away from the levee break during failure. While forensic work on the original positions of the earth blocks is still ongoing, the LIDAR data shows that blocks translated approximately 14 meters (46 feet) as measured from the existing alignment of the cyclone fence line to its new position within the displaced blocks. From the perspective shown in Figure 7.20, it can also be seen that the width of the 17^{th} St. Canal has been reduced about 6 meters (20 feet) by the placement of the earthen embankment.

A final example of the use of the LIDAR data is shown in Figure 7.21. Here, the dimensions of the scour trench in the vicinity of the east side IHNC – south breach are outlined. This view shows the depth of scour adjacent to the I-wall and into the embankment so that a direct comparison of the scour depth to sheet pile embedment can be made.

7.6 Summary

The LIDAR data presented herein present the scope of available data coverage of the failed sections of the New Orleans levee system following Hurricane Katrina. The methodology for processing the data has been outlined to provide important background information for maps, section views and calculations developed from the data and presented elsewhere in this report. Examples of specific applications of the utility of the data have also been presented to provide information on how the data sets may be utilized in ongoing and future investigations of the performance of the levee systems.

7.7 References

Collins, B.D. and Sitar, N. (2004) Application of High Resolution 3D Laser Scanning to Slope Stability Studies, 39th Symposium on Engineering Geology and Geotechnical Engineering, Butte, Montana, pp. 79-92.

Collins, B.D. and Sitar, N. (2005). Monitoring of Coastal Bluff Stability Using High Resolution 3D Laser Scanning, *ASCE Geo-Frontiers Special Publication 138:-* Site Characterization and Modeling, Remote Sensing in Geotechnical Engineering, E.M. Rathje, ed., ASCE, Austin, Texas, Jan 24-26, 2005.

I-SiTE (2005). I-SiTE 3D Laser Imaging Software (www.isite3d.com).

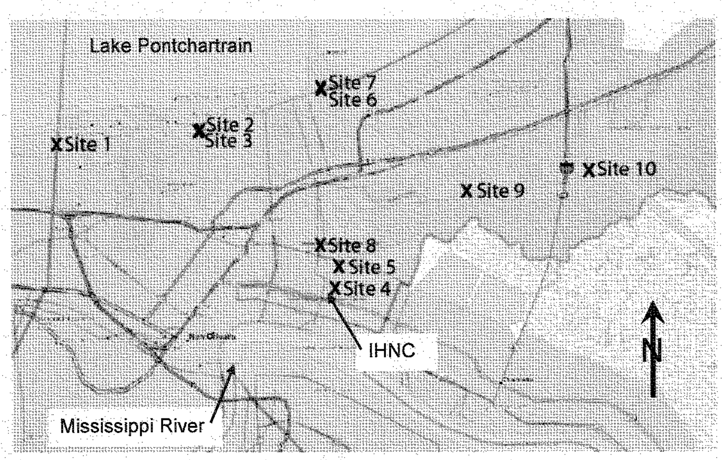
Kayen, R.,, Barnhardt, W., Carkin, B., Collins, B.D., Grossman, E.E., Minasian, D., Thompson, E. (2004) Imaging the M7.9 Denali Fault Earthquake 2002 Rupture at the Delta River Using LiDAR, RADAR, and SASW Surface Wave Geophysics, Eos Trans. AGU,85(47), Fall Meet. Suppl., Abstract S11A-0999.

Kayen, Robert, Robert T. Pack, James Bay, Shigetoshi Sugimoto, and Hajime Tanaka (In Press) Ground-LIDAR Visualization Of Surface And Structural Deformations Of The Niigata Ken Chuetsu, 23 October 2005, Earthquake, EERI, *Earthquake Spectra.*

Riegl (2005). Riegl 2D and 3D Measurement Systems (www.rieglusa.com).

Table 7.1 LIDAR Site Description Summary

LIDAR Site Number	Location	Latitude	Longitude	Number of LIDAR scans	Related Chapter in this Report
1	17th Street Canal	N30.0172°	W90.1214°	20	2
2	London Ave. Canal, North on east side	N30.0210°	W90.0704°	29 with Site 3	2
3	London Ave. Canal, North on west side	N30.0206°	W90.0708°	29 with Site 2	2
4	IHNC East Side, South Breach 9th Ward	N29.97243°	W90.02194°	13	4
5	IHNC East Side, North Breach 9th Ward	N29.97873°	W90.02042°	14	4
6	Lakefront Airport Levee Transition Breach	N30.03367°	W90.02622°	14 with Site 7	3
7	Lakefront Airport Levee I-Wall	N30.03436°	W90.02641°	14 with Site 6	3
8	Structural Distressed I-Wall at Container Wharf	N29.98614°	W90.0272°	20	2
9	Incipient Earth Levee Failure	N30.00200°	W89.97500°	14	3
10	Entergy Plant I-Wall Scour	N30.00900°	W89.93171°	20	3

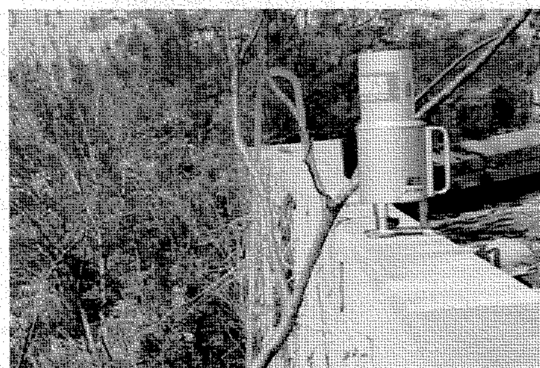


Source: Delorme TopoUSA

Figure 7.1: The ten sites investigated by the laser mapping method reside within the boundary of Orleans Parish.

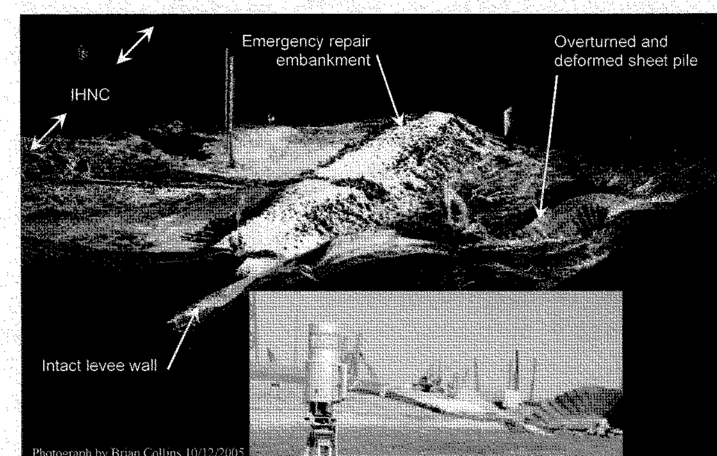
Photograph by Robert Kayen 10/13/2005

Figure 7.2: Entergy Plant I-Wall scanned using the USGS Coastal and Marine Geology Team terrestrial LIDAR unit and tripod mounted to the roof of our field vehicle. The fixed roof base allowed for the leveling of the tripod and LIDAR instrument on sloping ground.



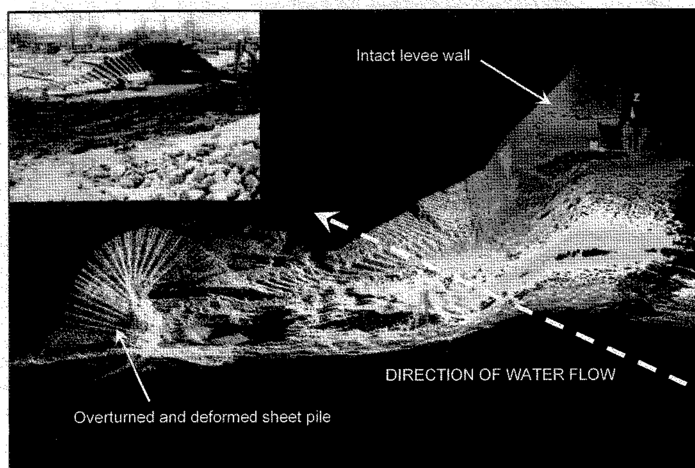
Photograph by Robert Kayen 10/10/2005

Figure 7.3: LIDAR scan system on top of the east I-wall at the London Avenue Canal. Scans of the canal side translational gap were made by placing the LIDAR on its side so the axis of rotation was horizontal.



Photograph by Brian Collins 10/12/2005

Figure 7.4. For complete coverage of the IHNC-North levee breach the laser was moved around objects that cast shadows. The sheet pile foundation and levee were imaged from both sides to complete the 3-D model.

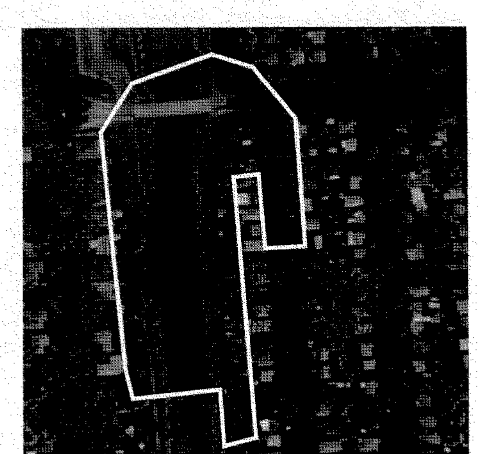


Photograph by Robert Kayen 10/11/2005

Figure 7.5: From another perspective, four separate LIDAR scans can be seen in the merged data file, each colored separately to differentiate them (red; white, purple, green). At the IHNC - North Site, 14 scans were merged into a single composite file.

Source: Modified from http://ngs.woc.noa7.gov/storms/katrina/24425575.jpg

Figure 7.6. Site 1, 17th Street Canal: (N30.0172° W90.1214°)

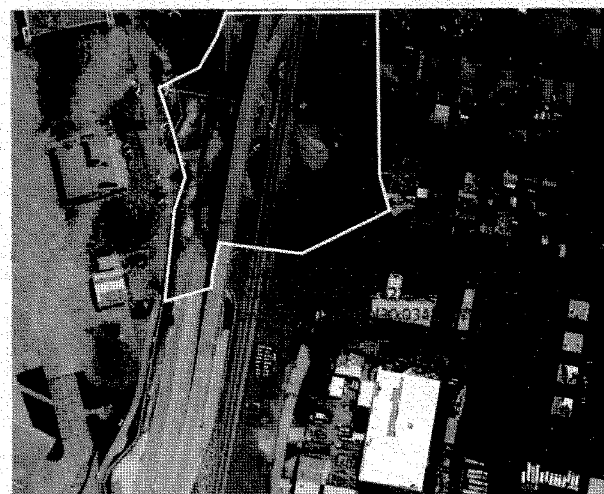


Source: modified from Google maps

Figure 7.7: Sites 2 & 3, London Ave. Canal, North on east side: (N30.0210° W90.0704°) and west side: (N30.0206° W90.0708°).

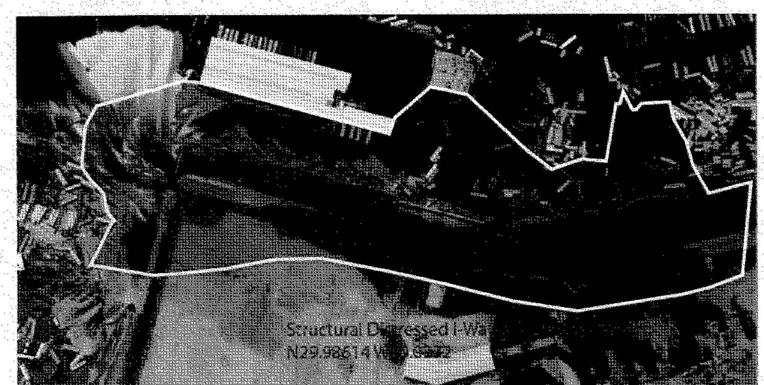
Source: modified from http://www.digitalglobe.com/images/katrina/new_orleans_surekote_levee_aug31_2005_dg.jpg

Figure 7.8: Sites 4 & 5, IHNC – South Breach: N29.97243° W90.02194° IHNC North Breach: N29.97873° W90.02042°.



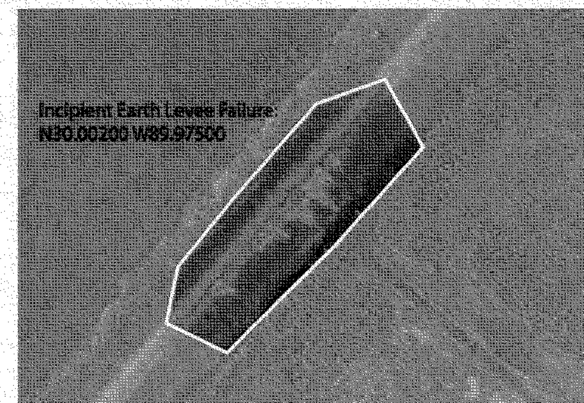
Source: Modified from http://ngs.woc.noaa.gov/storms/katrina/

Figure 7.9: Sites 6 & 7, Lakefront Airport Levee Transition Breach: (N30.03367° W90.02622°) and airport Levee I-Wall: (N30.03436°



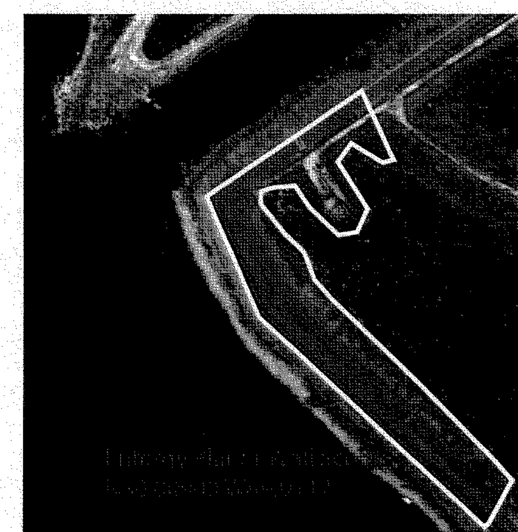
Source: Modified from http://ngs.woc.noaa7.gov/storms/katrina/

Figure 7.10: Site 8, Structural Distressed I-Wall at Container Wharf: (N29.98614° W90.0272°)



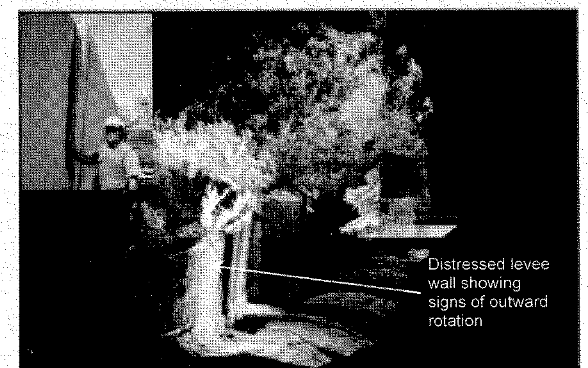
Source: Modified from http://ngs.woc.noaa.gov/storms/katrina/

Figure 7.11. Incipient Earth Levee Failure at N30.00200°, W89.97500°



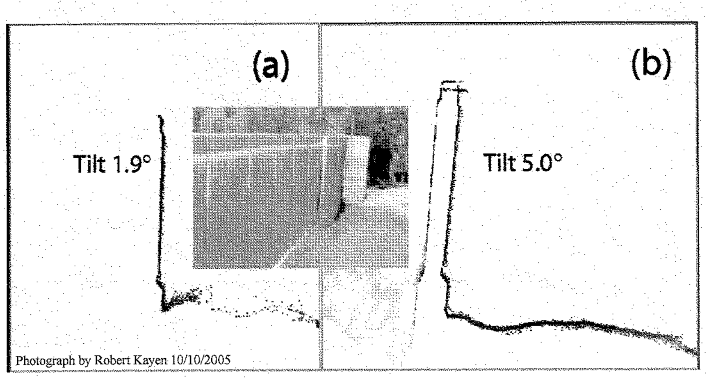
Source: Modified from http://ngs.woc.noaa.gov/storms/katrina/

Figure 7.12. Entergy Plant I-Wall Scour at N30.00900°, W89.93171°



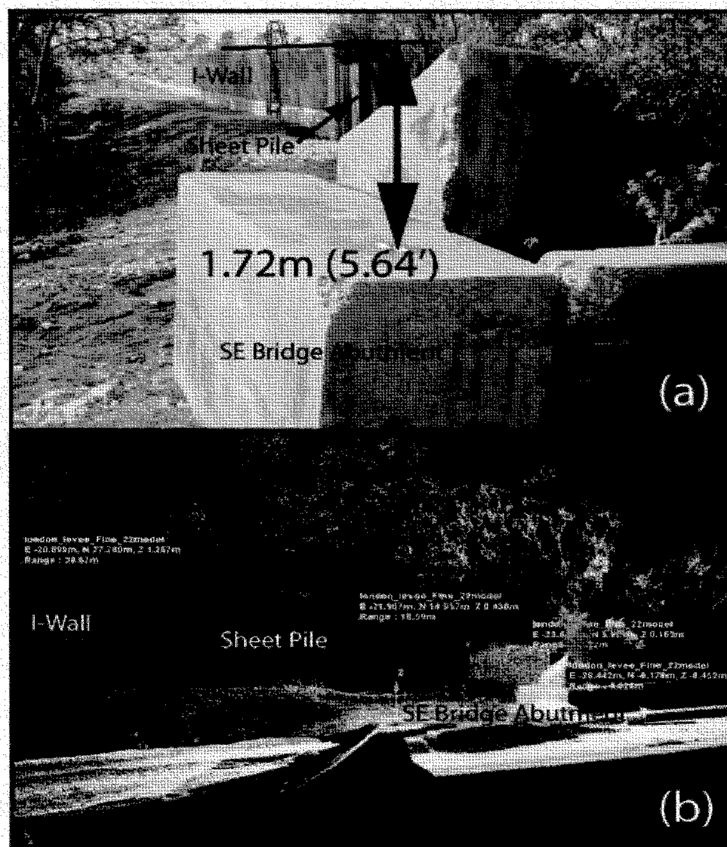
Photograph by Robert Kayen 10/10/2005

Figure 7.13: Leaning I-wall of a distressed portion of the London Avenue Canal. The wall leans toward the levee maintenance road and landside portion of the levee. In the right-most background is the abutment of the bridge on Robert E. Lee Blvd. along with vegetation on the canal side of the levee.



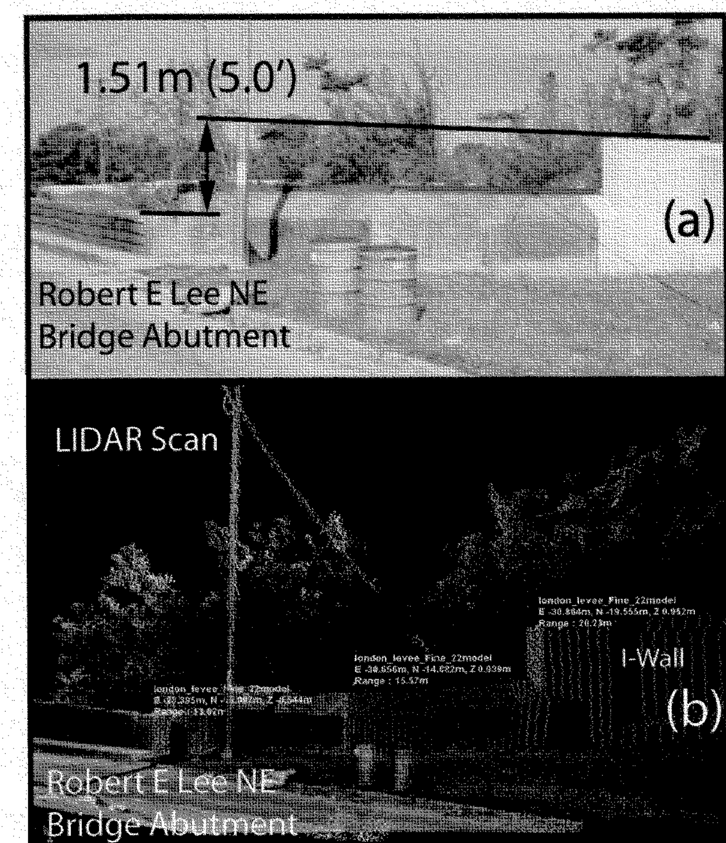
Photograph by Robert Kayen 10/10/2005

Figure 7.14: Cross sections through two segments of distressed I-wall at London Avenue Canal. Segment (a) is toward the south (left) of Figure 7.13 and has a modest 1.9 degree rotational deformation toward the landside of the levee. Near a position of maximum distress, the I-wall has 5.0 degrees of rotational deformation.



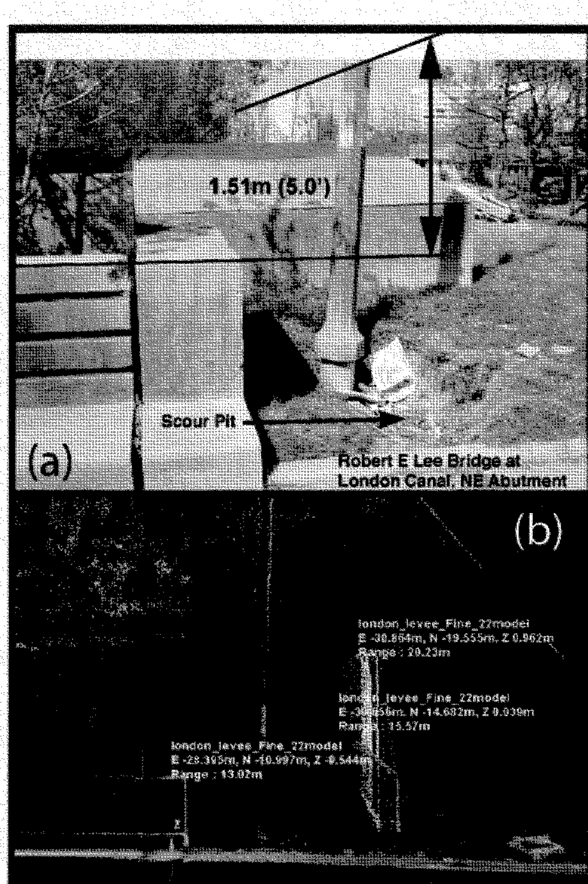
Photograph by Brian Collins 10/11/2005

Figure 7.15: Photograph of the southeast abutment of the London Avenue Canal bridge at Robert E. Lee Blvd (a), and LIDAR scan of the same location (b). New soil and rock apparently fills scour and sink hole erosion beneath the abutment. The relative height gap between the bridge abutment and the flood wall is 1.72 meters (5.6 feet).



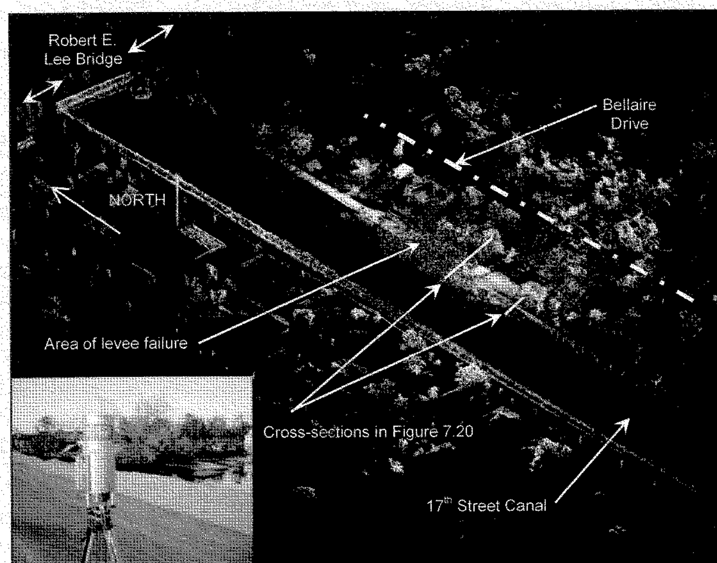
Photograph by Brian Collins 10/11/2005

Figure 7.16: The northeast abutment of the London Avenue Canal bridge on Robert E. Lee Blvd. in photograph taken from the lower portion of the bridge approach-fill embankment (a), and corresponding LIDAR scan (b). The wall gap here is 1.51 meters (5.0 feet).



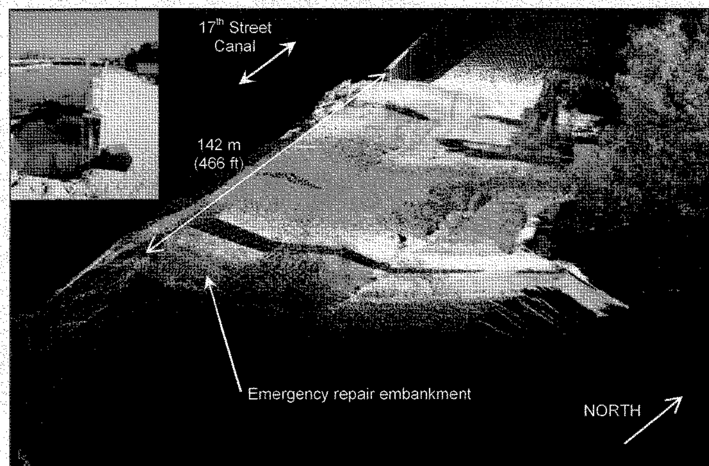
Photograph by Lee Wooten

Figure 7.17: Photograph taken directly south and adjacent to the northeast abutment of the Robert E. Lee Bridge (a), and corresponding LIDAR scan of the same location (b). A scour trench is clearly visible beneath the abutment. The wall gap here is 1.51 meters (5.0 feet).



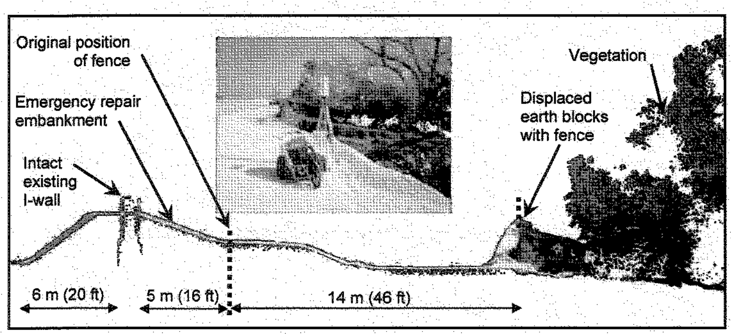
Photograph by Robert Kayen 10/9/2005

Figure 7.18: Overview oblique image of the 17th Street Canal area in the vicinity of the breach. The Robert E. Lee Blvd. Bridge is to the north (upper left) and the breach area is to the upper right (east). Houses within the neighborhood breach area and the scour pond were imaged from the new levee and Bellaire Drive.



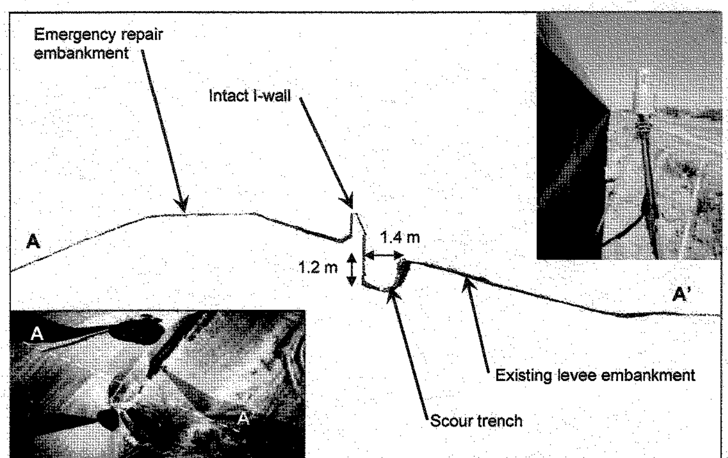
Photograph by Brian Collins 10/10/2005

Figure 7.19. An oblique close-in image of the as built replacement levee at the 17th Street Canal breach from the south. The remaining I-wall is visible on either side of the earthen embankment.



Photograph by Brian Collins 10/10/2005

Figure 7.20 Cross-section of the 17th Street Canal breach looking northward. Measurement of the lateral translation of the landside soil levee from its original position is approximately 14 meters (46 ft). The I-wall in this image is offset (out of the page) from the slide block.



Photograph by Brian Collins 10/11/2005

Figure 7.21: Measurement of scour trench dimensions at the IHNC – South site.

Chapter Eight: Summary of Observations and Findings

8.1 Summary and Findings

The storm surges produced by Hurricane Katrina resulted in numerous breaches and consequent flooding of approximately 75% of the metropolitan areas of New Orleans. Most of the levee and floodwall failures were caused by overtopping, as the storm surge rose over the tops of the levees and/or their floodwalls and produced erosion that subsequently led to failures and breaches.

Overtopping was most severe on the east side of the flood protection system, as the waters of Lake Borgne (which is directly connected to the Gulf of Mexico) were driven west producing a storm surge on the order of 18 to 25 feet that massively overtopped levees immediately to the west of this lake. A second very severe storm surge occurred farther to the south, along the lower reaches of the Mississippi River, and significant overtopping produced additional breaches in this region as well.

Overtopping was less severe along the Inner Harbor Navigation Canal and along the western portion of the Mississippi River Gulf Outlet/Gulf Intracoastal Waterway, but overtopping along these channels again produced erosion and caused additional levee failures.

Field observations suggest that little or no overtopping occurred along most of the levees fronting Lake Pontchartrain, but evidence of minor overtopping and/or wave splashover was observed at a few locations. One breach occurred in the lakefront levee system at the northwest corner of the New Orleans East protected area, near the Lakefront Airport.

Farther to the west, in the Orleans East Bank Canal District, three levee failures occurred along the banks of the 17th Street and London Avenue Canals, and these failures occurred at water levels below the tops of the floodwalls lining these canals. These three levee failures were likely caused by failures in the foundation soils underlying the levees, and a fourth "distressed" levee/floodwall segment on the London Avenue Canal shows signs of having neared the occurrence of a similar failure prior to the water levels having receded.

One common mode of both failure and damage was the erosion of soils at the land side toes of floodwalls as water cascaded over the tops of the concrete floodwalls atop the earthen levees. This was a problem at many I-walls, but was not a problem at most T-walls where the concrete base stems of the inverted T-wall sections acted to deflect the overtopping waters. T-walls also were constructed with more substantial and robust foundations. At a number of I-walls, the waters overtopped and then cascaded down the inboard side, producing very sharply etched erosional trenches, of varying depths, in the soils at the land side toes of the walls. That erosion reduced the lateral soil support otherwise offered at the land side sides of the walls, and reduced the walls' ability to withstand the elevated lateral forces exerted by the storm surge on their water sides.

A second issue noted at a number of both failed and distressed levee sites was an inconsistency in crest heights when multiple flood protection system elements came together. Often there were differences in crest heights between earthen embankment sections and adjacent concrete structural sections. Sometimes two adjacent concrete wall sections differed significantly in height.

Considerable erosional distress, and a number of failures, were noted at transitions between earthen levee and concrete structural segments. Many of these areas of erosion appeared likely to have been related to inadequate transition details (e.g. insufficient overlap, etc.), but these were also commonly exacerbated by inconsistencies in crest heights that tended to concentrate overtopping flows at vulnerable transition locations.

Another repeated issue noted in these field investigations was the potential hazard posed by penetrations through the perimeter flood protection systems required in order to permit through passage of trains or other surface transit (e.g. roads, port vehicles, etc.) These penetrations produced additional transitions between disparate sections, and also created the potential for overlapping or disjoint responsibilities among the authorities/agencies/owners at adjoining perimeter flood protection elements. At sections where infrastructure elements were designed and maintained by multiple authorities, and where their multiple protection elements came together, the weakest (or the lowest) segment or element controlled the overall performance.

Finally, three major breaches, and at least one significantly "distressed" levee/floodwall section, occurred at sites along the 17th Street and London Avenue Canals where the levees and floodwalls were clearly not overtopped. Currently available evidence suggests that the flood surge at these sites was on the order of 2 to 5 feet short of overtopping the floodwalls at these locations. Observations made at the sites of the 17th Street Canal breach and the north breach on the London Avenue Canal suggest that these failures were likely the result of stability failures within the embankment or foundation soils at or below the bases of the earthen levees. This would be consistent with instability due to underseepage flow, and resultant hydrostatic uplift and reduction of shear strength at the bases of the inboard sides of the earthen levee embankments, as well as the lateral "push" exerted against the sheetpile/floodwall diaphragms by the elevated waters on the canal sides of these wall systems. Evidence of piping erosion at the London Avenue Canal (north) breach, and at the distressed section directly across from this breach on the east bank, serves to illustrate the severity of the underseepage at high water stages. Another possibility that also needs to be investigated, however, is the potential presence of a weak stratum or soil unit (either within the lower embankment, or in the underlying foundation soils) with sufficiently low shear strength that it might have failed even without weakening due to underseepage flows. A third possibility at the north breach on the London Avenue Canal is that piping and internal erosion may have directly been the cause of failure, and this also needs to be investigated.

The third breach site (London Avenue Canal, south breach) was massively eroded, leaving relatively little evidence to examine, and it is less clear what the failure mechanism was at this location. Instability of the inboard side of the earthen levee embankment, again possibly associated with underseepage and the lateral push of the outboard side canal water levels, or with seepage erosion and piping, would be consistent with the data and observations made at this site, however, and with photos taken shortly after the failure.

Additional studies will be performed at most of the breached and distressed locations. These supplemental studies will enable better definition of embankment and foundation soil conditions and appropriate seepage flow and shear strength characteristics. The precise soil strata and most critical mechanisms that led to the observed failures at a number of sites remain to be conclusively determined.

Significant additional field investigations (including CPT probes, borings and sampling, etc.) as well as laboratory testing are already underway under the auspices of the USACE at many of the key sites, and the USACE has agreed to openly share the results of these field and laboratory studies with our investigation teams.

Similarly, the ASCE and NSF-sponsored investigation teams have met a number of times with the USACE levee investigation team from ERDC, as well as with representatives from the New Orleans District of the USACE, and have jointly developed lists of requested background documents including site investigation reports and boring logs, laboratory test data, design memoranda (including original design calculations and analyses), as-built section specifications and details, maintenance and field inspection records, etc. for many of the breached and heavily distressed levee and/or floodwall sections, and the USACE has promised to provide these as quickly as practicable.

8.2 Comments on Future Reconstruction

Major repair and rehabilitation efforts are underway to prepare the New Orleans Flood Protection System for future high water events. The next hurricane season will begin in June of 2006. Preparing the levees for the next hurricane season, however, should also include a review of how the system performed during Hurricane Katrina, so that key lessons can be learned and then used to improve the performance of the system.

Based on our observations, a number of initial comments are warranted concerning the rebuilding and rehabilitation of the levee system.

Although it is somewhat customary to expect levee failures when overtopping occurs, the performance of many of the levees and floodwalls could have been significantly improved, and some of the failures likely prevented, with relatively inexpensive modifications of the levee and floodwall system details. The addition of overtopping erosion protection at the land sides of the floodwalls through the provision of rip-rap, concrete splash slabs, or even paving of the ground surface at the inboard faces of the levee crest floodwalls might have been effective in reducing this erosion, and might have prevented some of the failures observed.

As the New Orleans regional flood protection system is now being repaired and rebuilt, it would appear advantageous to plan crest heights in a systematic and deliberate way, so that if and when overtopping does occur, it occurs preferentially at the desired locations along any given section of levee/floodwall frontage. Sections designed to better resist overtopping and erosion should take the larger share of the overtopping flows. Similarly, the transitions between disparate levee/floodwall sections (e.g.: transitions between earthen levees, sheetpiles, and/or concrete wall sections) should be more robustly designed and constructed (e.g. with more pronounced overlap, or embedment, of transitional sheetpile walls within adjacent earthen levee sections, etc.), so that such transitions do not represent locations of potential weakness in otherwise contiguous perimeter flood protection system.

Regardless of the modes or causes of the various failures, it should be also be noted that emergency operations to close some of the breaches were seriously hampered by the difficult access to the breach sites. The USACE's EM 1110-2-1913, "Design and Construction of Levees," Section 8-9, specifically addresses access roads on levees, and their need for "the general purpose of inspection, maintenance and flood-fighting operations." The majority of the levee miles constructed by the USACE in the United States meet these requirements.

In the case of New Orleans, which likely had one of the most developed urban areas behind any USACE levee system, most capability for high-level access at many locations had been foregone when it was decided to put the I-walls in the existing levee crowns without widening the crowns for vehicle access. Such widening would probably have required additional right-of-way in many of the developed areas. When the need for emergency operations arose, many years later, these decisions resulted in very significant increases in time and cost to effect the needed closures and repairs.

Areas in which piping erosion occurred, including reported instances of piping along the MRGO frontage, suggest that there are areas of foundation that were weakened to a state worse than "pre-Katrina" conditions. Similarly, there may be additional sections like the west bank across from the North breach on the east side of the London Avenue Canal that were distressed (but did not fully breach) and are in need of remedial work. It is important, as part of the current repair operations, to remember to thoroughly inspect, and to repair as necessary, levee sections that may have been damaged but that did not fail.

Levees are "series" systems, where the failure of one component (levee segment) equates to failure of the system. They have less redundancy than many other engineered systems. In the case of the canal levees, the three "weakest links" failed, and the "fourth weakest link" (near the north end of the London Avenue Canal, on the east bank) experienced a near failure. Should these and any other damaged sections be repaired, the fact remains that the "next weakest link" (and so on) has not yet been tested to its design water height. The failure of these levees at less than their design water height warrants an overall review of the design of the system.

In the short-term, as interim levee repairs continue, consideration should be given to retaining the use of sheetpiles placed against the bridges at the north ends of the 17^{th} Street and London Avenue Canals to control storm and tidal surges. Until the levees in these canals are more fully repaired and/or more permanent canal surge check structures are emplaced, having the ability to rapidly prevent storm surges down these canals is still needed.

The USACE, like many public agencies, uses Independent Boards of Consultants to review the adequacy of the design and construction (and remediation) of major water resources, including major dams. The levee system in New Orleans is critical to the public health, safety and welfare of its residents, and actually protects more life and property than most major dams in the United States. We recommend that the Corps should retain an

Independent Board of Consultants to review the adequacy of the interim and permanent levee repairs being carried out in the aftermath of Hurricane Katrina.

The ASCE and NSF-sponsored levee assessment teams have already been instrumental in providing insights and recommendations for mitigating potentially serious deficiencies in the temporary/emergency repairs at a number of breached sections. It is anticipated that additional potentially important lessons will be learned in the months ahead as these investigations continue, and that some of these lessons are also likely to be useful in moving forward with the ongoing repair and long-term rebuilding of the New Orleans regional flood protection systems. As much of the population is currently being permitted to re-occupy portions of the New Orleans area, doing everything possible to ensure the safety of these people and their neighborhoods must continue to be the highest priority.

Acknowledgements

Support for these studies was provided by the National Science Foundation under Grant No. CMS-0413327, by the American Society of Civil Engineers, and by the Center for Information Technology Research in the Service of Society (CITRIS), and this support is gratefully acknowledged. The research teams also wish to acknowledge the gracious logistical support and technical interaction provided by the U. S. Army Corps of Engineers own levee investigation team from the Engineer Research Development Center (ERDC.) Valuable insight regarding water levels and storm surge behaviors was provided by Dr. Hassan Mashriqui of the Louisiana State University Hurricane Center. The U.S. Army Corps of Engineers provided a very useful situation summary briefing as our field teams arrived on site, and this greatly facilitated our investigations.