

Appendix A: Terrestrial LIDAR Imagery of New Orleans Levees Affected by Hurricane Katrina

A.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 eleven 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. An additional day of data collection was performed on March 15, 2006 at the Orleans Canal Pump Station during a follow-up survey effort to collect high-accuracy control point data via differential GPS surveying. 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, eleven sites were visited for LIDAR scanning (Figure A-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 A-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.

A.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 A-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. 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. 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 for initial data processing. An additional site visit was made to New Orleans in March 2006 to collect high-accuracy survey data to process and georeference all of the acquired data sets. Details on these procedures are provided in this report.

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 0.8-1.5 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 A-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 A-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 A-5). The levee scans involved 7 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.

A.3 Georeferencing of LIDAR survey data

Due to the difficult logistics of the initial data collection reconnaissance, each LiDAR data set was collected and processed using a local coordinate system, centered on the origin of the first scan collected at each site. This provided a basis for understanding each site’s morphology and for making relative measurements within a single site. However, this also limited the ability to make absolute measurements in terms of other georeferenced data sets, including elevation measurements relative to sea-level datums. A dedicated survey effort was therefore conducted from March 13-17, 2006 to collect high-accuracy survey data on local control points identified within each sites LiDAR data set. Survey data was collected at eight of the data sets (Site 1: 17th Street Canal, Site 2 and 3: London Ave. Canal, Site 4 and 5: IHNC Breaches, Site 6: Lakeside Airport Levee, and Site 11: Orleans Canal Pump Station and Spillway). Georeferencing data was not collected at Sites 8, 9, and 10, and these sites remain as locally referenced data sets.

Data was collected on cultural features clearly visible with the scans sets (house roof corners, fence posts, concrete foundation corners, etc.) using the USGS’ in-house GPS survey capabilities. Using a network of base stations throughout the New Orleans area, approximately 15 local control points were collected at each site with centimeter-level accuracy. A registration procedure was then performed for each data set to transform the locally referenced data to real-world coordinates, referenced to NAD83, UTM Zone 15 for the horizontal projection, and NAVD88 for the vertical datum. The georeferencing procedures resulted in a registered fit of local to GPS survey points on the order of 10 centimeters, with the exception of Sites 4 and 5 (IHNC Breaches). The georeferenced status for each site investigated in this study is presented in Table 1 for reference.

A.4 Processing of LIDAR Imagery

At each levee site, the topographical surroundings were imaged on seven 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 are 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.

A.5 Data Coverage: LIDAR scan sites at Levee Breaks within the New Orleans Area

Figures A-6 through A-13 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.

A.6 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 Avenue 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 A-14, 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 sides of the levees 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 A-15) display highly accurate cross sections of the distressed I-wall at London Canal. Segment (a) is toward the south (left) of Figure A-14 and has a modest 1.9 degree rotational deformation. Near the

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 the I-wall prevents water from overtopping these I-walls. 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 A-16 shows this considerable wall gap, as well as moderate scour at the southeast edge of the bridge abutment (Figure A-16a). 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 A-17 and A-18 show this gap, as well as a scour trench at the base of the northeast abutment (Figure A-18a).

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 A-19 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 A-20, 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 ft) 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 A-21. 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. The LIDAR data shows that blocks translated approximately 14 meters (46 ft) 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 A-21, it can also be seen that the width of the 17th St. Canal has been reduced about 6 meters (20 ft) by the placement of the earthen embankment.

A final example of the use of the LIDAR data is shown in Figure A-22. 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.

A.7 Summary

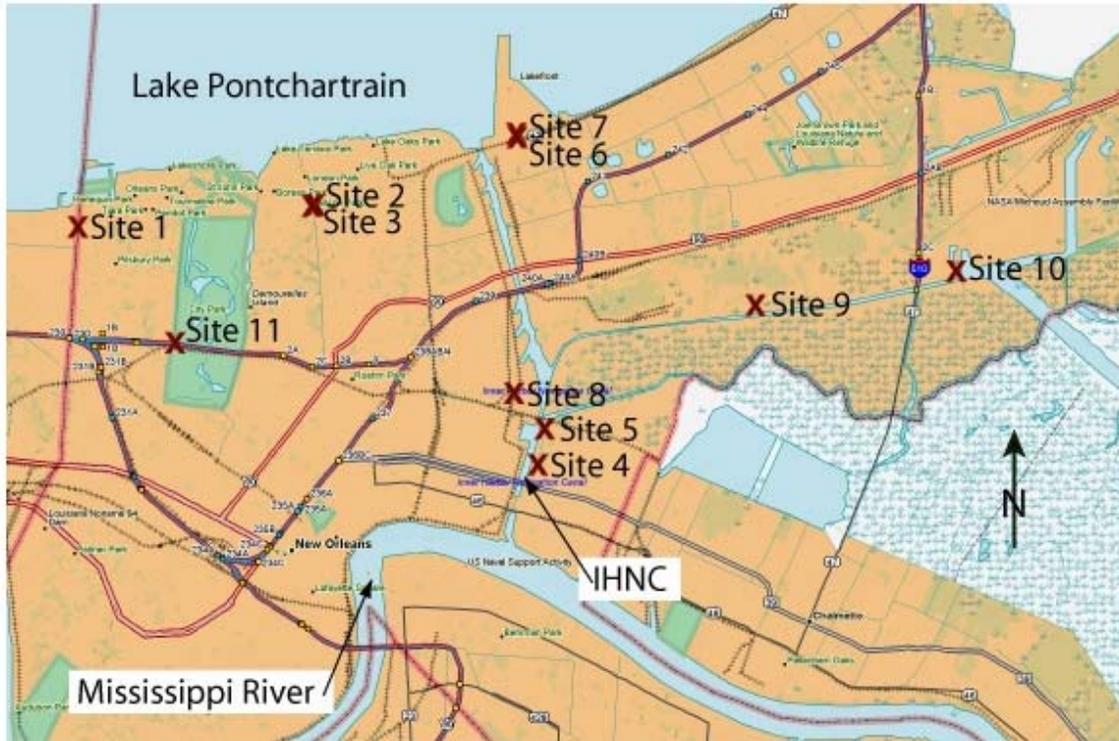
The LIDAR data presented herein present the scope of available data coverage of the failed sections of the New Orleans levee system following Hurricane Katrina. The methodology for processing the data has been outlined to provide important background information for maps, section views and calculations 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.

A.8 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 A-1 LIDAR Site Description Summary

LIDAR Site Number	Location	Latitude	Longitude	Number of LIDAR scans	Data Georeferenced?
1	17th Street Canal	N30.0172°	W90.1214°	20	Yes
2	London Ave. Canal, North on east side	N30.0210°	W90.0704°	29 with Site 3	Yes
3	London Ave. Canal, North on west side	N30.0206°	W90.0708°	29 with Site 2	Yes
4	IHNC East Side, South Breach 9th Ward	N29.97243°	W90.02194°	13	Yes
5	IHNC East Side, North Breach 9th Ward	N29.97873°	W90.02042°	14	Yes
6	Lakefront Airport Levee Transition Breach	N30.03367°	W90.02622°	14 with Site 7	Yes
7	Lakefront Airport Levee I-Wall	N30.03436°	W90.02641°	14 with Site 6	Yes
8	Structural Distressed I-Wall at Container Wharf	N29.98614°	W90.0272°	20	No
9	Erosionally Distressed Earth Levee	N30.00200°	W89.97500°	14	No
10	Entergy Plant I-Wall Scour	N30.00900°	W89.93171°	20	No
11	Orleans Canal Pump Station and Spillway	N29.99476°	W90.10070°	7	Yes



Source: Delorme TopoUSA

Figure A-1: The eleven sites investigated by the laser mapping method reside within the boundary of Orleans Parish.



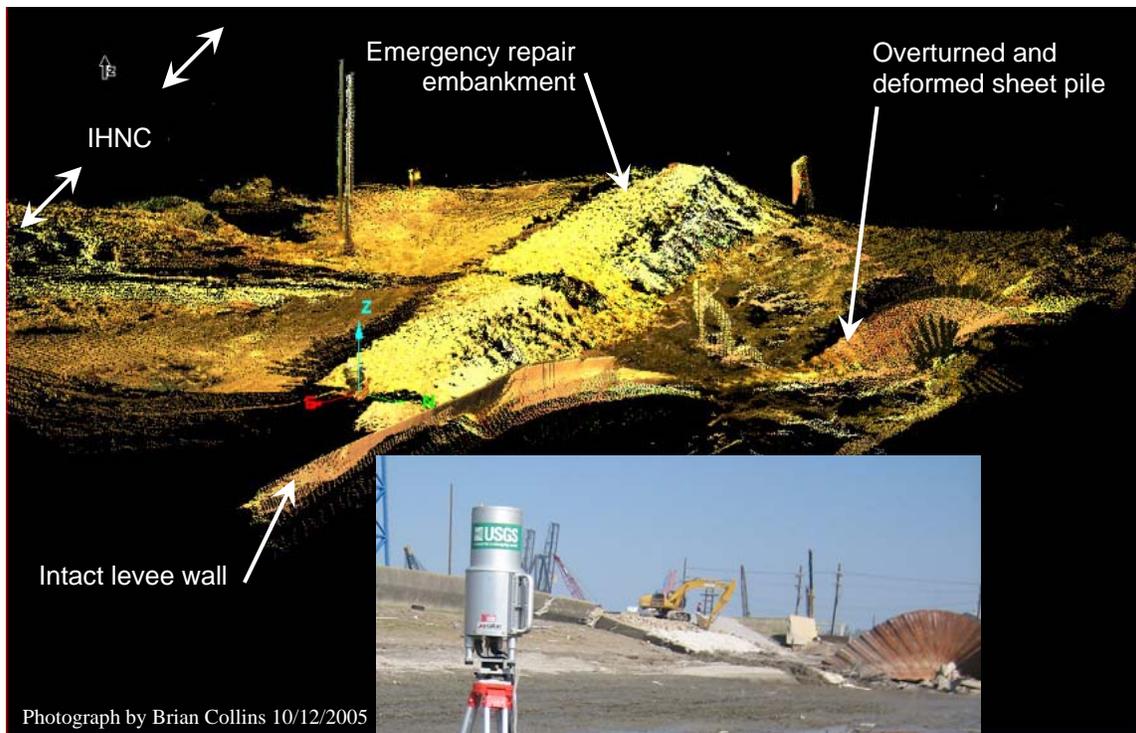
Photograph by Robert Kayen 10/13/2005

Figure A-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.



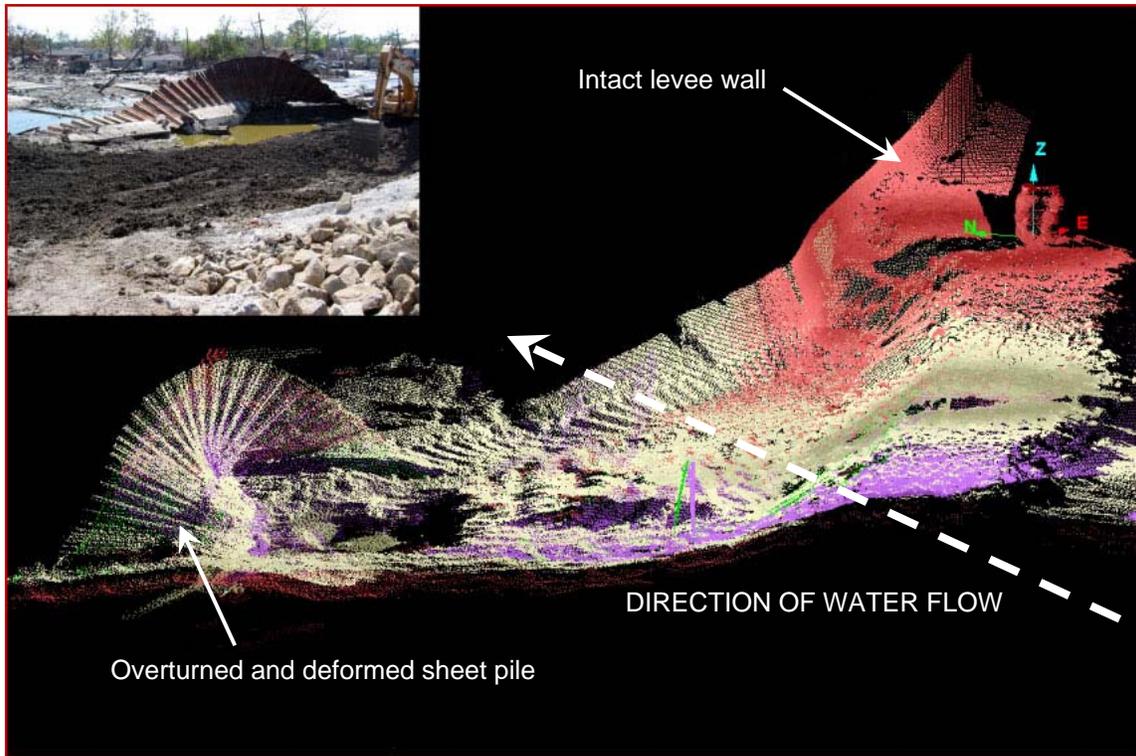
Photograph by Robert Kayen 10/10/2005

Figure A-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 A-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 A-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.noaa.gov/storms/katrina/24425575.jpg>

Figure A-6: Site 1, 17th Street Canal: (N30.0172° W90.1214°)



Source: modified from Google maps

Figure A-7: Sites 2 & 3, London Ave. Canal, North
on east side: (N30.0210° W90.0704°)
and west side: (N30.0206° W90.0708°).



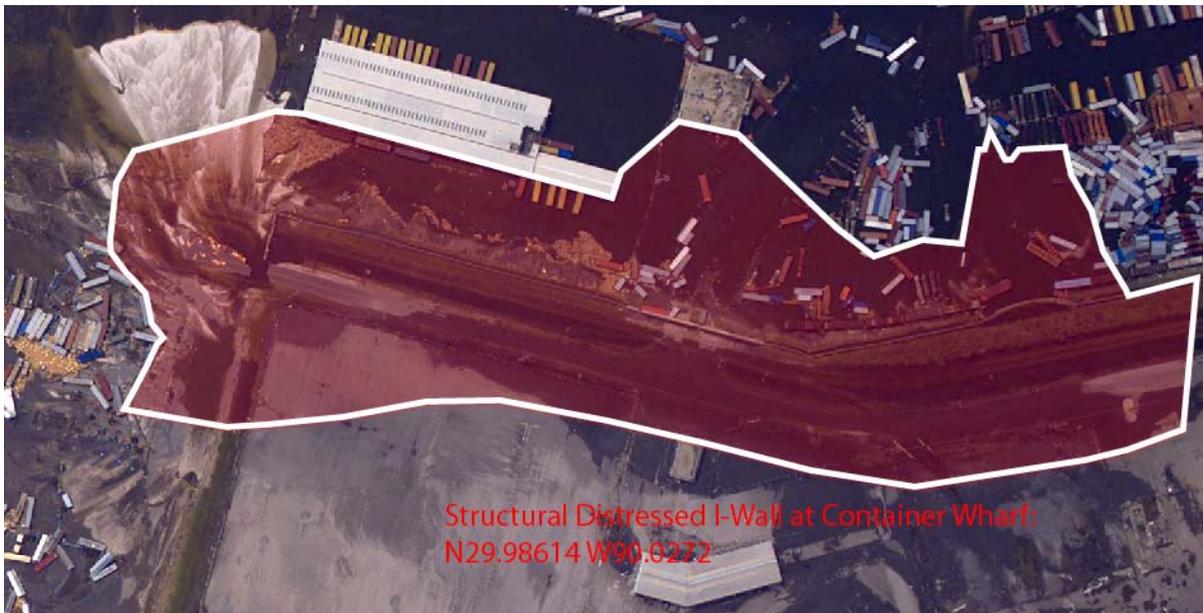
Source: modified from http://www.digitalglobe.com/images/katrina/new_orleans_surekote_levee_aug31_2005_dg.jpg

Figure A-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 A-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.noaa.gov/storms/katrina/>

Figure A-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 A-11: Site 9, Earthen Levee Section Distressed by Overtopping Erosion at N30.00200°, W89.97500°



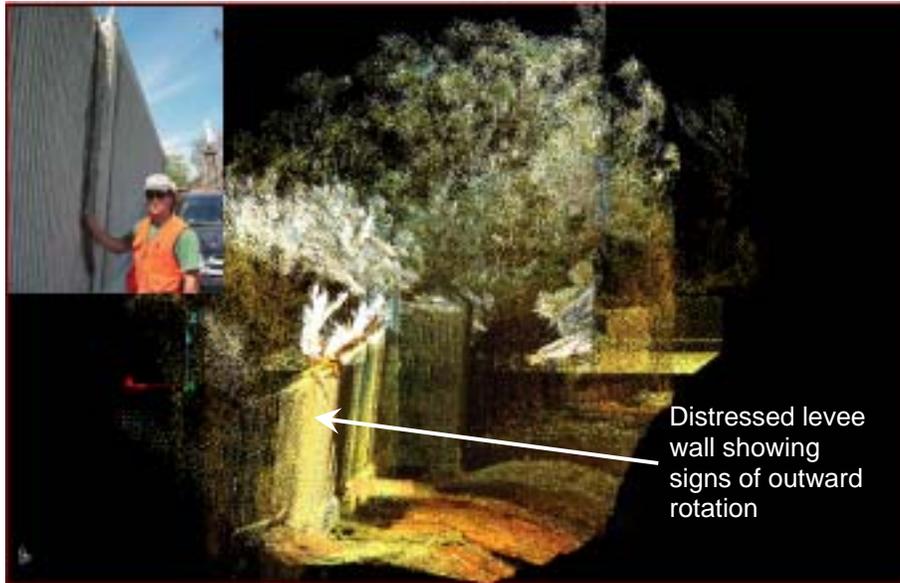
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Figure A-12: Site 10, Energy Plant I-Wall Scour at N30.00900°, W89.93171°



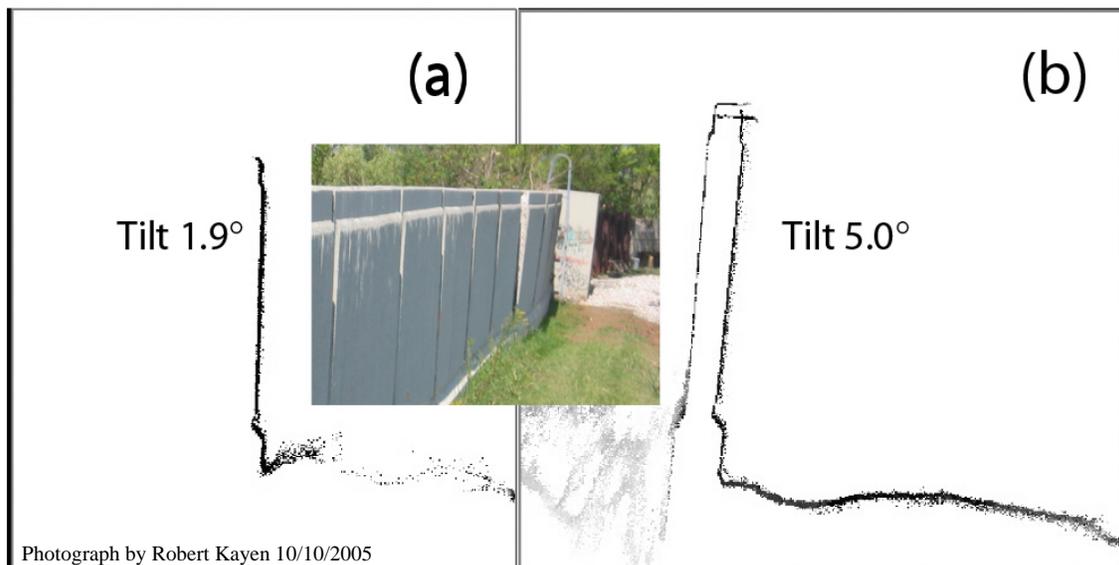
Source: Modified from <http://ngs.woc.noaa.gov/storms/katrina/>

Figure A-13: Site 11, Orleans Canal Pump Station Spillway at N29.99476°, W90.10070°



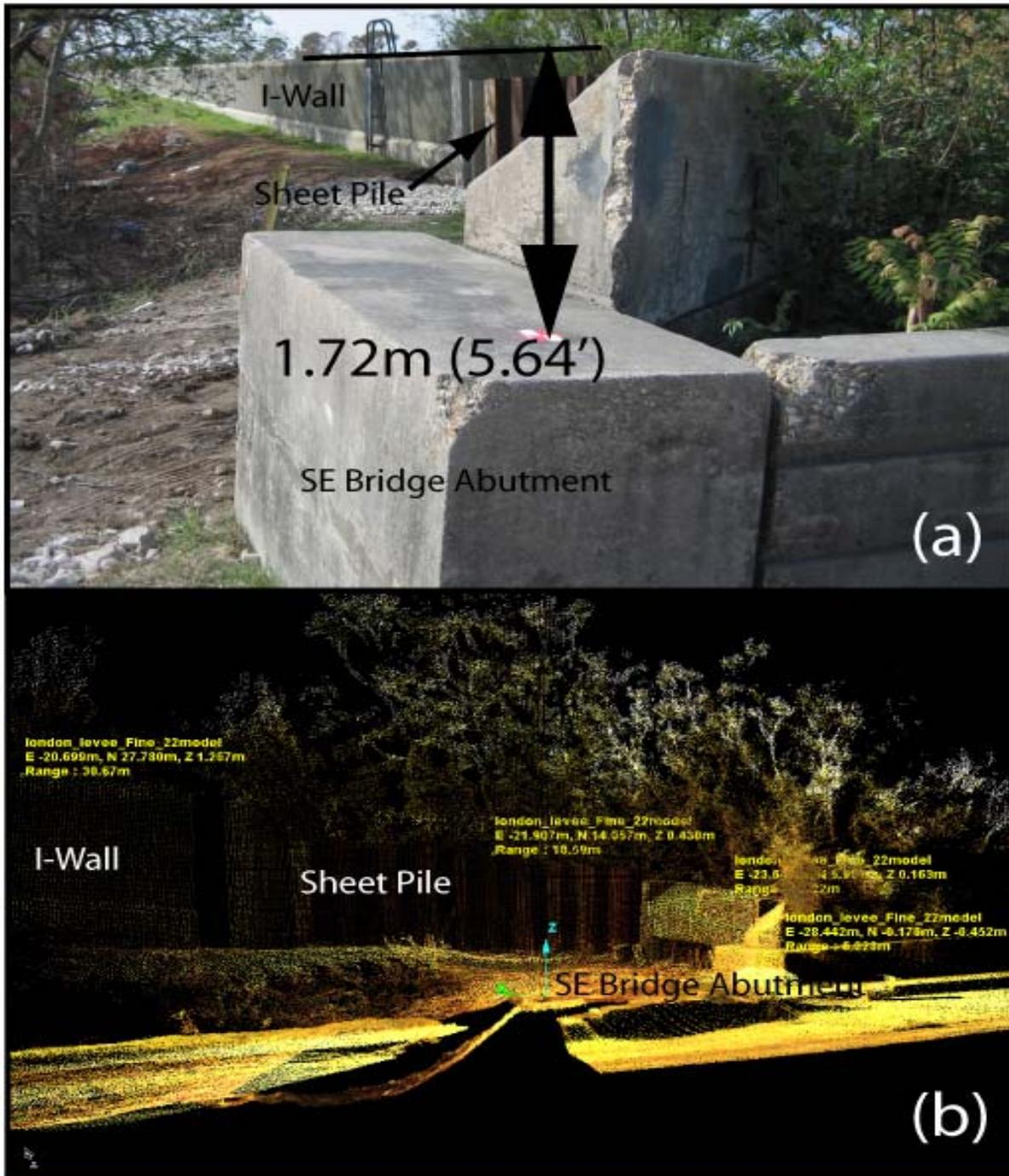
Photograph by Robert Kayen 10/10/2005

Figure A-14: 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.



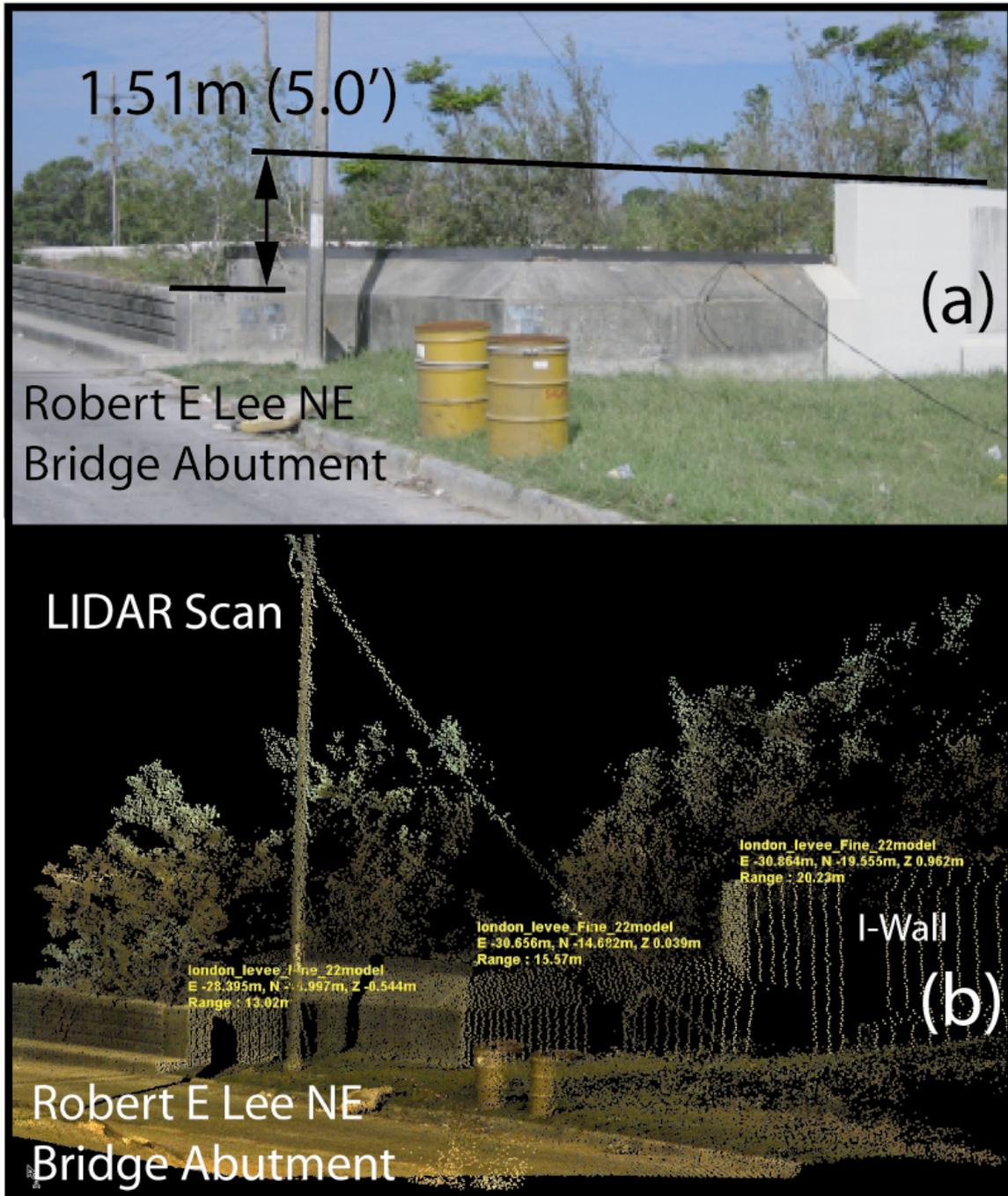
Photograph by Robert Kayen 10/10/2005

Figure A-15: Cross sections through two segments of distressed I-wall at London Avenue Canal. Segment (a) is toward the south (left) of Figure A-14 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.



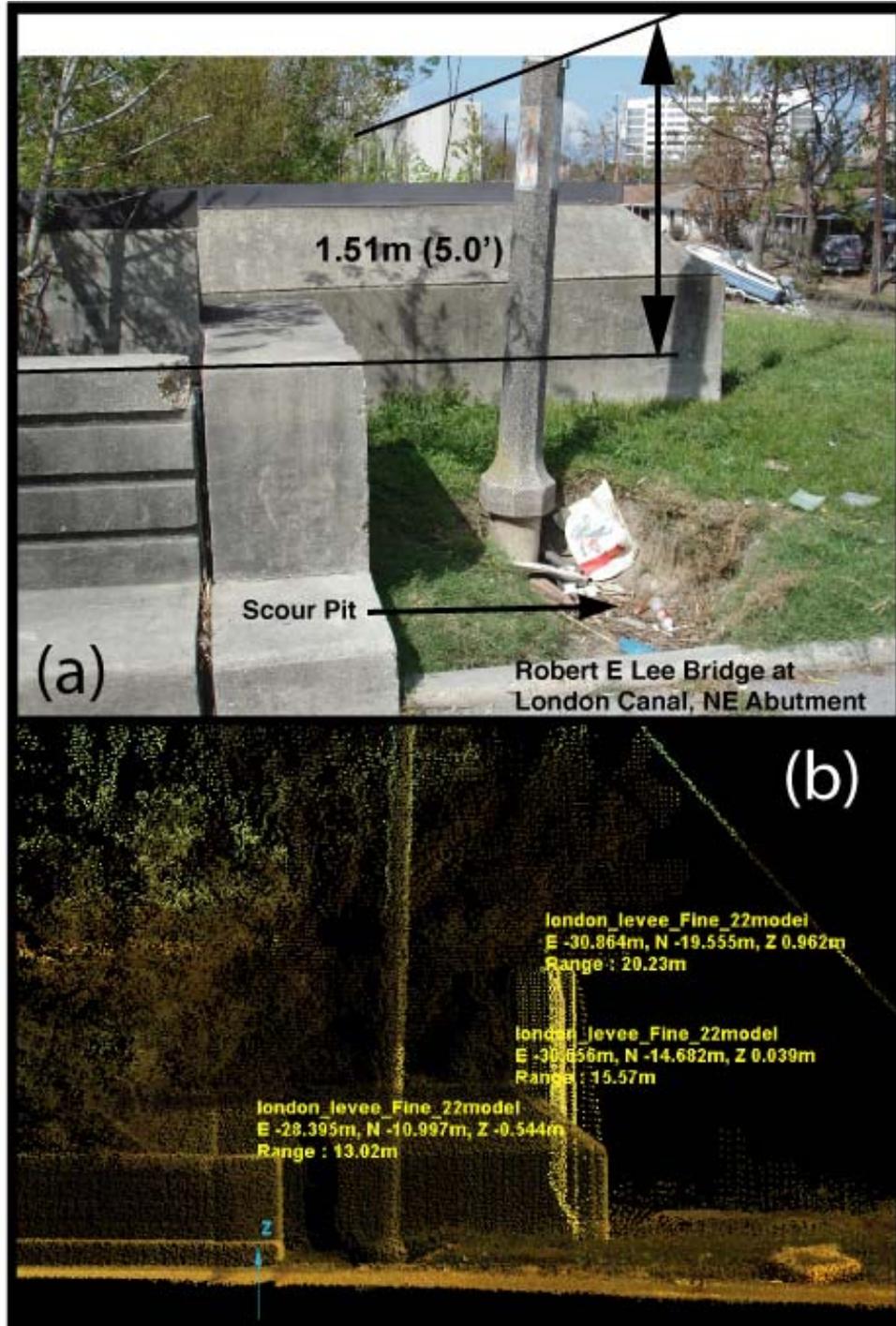
Photograph by Brian Collins 10/11/2005

Figure A-16: 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). Local coordinates are shown.



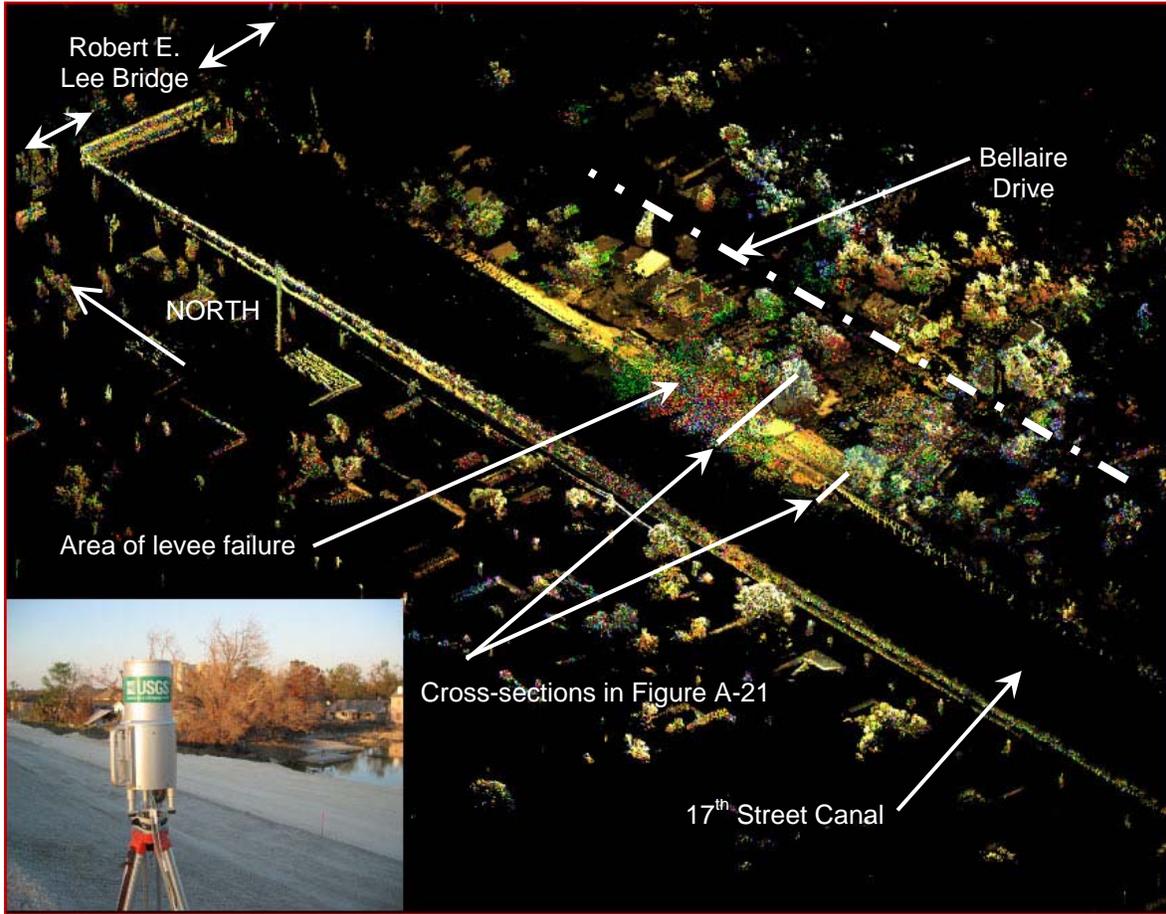
Photograph by Brian Collins 10/11/2005

Figure A-17: 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). Local coordinates are shown.



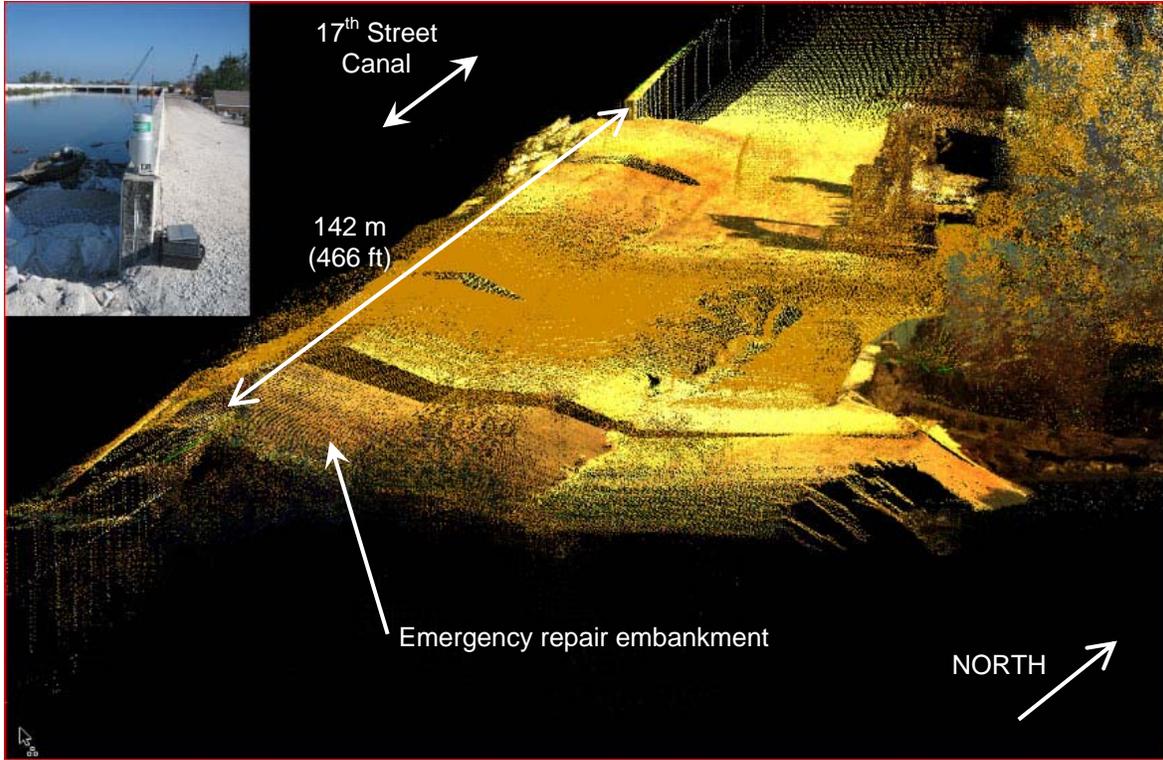
Photograph by Lee Wooten

Figure A-18 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). Local coordinates are shown.



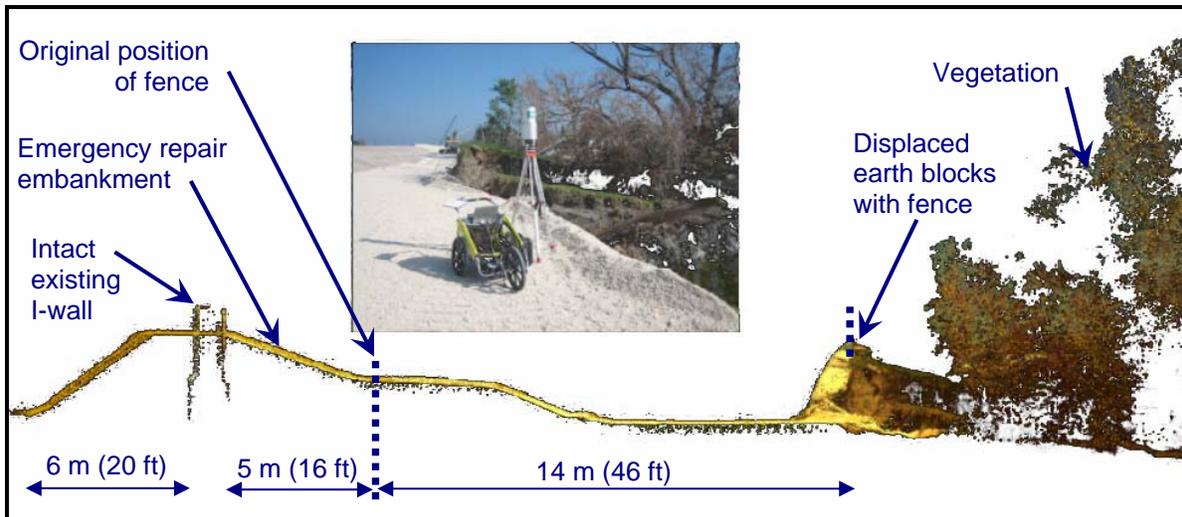
Photograph by Robert Kayen 10/9/2005

Figure A-19: 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.



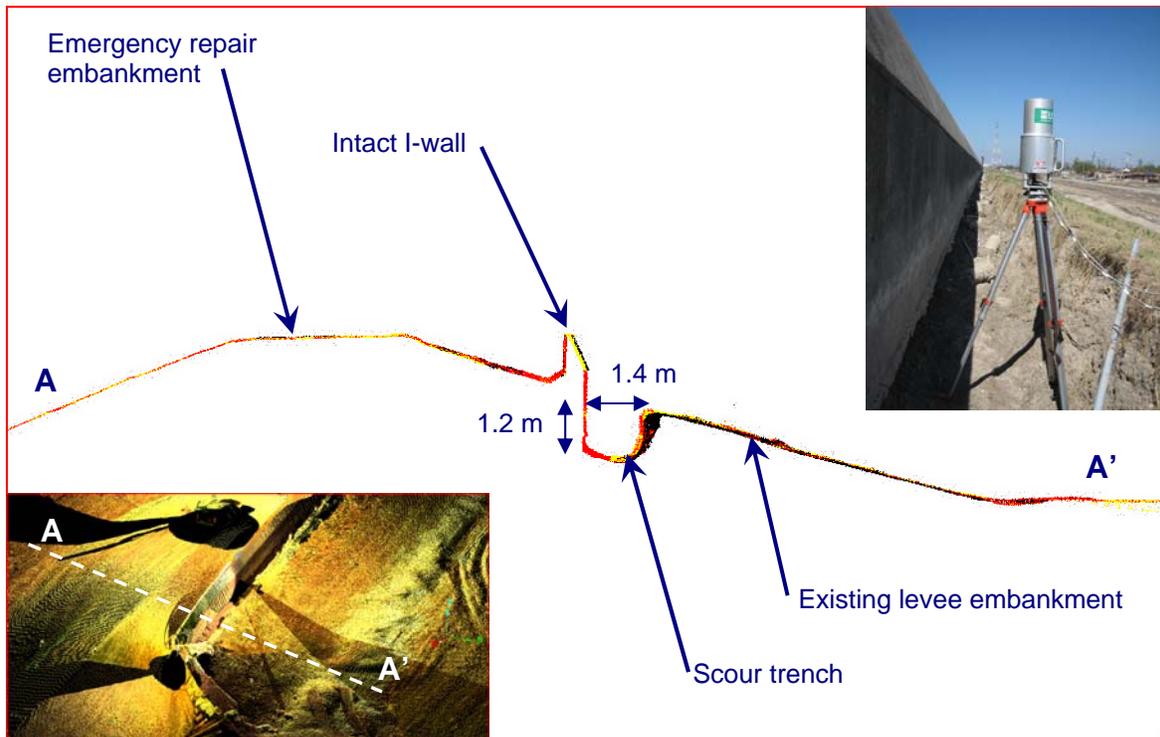
Photograph by Brian Collins 10/10/2005

Figure A-20. 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 A-21 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 A-22: Measurement of scour trench dimensions at the IHNC – South site.