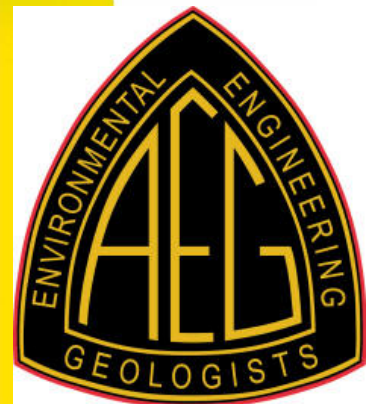


ENGINEERING GEOLOGIC CHARACTERIZATION OF LEVEE FAILURES IN NEW ORLEANS DURING HURRICANE KATRINA

J. David Rogers, Ph.D., P.E., R.G.

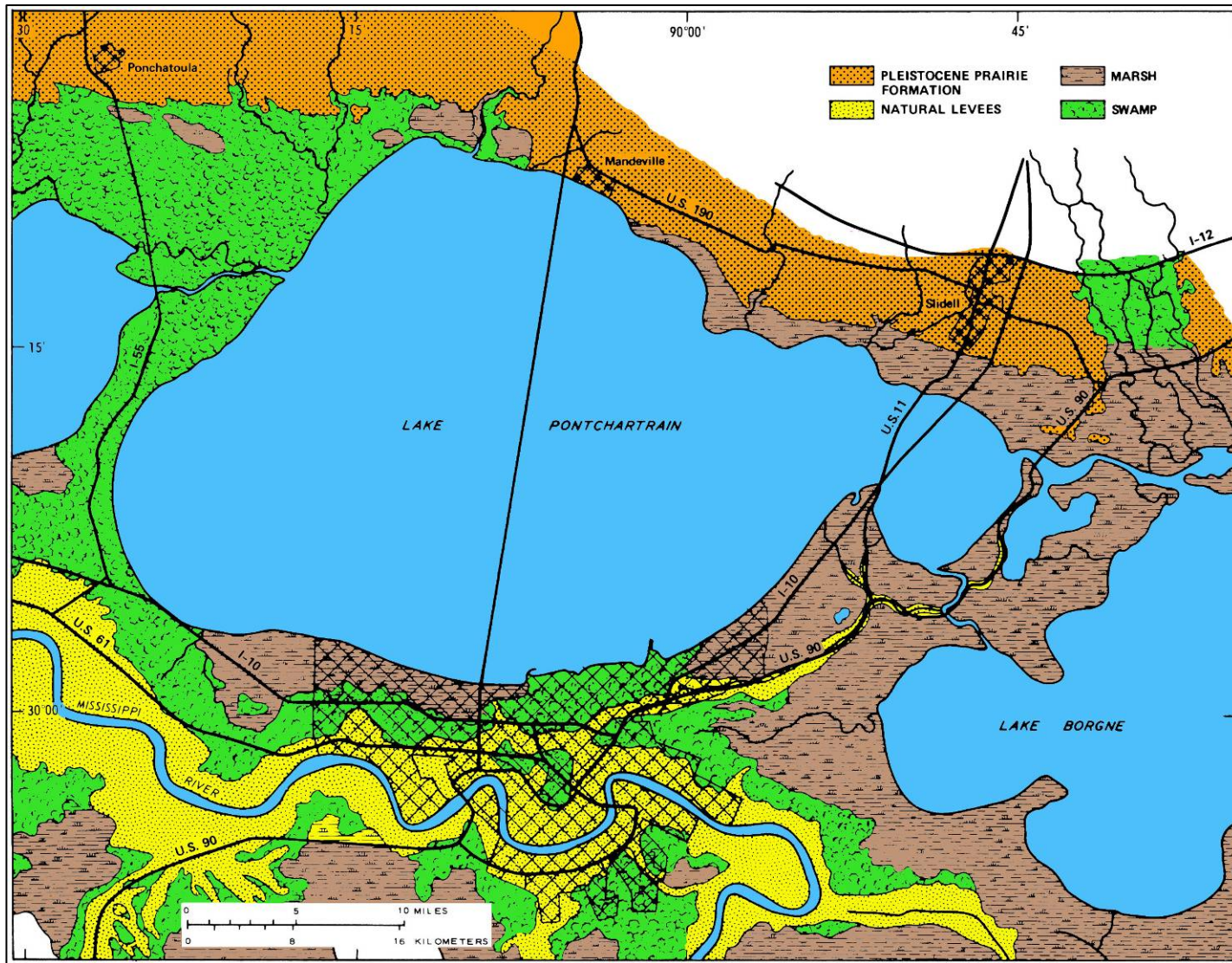
**Member, National Science Foundation Independent Levee Investigation Team and
Karl F. Hasselmann Chair in Geological Engineering
University of Missouri-Rolla**

**2007 Annual Meeting
Association of Environmental and Engineering Geologists
Los Angeles, California
September 28, 2007**

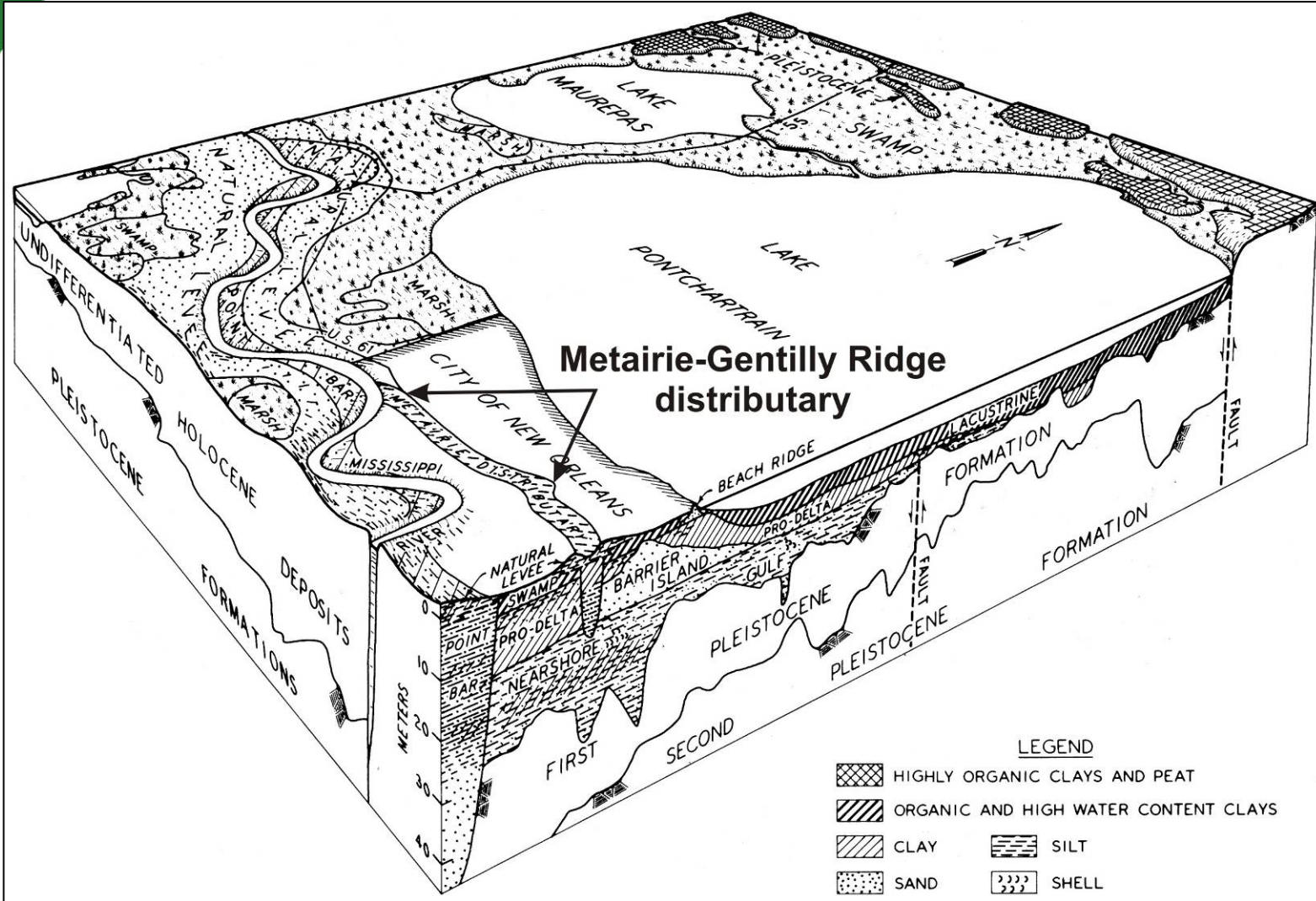


Part 1

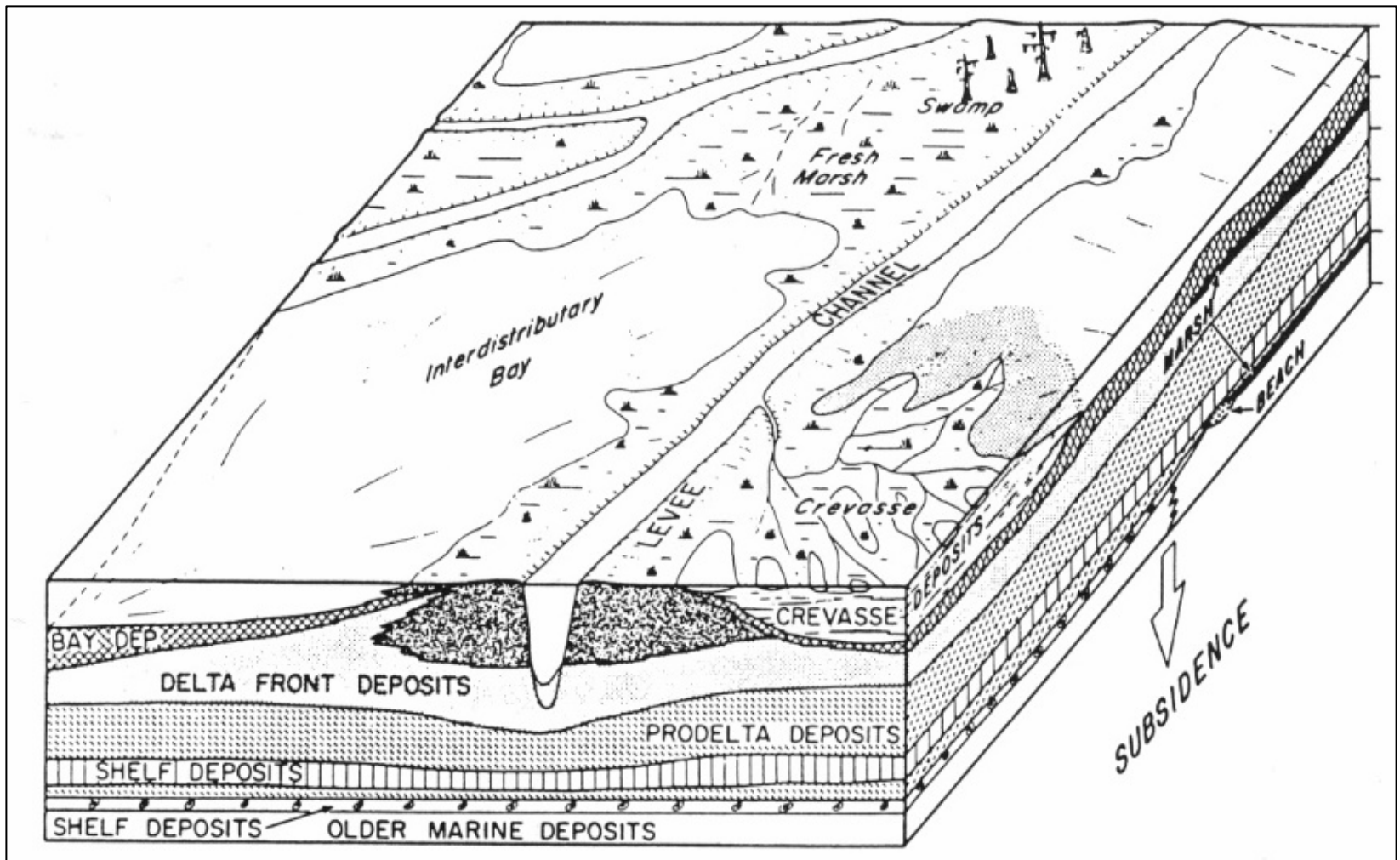
GEOLOGIC SETTING OF NEW ORLEANS



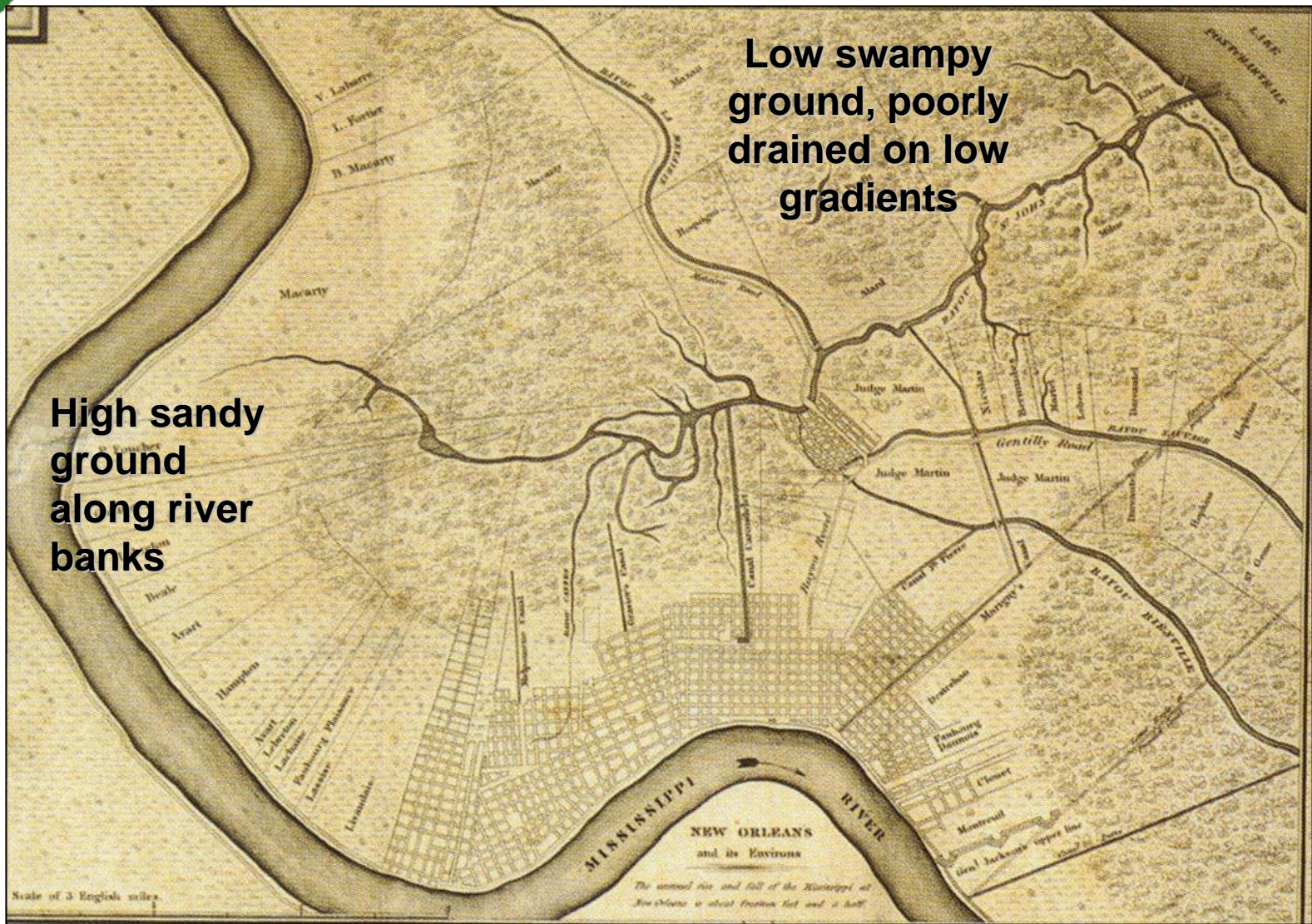
- **Geologic map of the greater New Orleans area. The sandy materials shown in yellow are natural levees, green areas denote old cypress swamps and brown areas are historic marshlands. The stippled zone indicates the urbanized portions of New Orleans.**



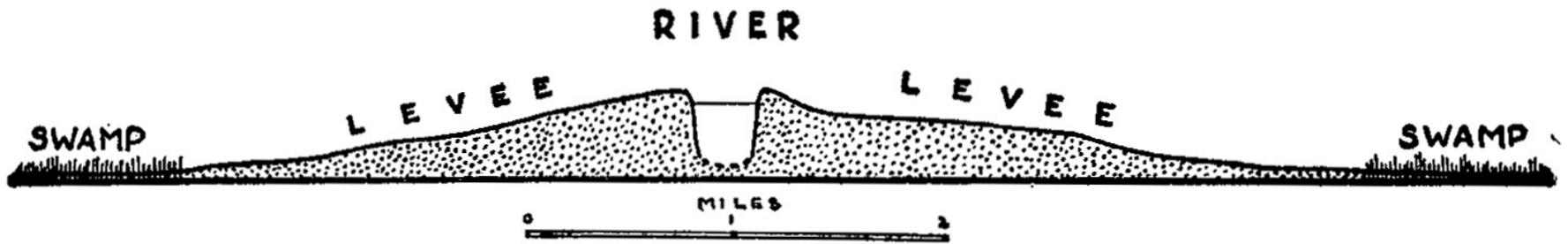
- Block diagram of the geology underlying New Orleans. The principal feature dividing New Orleans is the **Metairie distributary channel**, shown here, which extends to a depth of 50 feet below MGL and separates geologic regimes on either side. Note the underlying faults, beneath Lake Pontchartrain.



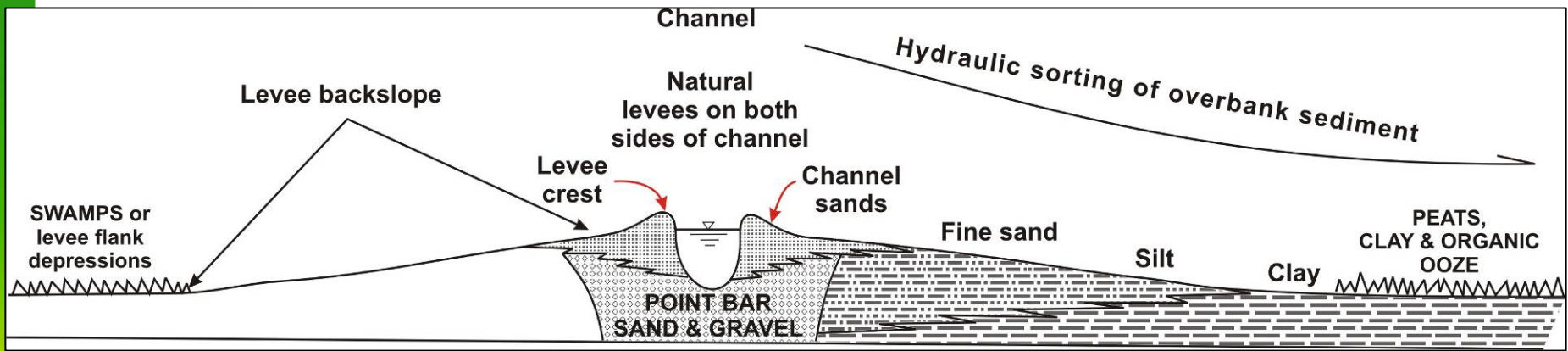
- Block diagram illustrating relationships between **subaerial and subaqueous deltaic environments** in relation to a single distributary lobe.
- The Lakeview and Gentilly neighborhoods of New Orleans are underlain by interdistributary sediments, overlain by peaty soils laid down by fresh water marshes and cypress swamps.



- Plan of the City of New Orleans prepared by Francis Ogden in 1829. Note the linear drainage canals feeding into Bayou St. John, thence into Lake Pontchartrain.



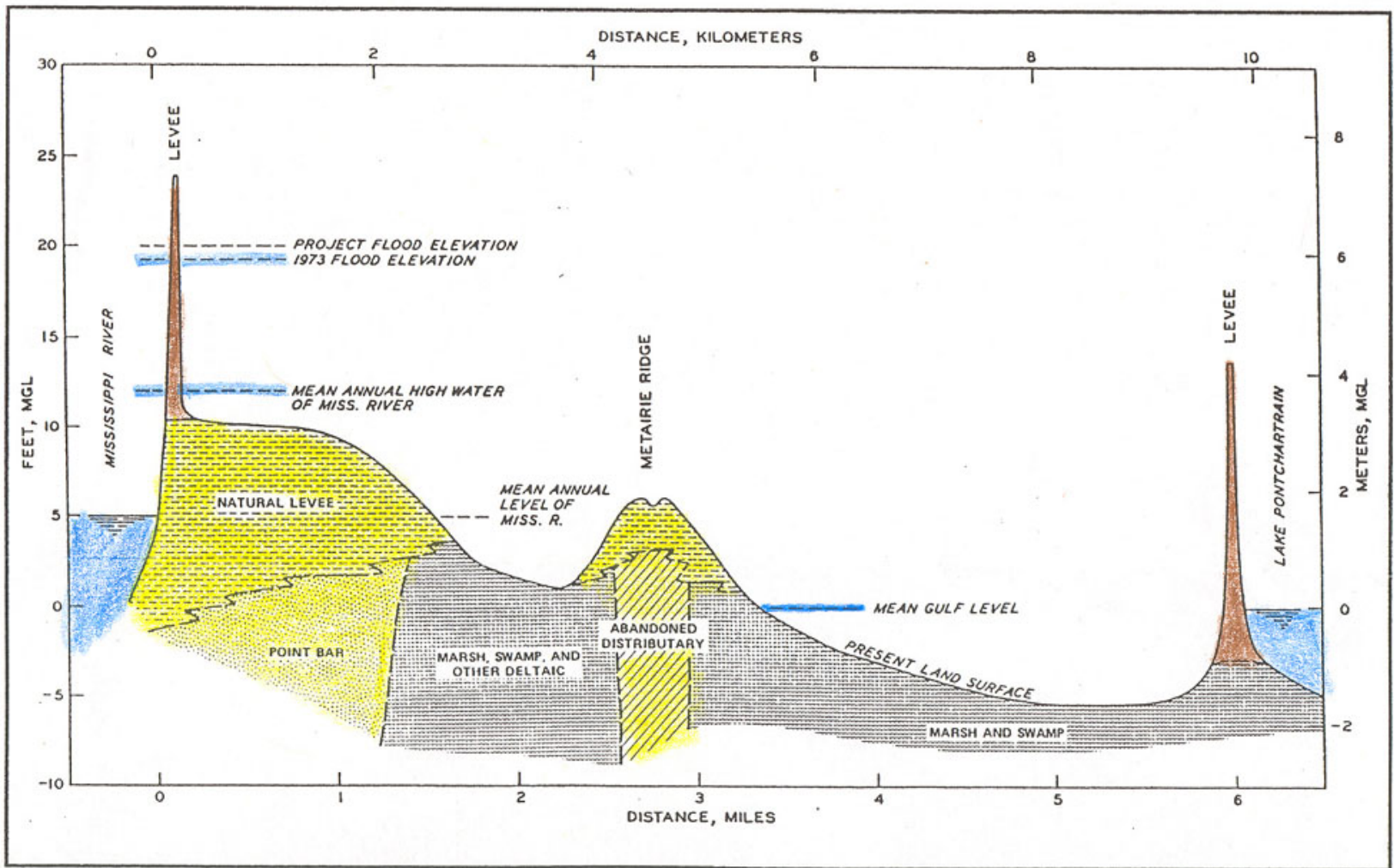
PROFILE OF THE MISSISSIPPI RIVER AT BELLE POINT



- Typical cross section through the sandy bank levees of the Mississippi River, illustrating how the river's **main channel lies above the surrounding flood plain**, which were poorly drained swamp lands prior to reclamation.
- There is significant **hydraulic sorting** of materials deposited on either side of these levees, as sketched below.

Part 2

CRITICAL ROLE OF FLOOD CONTROL INFRASTRUCTURE IN NEW ORLEANS



Much of lower New Orleans, developed after the First World War, lies below Mean Gulf Level, as shown here. Water that finds its way into the City must be pumped out.

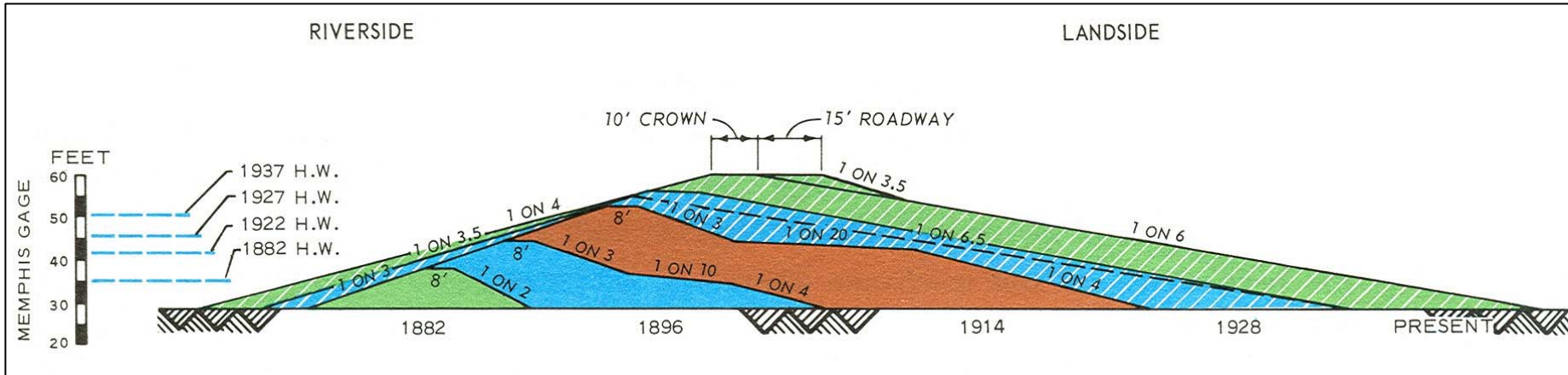


- All 36 miles of drainage canals in the Lakeview and Gentilly areas are shown in this portion the 1878 Hardee Map. The canals are, from left: 17th Street, New Basin (infilled), Orleans, Bayou St. John, and London Avenue, and the Lower Line Protection Levee.



- **Photo taken in 1890 looking north along the “shell road” than ran along the west side of the [New Basin Canal](#), seen at extreme right.**
- **Note the modest height of the embankment, no more than 5 feet above the adjacent cypress swamp. The canal embankments were heightened by earth filling after hurricane-induced overtopping of these canals in [1915](#) and [1947](#) (image from University of New Orleans historic collection).**

Problem with houses next to levees



- Evolution of the Corps of Engineers' **standard levee section, 1882 to 1972** (from Moore, 1972).
- Earth embankments levees are generally **heightened** sequentially by compacting additional soil on the **land side of the embankments** (each sequence of heightening shown as different colors).
- Levees adjacent to drainage canals or perennial channels are not raised on the river side of the embankment because excess moisture would prevent meaningful compaction of the fill.
- **Existing homes abutted the land side of the drainage canal levees in New Orleans by the time the Corps of Engineers began analyzing them in the 1960s.**

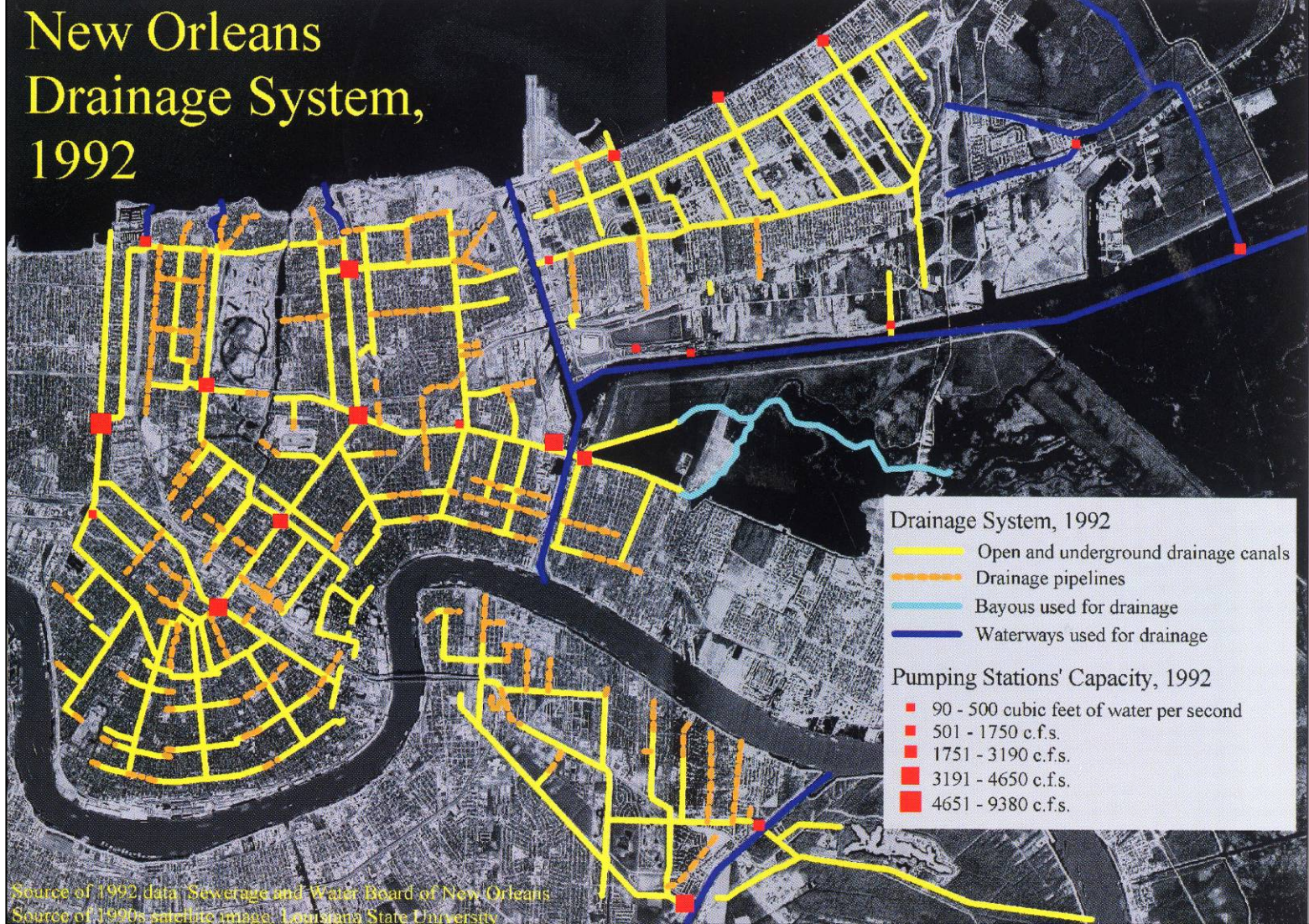


- View looking up the east side of the London Avenue Canal near Robert E. Le Boulevard crossing showing the **encroachment of homes against the slope of the levee**. This situation was common across New Orleans

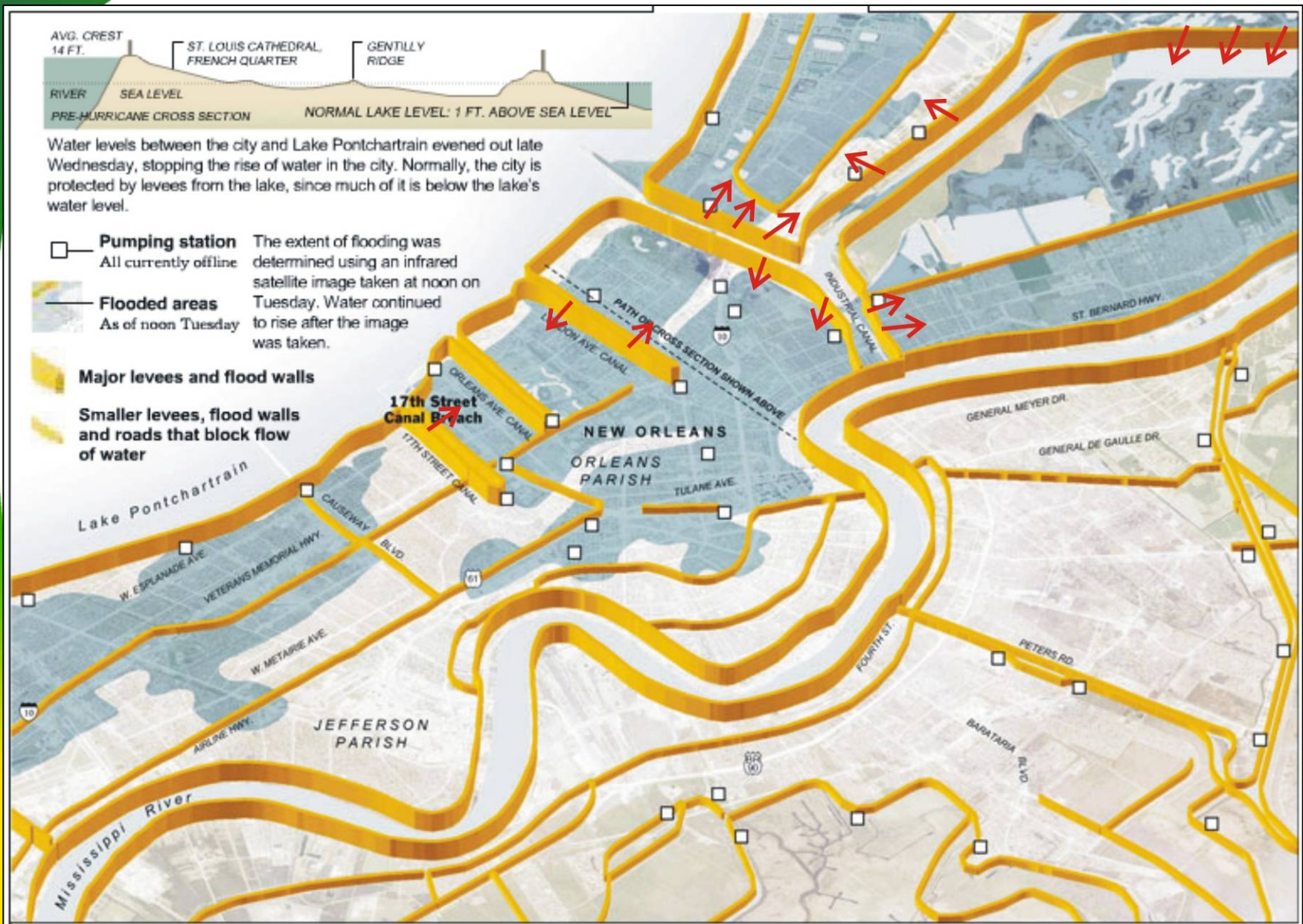


- **Concrete flood wall** along the west side of the 17th Street Canal in Jefferson Parish, where a street runs along the toe of the embankment. This scene is typical of the concrete I-walls constructed on steel sheetpiles driven into the crest of the drainage canal embankments in New Orleans in the 1990s to provide additional flood freeboard from hurricane-induced storm surges

New Orleans Drainage System, 1992



- **Principal elements of the pre-Katrina drainage system infrastructure as it existed in 1992 (taken from Campanella, 2002).**
- **In 2005 the aggregate pump capacity could have cleared the city of flood waters from Katrina in less than three days if the levees had simply been overtopped without failing.**



- **New Orleans flood protection system at the time Hurricane Katrina struck the city on August 29, 2005 (from the New New York Times). New Orleans has not been molested by flooding from the Mississippi River since 1859; all of the destructive floods have emanated from storm surges on Lake Pontchartrain and Lake Borgne.**

Part 3

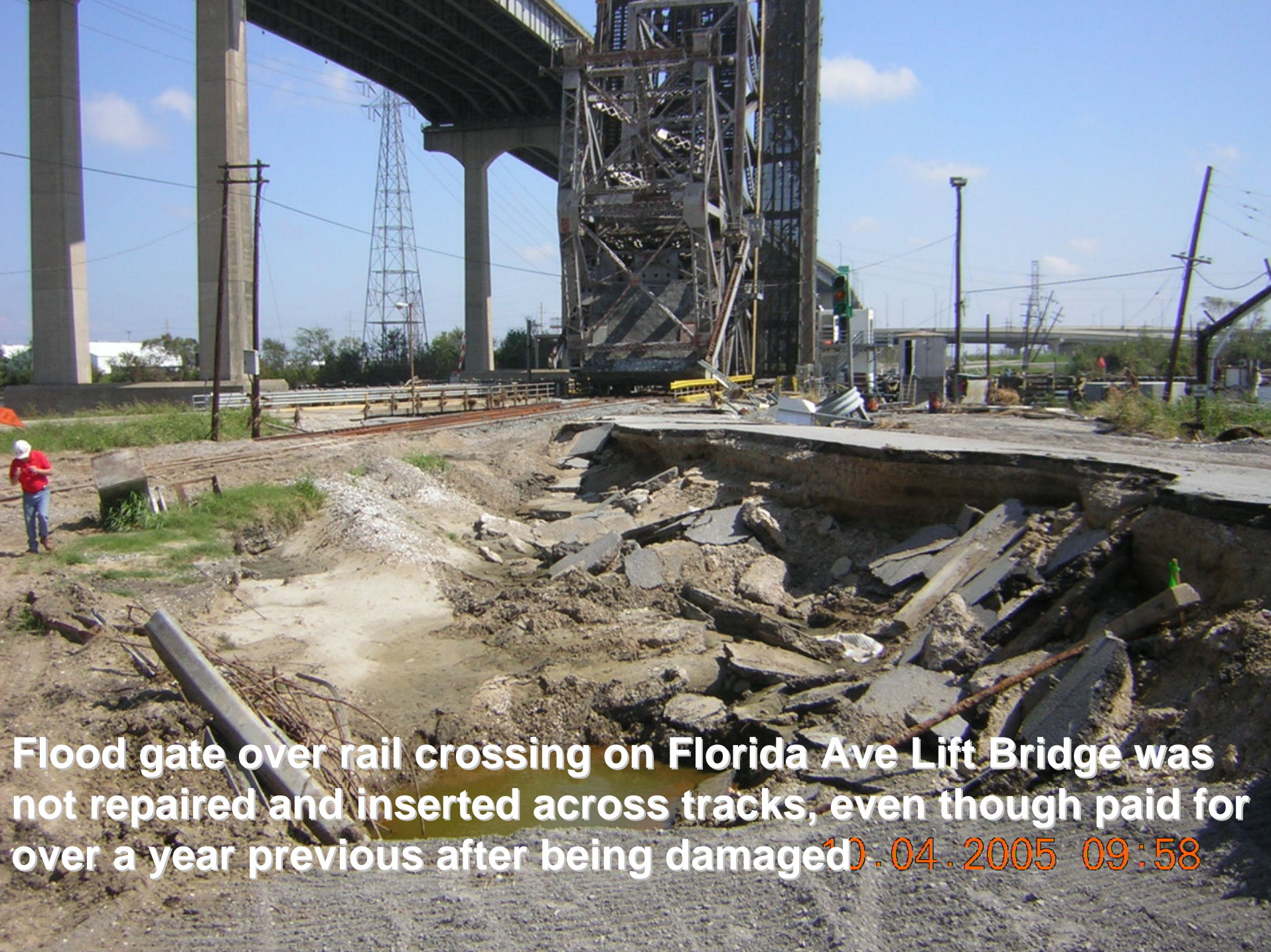
SYSTEMIC FAILURES OF FLOOD CONTROL INFRASTRUCTURE DURING KATRINA



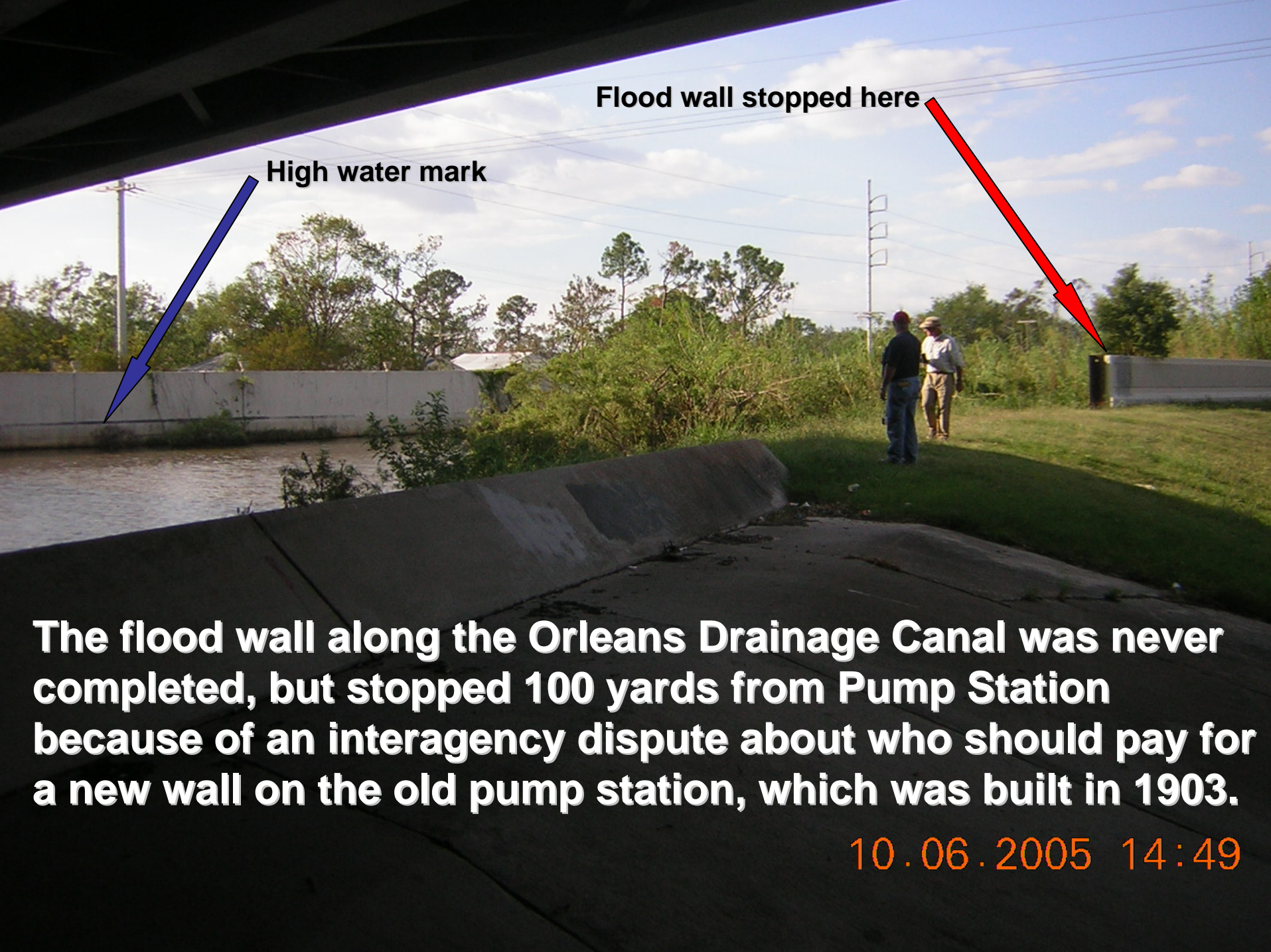
- **Around 6 AM on August 29th the 9 ft storm surge swept into the Inner Harbor Navigation Canal area, engulfing the Entergy Power Plant area with waves up to 17 ft high.**



- **Miles of levees just disappeared: MRGO levee completely washed away about two miles southeast of Bayou Dupree.**



Flood gate over rail crossing on Florida Ave Lift Bridge was not repaired and inserted across tracks, even though paid for over a year previous after being damaged 10.04.2005 09:58



Flood wall stopped here

High water mark

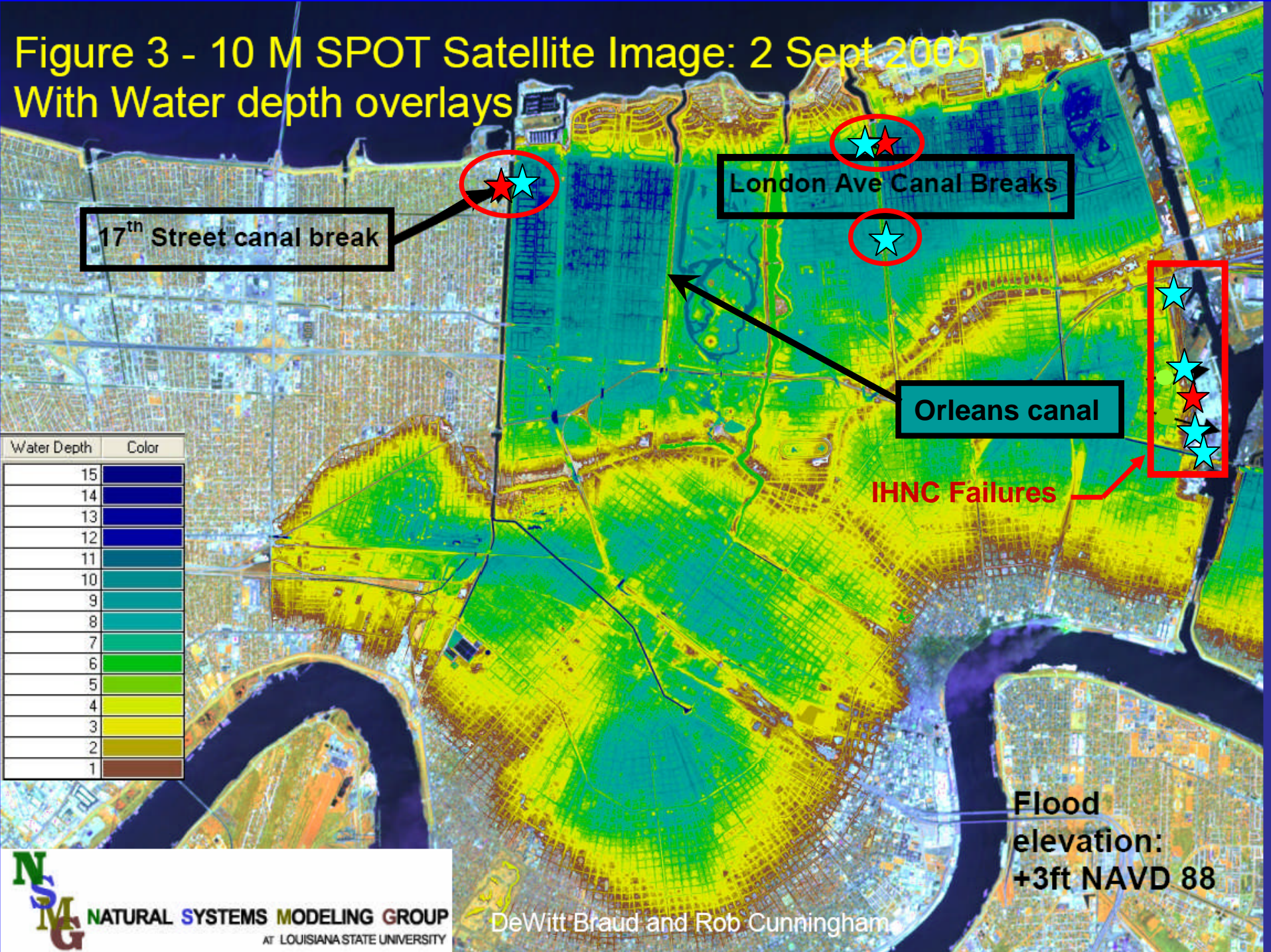
The flood wall along the Orleans Drainage Canal was never completed, but stopped 100 yards from Pump Station because of an interagency dispute about who should pay for a new wall on the old pump station, which was built in 1903.

10.06.2005 14:49



- **Army helicopters and contractors worked for weeks to fill the enormous gaps in the levee system, BEFORE pumping could begin.**

Figure 3 - 10 M SPOT Satellite Image: 2 Sept 2005
 With Water depth overlays



17th Street canal break

London Ave Canal Breaks

Orleans canal

IHNC Failures

Flood elevation:
 +3ft NAVD 88

Water Depth	Color
15	Dark Blue
14	Blue
13	Dark Teal
12	Teal
11	Light Teal
10	Greenish Teal
9	Green
8	Light Green
7	Yellow-Green
6	Yellow
5	Light Yellow
4	Yellow
3	Light Yellow
2	Yellow
1	Brown



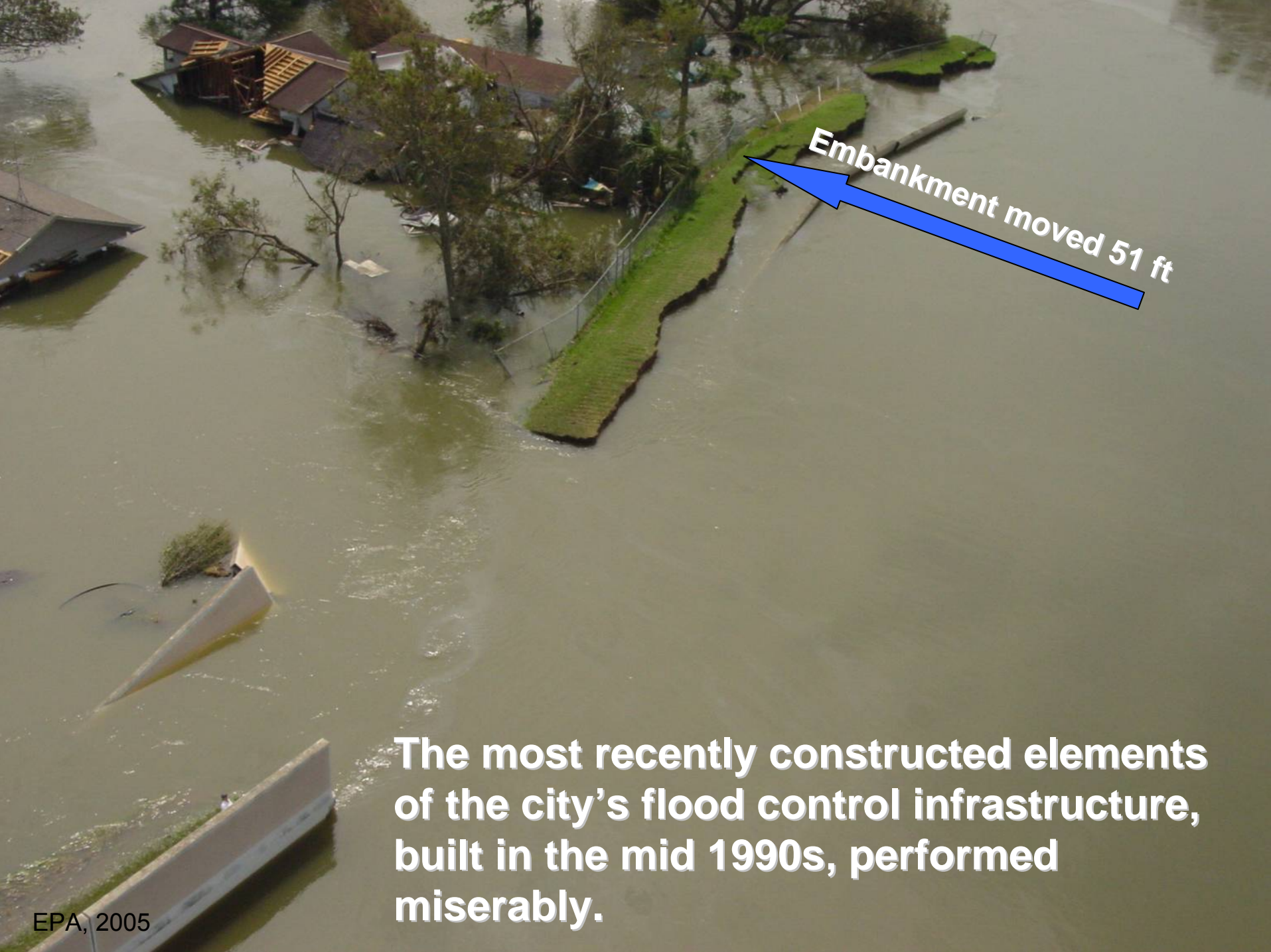
- **New Orleans neighborhoods were filled with as much as 12 feet of water, for up to 6 weeks**



- Katrina left New Orleans under water, creating the worst flood in American history and the most expensive disaster, causing **\$24 billion** in claims to the **National Flood Insurance Program** and **\$200 billion** in overall damage.

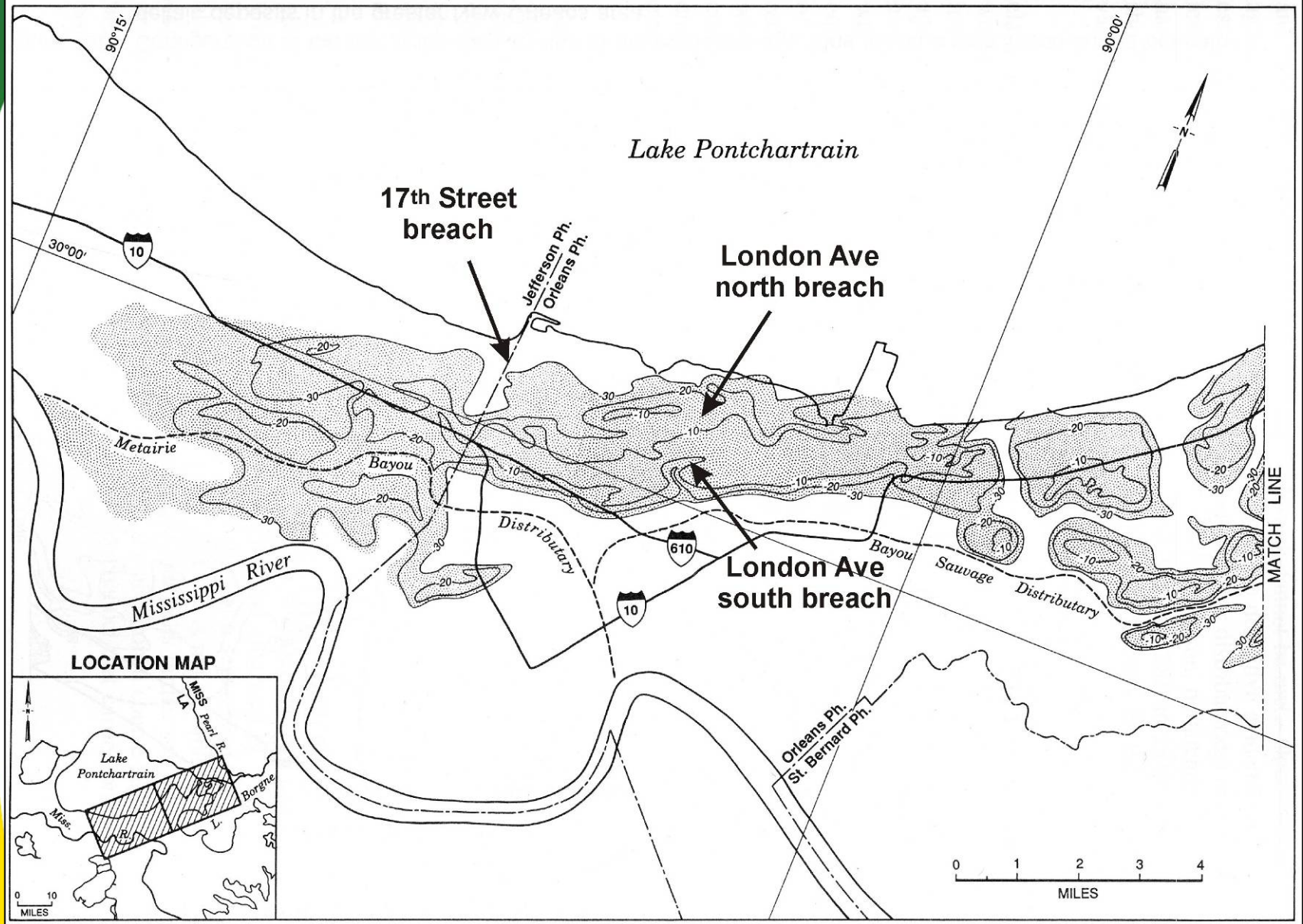
Part 4

17TH STREET DRAINAGE CANAL FAILURE

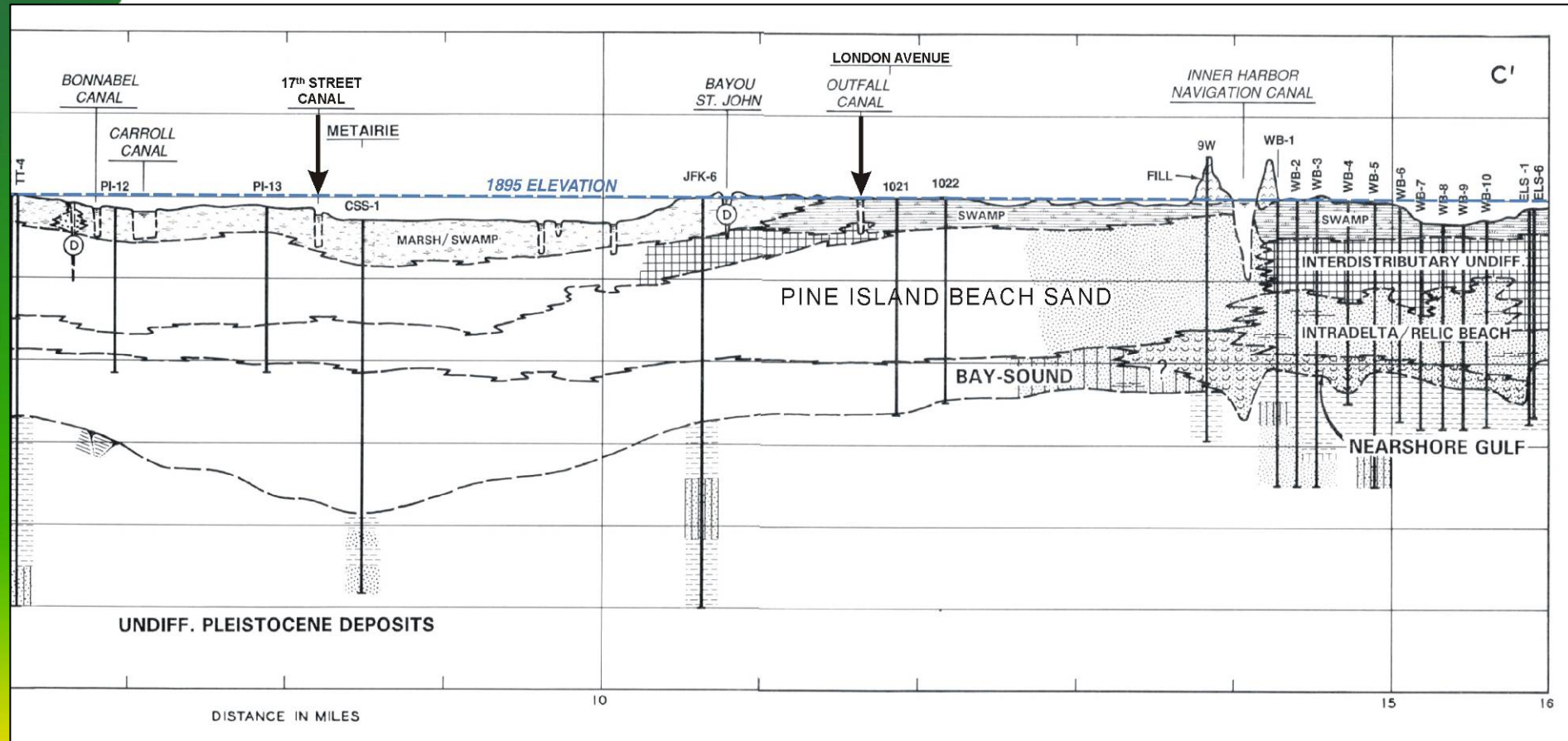


Embankment moved 51 ft

The most recently constructed elements of the city's flood control infrastructure, built in the mid 1990s, performed miserably.



- **Areal distribution and depth to top of formation isopleths for the Pine Island Beach Trend beneath lower New Orleans.**



- **Geologic cross section along south shore of Lake Pontchartrain in the Lakeside, Gentilly, and Ninth Ward neighborhoods, where the 17th Street, London Avenue, and IHNC levees failed during Hurricane Katrina on Aug 29, 2005.**
- **Note the apparent settlement that has occurred since the city survey of 1895 (blue line), and the correlation between settlement and non-beach sediment thickness.**

Drilling at last, in February



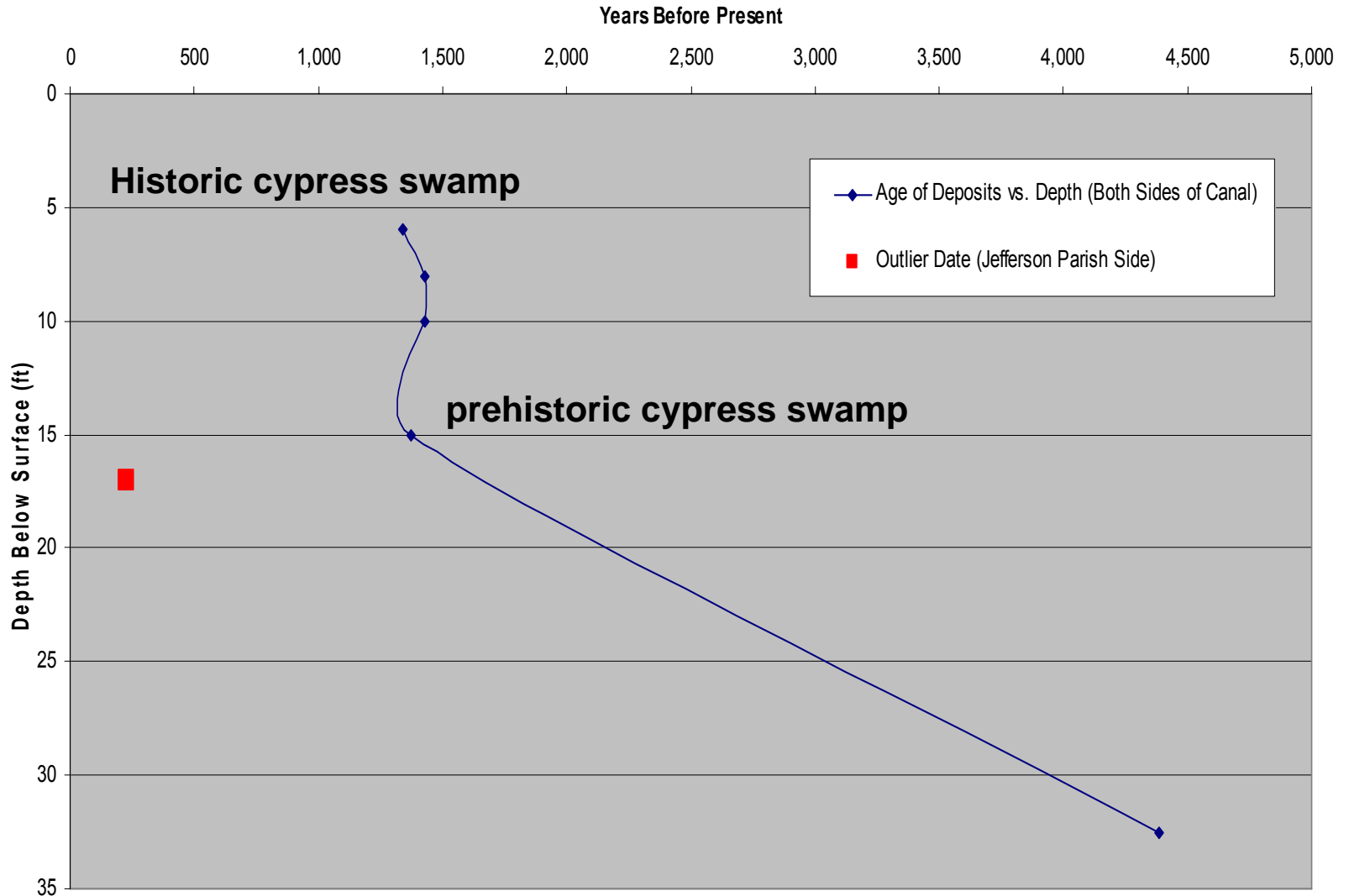
- After months of waiting, we were finally given permission to drill and sample the soils around the failed levees
- We soon learned that the foundation conditions beneath New Orleans were both unusual and treacherous
- Former Corps employees and local consultants provided the technical expertise our team needed to make the interpretations



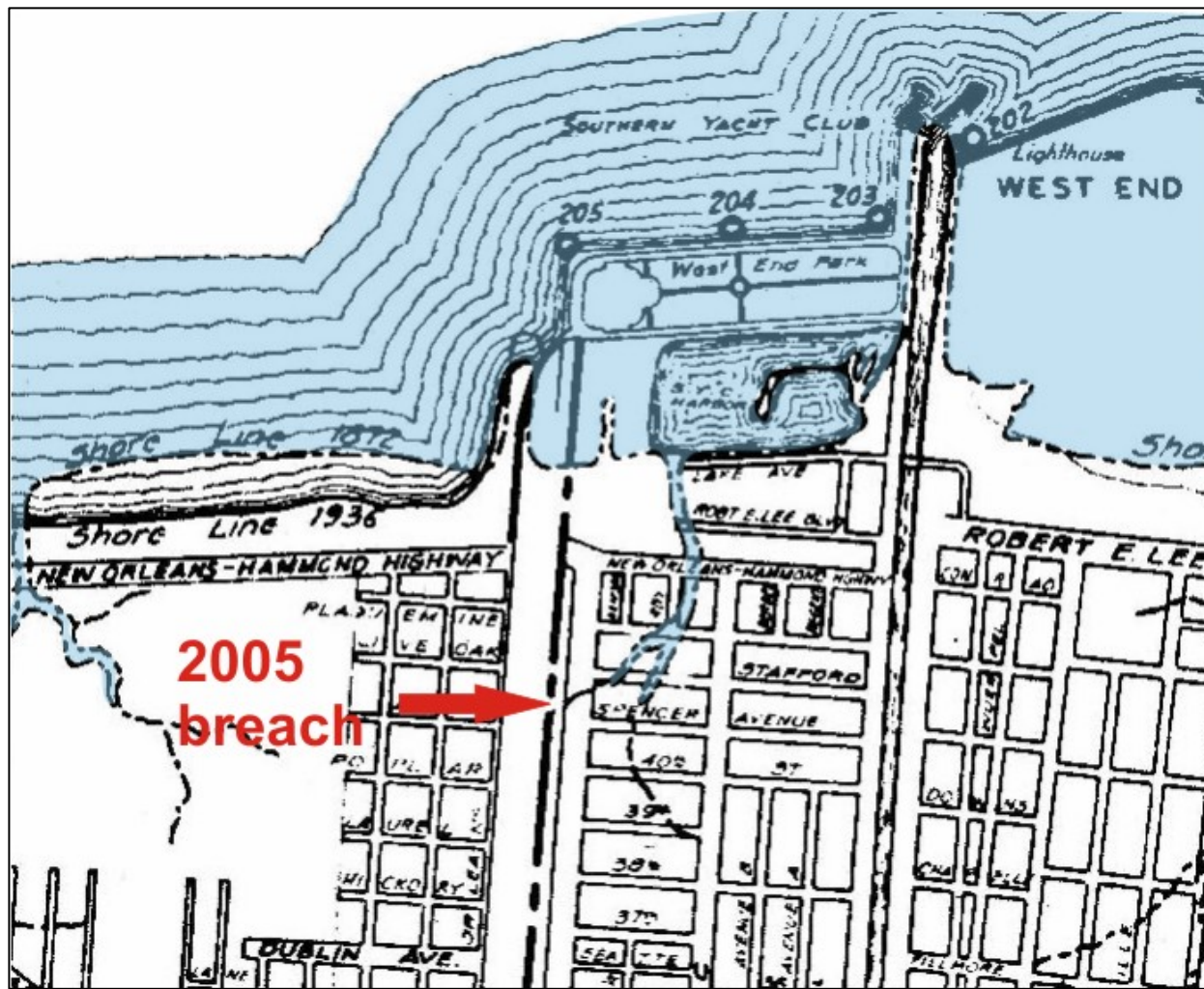


- **Drilling in a swamp environment.** It took us three tries to get one successful sample of the basal slip surface at each place we drilled

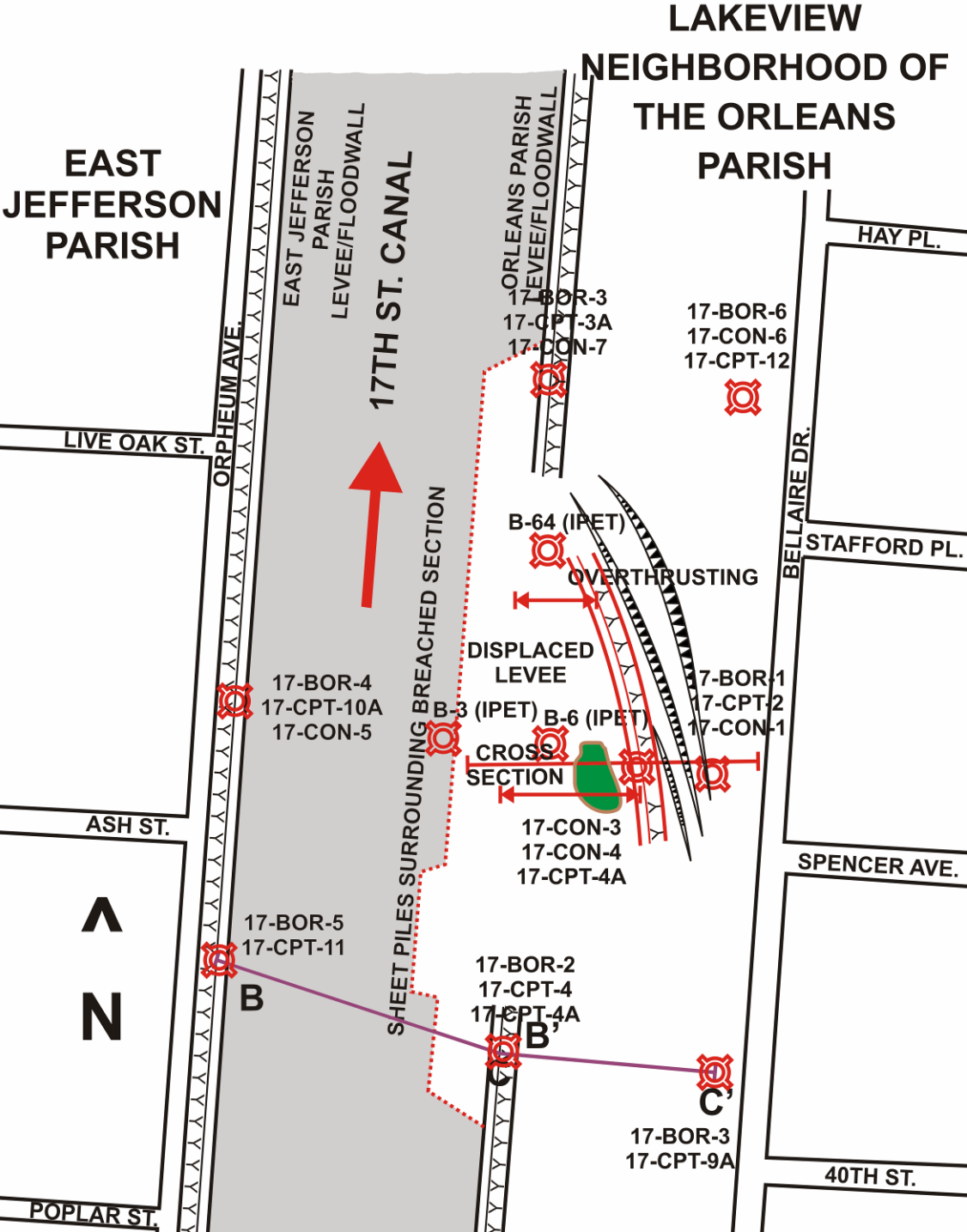
Age of Deposits vs. Depth in Vicinity of 17th St. Canal Breach



- **C14 dates and depths suggest a rapidly filling paludal environment during the late Holocene**



- **Map overlay** assembled by Prof. Joe Suyhada at LSU by overlaying 1872 Sulakowski map on the 1937 WPA map, showing the 1872 shoreline and sloughs (in blue) along Lake Pontchartrain.
- The position of the 2005 breach along the east side of the 17th Street Canal is indicated by the red arrow.

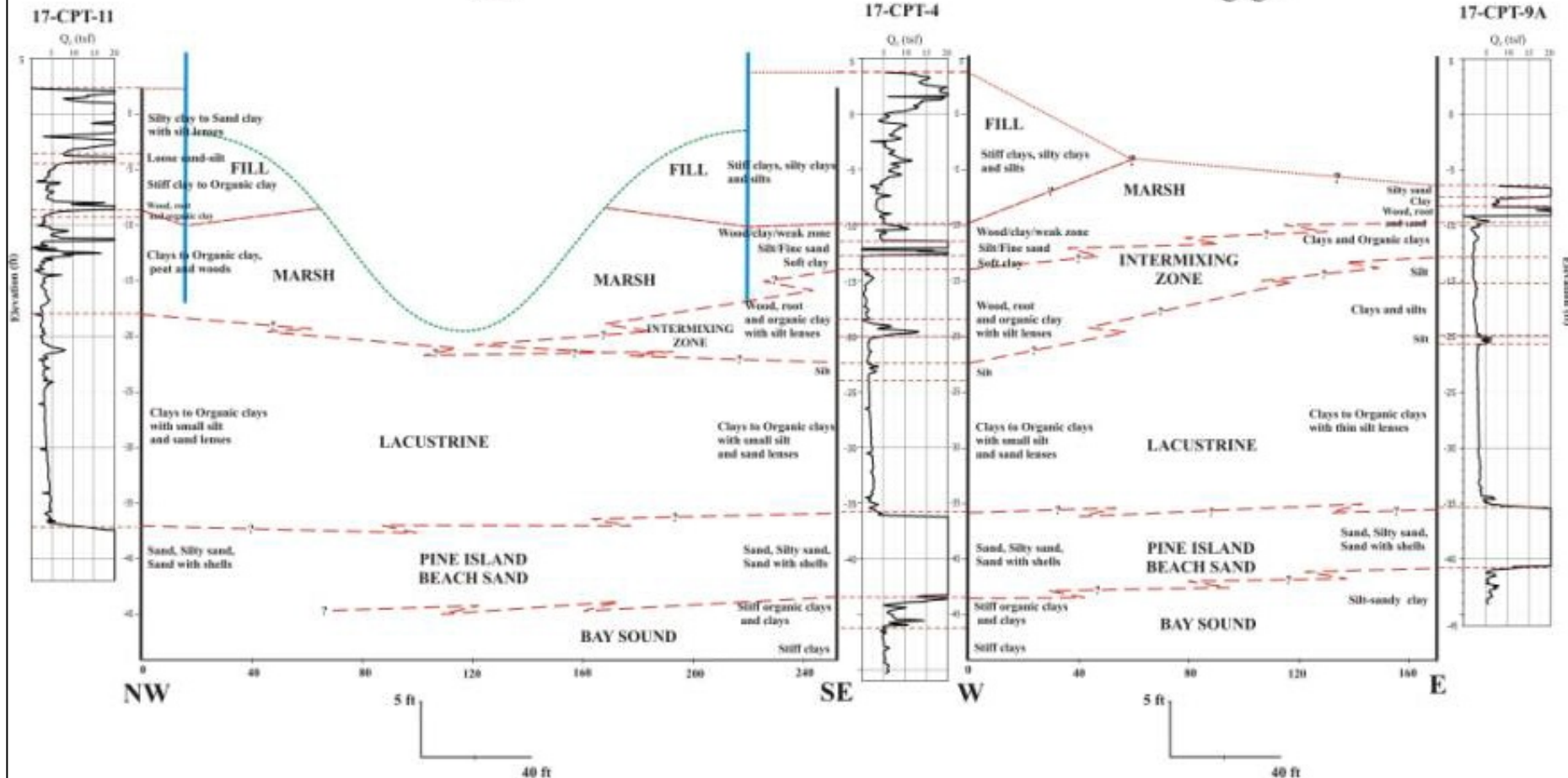


17th St Canal failure area

- Plan view of the 17th Street Canal breach site
- Locations of NSF team borings and CPT soundings noted in red
- The red lines indicate the positions of the NSF team's geologic sections.

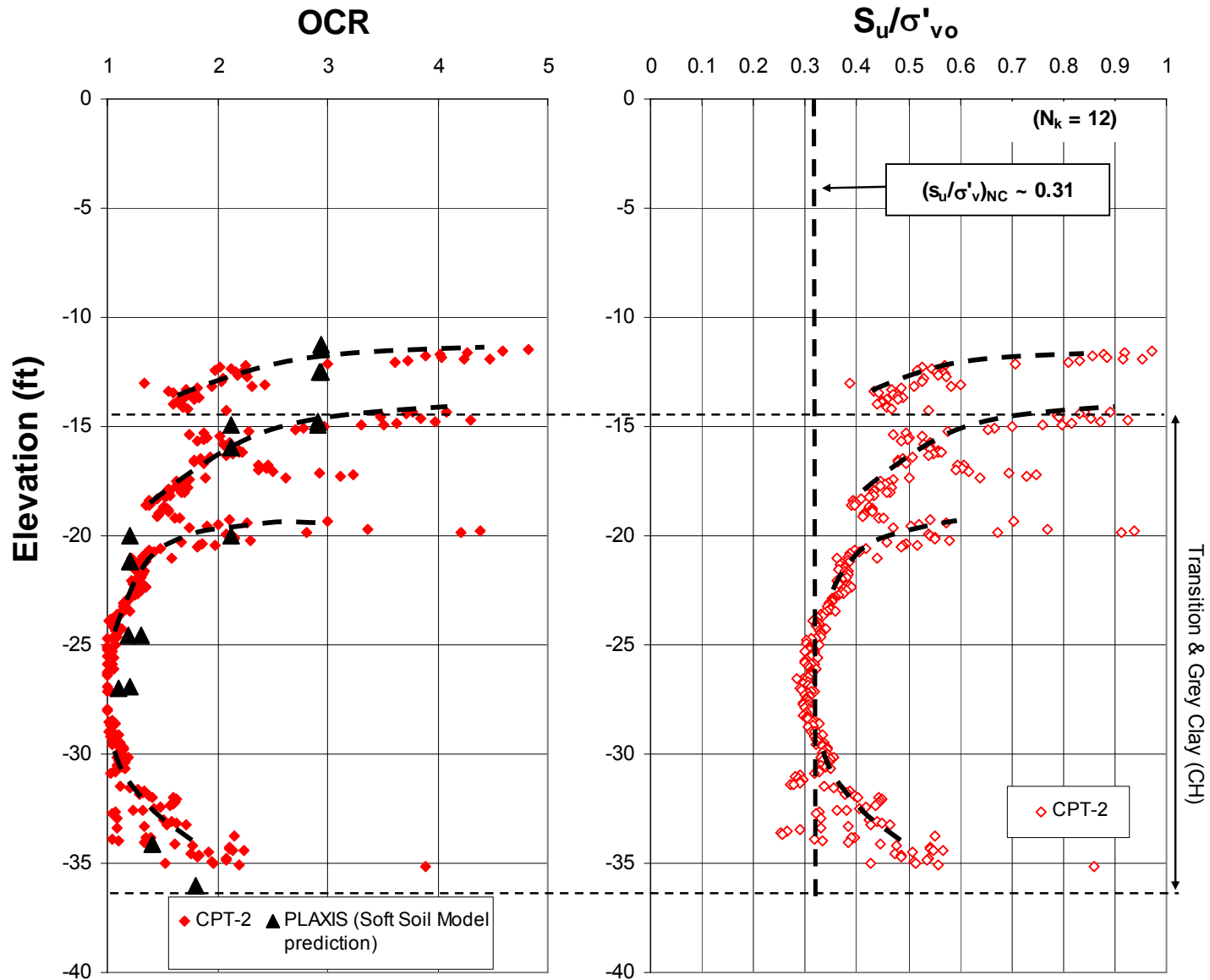
17th Street Canal Cross-section
B-B'

17th Street Canal East Bank Cross-section
C-C'



- **Stratigraphic interpretations across the 17th Street Canal breach.** The swamp much appeared to be thinning northerly, as does the underlying **Pine Island Beach Trend**. The lacustrine clays appear to thicken southward, as shown.
- The approximate positions of the flood walls (light blue) and canal bottom (dashed green) are based on information provided by the Corps of Engineers.

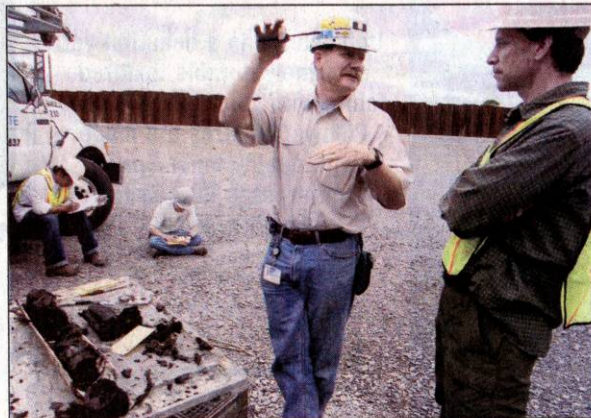
17th Street Canal: Soft Gray Clay (CH) Beneath the Toe of the Levee





STAFF PHOTOS BY TED JACKSON

This piece of clay was just above the peat area at the site of the 17th Street Canal floodwall breach.



J. David Rogers, center, and Joseph Wartman discuss soil borings at the 17th Street Canal floodwall.

the words “wood” or “shells” written between the lines, indicating a mixture, although the written description of the layers on the log indicates these layers were composed of mostly weak material.

But on the project cross section, that same area shows the symbols for such soils ending at about 15 feet below sea level. Below that depth, the symbols show soils of “fat clay” or “lean clay” — sticky, impervious soils considered very good for resisting water, Rogers said.

‘Significant finding’

After doing its own soil borings at the breach this week, the National Science Foundation

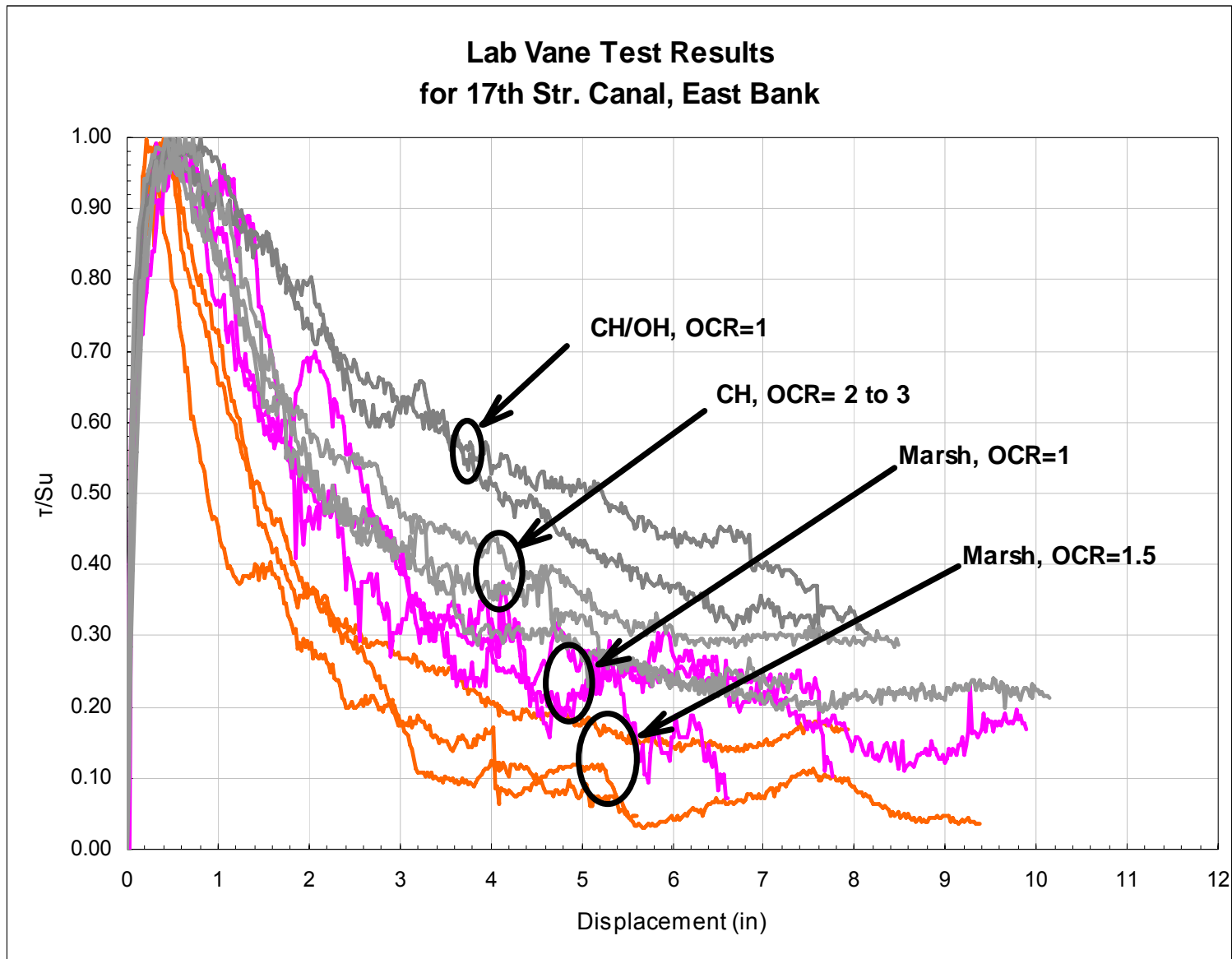
The 17th St Canal slip surface

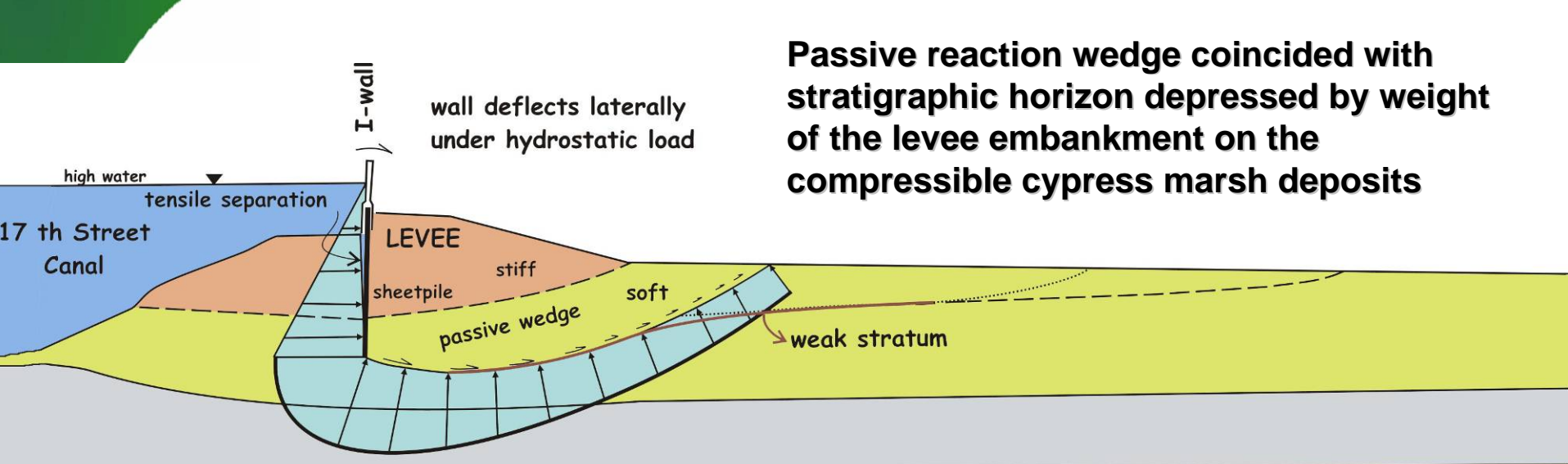
- Sampling the slip surface was only the first hurdle
- Shear testing of this toothpaste consistency paludal clay proved far more difficult
- The results eventually showed a peak shear strength of 50 psf, degrading to zero after a half inch of rotation

Miniature laboratory vane shear testing at U.C. Berkeley

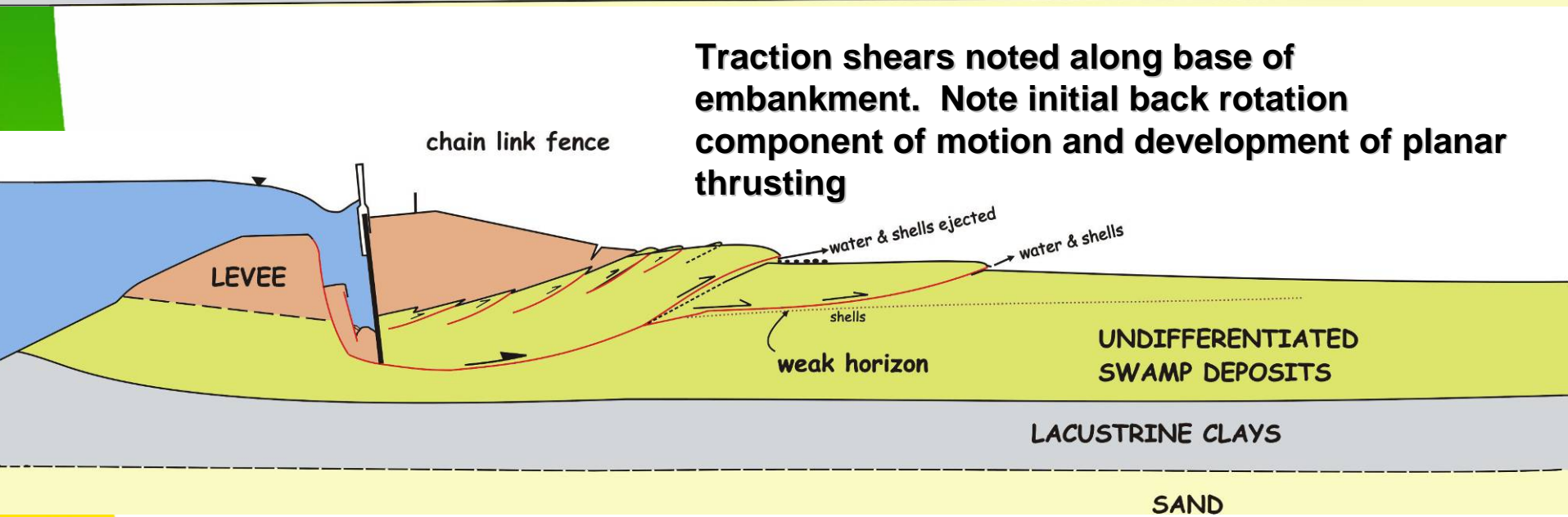


17th Street Canal: Sensitivity of the Sensitive Organic Clay within the Marsh Stratum vs. Sensitivity of the Deeper Gray Clay (CH)



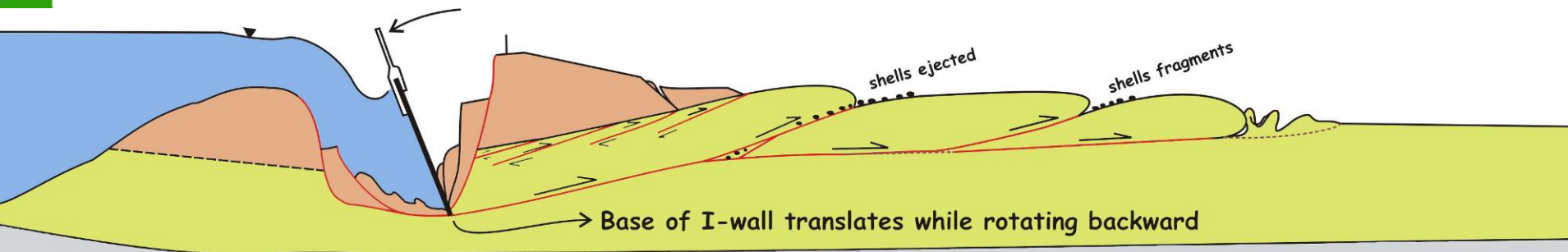
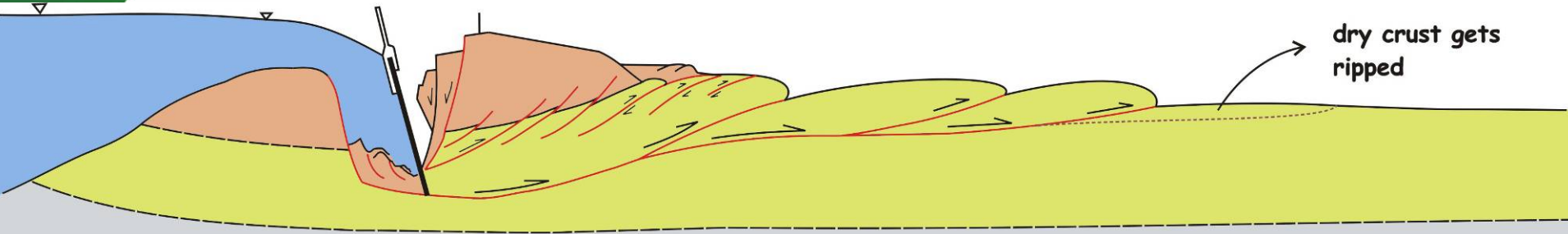


Passive reaction wedge coincided with stratigraphic horizon depressed by weight of the levee embankment on the compressible cypress marsh deposits

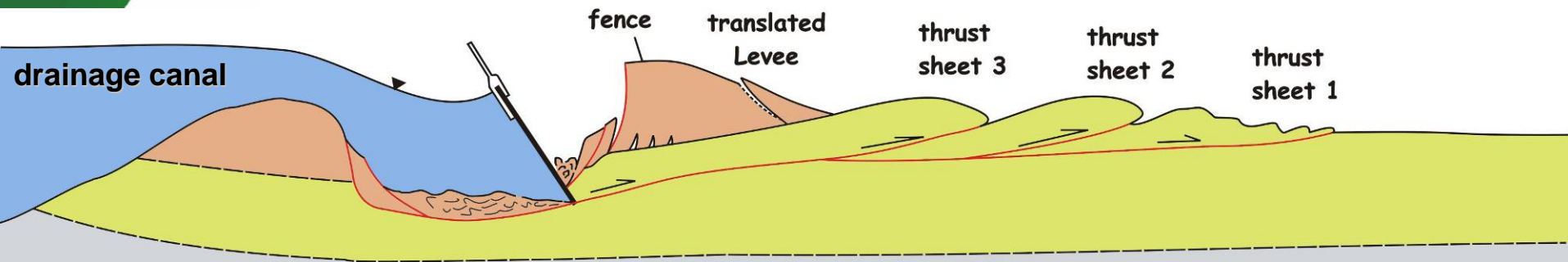


Traction shears noted along base of embankment. Note initial back rotation component of motion and development of planar thrusting

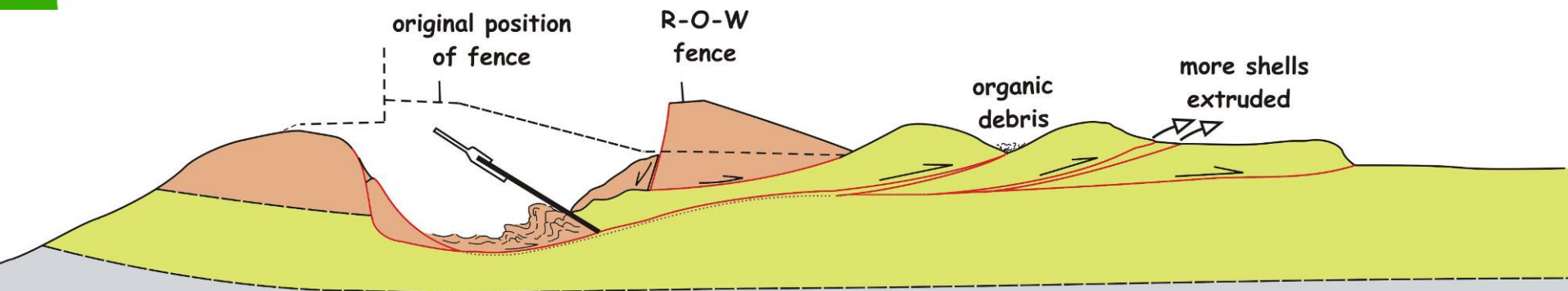
Initial loading conditions. Storm surge rises to within 4 feet of flood wall crest. Hydrostatic pressures on sheetpile supported I-wall highlighted in blue. Translational failure begins.



Progression of translational failure sequence. Multiple thrust sheets develop in partially saturated crust, comprised of sandy fill over organic cypress swamp deposits. The upper crust buckles like a rug being rolled up.



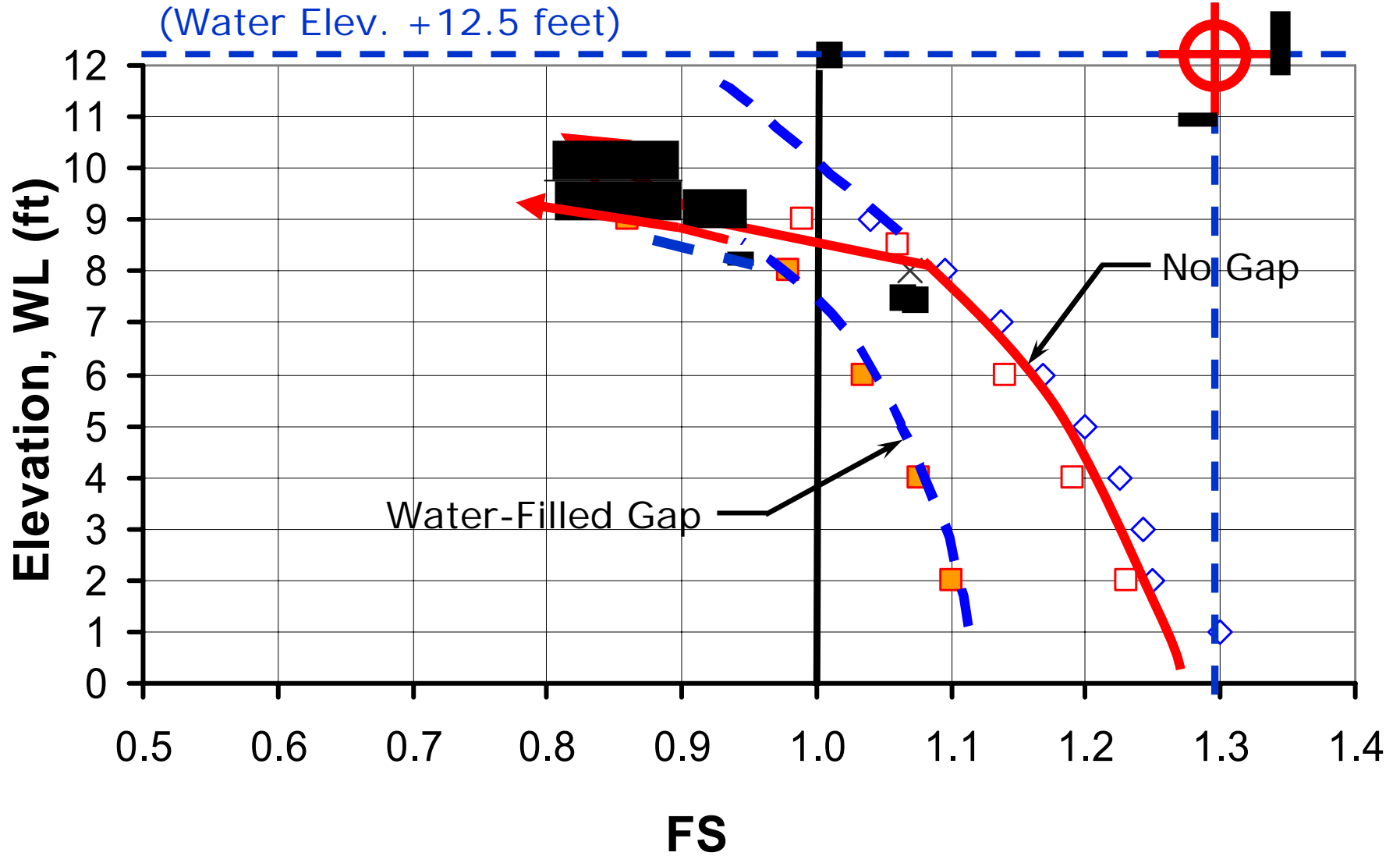
Some sheetpile supported I-walls fell backward; others fell forward



Final stages of translational failure sequence. Lower section shows failed levee after 51 feet of displacement. The void was quickly backfilled with gravel as part of sealing the breach.

17th Street Canal East Side

(FS = 1.3)

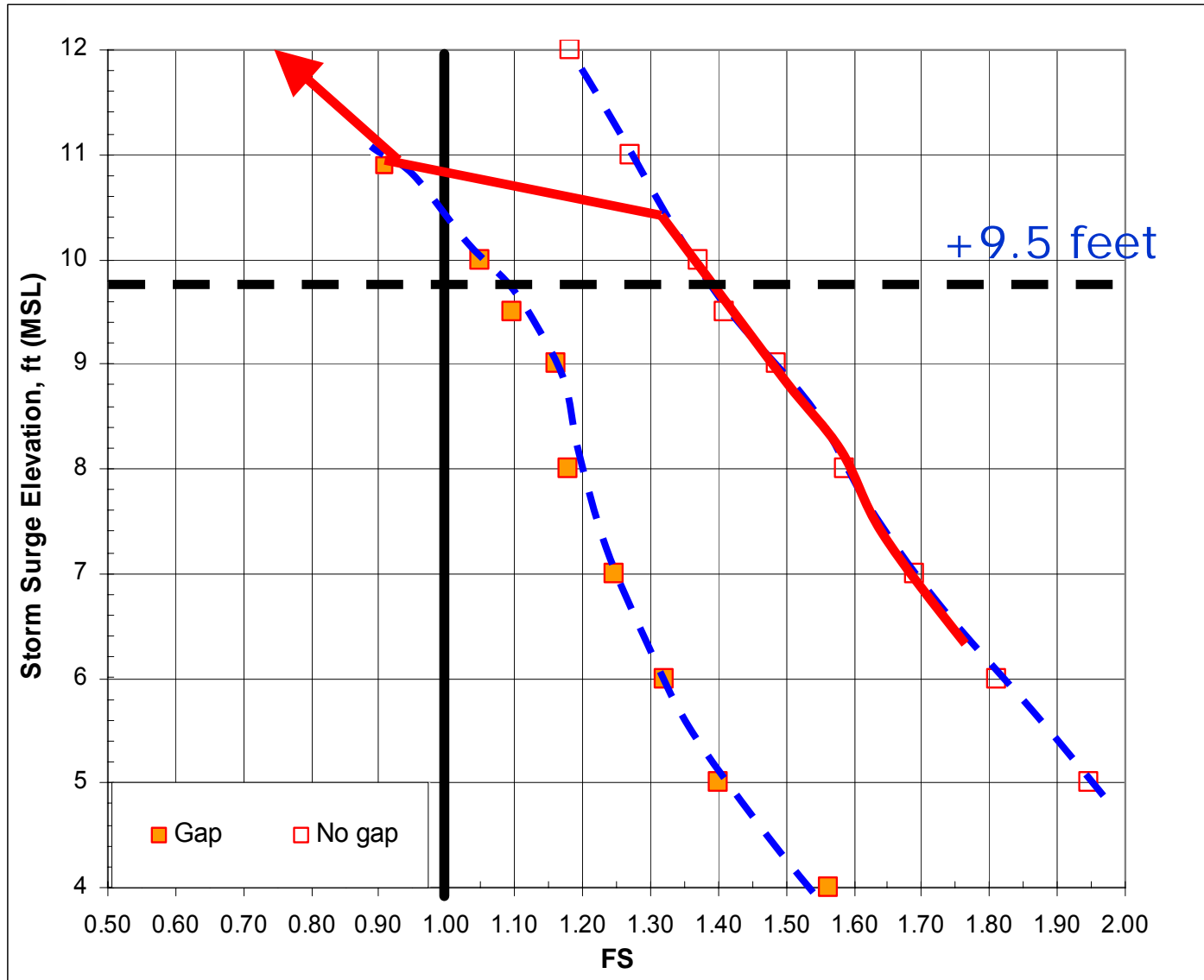




The tilting wall controversy

- The NSF team assuaged that the bend in the flood wall on the west (unfailed) side of the 17th St Canal was evidence of an incipient failure
- The Corps didn't initially agree publicly

17th Street Canal, West Bank



The design of the 17th St Canal I-walls violated the “three deadly sins”:

- 1) Never allow yourself to draw geologic cross sections using a ruler. ***There is no such thing as a ruler straight line in geology.***
- 2) Always construct multiple cross sections without vertical exaggeration to ascertain loading and reaction geometry, just like a ***free body diagram***. Use multiple orientations to appreciate apparent dips of various units.
- 3) Never allow yourself to ***average*** shear strength values when you get a low factor of safety. ***Slope failures tend to occur along the weakest horizons*** – finding and sampling those horizons is almost always difficult, requiring considerable judgment and experience.

Part 5

LONDON AVENUE DRAINAGE CANAL FAILURES

London Avenue (North) breach



Similar failure mechanism as 17th St Canal

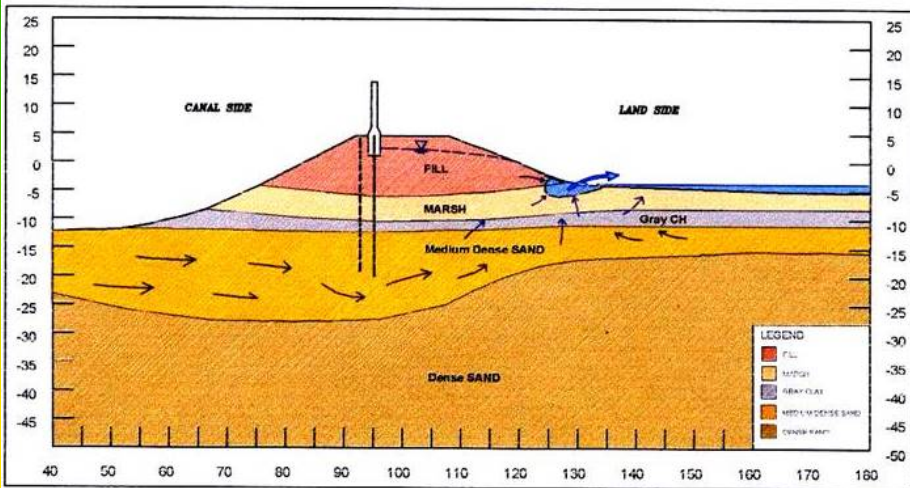
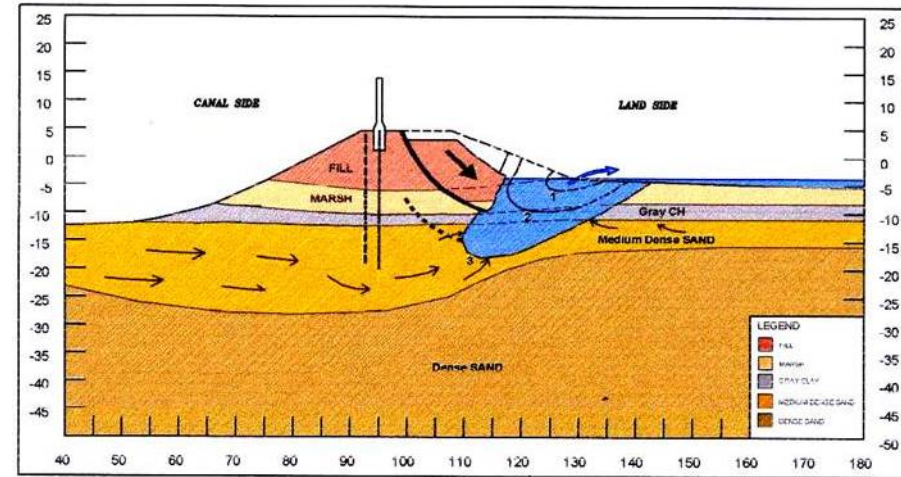
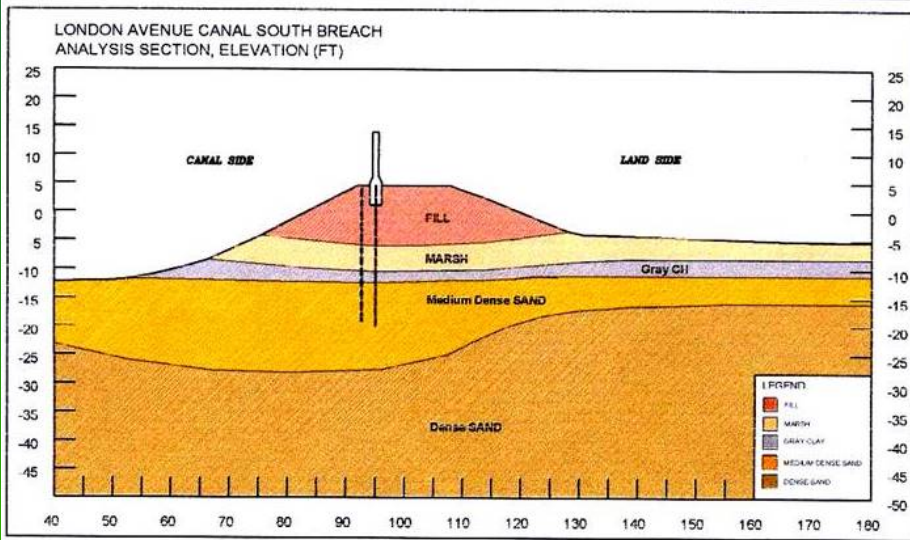


Incipient failure

- **Tilted flood wall opposite the London Avenue North breach, at Robert E. Lee Blvd.**
- **Forensic scientists learn more from a partial failure than a complete one, because much of the critical evidence remains**

London Avenue (South) breach





The South Breach of the London Avenue Canal was caused by **excess seepage pressures** developed in the sand underlying the canal, which had been dredged

Part 6

INNER HARBOR NAVIGATION CHANNEL AREA

Post Failure Analyses of East Side IHNC South Breach

Possible failure modes:

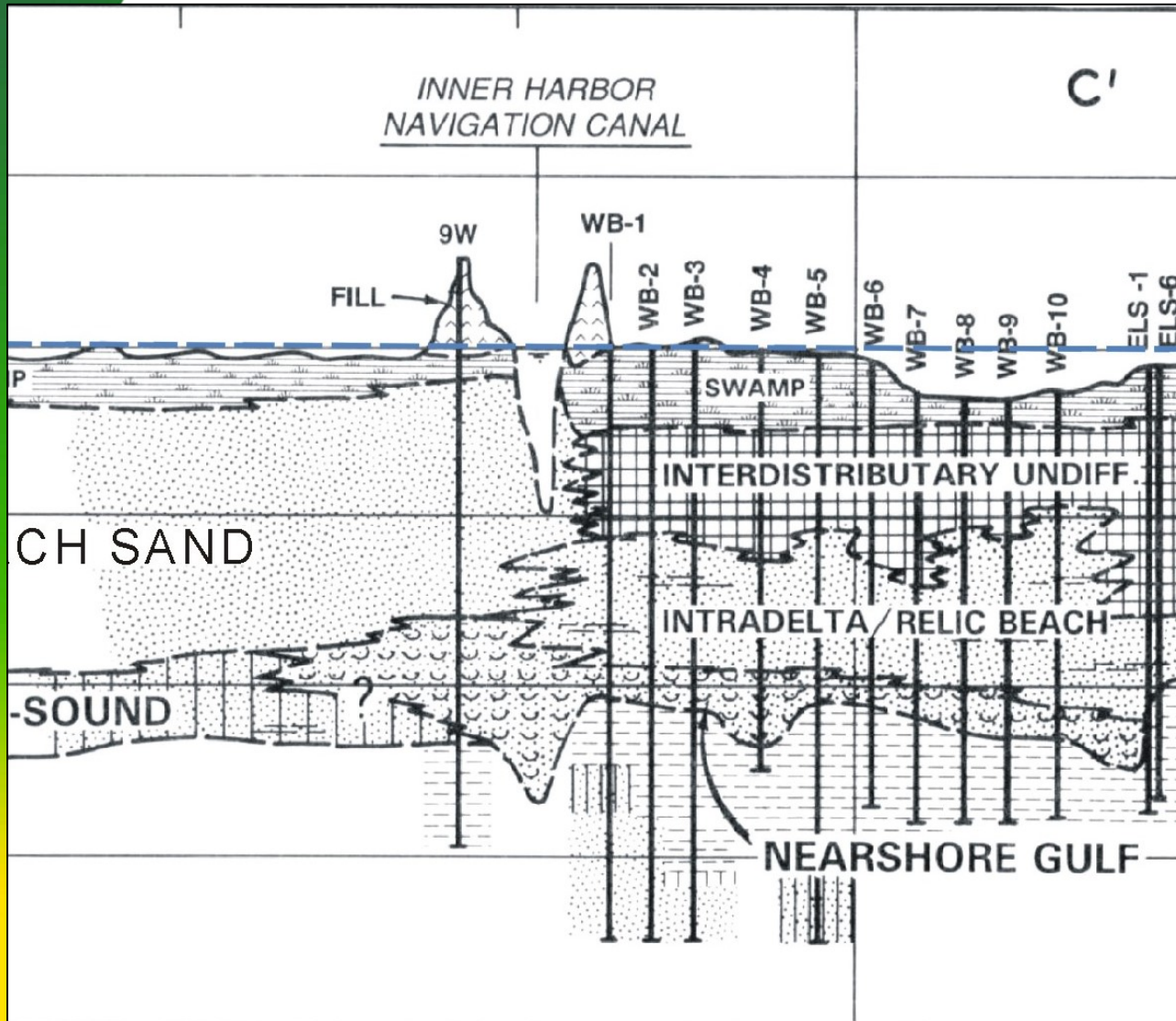
- **Overtopping scour trench-induced flood wall failure; and**
- **Underseepage, piping and uplift induced translational stability failure**
- **Multiple failure modes likely competed with one another**

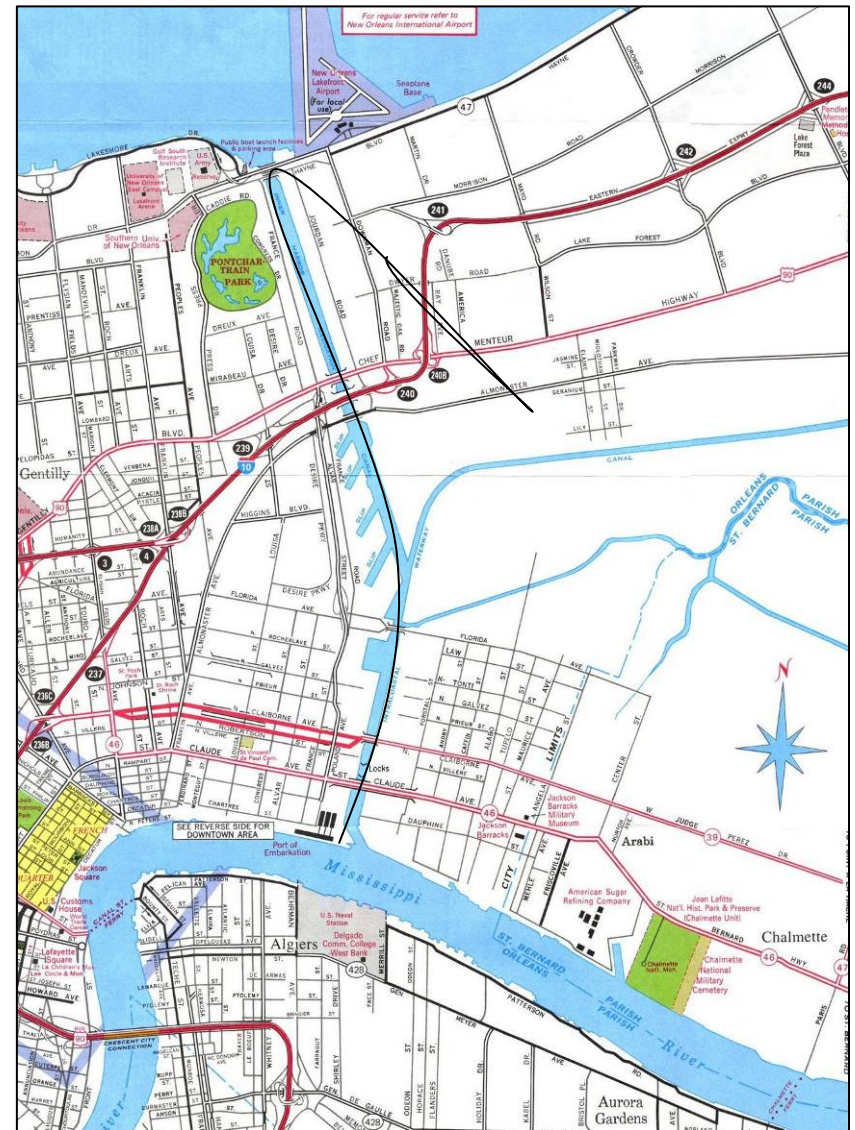
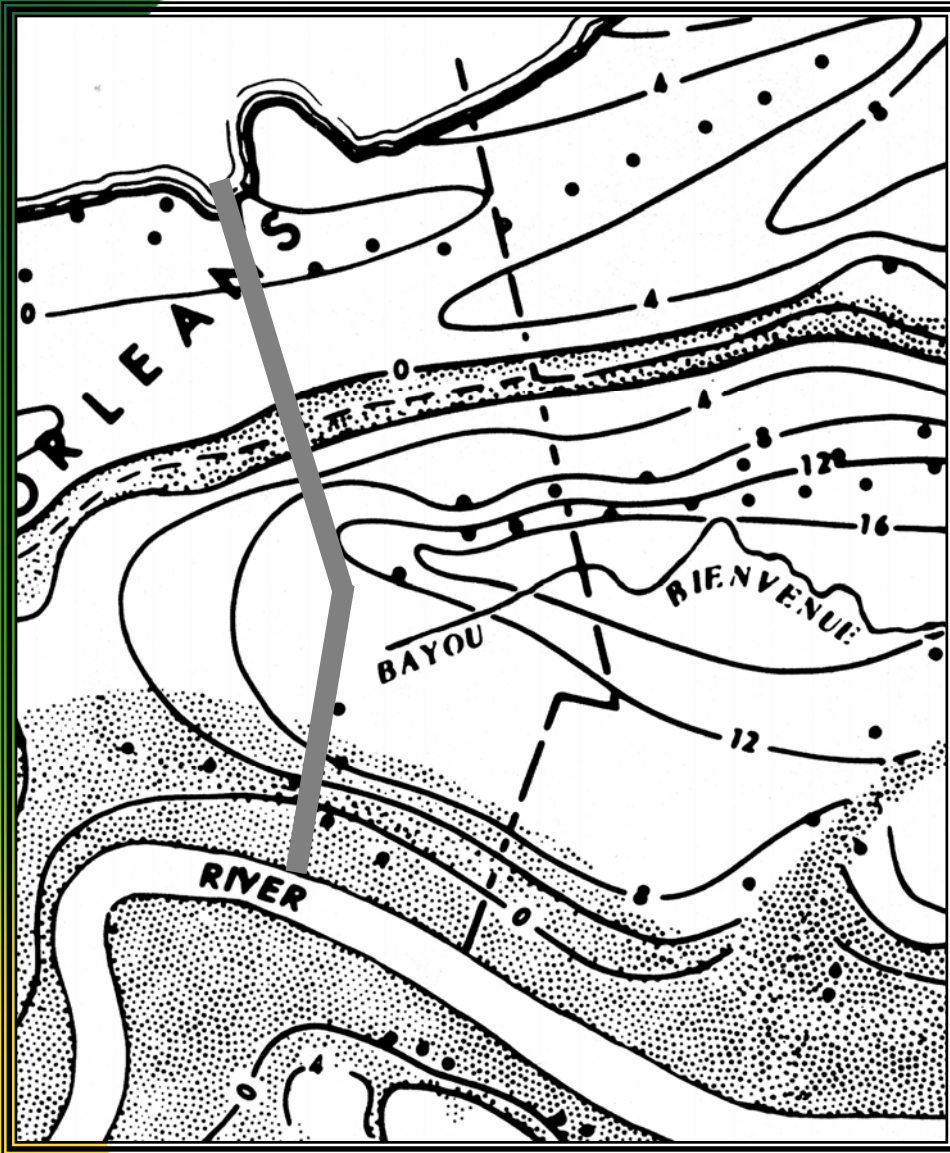


- Aerial oblique view of the **Inner Harbor Navigation Canal** between 1960-64, after the entry to the Mississippi River-Gulf Outlet Channel had been enlarged (upper right), connecting to the inner harbor area.

Geology under the IHNC

- The units lying beneath the IHNC channel vary from the west to the east side





- Detail showing thickness of surficial peat in vicinity of the IHNC. Thickness varies from 0 to 12 feet along Section III, between Claiborne and Florida Avenues.



- **Some sections survived:** Evidence of sustained overtopping of concrete flood wall along the IHNC in the Lower Ninth Ward.



- **Overtopping scour holes along landside of flood wall on west side of the IHNC. Note broken wall in background. A splash pad on inboard side could have prevented this failure mode.**

Lower Ninth Ward



- Aerial view of the south breach of the Inner Harbor Navigation Channel (IHNC) in the Lower Ninth Ward of New Orleans.



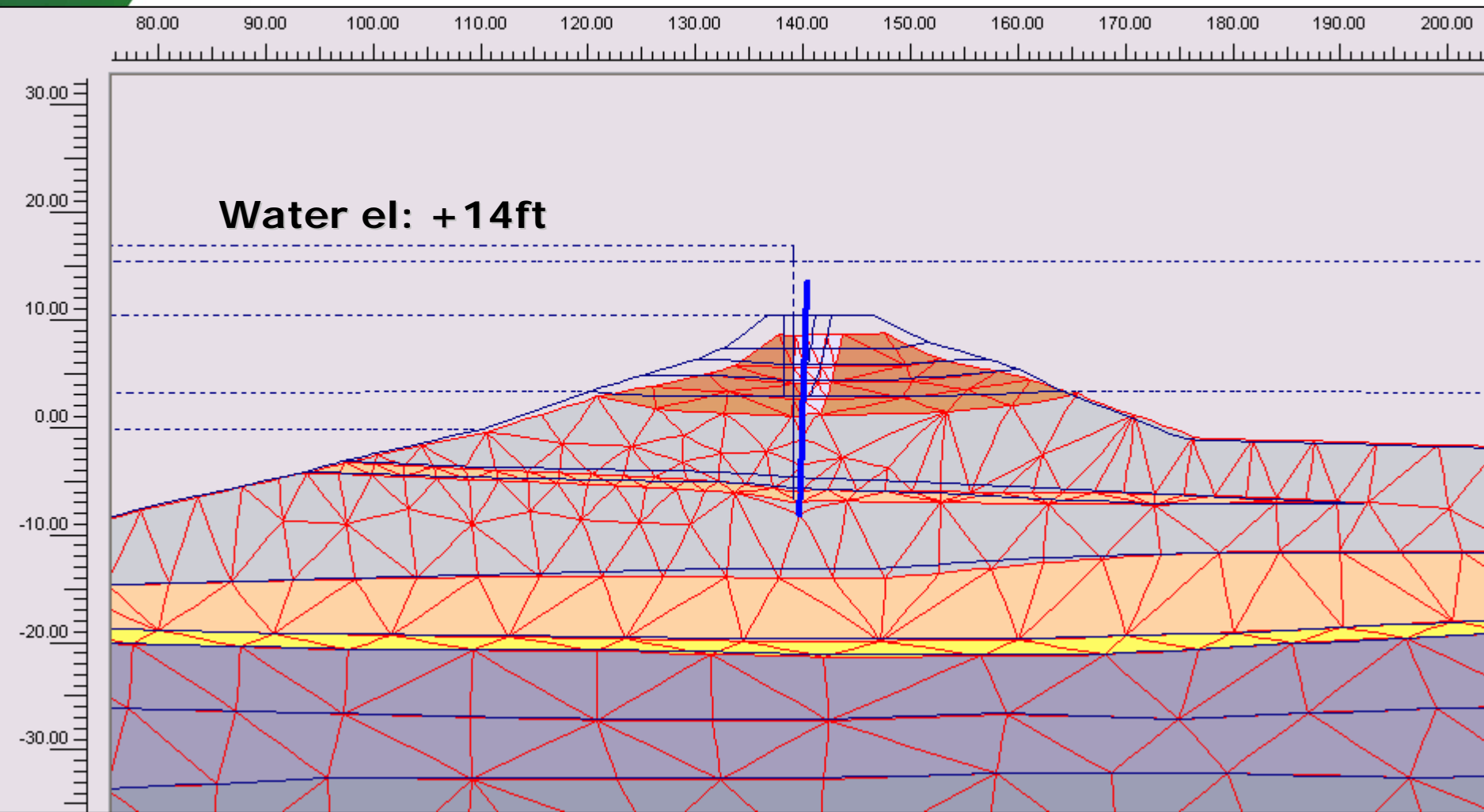
- **ING 4727 was built in 1990 as a dry cargo cover-top barge with a steel hull. It was 200 feet long, 35 feet wide, and 12 ft high, with a cargo volume of 84,659 ft³ (1877 tons). It was being leased to Lafarge North America, and was tied up along the MRGO channel.**



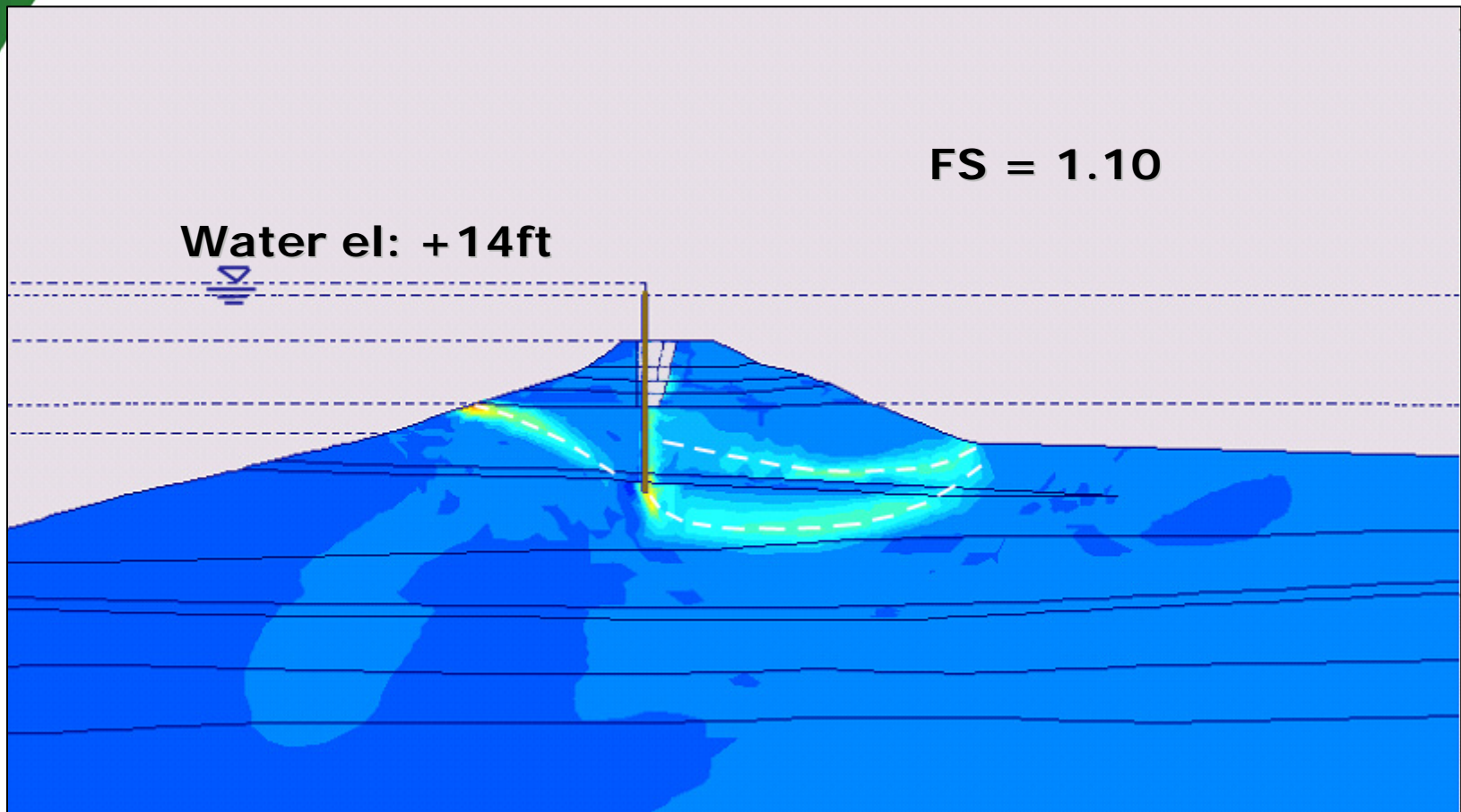
- **Damage to concrete flood wall where ING 4727 Barge collided with it, along the south side of the IHNC adjacent to the Lower Ninth Ward**

ANALYSES: Stability of Flood Wall East IHNC South Breach

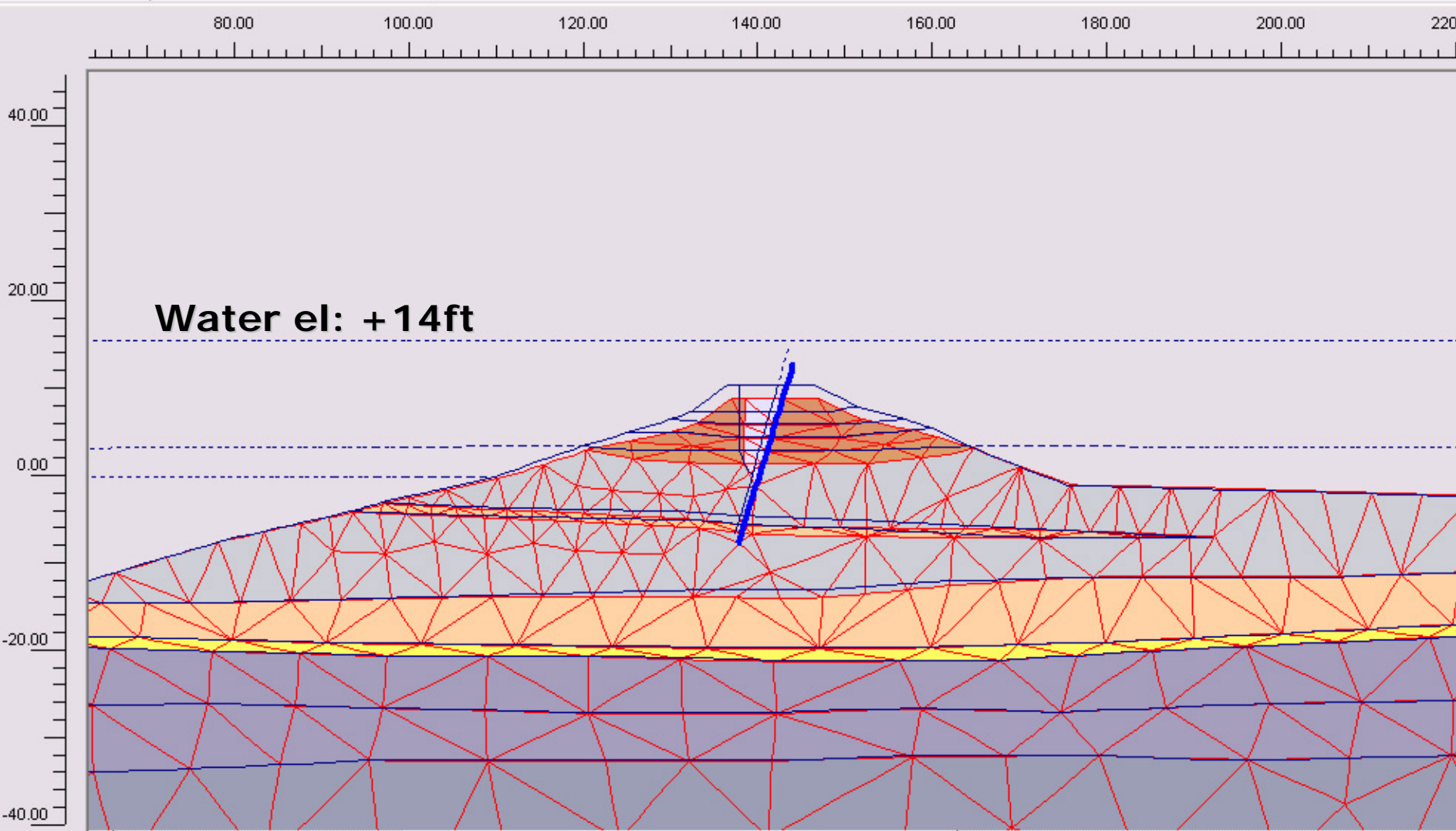




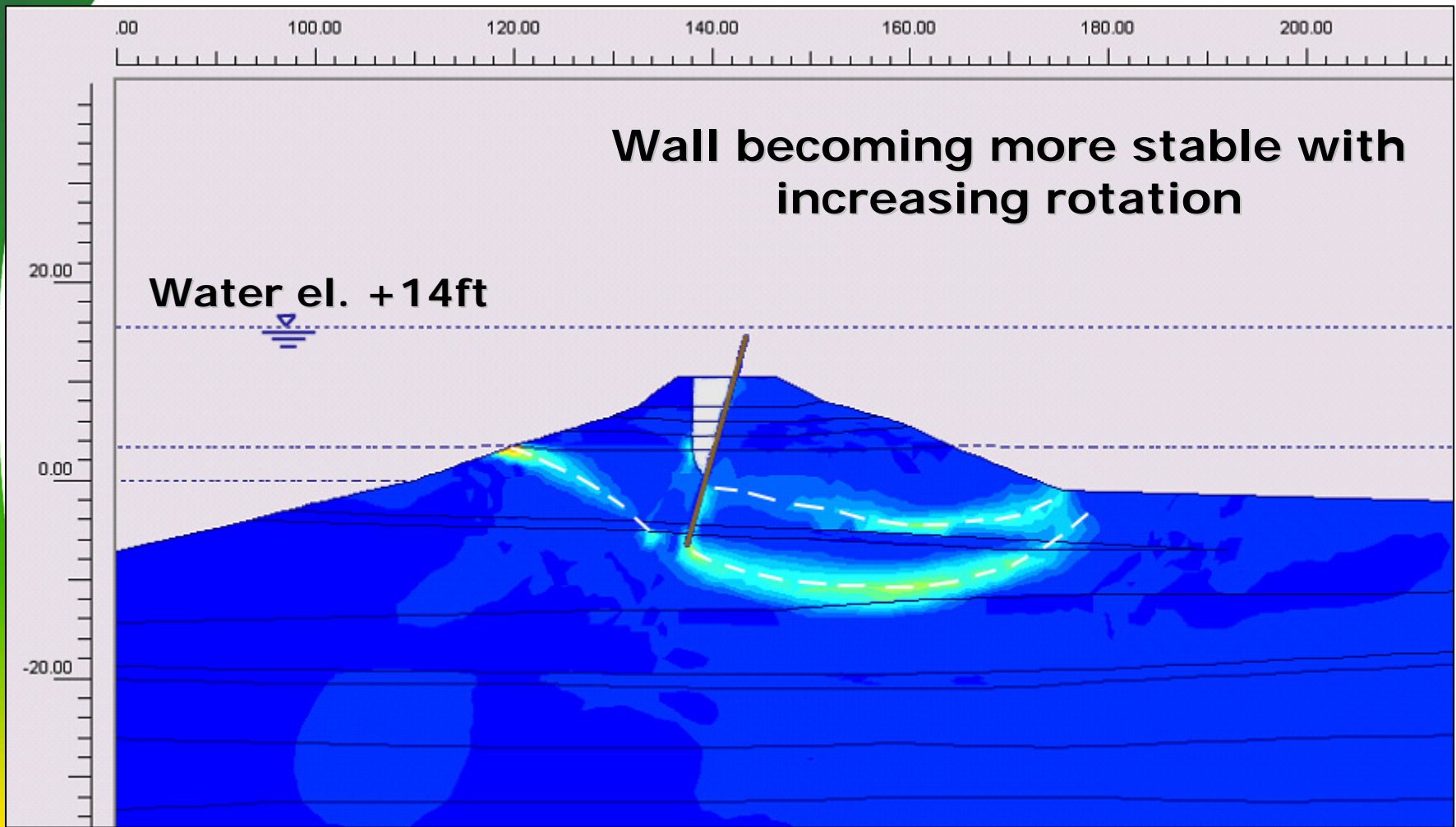
Plaxis soft soil constitutive modeling of 7.5 ft deep scour trench and 4.5 ft gap – deformed mesh – true scale (max displacement of embankment crest = 1.2 ft)



Shear strains predicted by the Plaxis model, assuming a 7.5 ft deep scour trench and 4.5 ft wall gap – using “best estimates” of c and ϕ – Factor of Safety = 1.10. Underseepage-induced pore pressure trapped along base of less pervious clay stratum, overlying the more pervious marsh deposits.



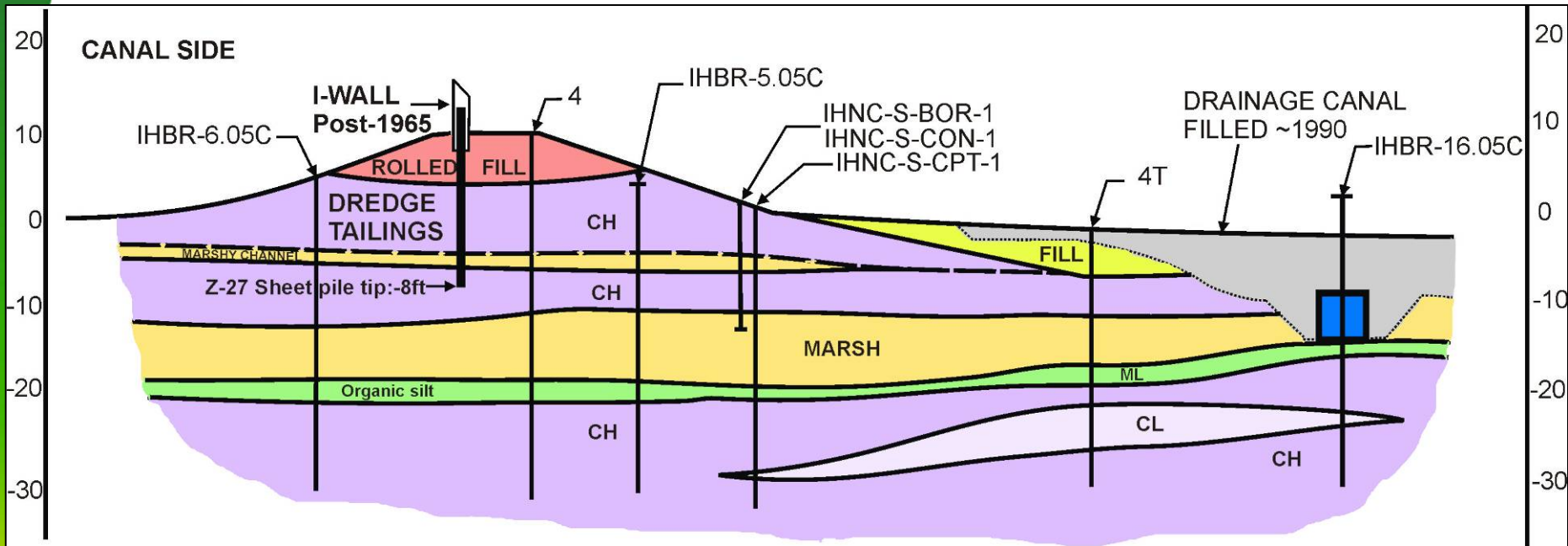
Leaning wall with 8.5 ft of gap – deformed mesh – true scale (max displacement = 1.71 ft)



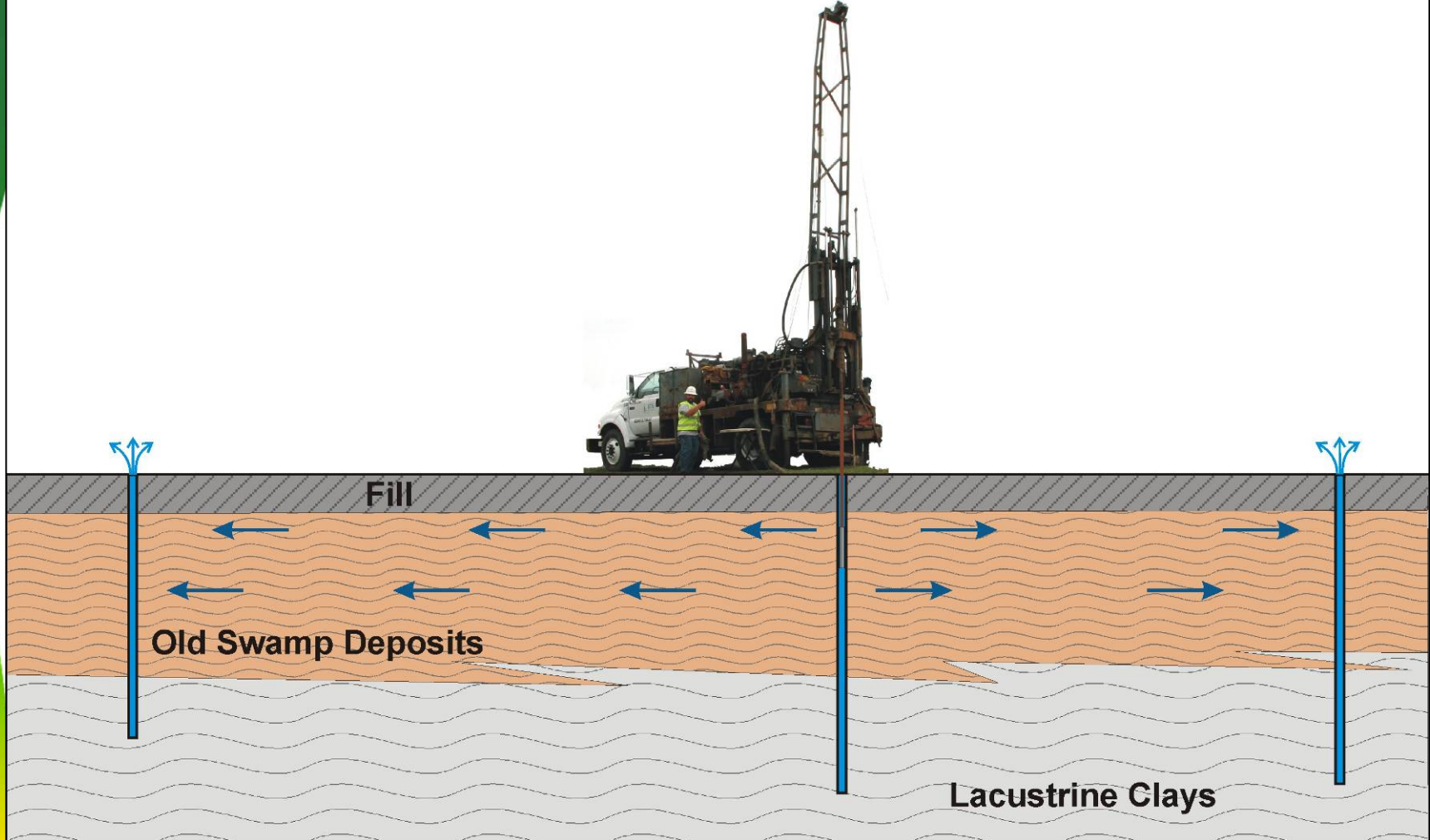
Leaning wall with 8.5 ft of gap. Predicted shear strains using "best estimates" of c and phi. Factor of Safety now = 1.15

Coupled Seepage Analyses of Embankment along East IHNC South Breach

East Bank IHNC South Breach

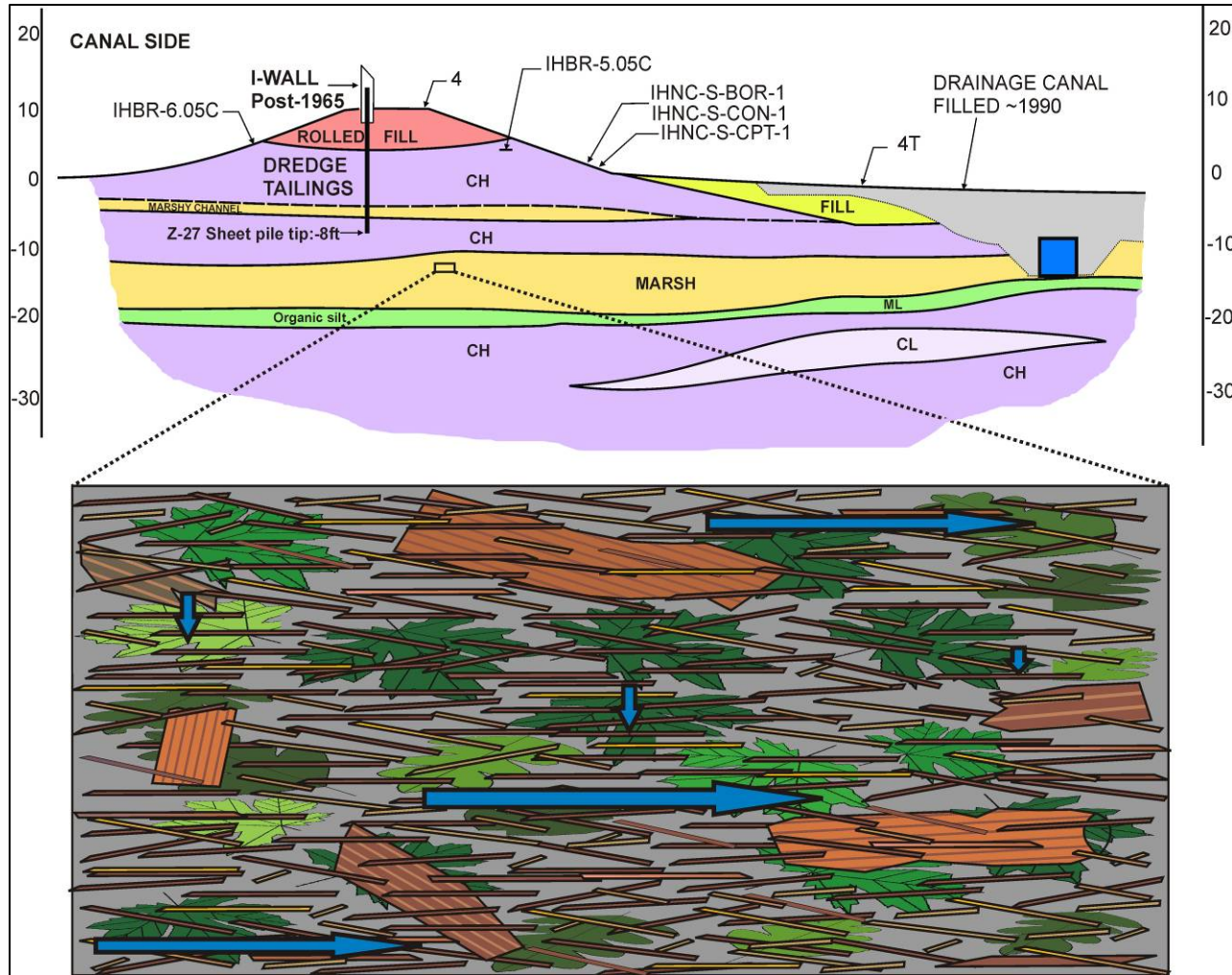


Geologic cross-section showing projections of borings and tentative stratigraphic correlations for the 800 ft long IHNC East Bank-South Breach, adjacent to the Lower Ninth Ward

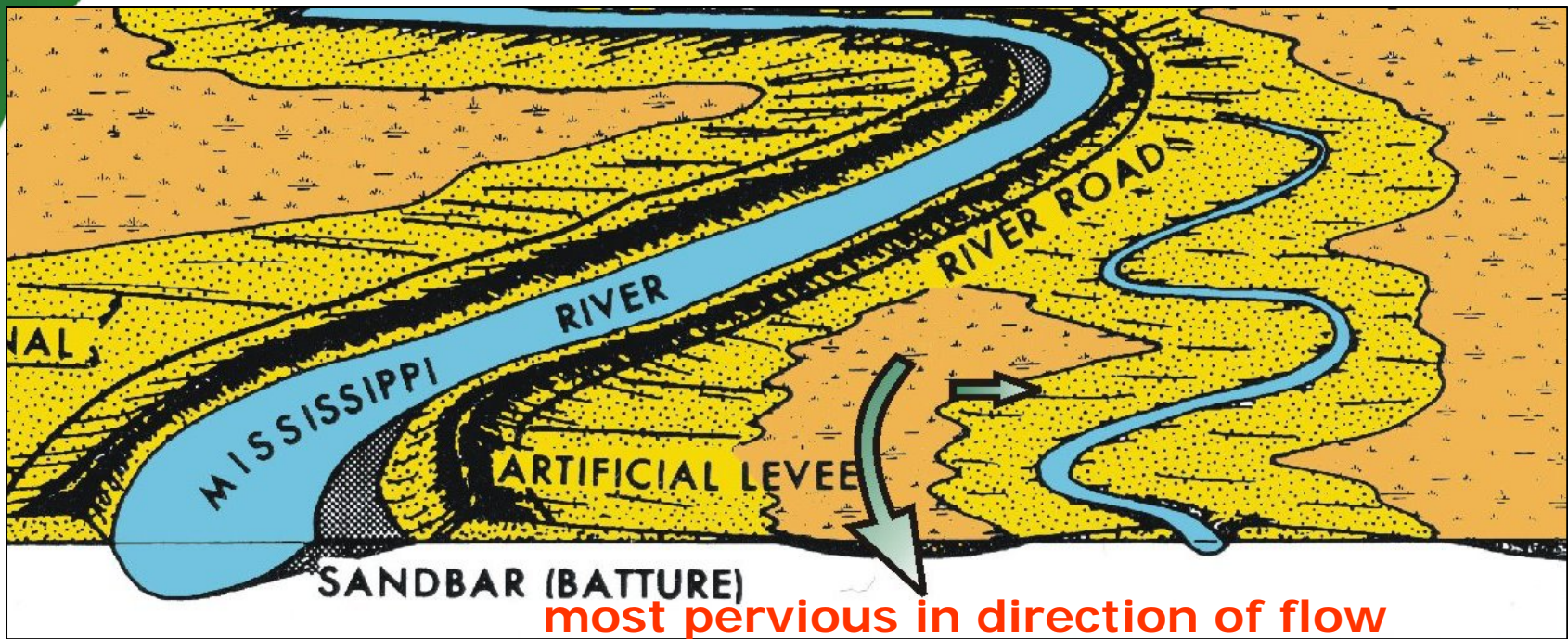


- The porous and **highly conductive** nature of the backswamp deposits was revealed during post-Katrina drilling and sampling operations.
- Highly conductive in horizontal plane, especially, parallel to original surface drainage.

Anisotropy of backswamp deposits

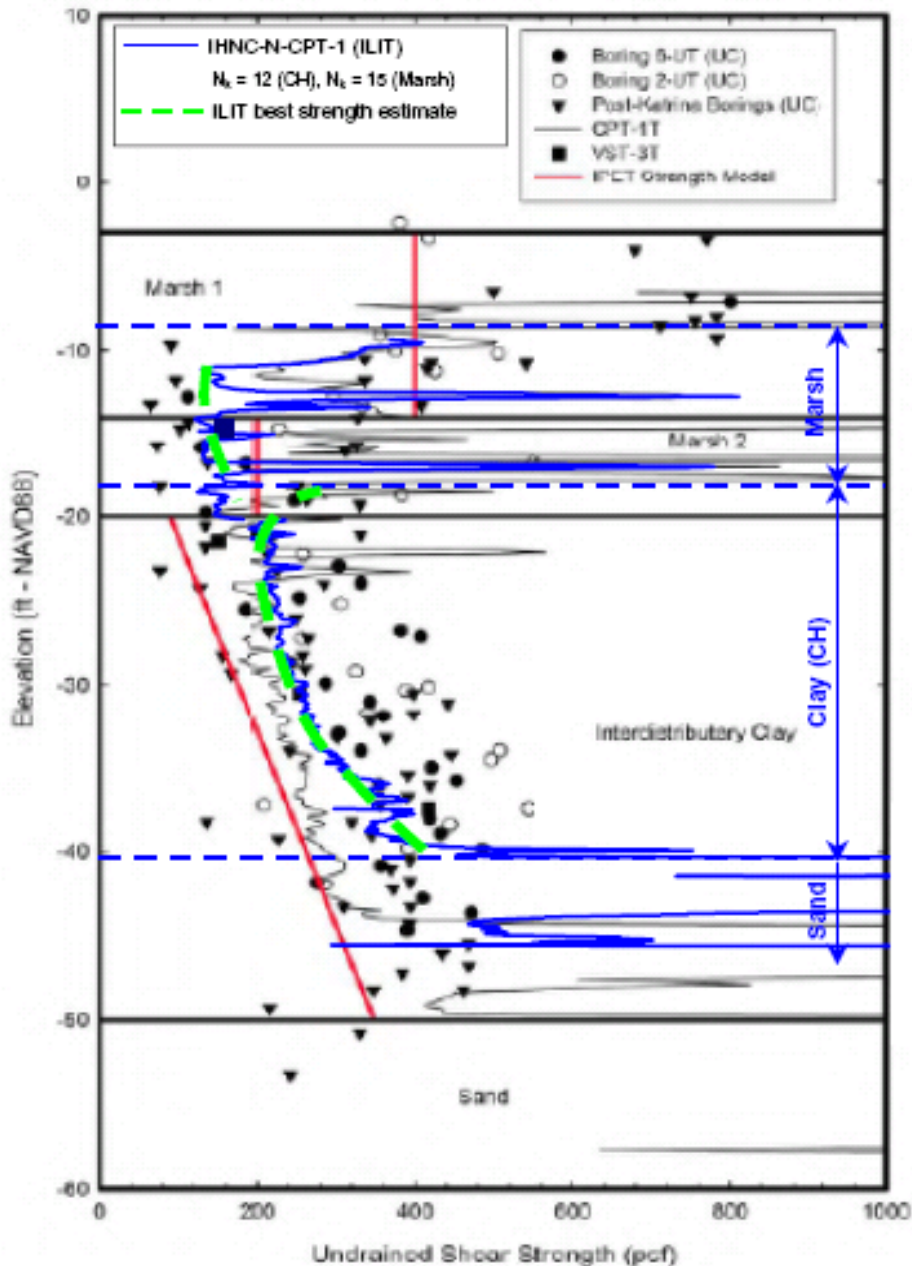


- Sudden die-off of organics creates highly anisotropic fabric; preferentially layered



- **Drainage swales in the backswamps are subject to sieving of fines by runoff**
- **This causes hydraulic conductivity to increase along the runoff path, as opposed to other seepage paths, within the plane of sediment accretion**

Shear Strength under Toe



Undrained shear strength vs depth at the East IHNC North Breach

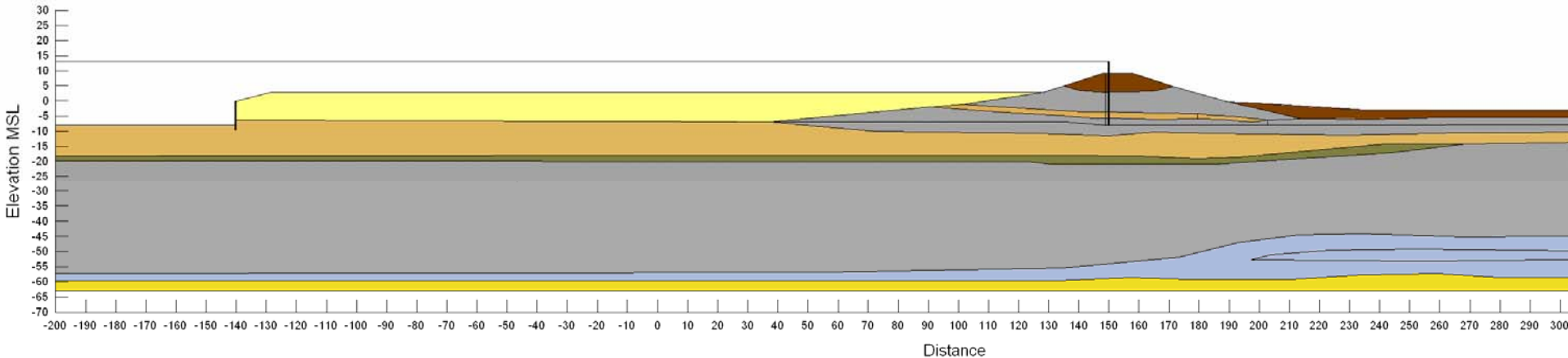
Blue lines shows profile of CPT-1, with NGI tip corrections for the three units encountered

Green line shows strength profile selected by the NSF team

Red lines shows strength profile used by the IPET team; which allows a rotational stability failure sometime between 5:30 and 6:00 AM

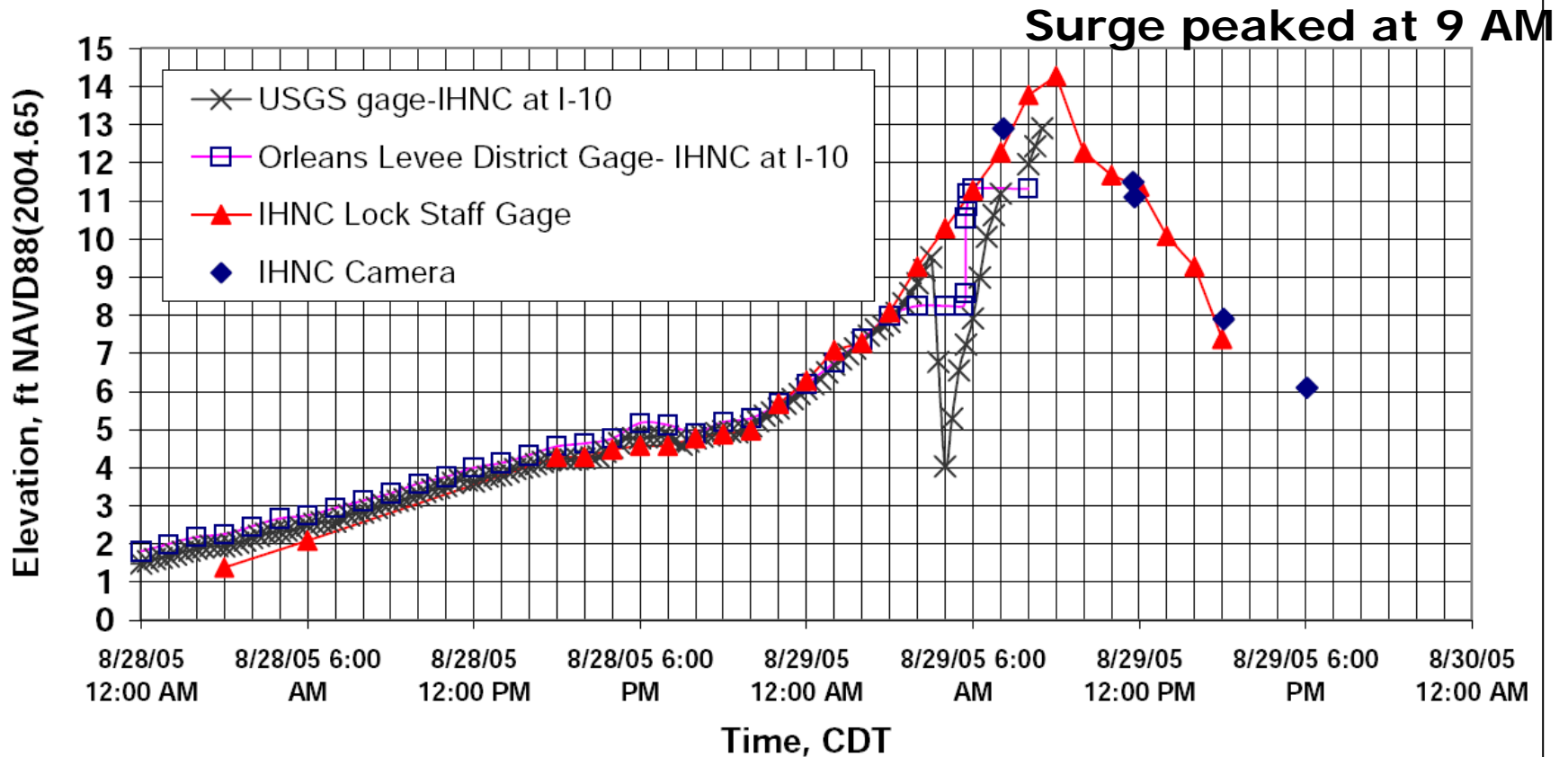
MATERIAL	PARAMETER						
	γ (pcf)	ϕ	c (psf)	Kh (ft/hr)	Kh (cm/s)	Kv/Kh	Θ *
Fill	105	0	900	1.17E-04	9.91E-07	1	0.35
Upper CH	95	0	800	2.00E-04	1.69E-06	0.333	0.35
Upper Marsh	85	28	0	1.10E+00	9.31E-03	0.25	0.5
OC Grey CH	95	0	500	2.00E-04	1.69E-06	0.333	0.35
NC Grey CH	95	0	Su/p: 0.28	2.00E-04	1.69E-06	0.333	0.35
Lower Marsh	85	28	0	1.10E+00	9.31E-03	0.25	0.5
Silt	110	0	600	1.17E-04	9.91E-07	0.333	0.41
Lean Clay	100	0	600	2.00E-04	1.69E-06	0.333	0.38
Sands	120	30	0	1.00E+00	8.5E-03	0.5	0.42
Gaps				100		10	1

* Fredlund et al, Green and Corey, Van Genuchten

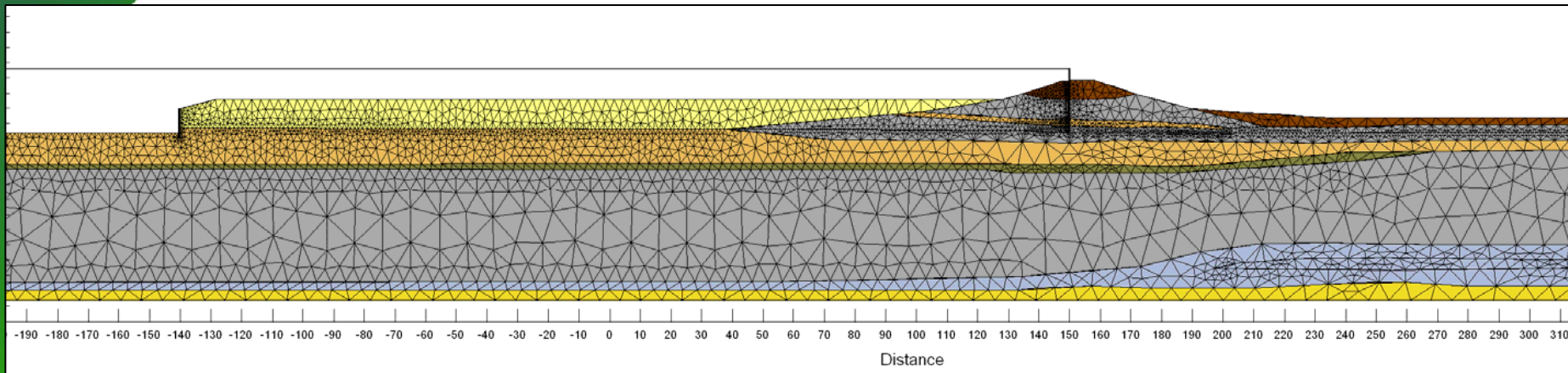


Geotechnical cross-section for conventional limit equilibrium and coupled seepage analyses of the east bank IHNC south breach.

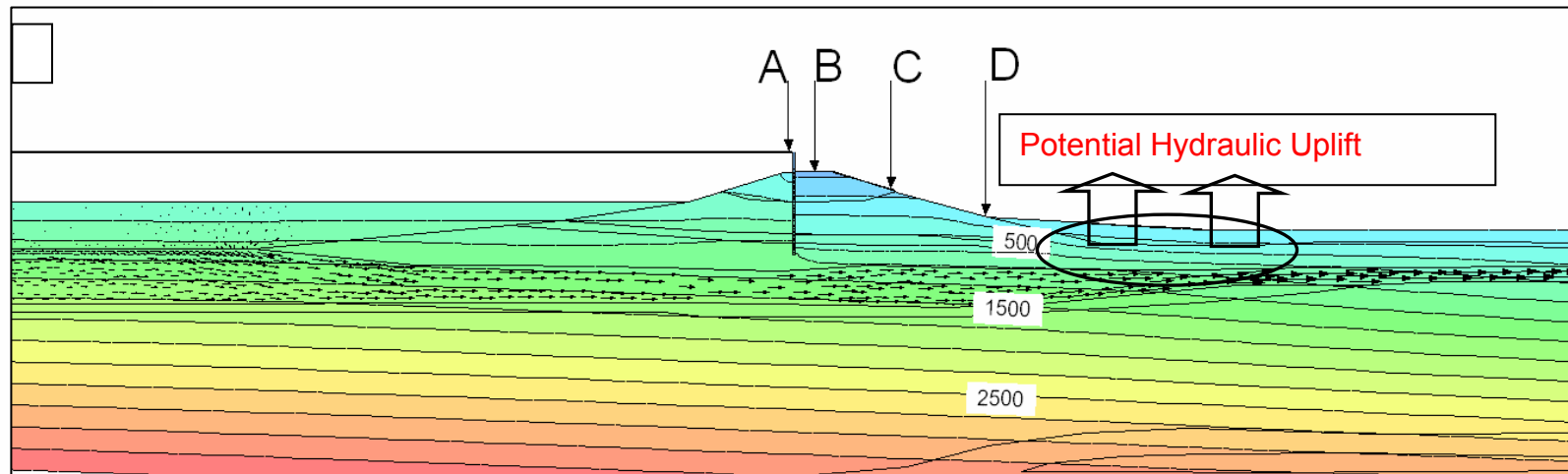
Hydrographs on IHNC



The horizontal permeability in the pervious marsh deposits likely **varies between 1×10^{-3} and 1×10^{-6} cm/sec.**, locally (within the marsh stratum), depending on a number of factors.

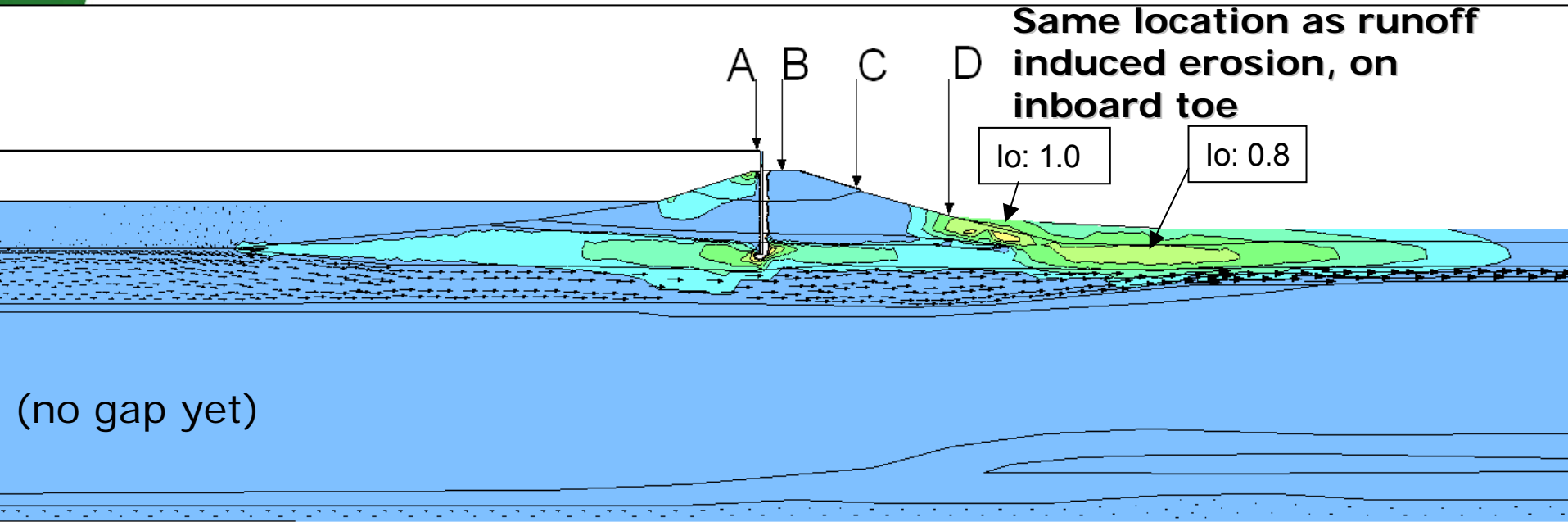


Finite difference mesh for seepage analyses for east bank IHNC south breach.



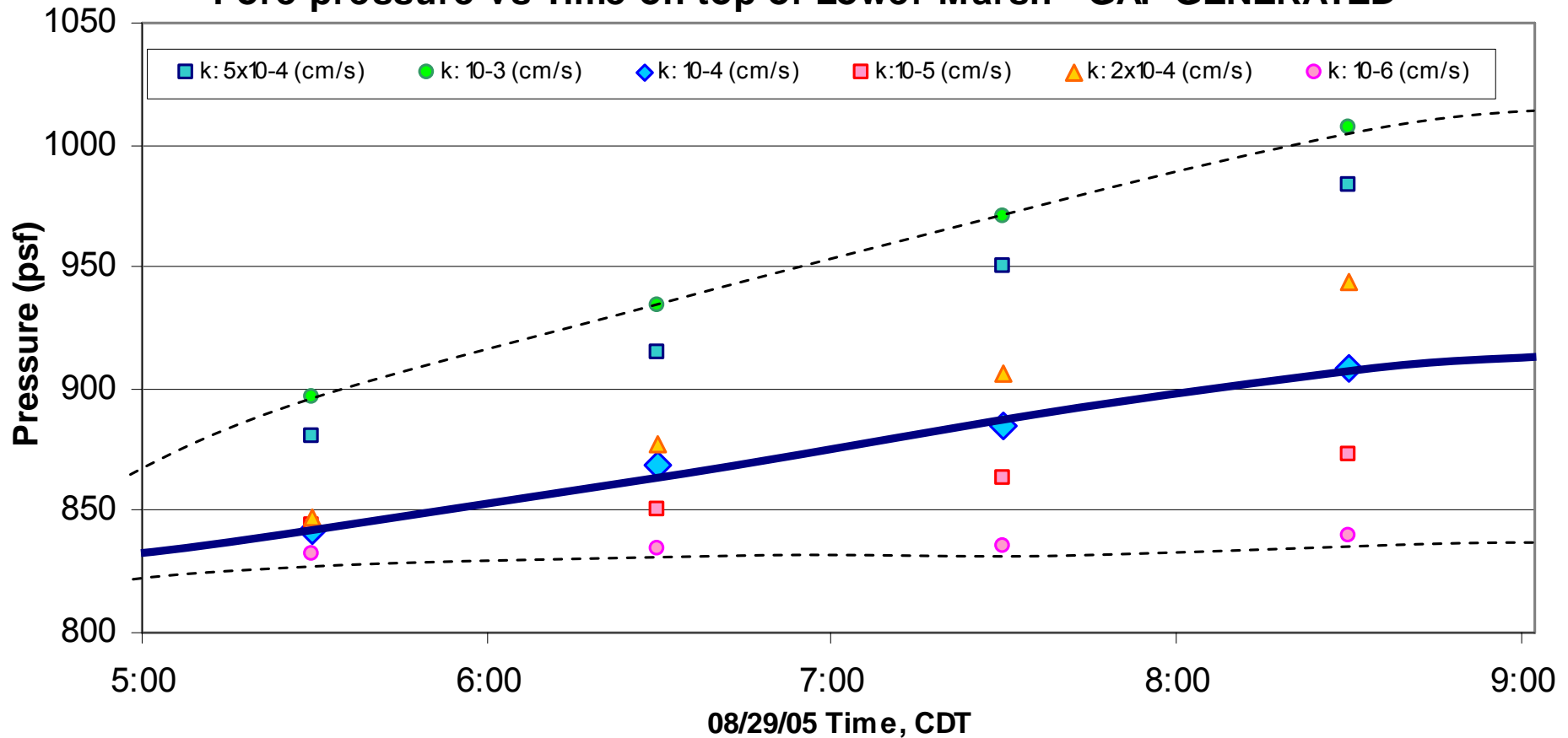
Pressure contours for the south breach on IHNC with storm surge at 14.4ft (MSL).

Hydraulic gradients for piping and uplift



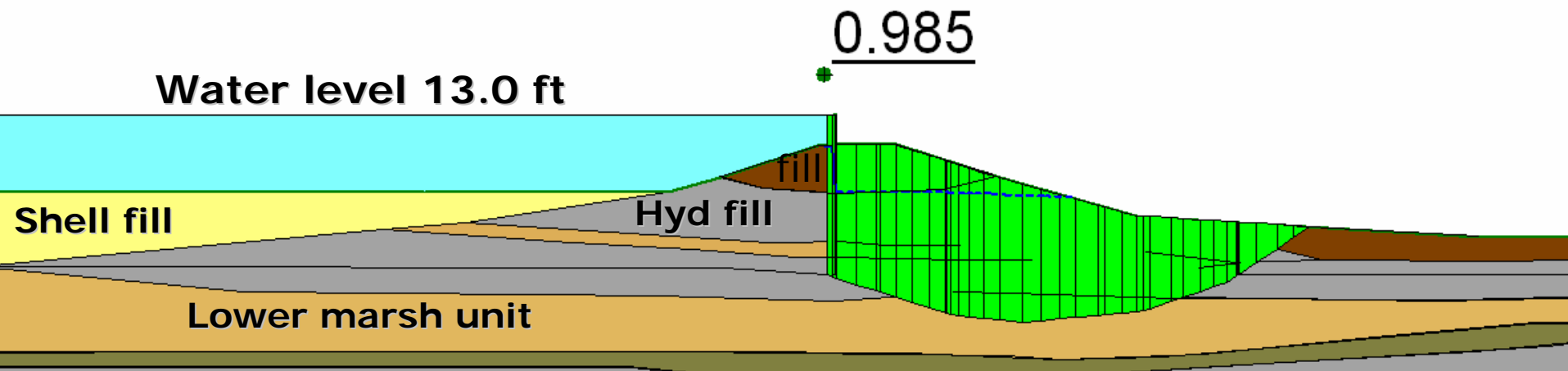
- Hydraulic gradients for the south breach on IHNC east bank; storm surge at 14.4ft (MSL). Maximum exit gradient at the levee toe is $i_o \approx 0.8$ to 1.0, at threshold for hydraulic piping.
- This may help to explain the persistent wet spot noted on the backfill of the Jourdan Avenue conduit backfill for weeks afterward.

Pore pressure vs Time on top of Lower Marsh - GAP GENERATED



Estimated range in pore pressures at top of lower marsh unit **if the flood wall developed a gap**; assuming a range of horizontal hydraulic conductivity (k) in the marsh units, varying between 10^{-3} and 10^{-6} cm/sec

Deep failure mode (in lower marsh) with wall gap– FS=0.985



Deeper slope failure most likely, with k values as low as 3×10^{-5} cm/sec; with wall gap forming around 7:30 AM, at a water level of 13 ft (MSL).

This would appear to be the best explanation for a massive translational failure, 800 feet long.



Aerial view of the south breach at the east bank of the IHNC (at the west end of the Ninth Ward), showing the 'wet spot' along the inboard side and the crevasse splay generated by reverse drainage flow. [Photograph by U.S. Army Corps of Engineers]

Part 7

PRELIMINARY CONCLUSIONS

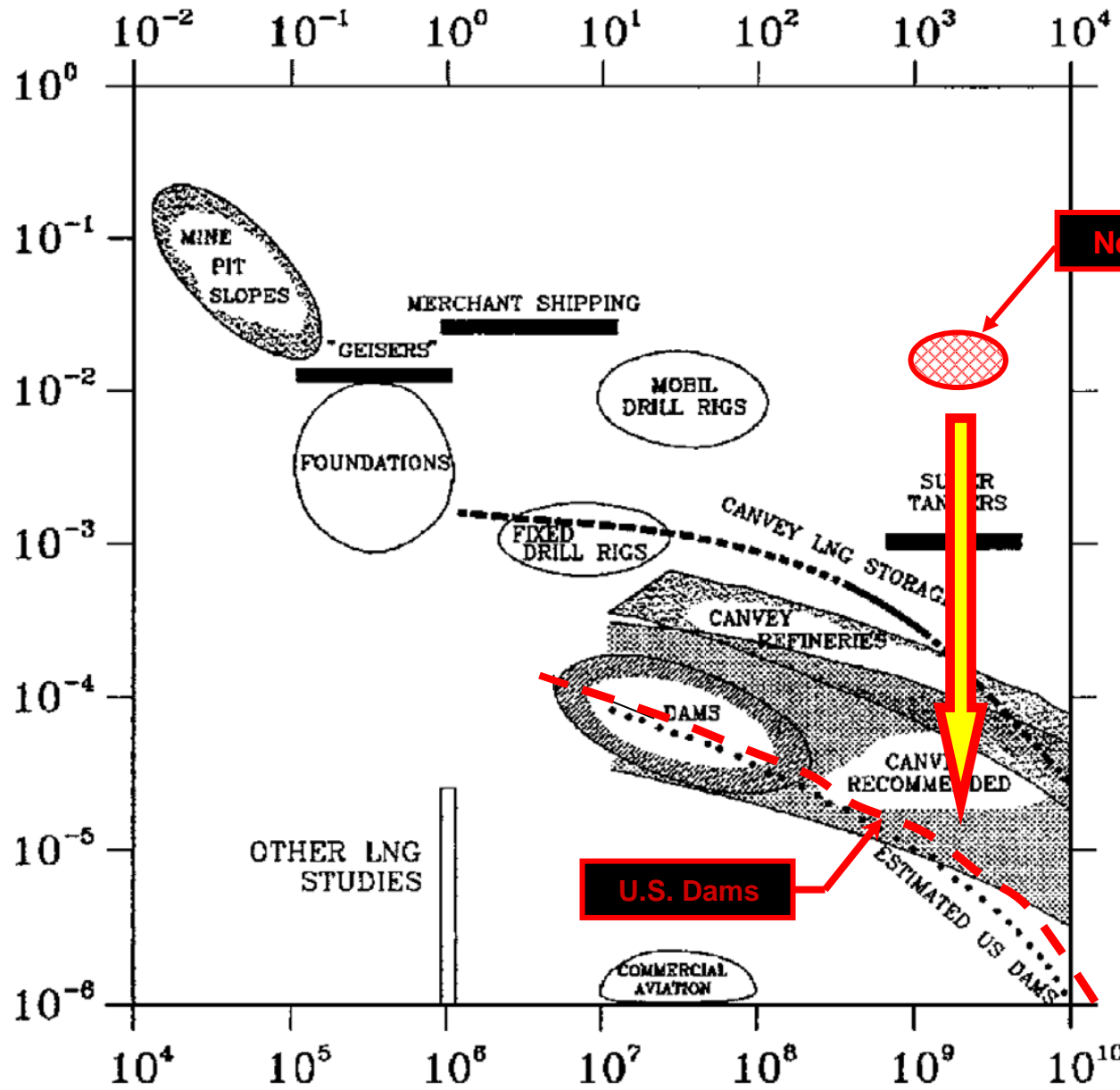
–

The Katrina disaster was not a 200 or 300 yr recurrence frequency event; equally damaging hurricanes struck New Orleans in 1915, 1947, 1965, and 1969....

The difference was there were 566,000 people living in New Orleans in August 2005

ANNUAL PROBABILITY OF "FAILURE"

LIVES LOST



New Orleans

The New Orleans levees and flood walls were 1000 times more vulnerable to failure than the average American dam

U.S. Dams

- Nine different physical factors appear to be responsible for **ground settlement** in the lower Mississippi Delta region. These factors, and **sea level rise**, have created a **never-ending battle** to maintain flood control
- Flood control infrastructure of New Orleans needs to be under a **single overarching authority**; with **external peer review** and **redundant safety factors**, like dams
- Must be an **integrated system**, which can sustain temporary overtopping without failing
- New Orleans should consider construction of **drainage polders**, to store excess water within the confines of the flood protection system
- Must consider cost-benefit aspects. City and regional planning authorities should consider **cost-effectiveness** of providing **redundant flood protection** to more sparsely populated areas, such as Plaquemines Parish, below New Orleans



For engineers
designing flood
protection systems,
the core value should
be **SURVIVABILITY**

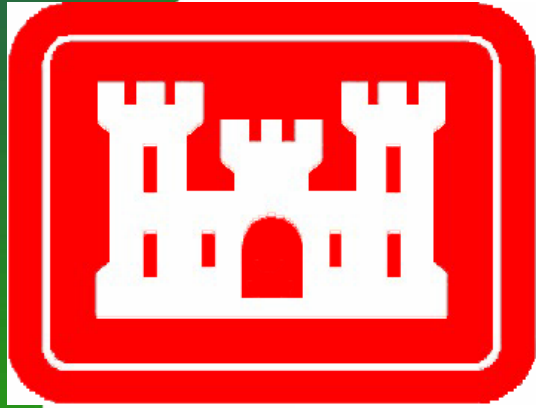
Above all else, flood barriers, such as levees or flood walls, should be constructed to withstand short-term overtopping *without* catastrophic failure.

Flood structures must be “Class 3 survivable”

- It is impossible to accurately predict **actual flood surge heights**, because of a number of unknown factors
- Engineers have to select a flood height commensurate with **risk-consequence assessments** and **probabalistic analyses**.
- Consequences in a densely populated urban areas never a factor previously
- Flood control infrastructure, such as levees and flood walls, must be designed to withstand sustained overtopping.



Protective **concrete splash pads** would have protected the I-walls for about 0.5 % of the I-wall construction cost. They are being retrofitted to the flood walls. This is a cost-effective measure.



Major Disagreements

Between June 1st and October 25th 2006 five additional forensic reports were released (two by the Corps of Engineers). All of these agreed with most of the basic failure mechanisms proposed in the May 22nd NSF panel report, after months of argument and intrigue.



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This lecture will be posted at

www.umn.edu/~rogersda/levees

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http://www.ce.berkeley.edu/~new_orleans

