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

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Part 1

GEOLOGIC SETTING OF NEW ORLEANS

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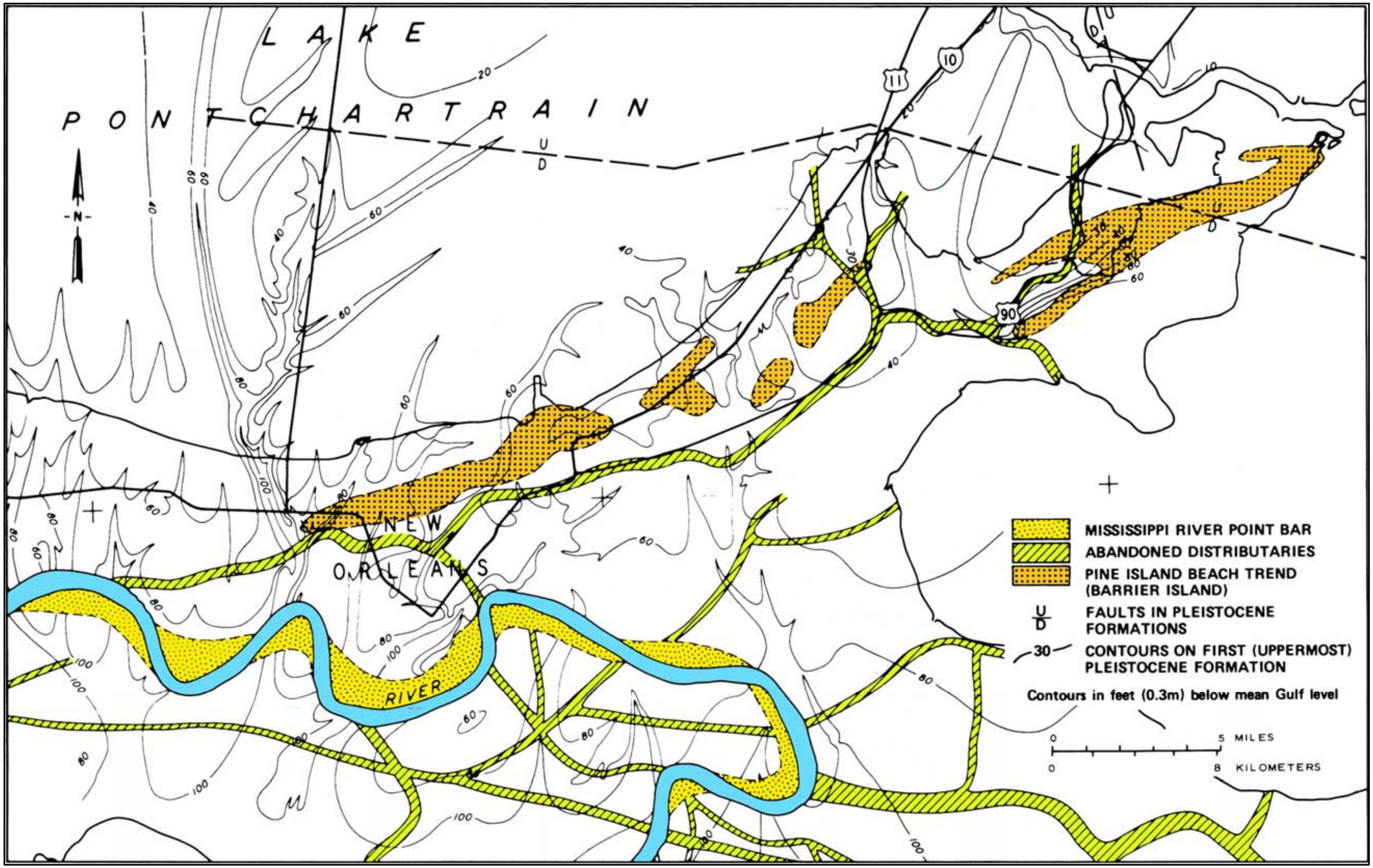
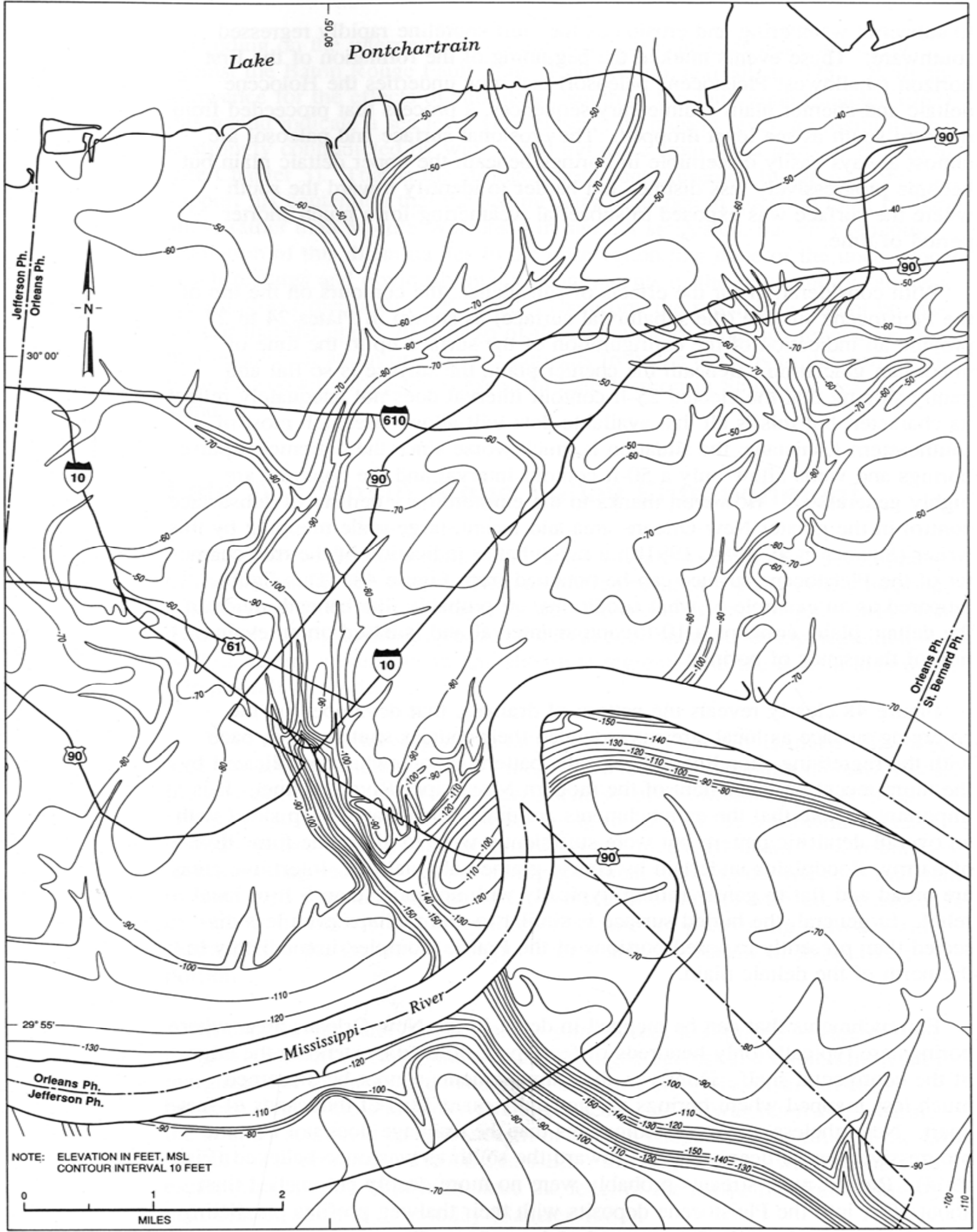
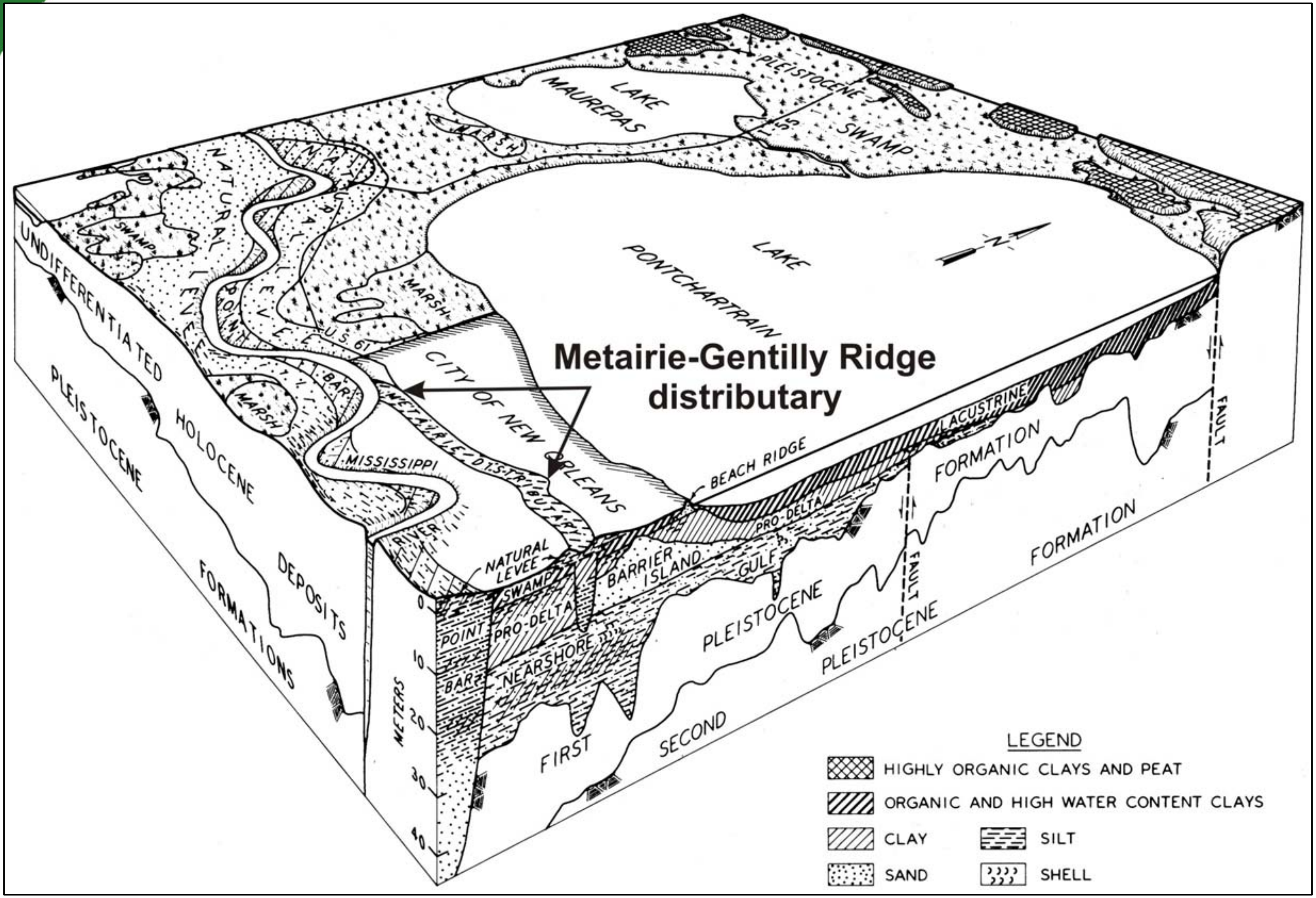


- **Pleistocene geologic map of the New Orleans area. The yellow stippled bands are the principal distributory channels of the lower Mississippi River, with the present channel shown in light blue. The Pine Island Beach Trend is shown in the ochre dotted pattern. Depth contours on the upper Pleistocene age horizons are also shown.**



- **Contours of the entrenched surface of the Wisconsin glacial age deposits underlying modern New Orleans.**
- **Note the well developed channel leading southward, towards what used to be the oceanic shoreline. This channel reaches a maximum depth of 150 feet below sea level.**



- **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.**

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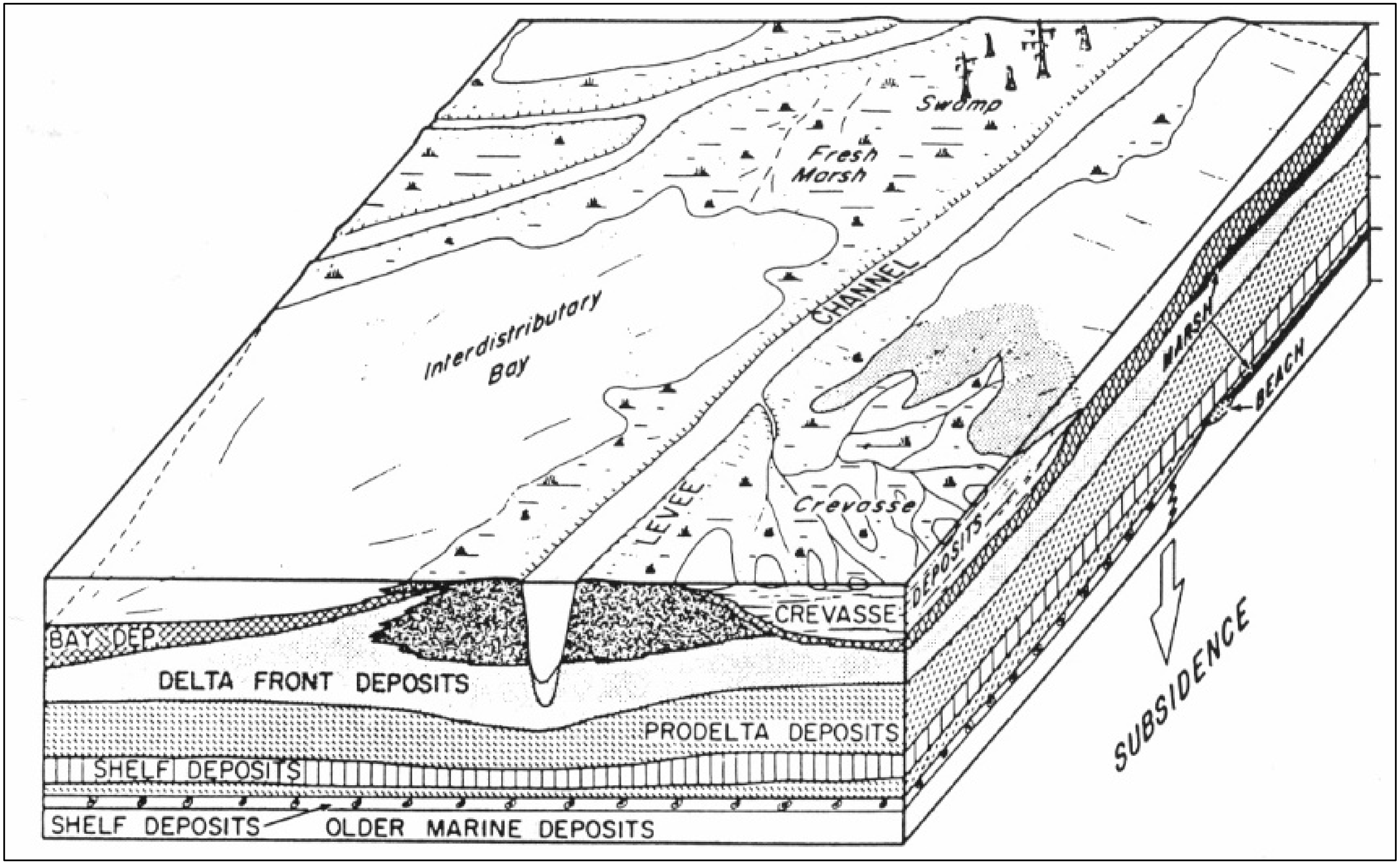
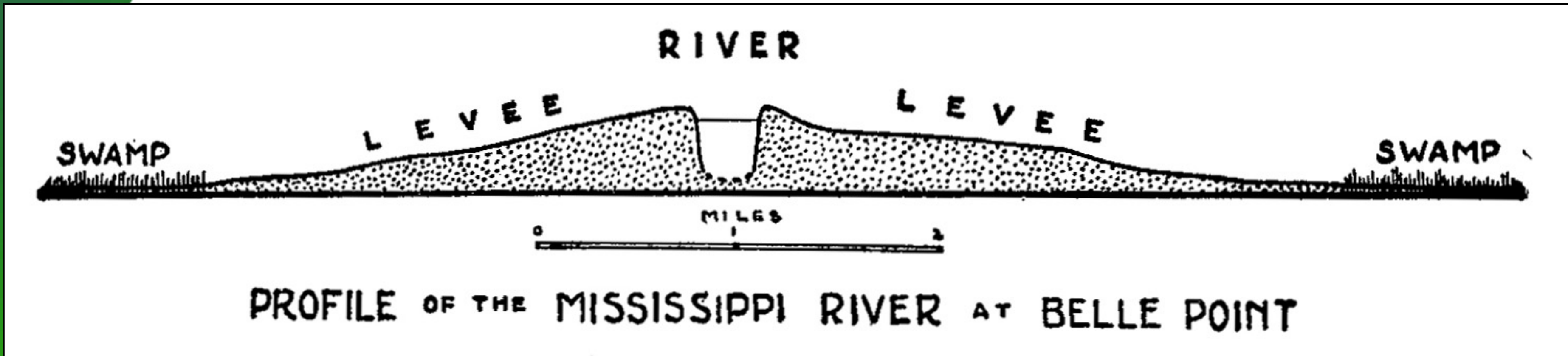
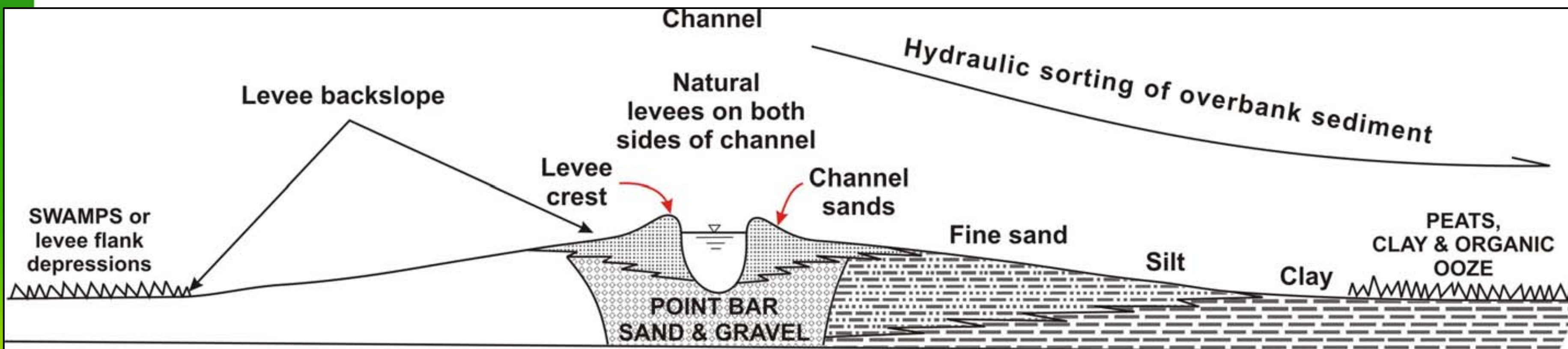


- **Block diagram illustrating relationships between subaerial and subaqueous deltaic environments in relation to a single distributary lobe.**
- **The Lakeview and Gentilly neighborhoods of New Orleans are underlain by interdistributary sediments, overlain by peaty soils lain down by fresh water marshes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





- **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.**

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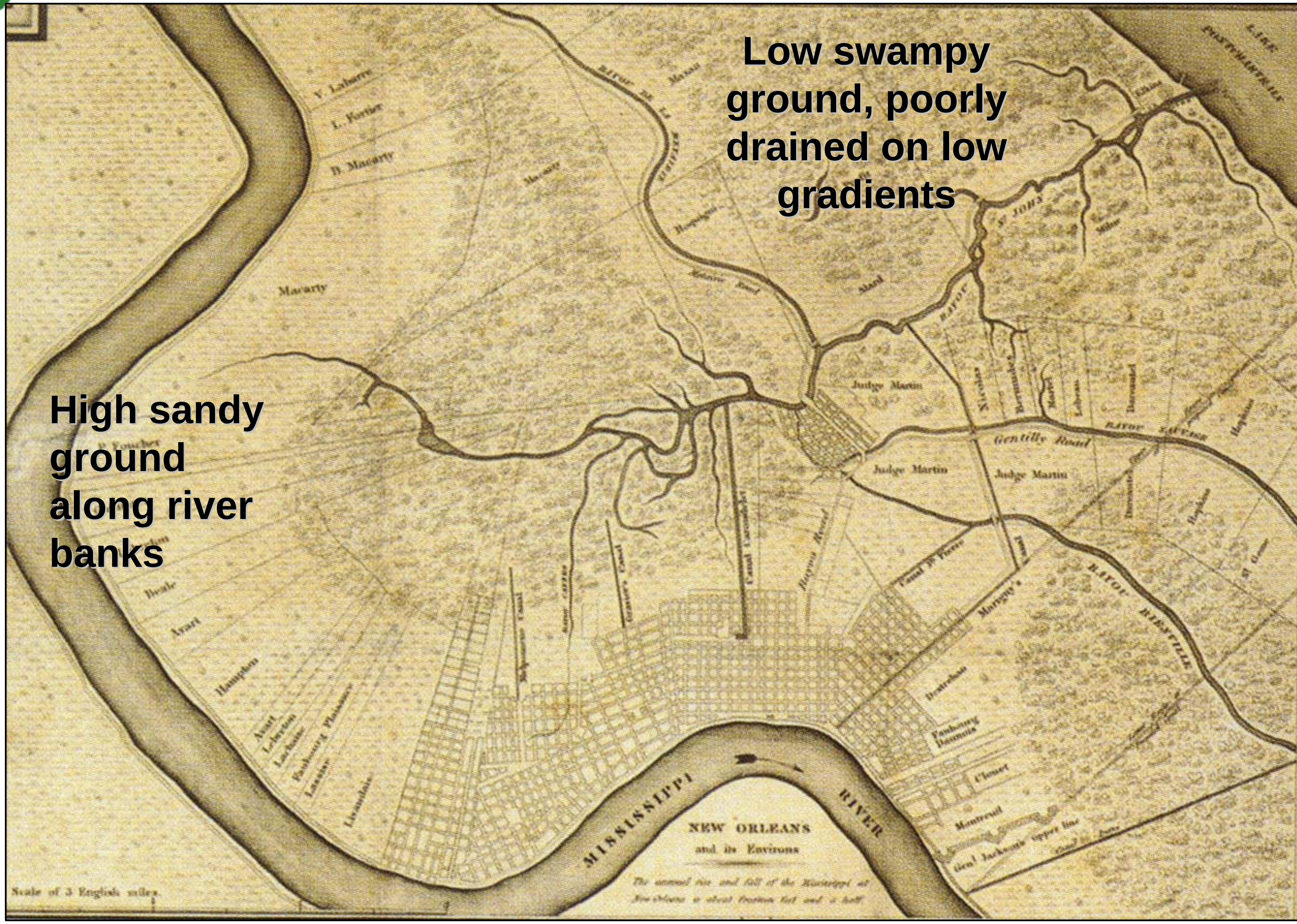
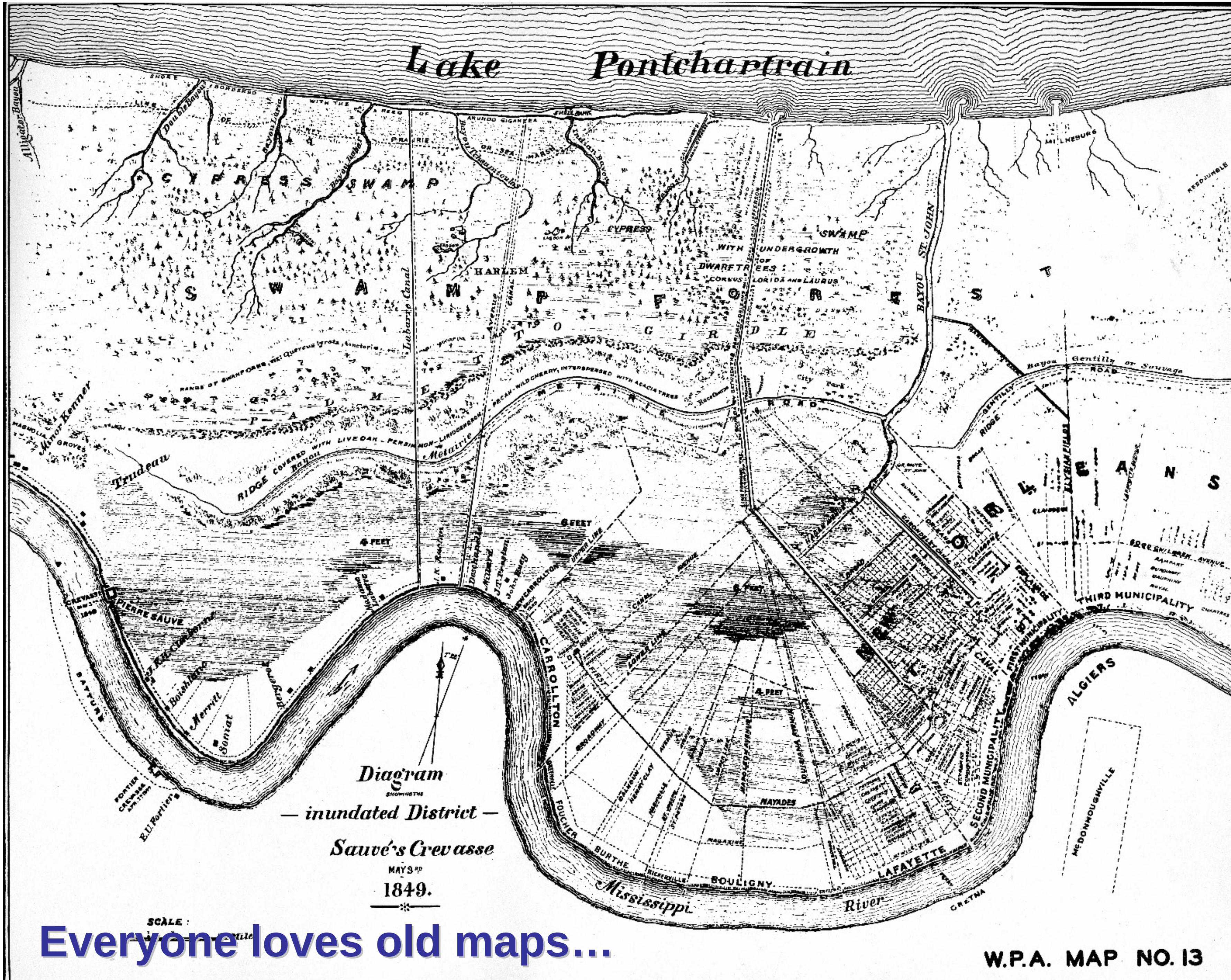


- **Plan of the City of New Orleans prepared by Francis Ogden in 1829. Note the linear drainage canals feeding into Bayou St. John, thence into Lake Pontchartrain.**



Everyone loves old maps…

- Portion of the 1849 flood map showing the mapped demarcation between brackish and fresh water marshes along Lake Pontchartrain. This delineation is shown on many of the historic maps, dating back to 1749.

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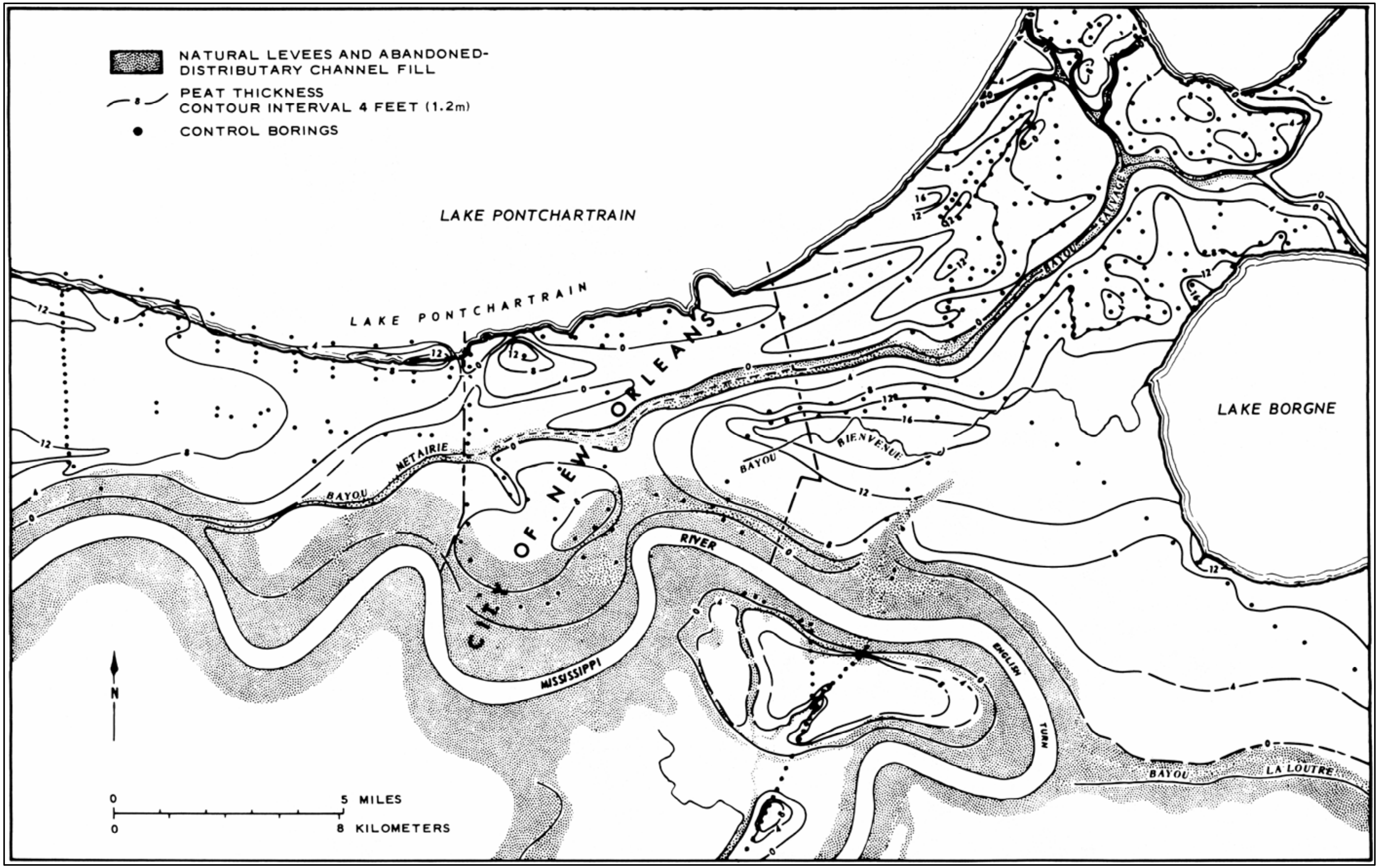
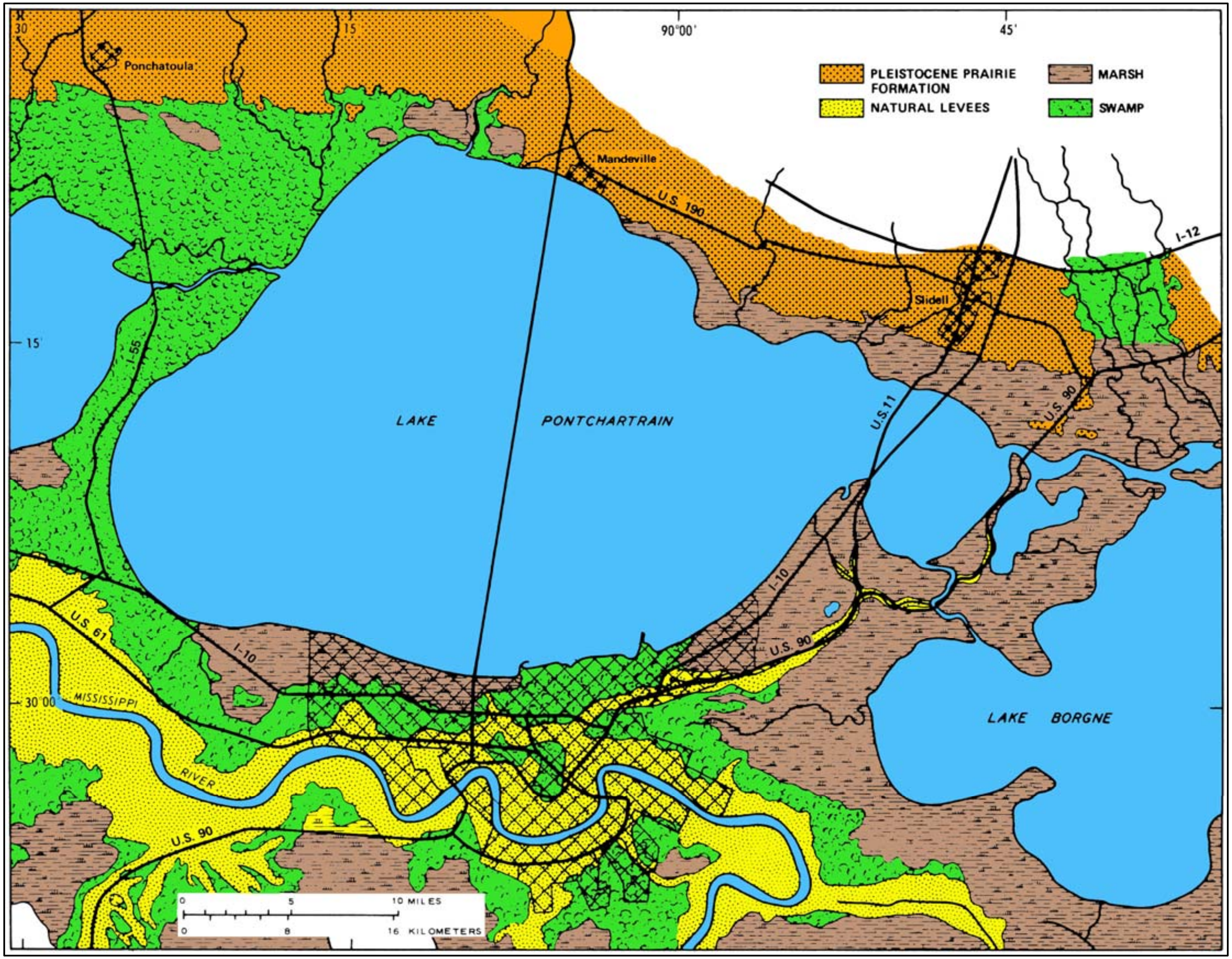


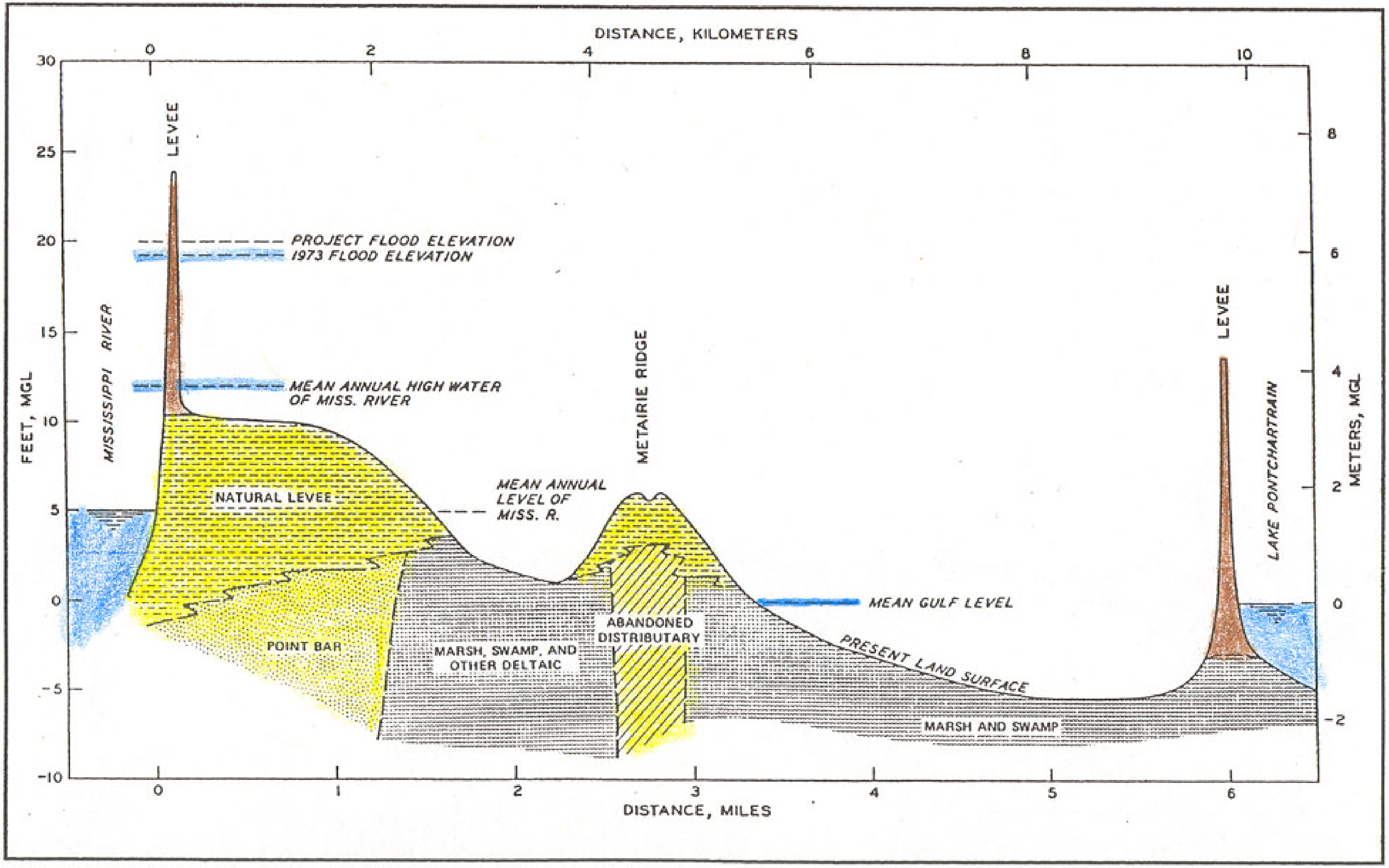
- **The Corps of Engineers had prepared many impressive maps depicting the geologic conditions beneath New Orleans. This one shows the apparent thickness of surficial peat deposits, which correlate with areas of anomalously high ground settlement after development.**



- **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.**

Part 2

CRITICAL ROLE OF FLOOD CONTROL INFRASTRUCTURE IN NEW ORLEANS

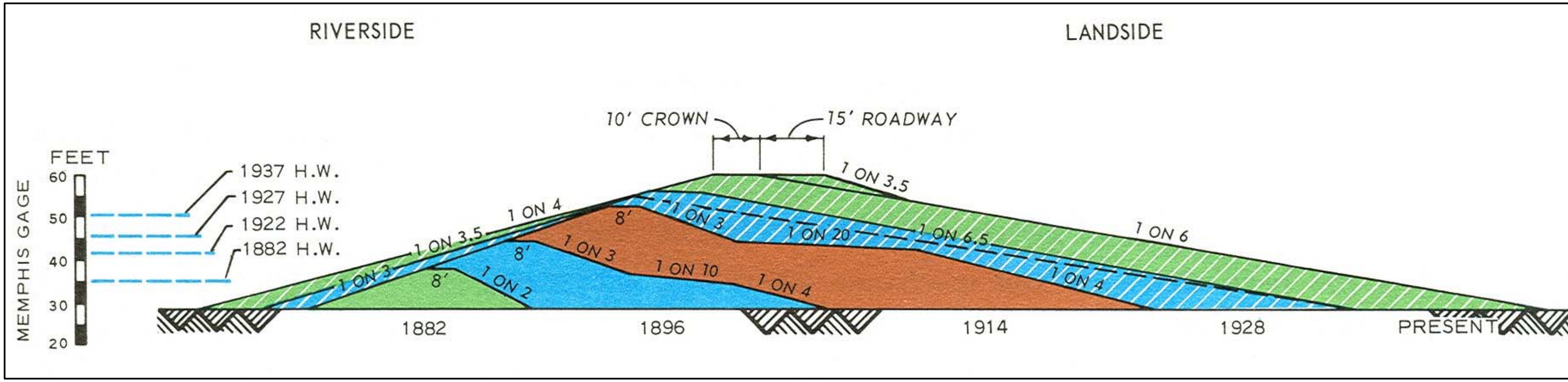


Much of lower New Orleans, developed after the First World War, lies below Mean Gulf Level, as shown here. Water that finds its way into the City must be pumped out.

- **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).

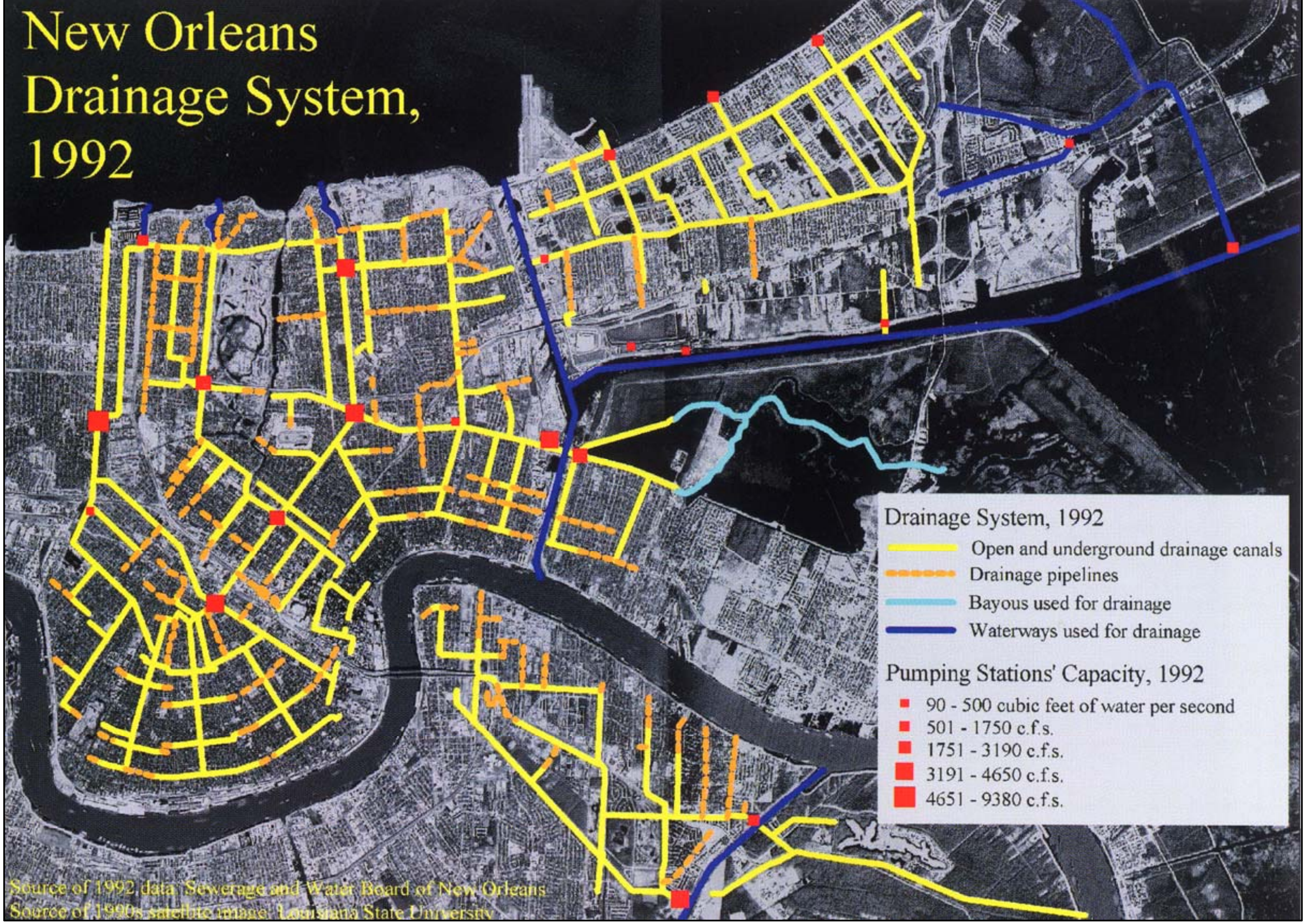
Problem with houses next to levees



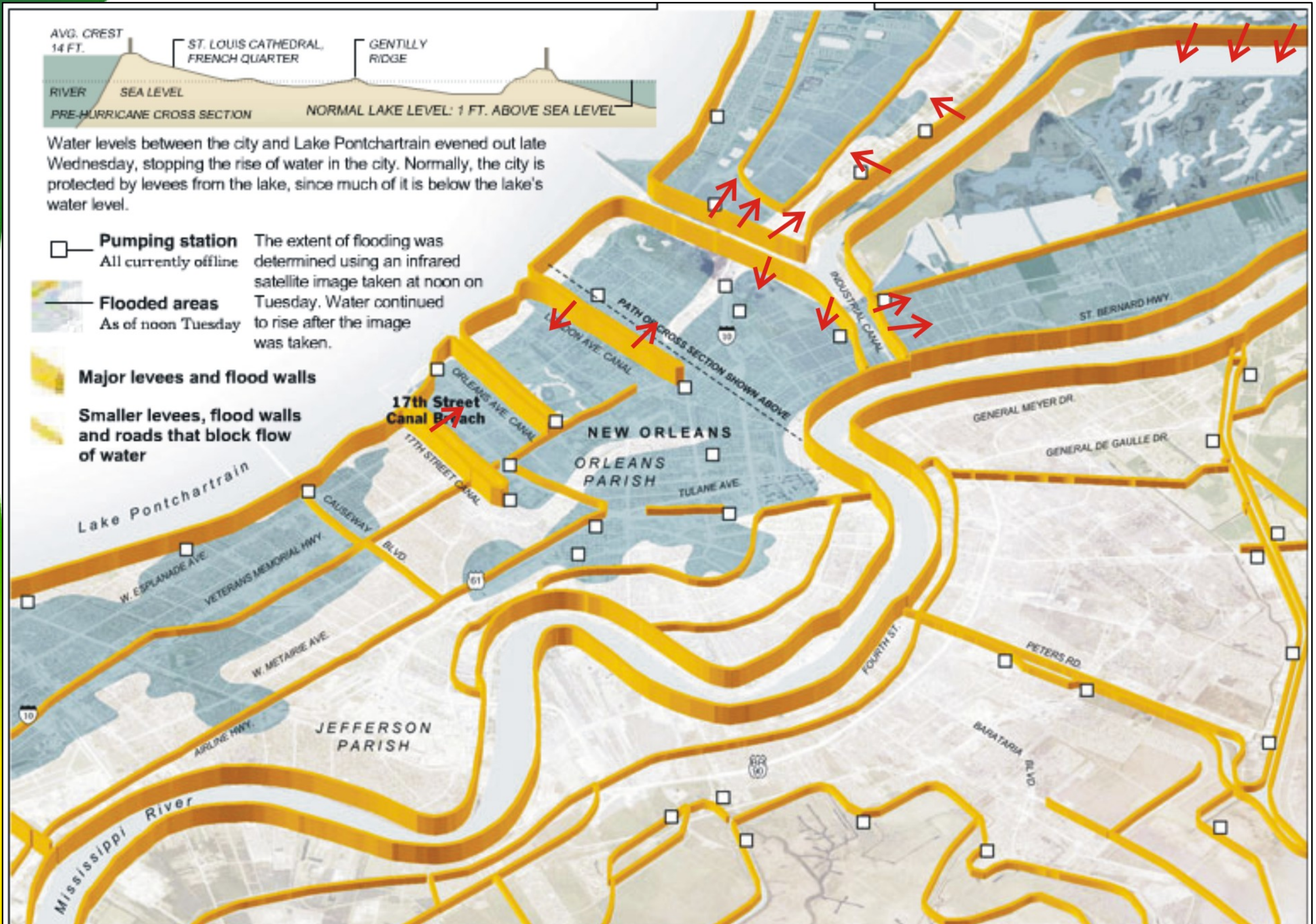
- Evolution of the Corps of Engineers' standard levee section, 1882 to 1972 (from Moore, 1972).
- Earth embankments levees are generally heightened sequentially by compacting additional soil on the land side of the embankments (each sequence of heightening shown as different colors).
- Levees adjacent 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**



- **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 Ponchartrain and Lake Borgne.**

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Part 3

SYSTEMIC FAILURES OF FLOOD CONTROL INFRASTRUCTURE DURING KATRINA

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- **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.**

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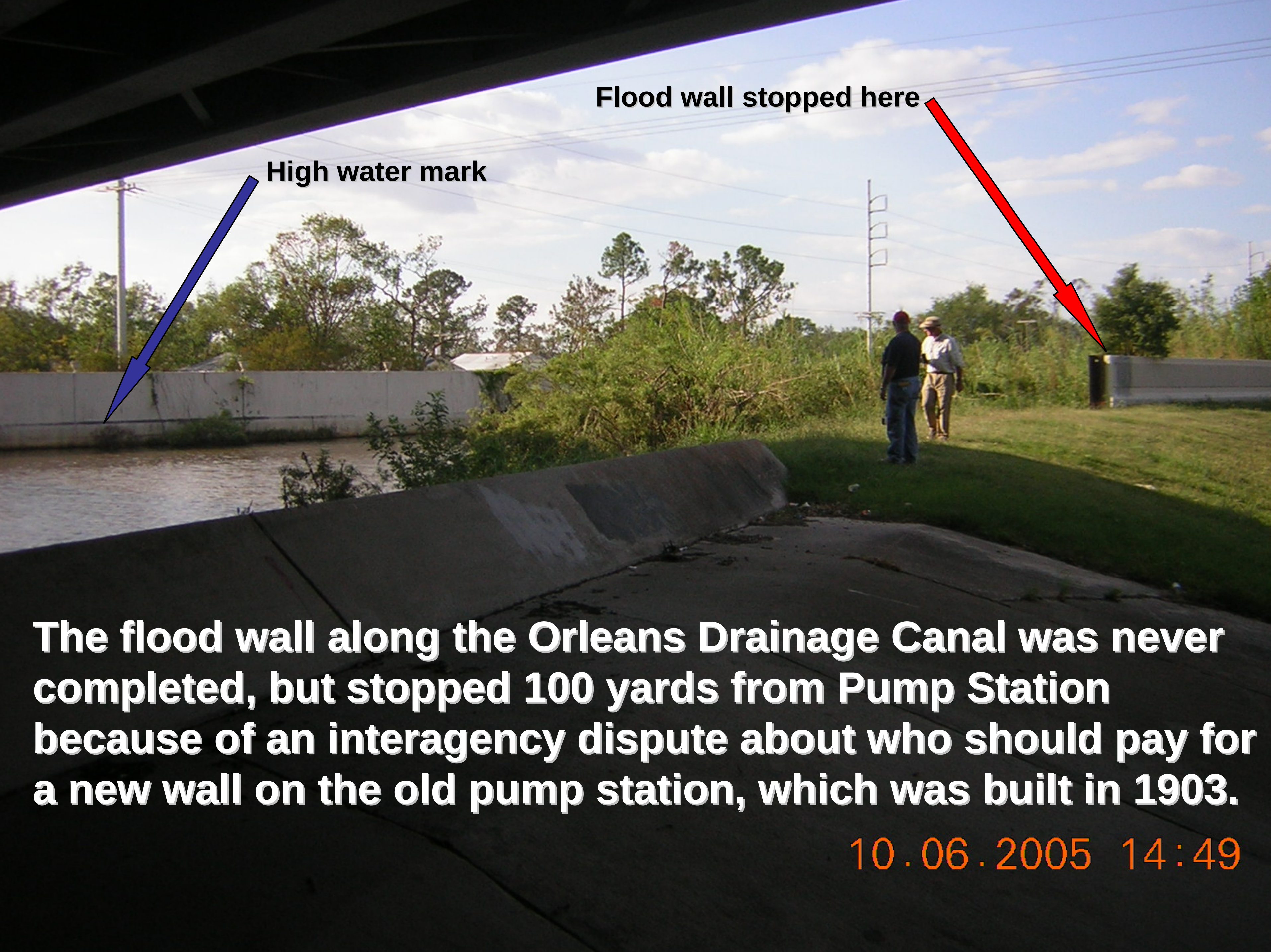
Flood gate over rail crossing on Florida Ave Lift Bridge was not repaired and inserted across tracks, even though paid for over a year previous after being damaged
0.04.2005 09:58


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.**

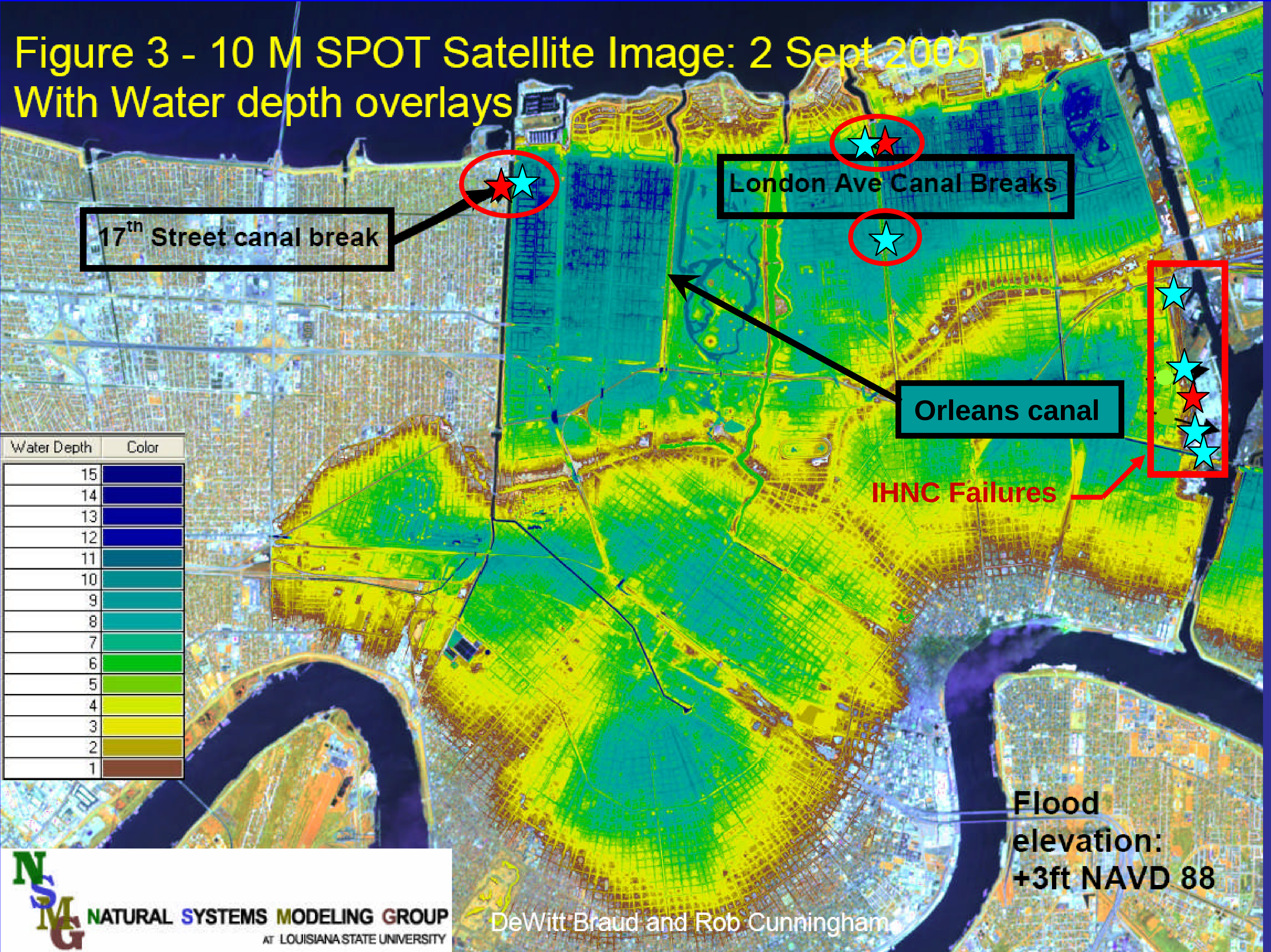


Figure 3 - 10 M SPOT Satellite Image: 2 Sept 2005
With Water depth overlays
17th Street canal break
London Ave Canal Breaks
Orleans canal
IHNC Failures
Water Depth
Color
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Flood elevation: +3ft NAVD 88
NATURAL SYSTEMS MODELING GROUP
AT LOUISIANA STATE UNIVERSITY
DeWitt Braud and Rob Cunningham

- **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

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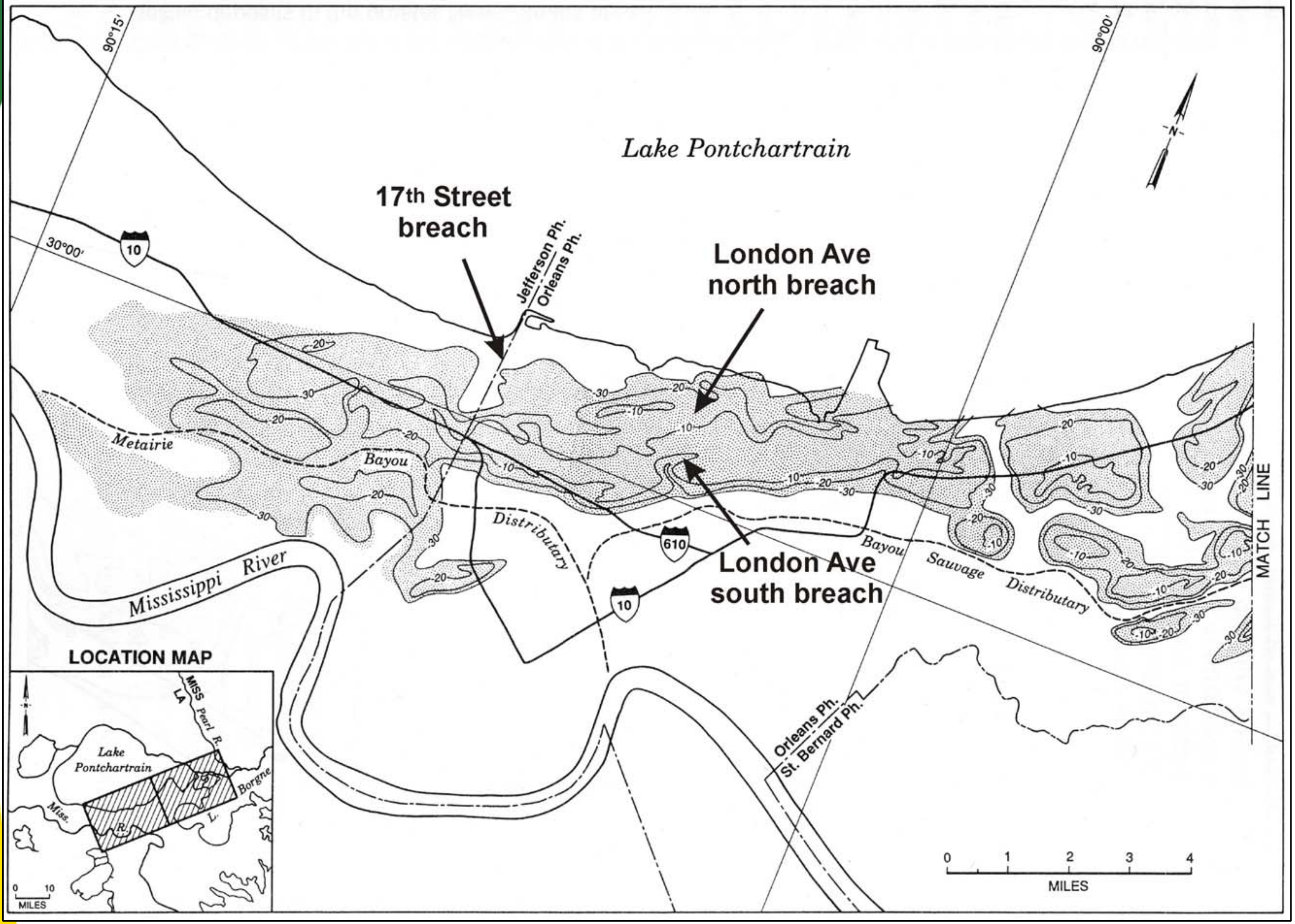
Embankment moved 51 ft
The most recently constructed elements of the city's flood control infrastructure, built in the mid 1990s, performed miserably.
EPA, 2005



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

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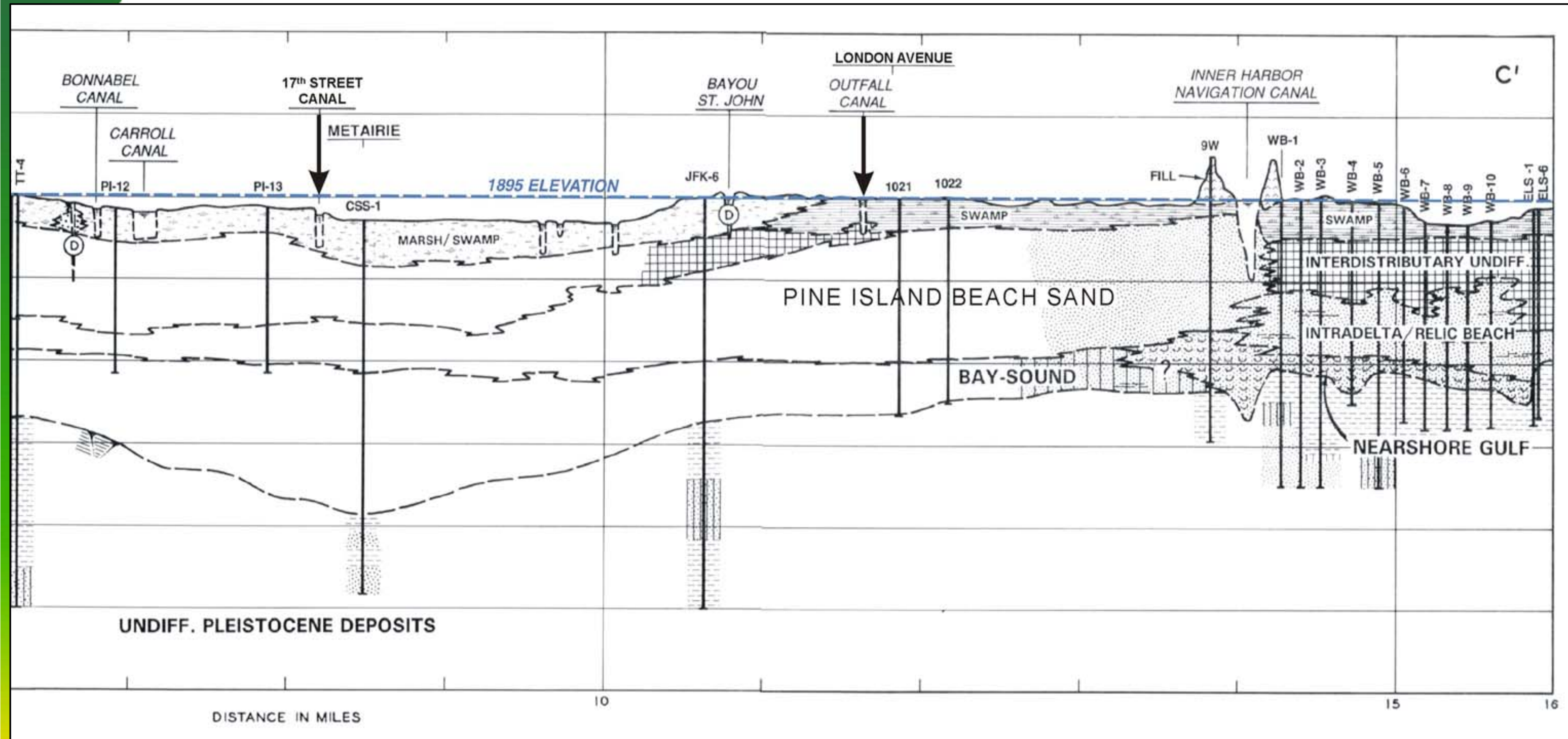

- **Geologic cross section along south shore of Lake Pontchartrain in the Lakeside, Gentilly, and Ninth Ward neighborhoods, where the 17th Street, London Avenue, and IHNC levees failed during Hurricane Katrina on Aug 29, 2005. Notice the apparent settlement that has occurred since the city survey of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

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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**

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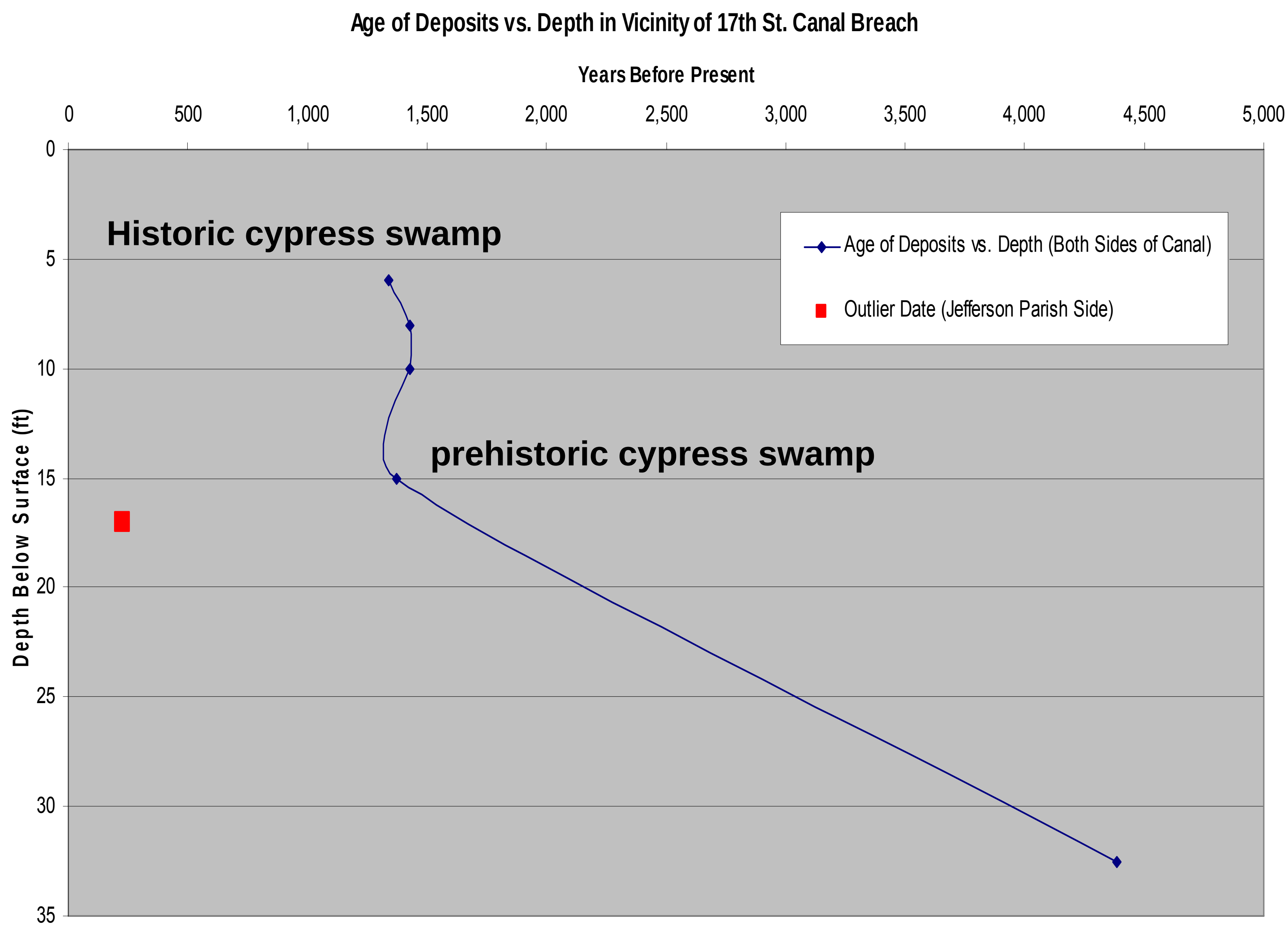

- **C14 dates and depths suggest a rapidly filling paludal environment during the late Holocene**

17th St. OUTFALL CANAL LEVEE BREAK
CROSS SECTION LOCATIONS

- **Aerial photo of the 17th Street Canal breach site before the failure of August 29, 2005. The red lines indicate the positions of the NSF team's geologic sections.**

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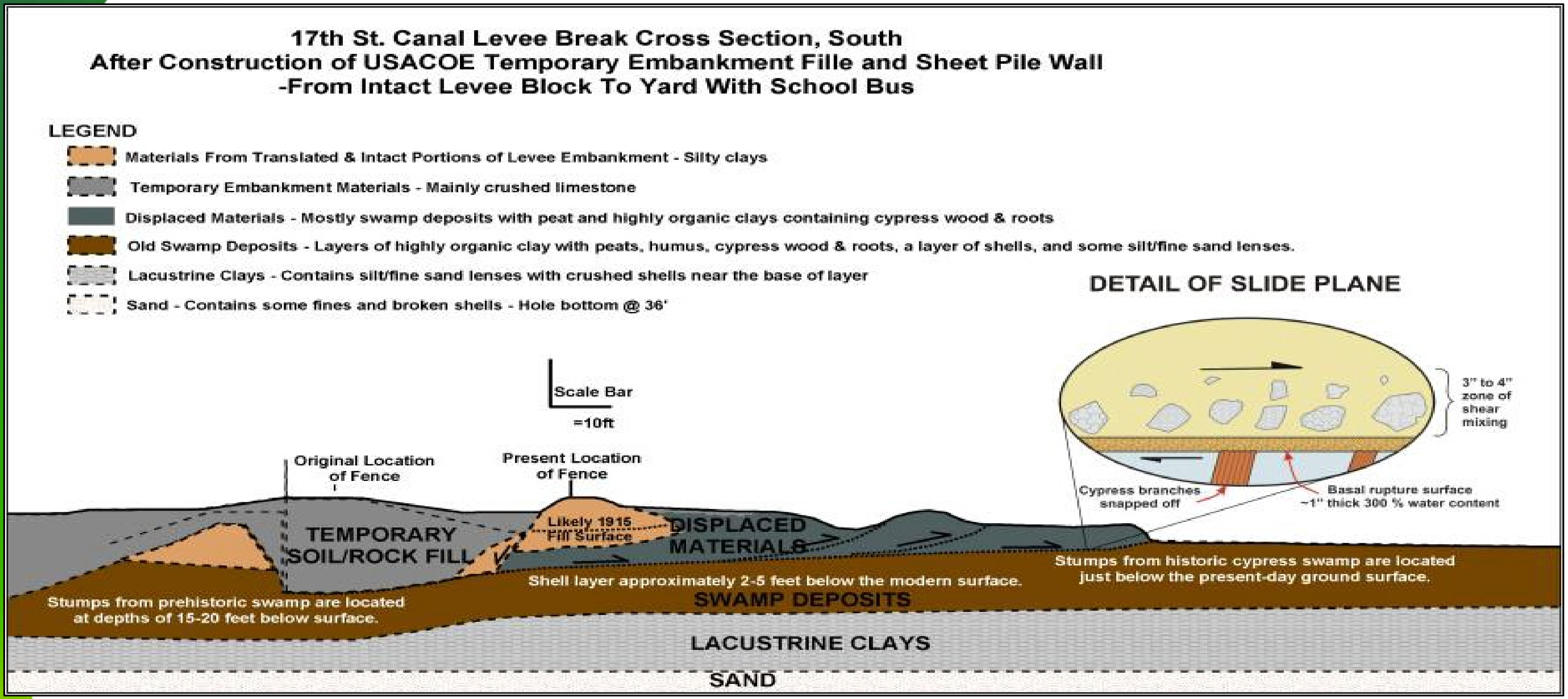
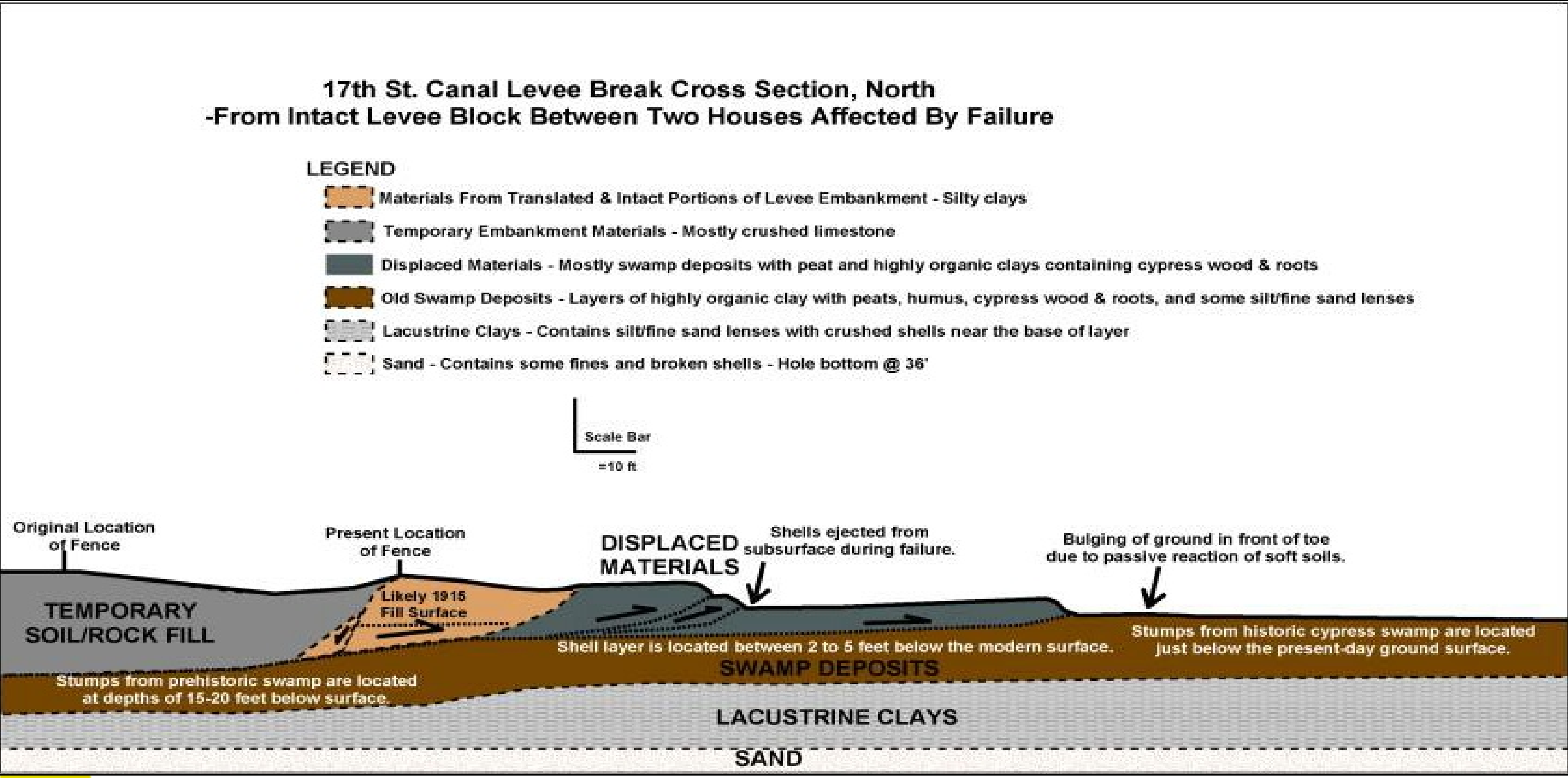


- **West-to-east geologic cross section through the 17th Street Canal failure approximately 60 feet north of Spencer Avenue. A detailed sketch of the basal rupture surface is shown above right.**
- **The slip surface was about one inch thick with a high moisture content (watery ooze). A zone of mixing 3 to 4 inches thick lay above this. Numerous pieces of cypress wood, up to 2 inches diameter, were sheared off along the basal rupture surface.**



- **West-to-east geologic cross section through the 17th Street Canal failure approximately 140 feet north of the northern curb of Spencer Avenue.**
- **Large quantities of bivalve shells were extruded by high water pressure along the advancing toe thrusts. Note the slight back rotation of the distal thrust sheet.**

- **Bivalve shells ejected by high pore pressures emanating from toe thrusts on landside of failed levee at the 17 Street Canal (detail view at upper left). These came from a distinctive horizon at a depth of 2 to 5 feet below the pre-failure grade.**

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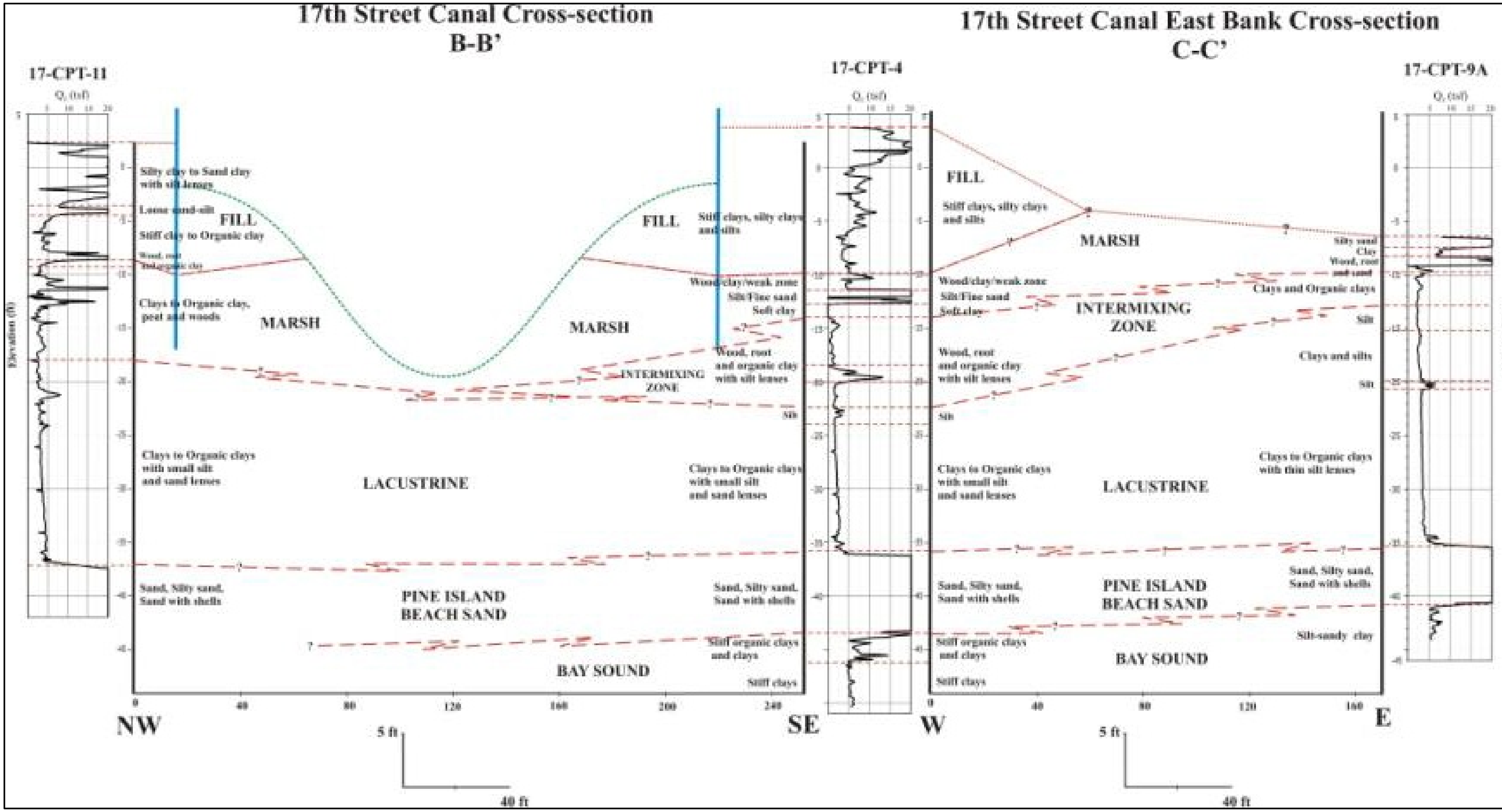
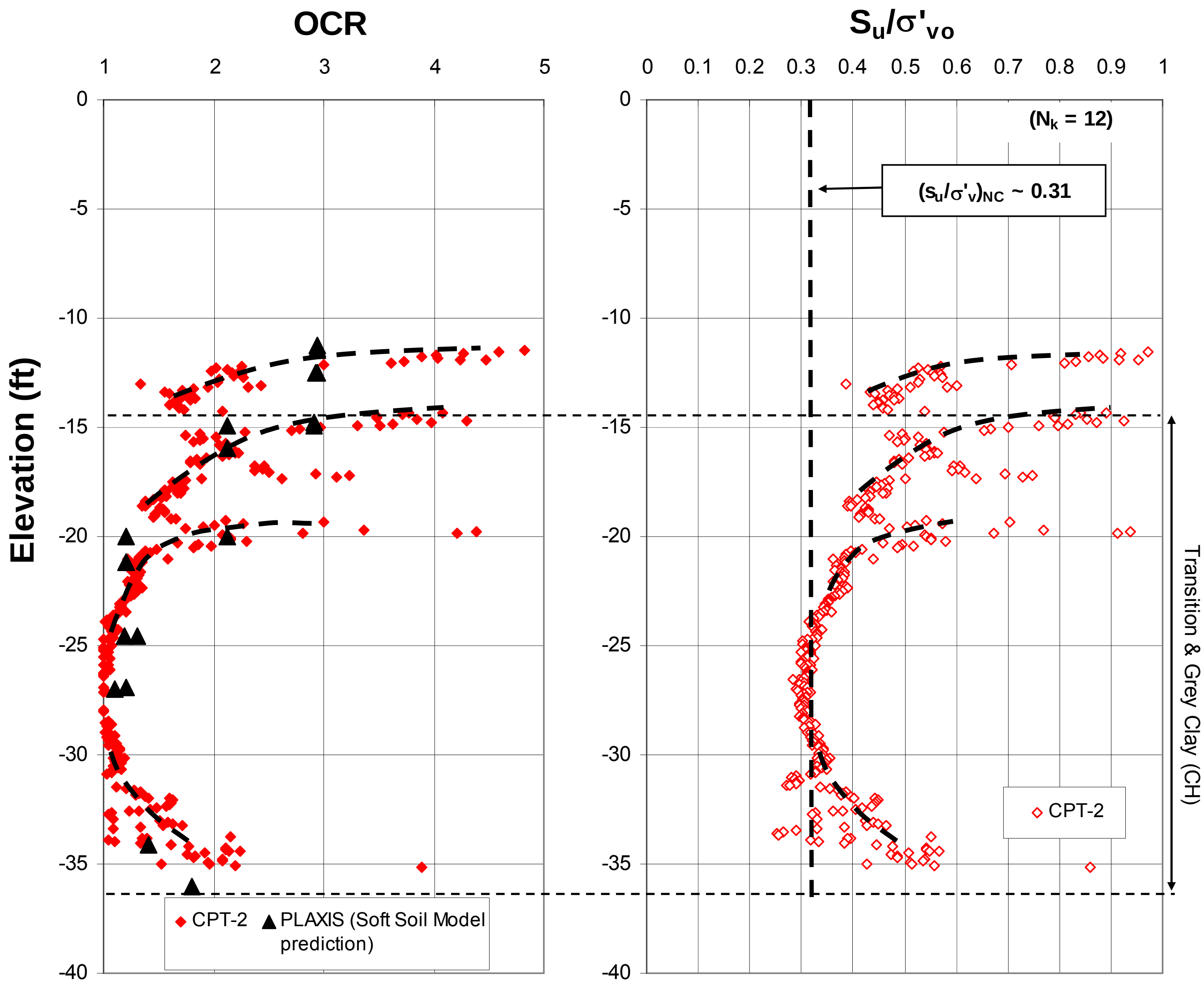


- **Stratigraphic interpretations across the 17th Street Canal breach**. **The swamp much appeared to be thinning northerly, as does the underlying Pine Island Beach Trend. The lacustrine clays appear to thicken southward, as shown.**
- **The approximate positions of the flood walls (light blue) and 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



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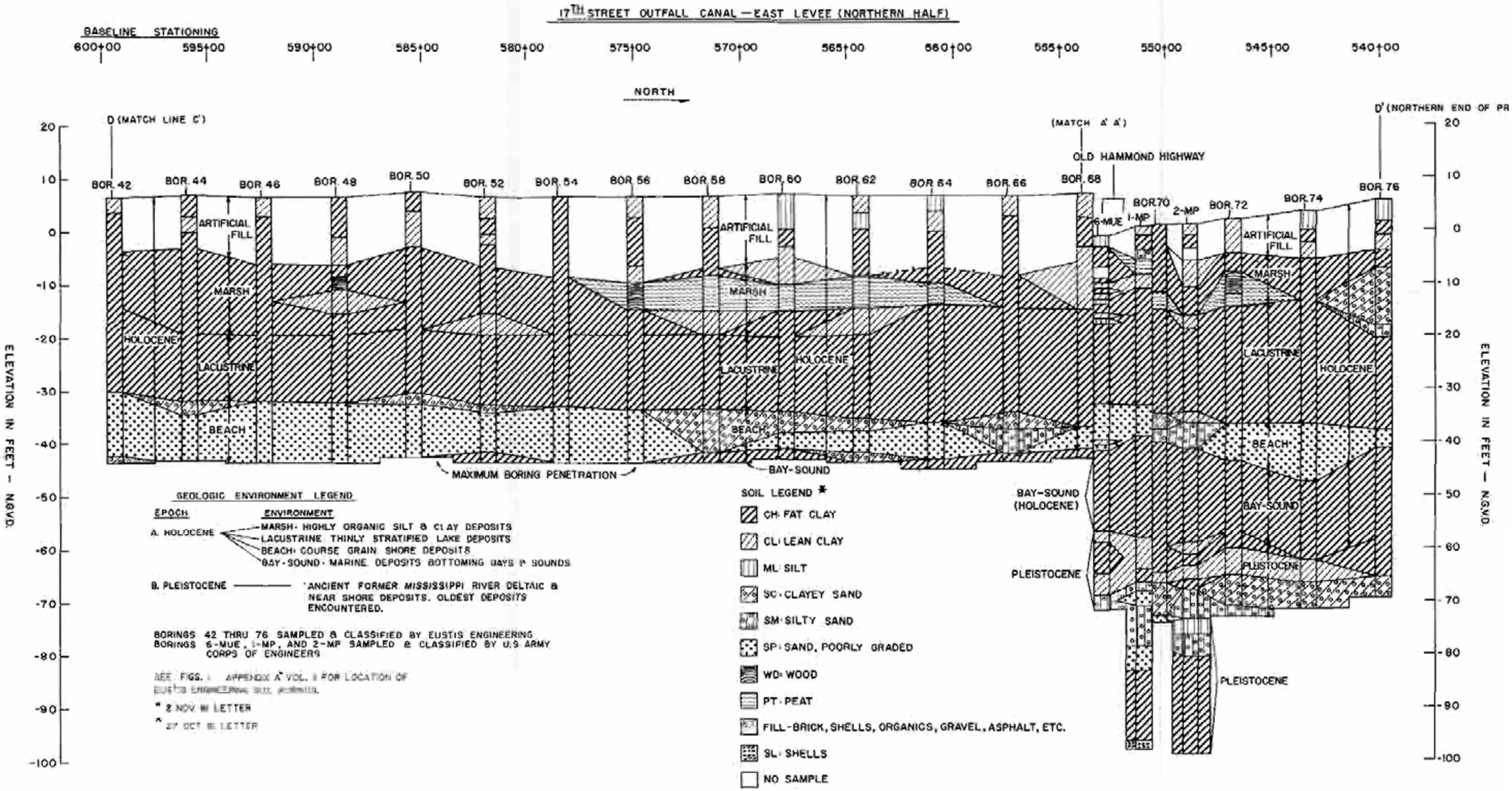
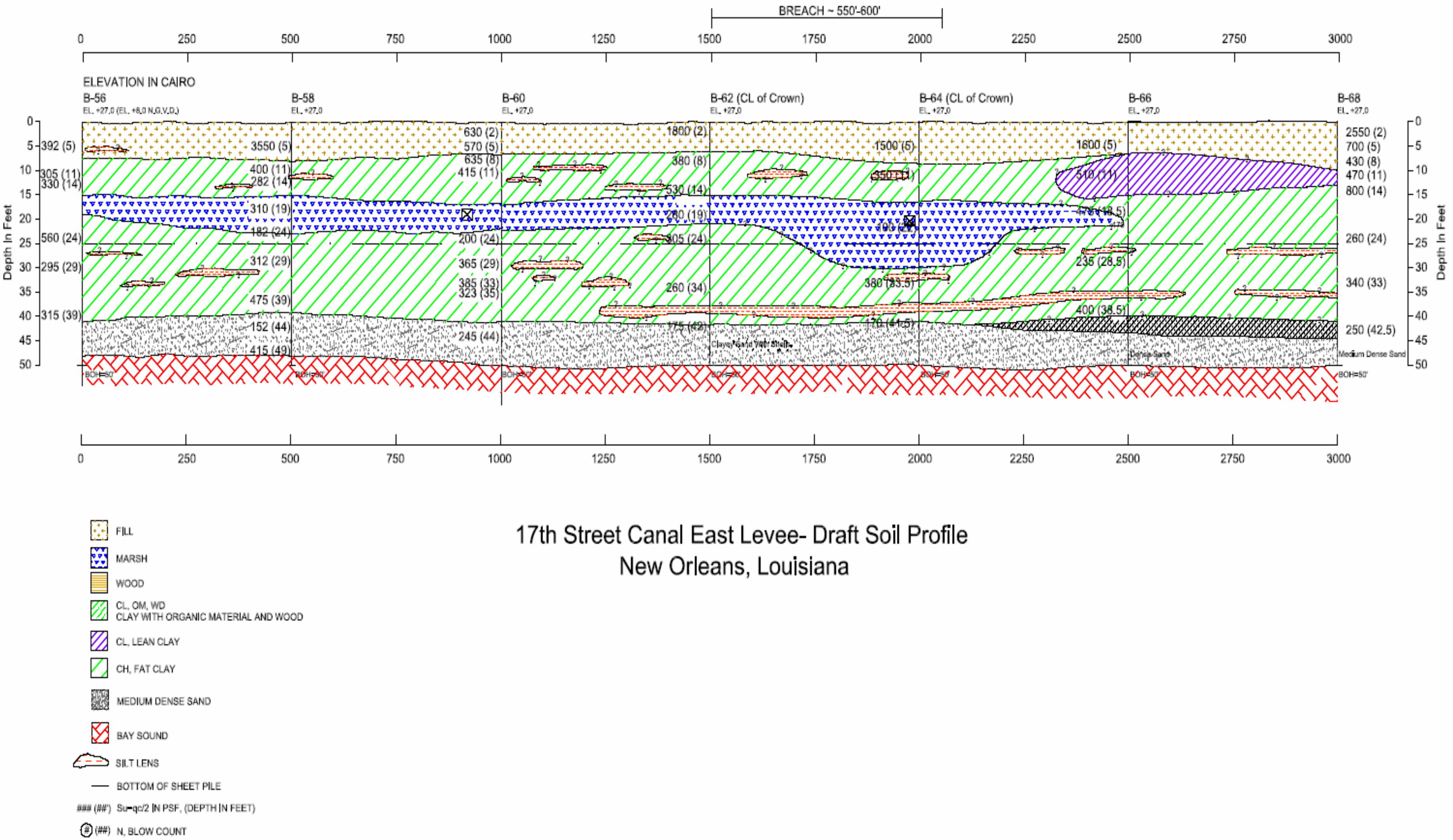
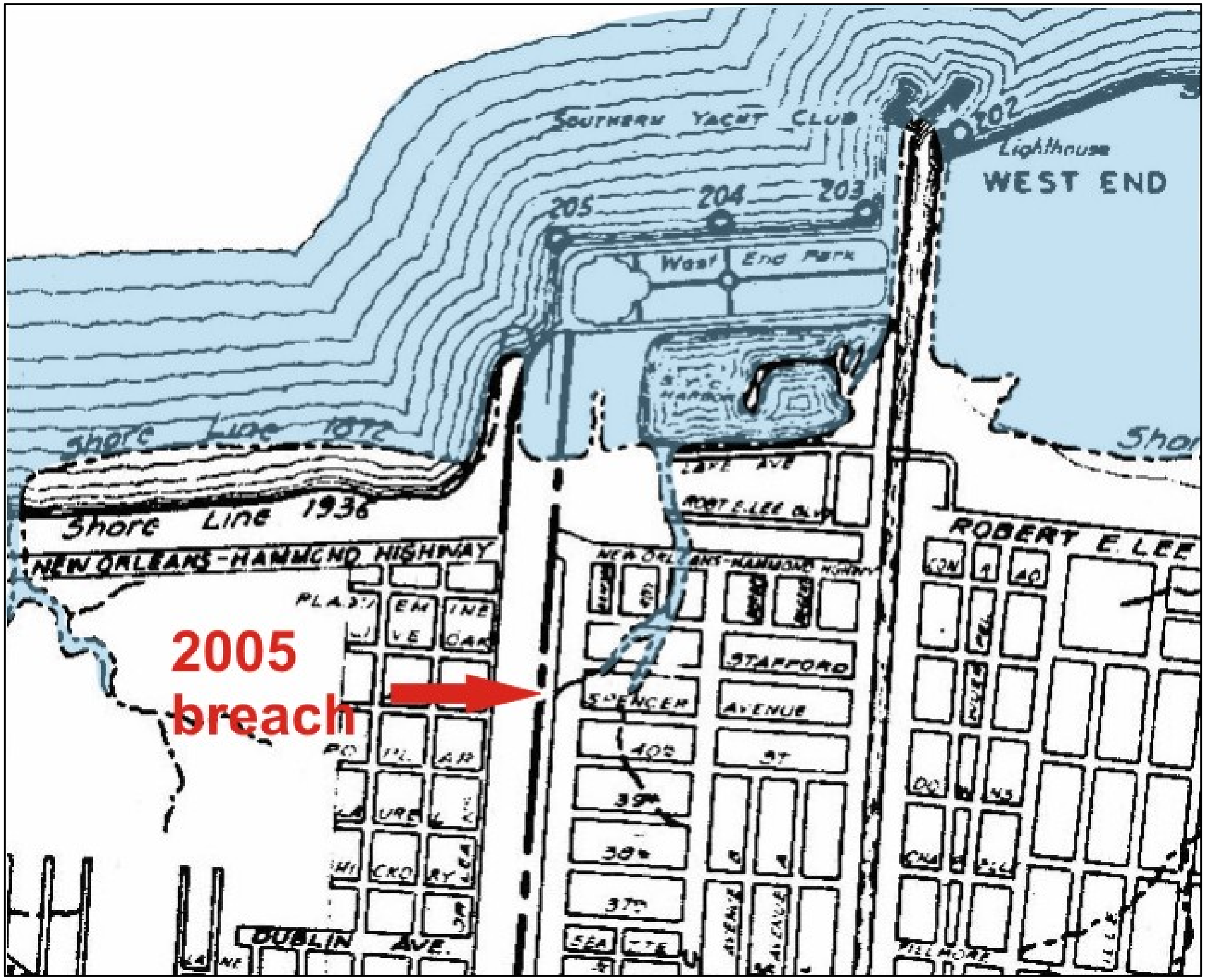


Geologic profile for the 17th St Canal flood wall prepared by Corps' New Orleans District office in 1990. Three of four holes in vicinity of the 2005 failure (spaced 500 ft apart) had zero sample recovery. These contacts were projected and sheet pile tips designed, accordingly.



17th Street Canal East Levee- Draft Soil Profile
New Orleans, Louisiana

- **Alternative interpretation of the Eustis 1982 borings for the 17th Street Canal East Levee, near the 2005 break. In this case the swamp deposits would extend beneath the sheetpile tips over a zone 300 feet long, where the break occurred.**

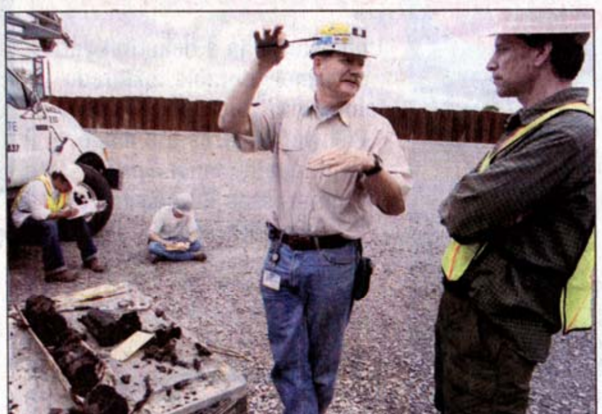


- **Map overlay** assembled by Prof. Joe Suyhada at LSU by overlaying 1872 Sulakowski map on the 1937 WPA map, showing the 1872 shoreline and sloughs (in blue) along Lake Pontchartrain.
- **The position of the 2005 breach along the east side of the 17th Street Canal is indicated by the red arrow.**

HURRICANE AFTERMATH

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**

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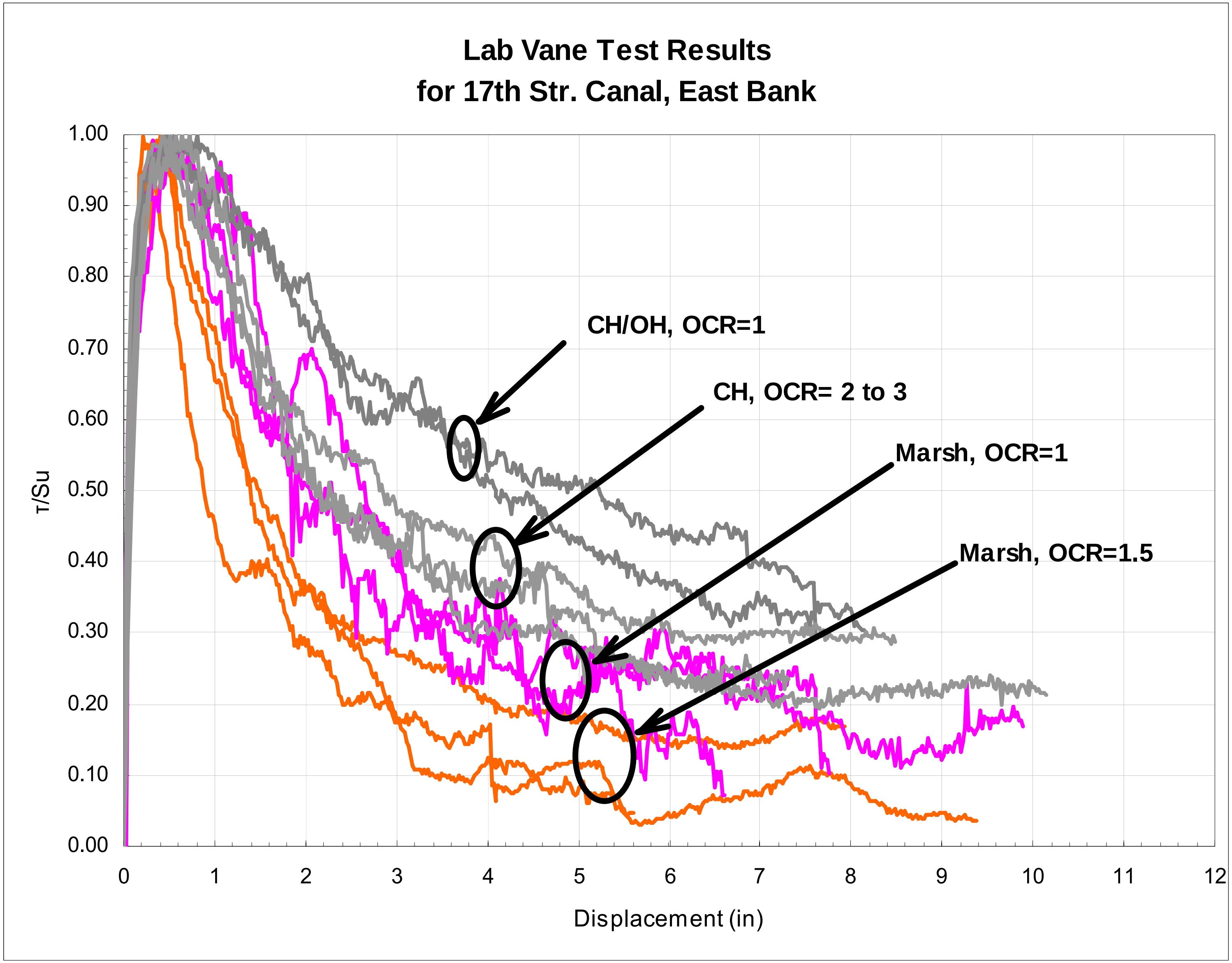
Miniature laboratory vane shear testing at U.C. Berkeley

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



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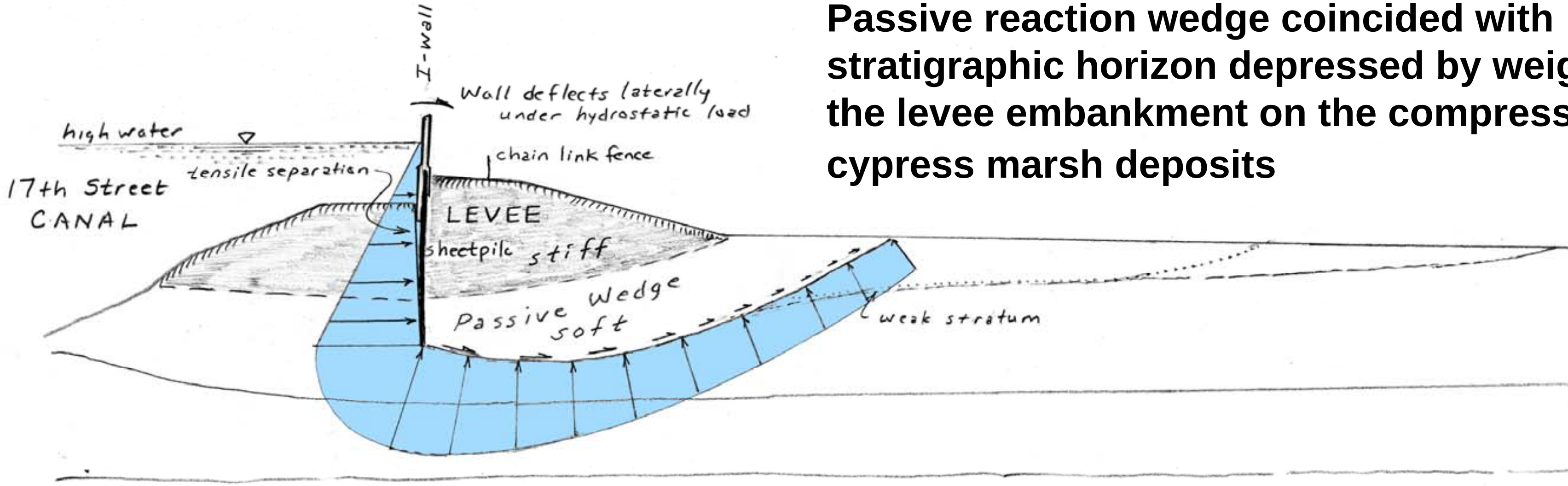
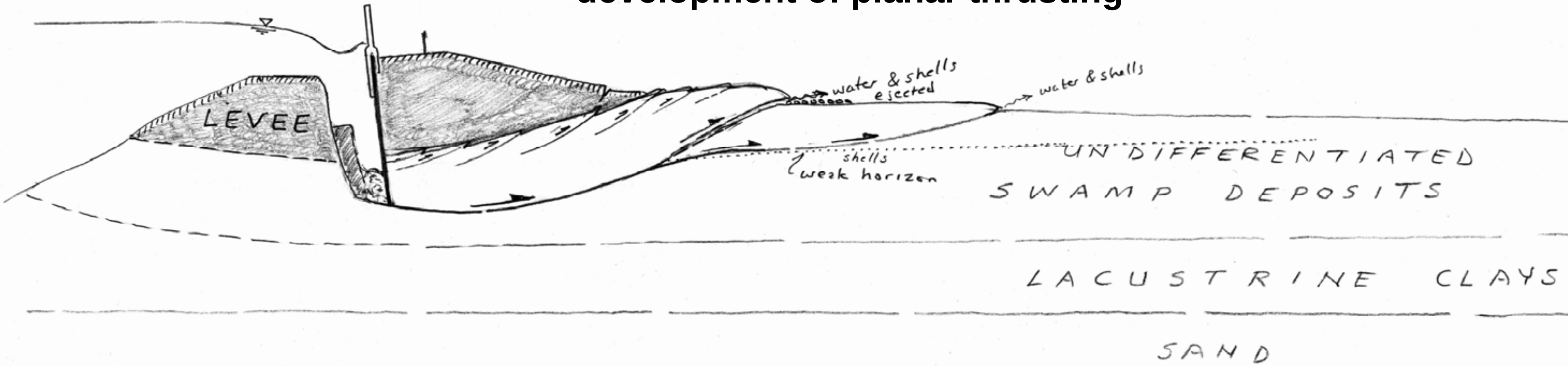


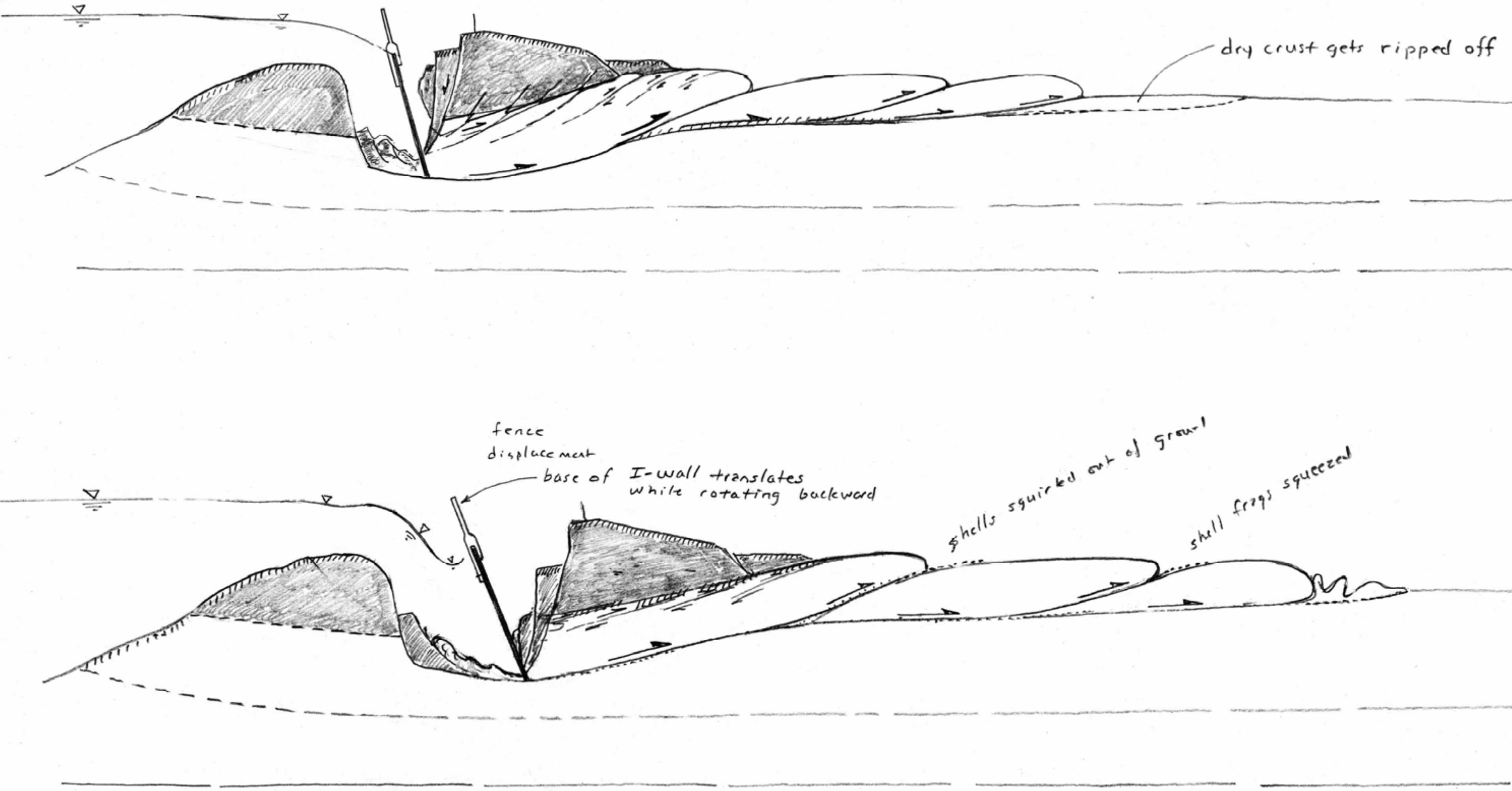
Passive reaction wedge coincided with stratigraphic horizon depressed by weight of the levee embankment on the compressible cypress marsh deposits

drainage canal

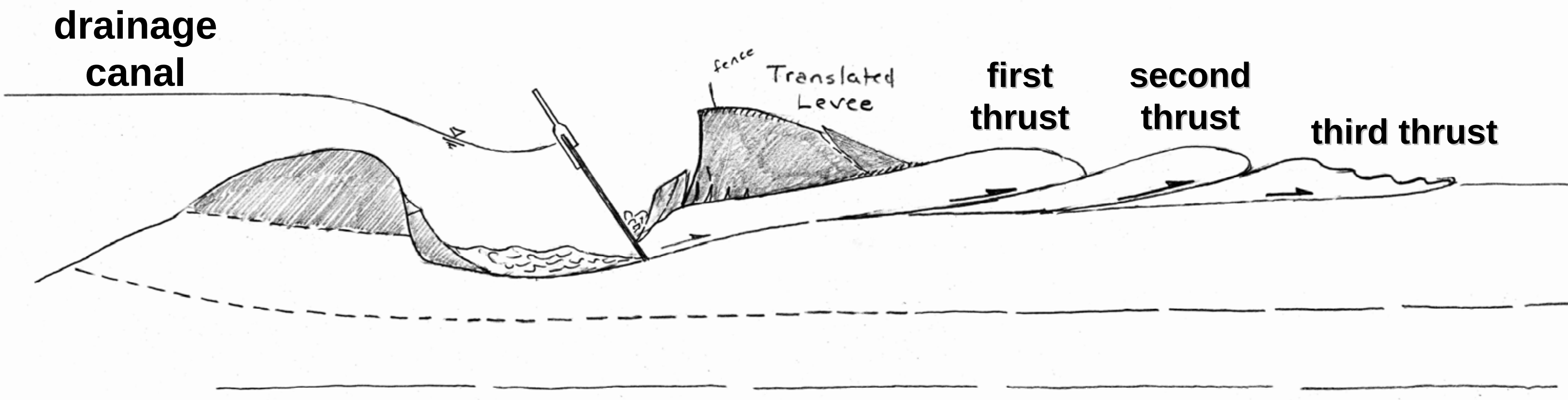
Traction shears noted along base of embankment. Note initial back rotation component of motion and development of planar thrusting



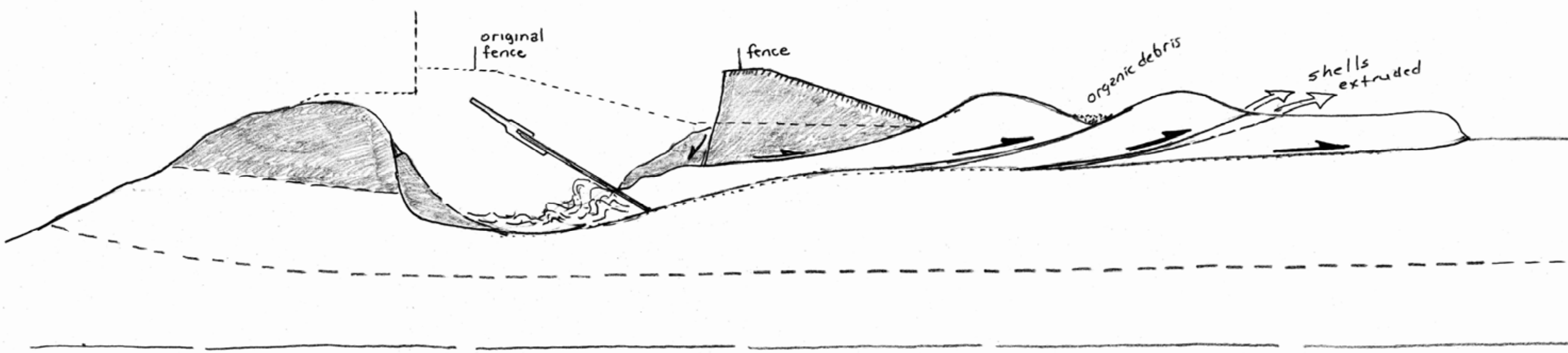
Initial loading conditions. Storm surge rises to within 4 feet of flood wall crest. Hydrostatic pressures on sheetpile supported I-wall highlighted in blue. Translational failure begins.



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



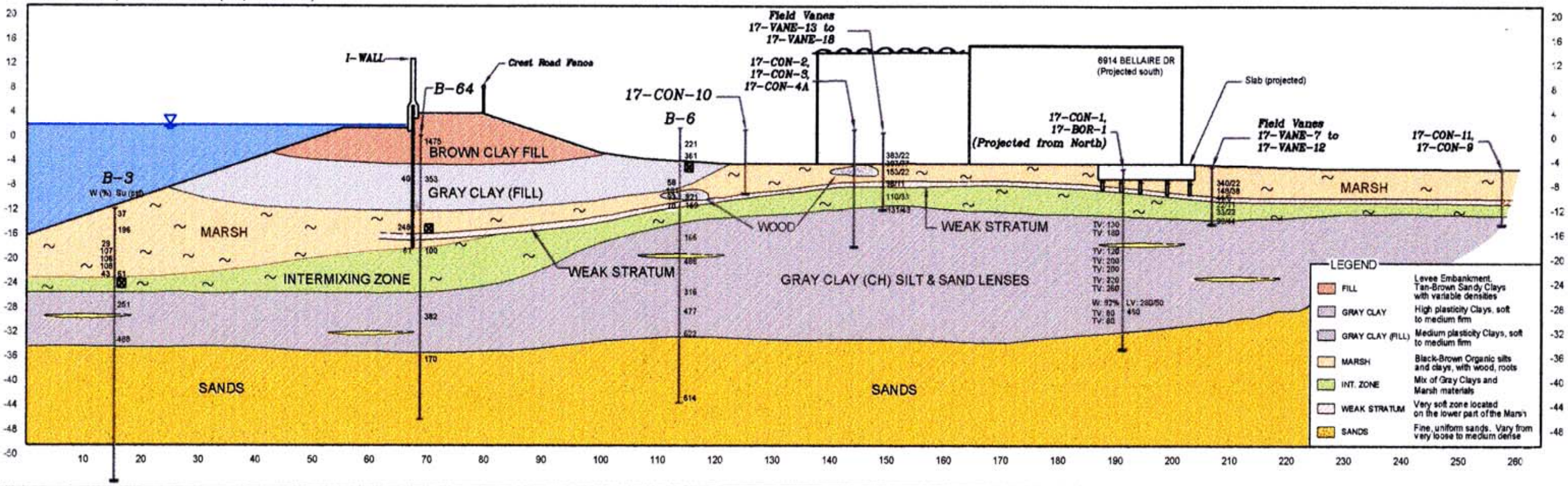
Some sheetpile supported I-walls fell backward; others fell forward



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.

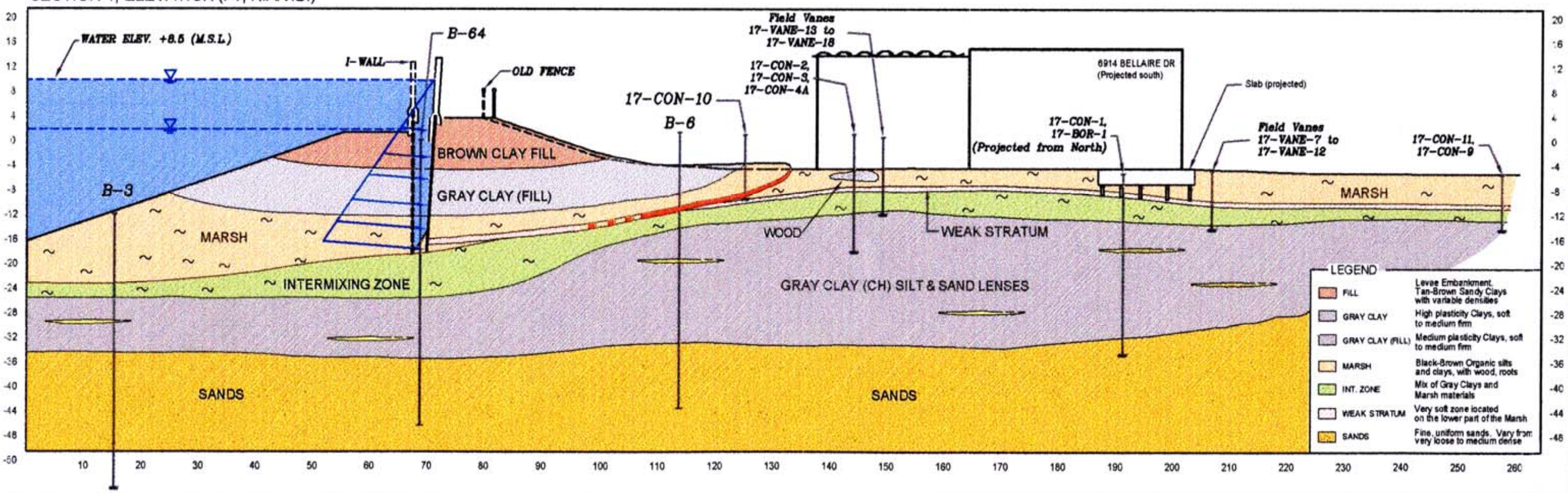
17th STREET CANAL EAST BANK BREACH
SECTION 1, ELEVATION (FT, N.A.V.D.)

ANALYSIS SECTION



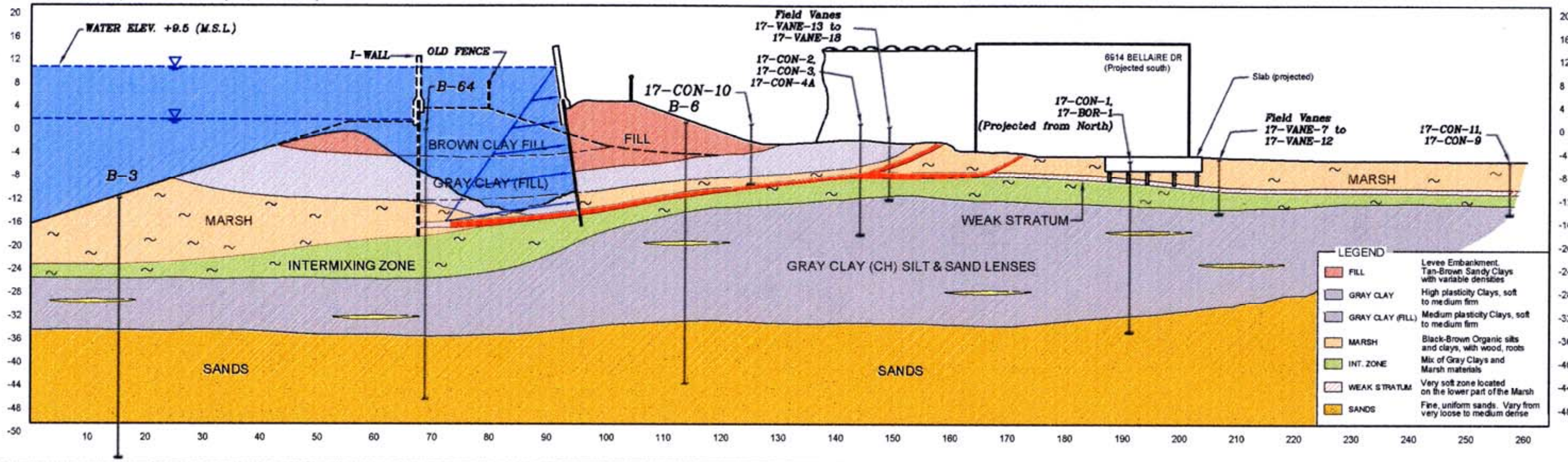
17th STREET CANAL EAST BANK BREACH
SECTION 1, ELEVATION (FT, N.A.V.D.)

OPENING OF THE GAP



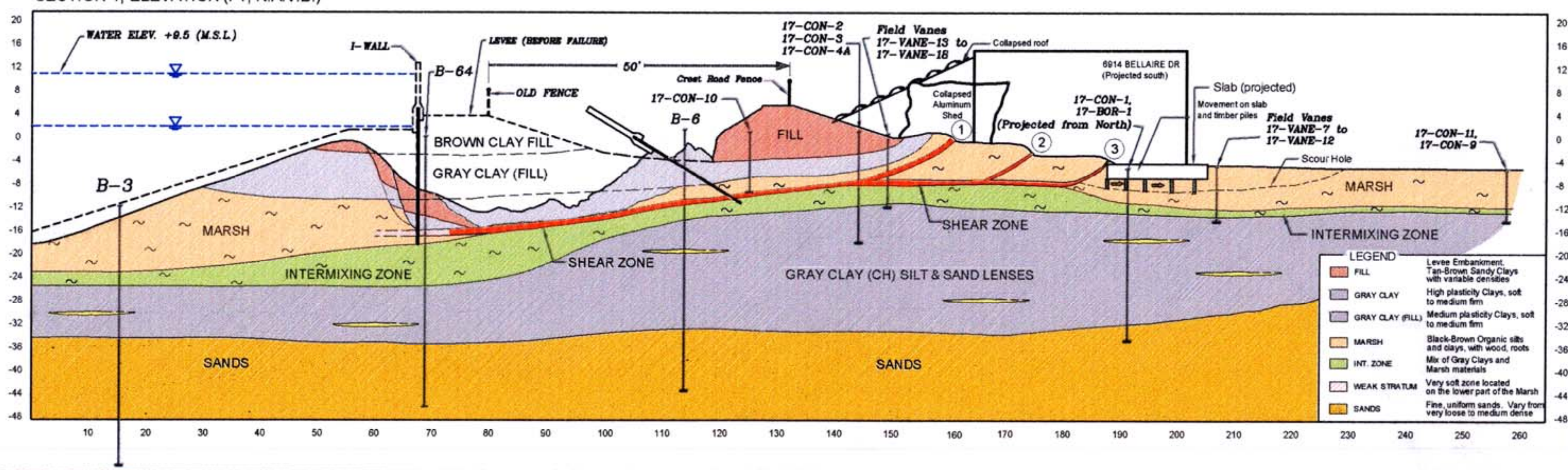
17th STREET CANAL EAST BANK BREACH
SECTION 1, ELEVATION (FT, N.A.V.D.)

LATERAL TRANSLATION IN PROGRESS

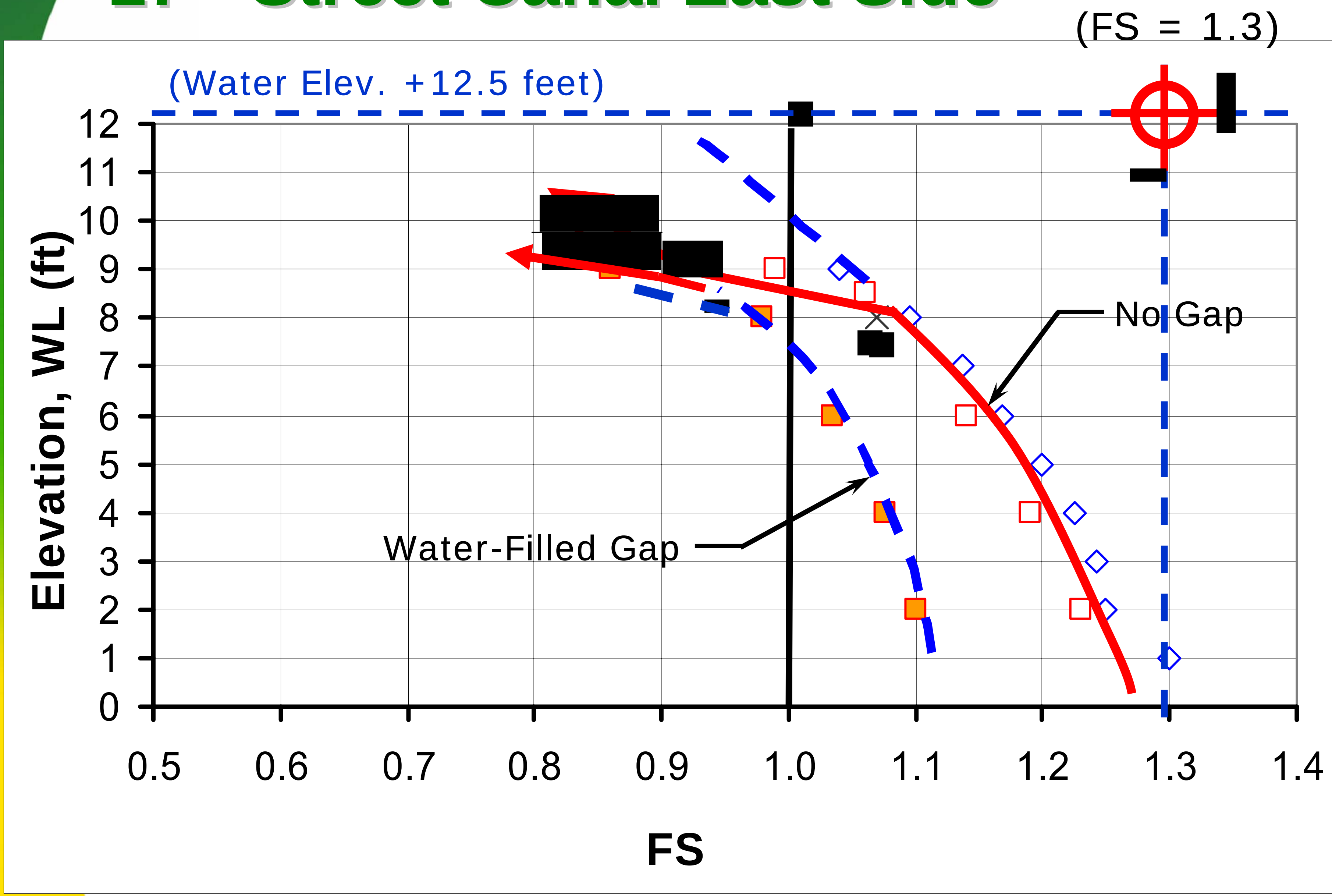


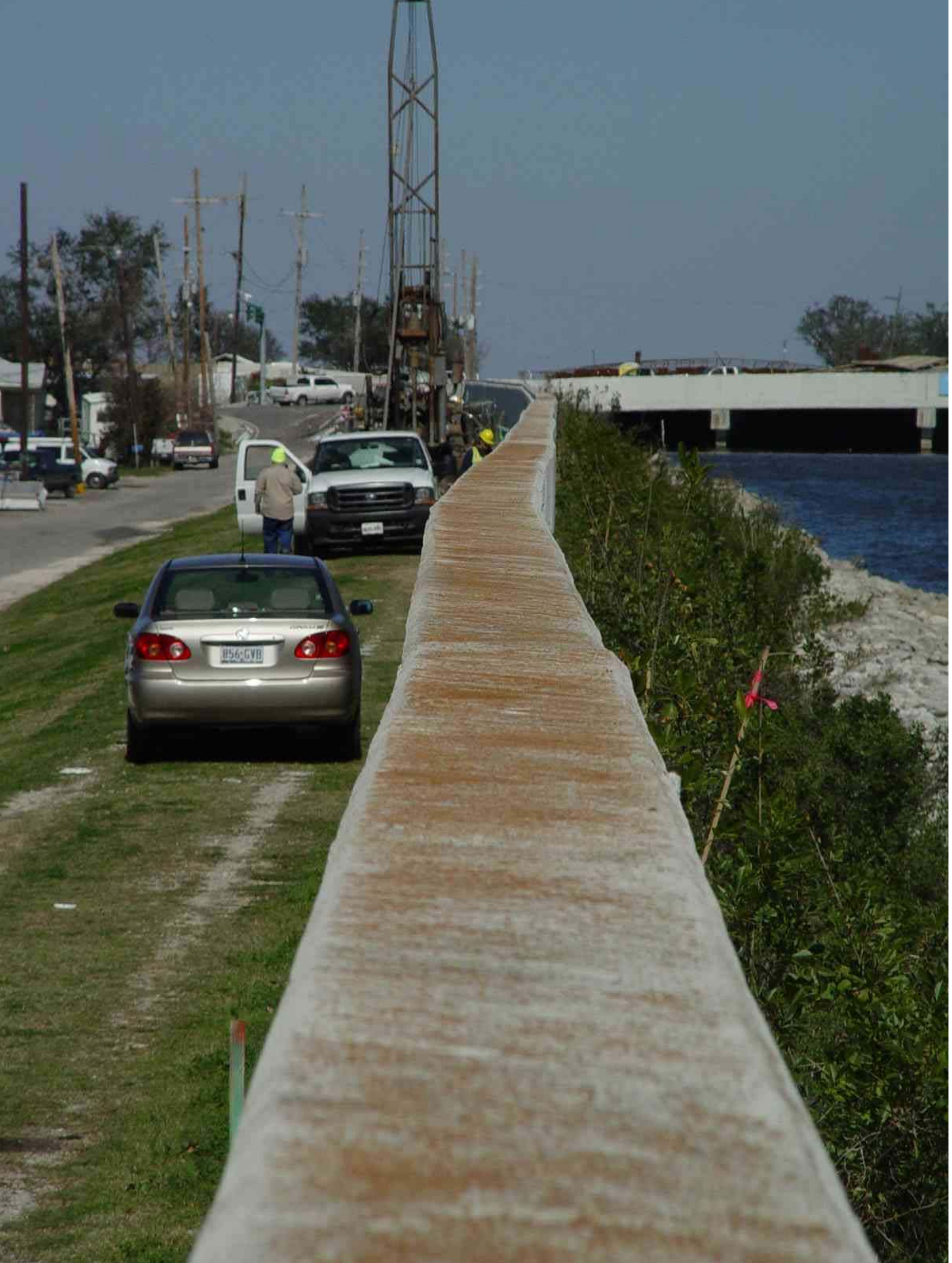
17th STREET CANAL EAST BANK BREACH
SECTION 1, ELEVATION (FT, N.A.V.D.)

DISPLACED



17^{th} Street Canal East Side

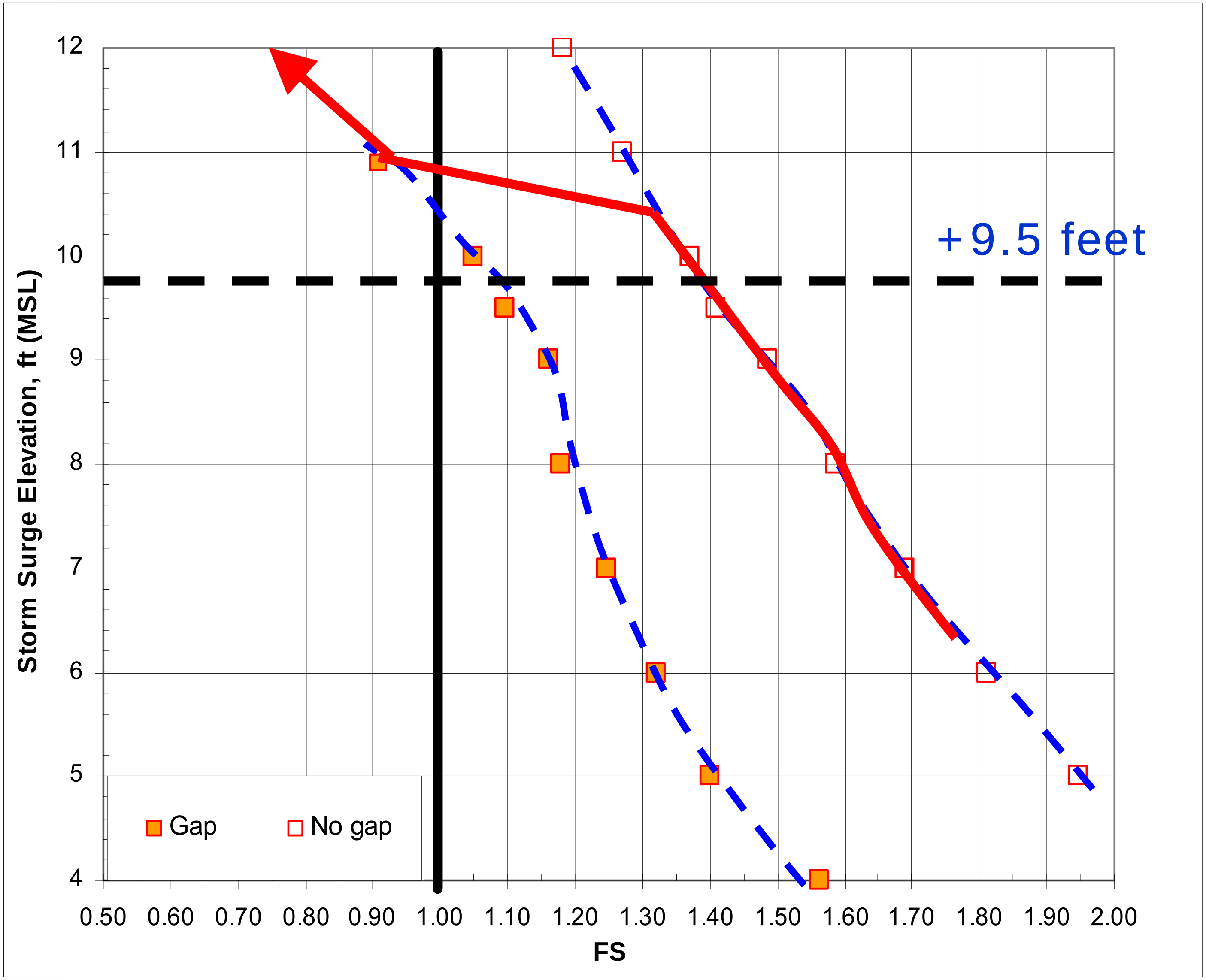




The tilting wall controversy

- 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

17^{th} Street Canal, West Bank



The design of the 17th St Canal I-walls violated the "three deadly sins" espoused in Rogers' GE 341 Engineering Geology and Geotechnics course:

- **Never allow yourself to draw geologic cross sections using a ruler. There is no such thing as a ruler straight line in geology.**
- **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.**
- **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.**

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Part 5

LONDON AVENUE DRAINAGE CANAL FAILURES

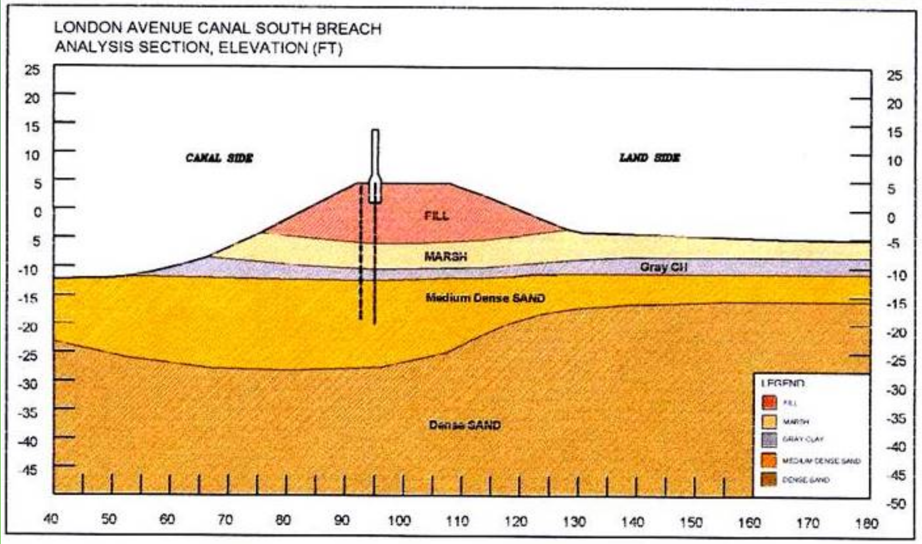
London Avenue (North) breach

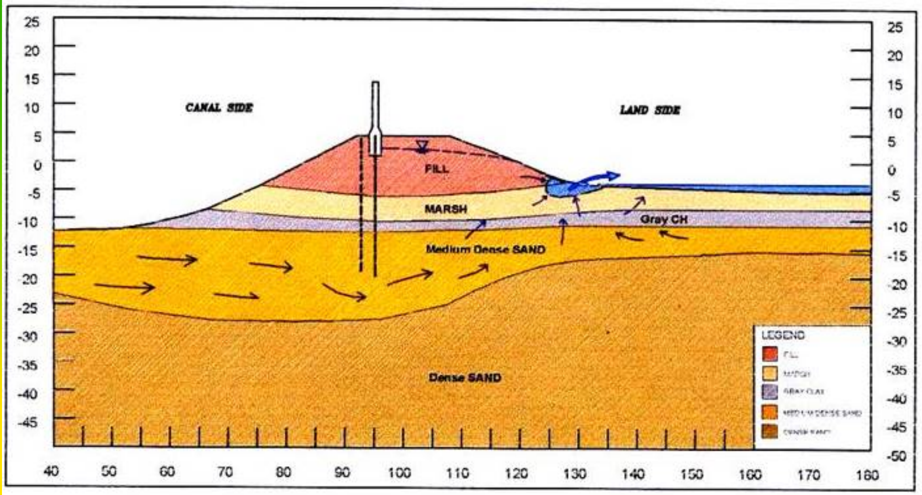
Similar failure mechanism as 17th St Canal

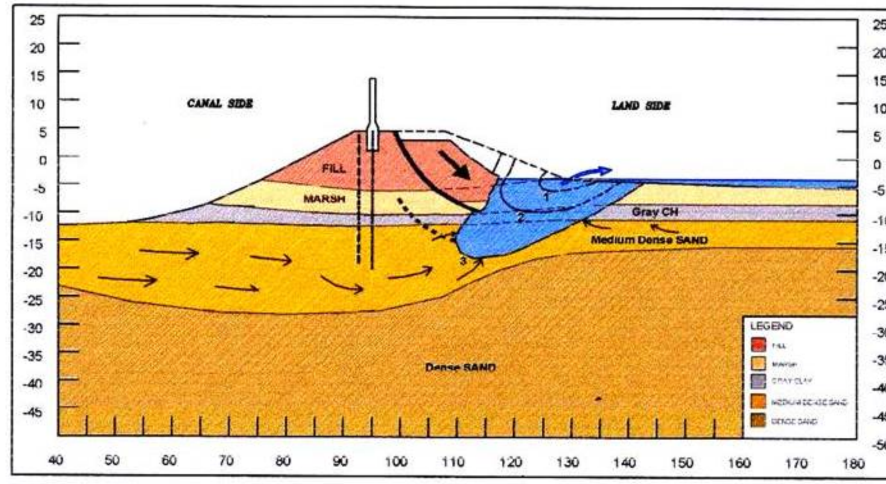
Incipient failure

- **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

UMR

- **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.**

UMR

- **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.**

UMR

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

UMR

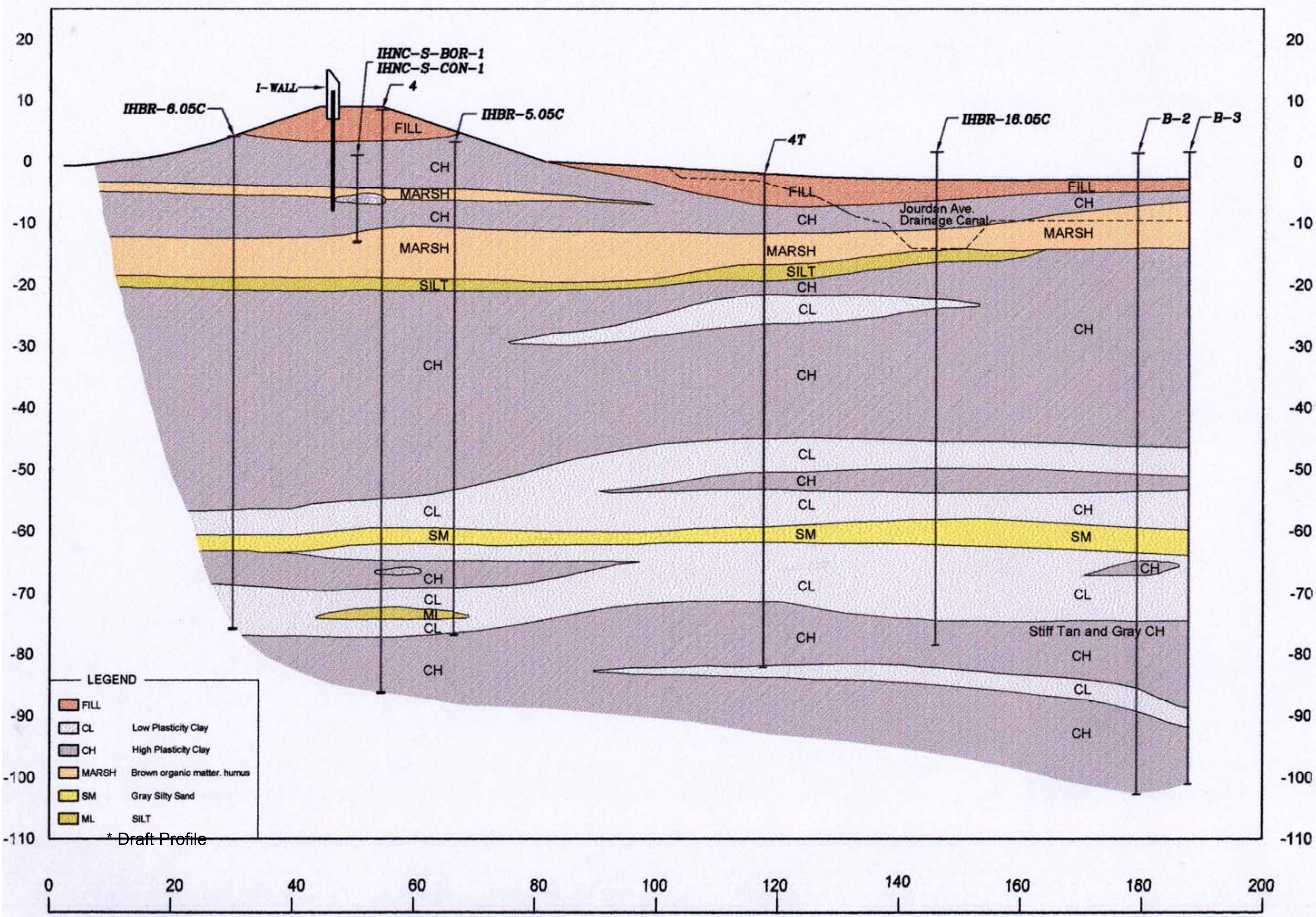
- ING 4727 was built in 1990 as a dry cargo cover-top barge with a steel hull. It was 200 feet long, 35 feet wide, and 12 ft high, with a a cargo volume of 84,659 ft^3 (1877 tons). It was being leased to Lafarge North America, and was tied up along the MRGO channel.

UMR

- **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**

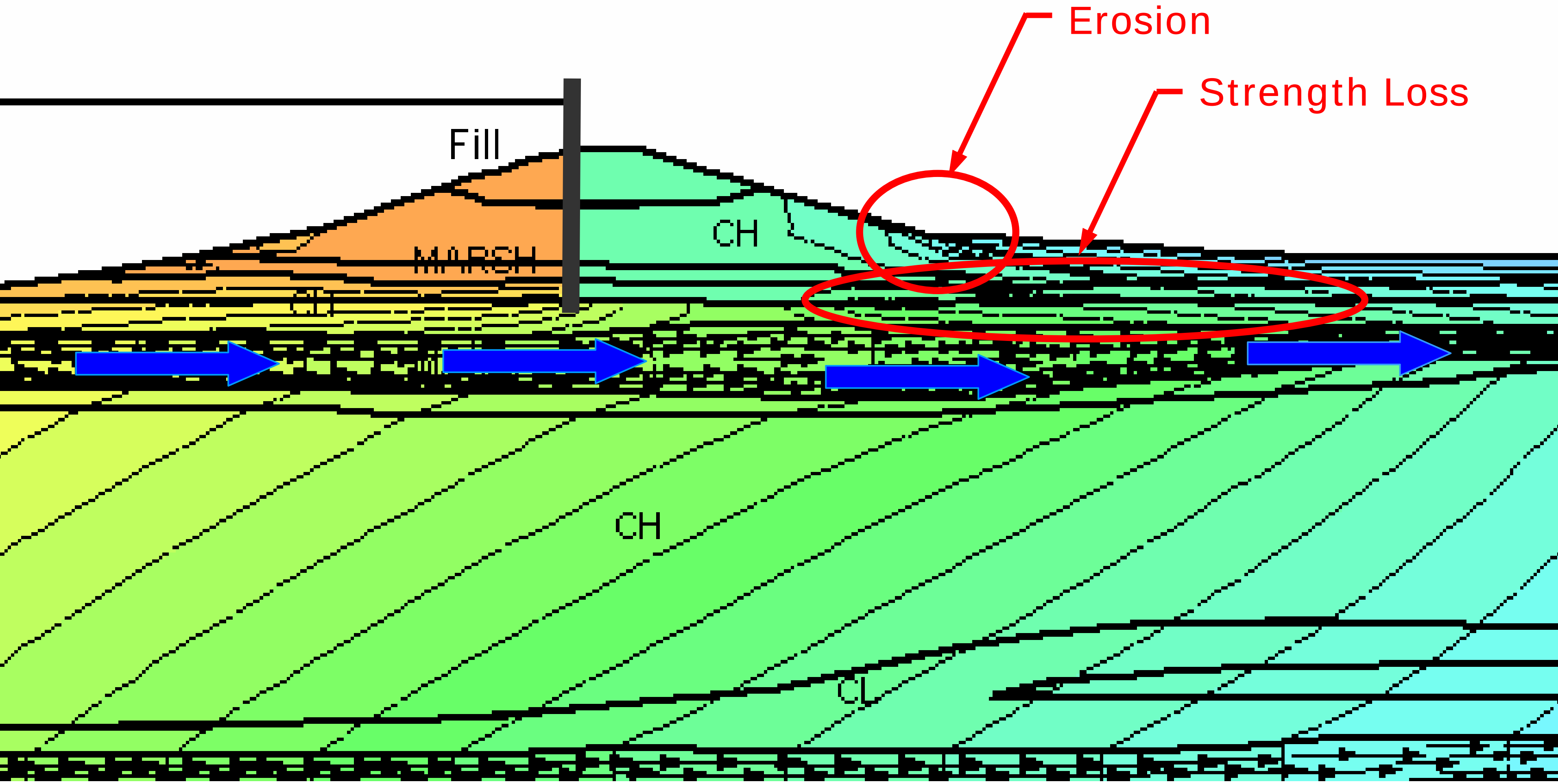
UMR

LOWER NINTH WARD, IHNC EAST BANK
SOUTH OF SOUTHERN BREACH
ELEVATION, FT (N.A.V.D.88)



- Seepage crevasse splay exposed on the water side of the east levee of the IHNC breach after Hurricanes Katrina and Rita. This same section of the IHNC levee failed in 1965 during Hurricane Betsy.
- Note the anomalous seepage in lower foreground, which suggests much higher permeability in this particular portion of the dike, close to the south end of the failed section.

Industrial Canal at the Ninth Ward

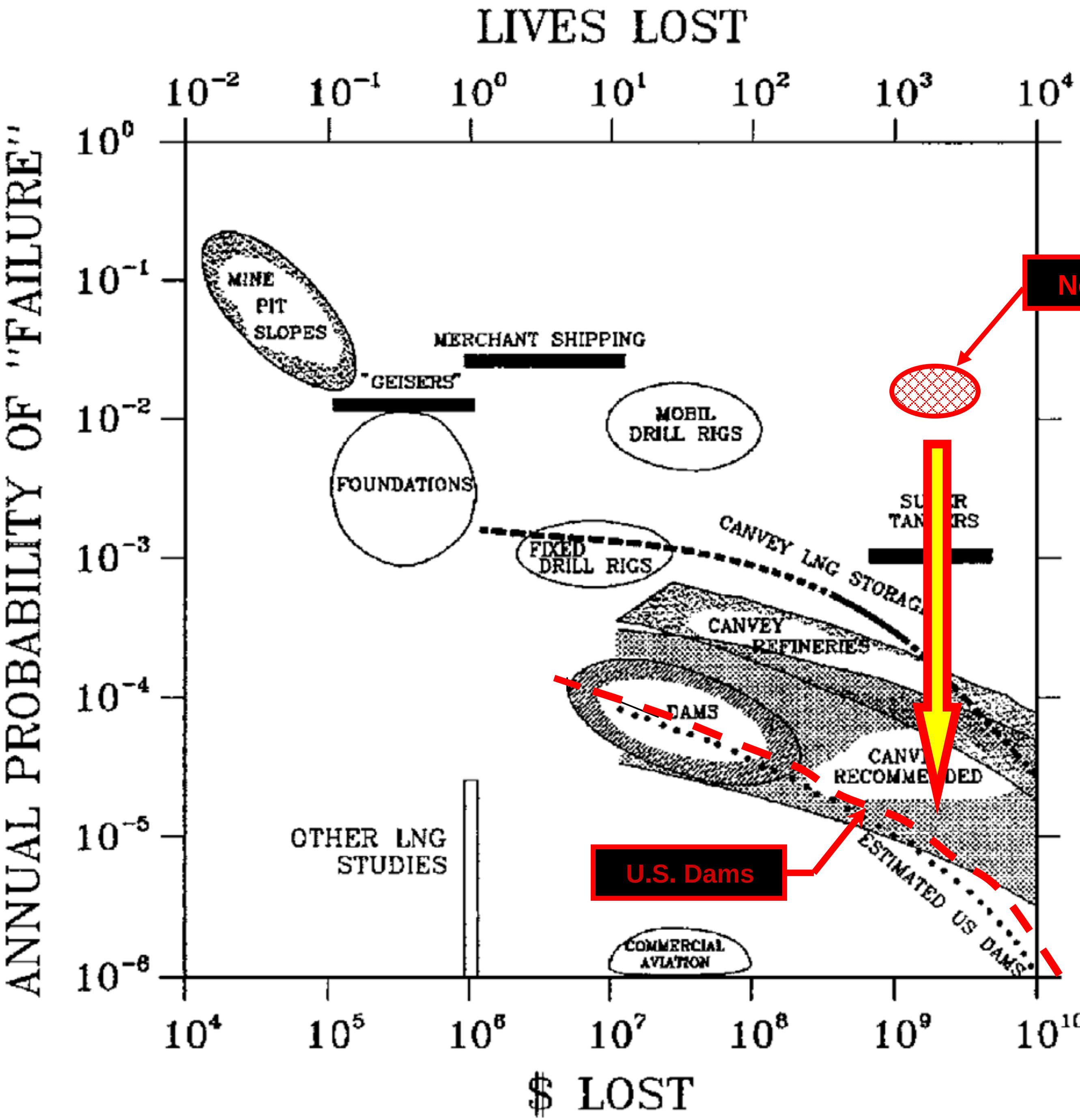


Part 7

PRELIMINARY CONCLUSIONS –

The Katrina disaster was literally “off the charts”

UMR



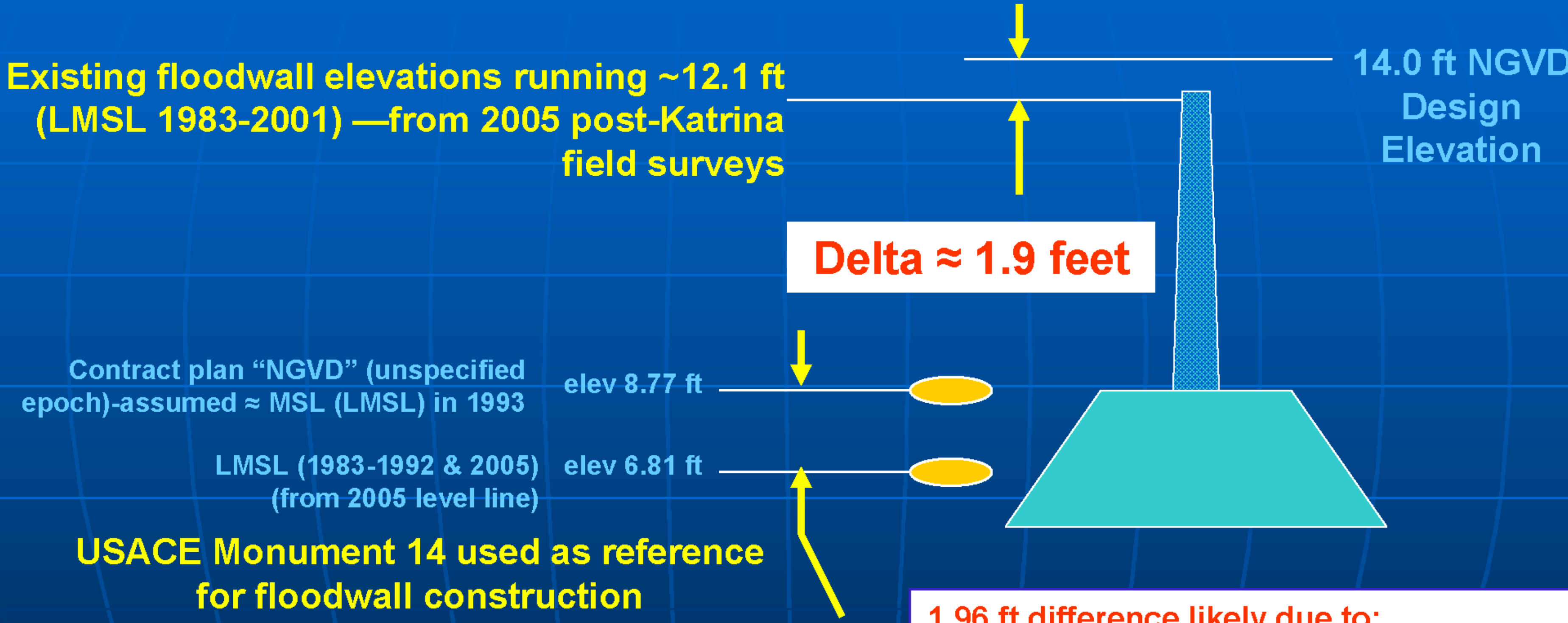
The New Orleans levees and flood walls were 1000 times more vulnerable to failure than the average American dam

- 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

17th Street Outfall Canal
East Bank Floodwall Construction

ca 1993 Floodwall Protection/Capping Project (High Level Plan)

Hammond Hwy to Veterans Blvd Sta. 8+50 to 80+00 (±) -- Typical



1.96 ft difference likely due to:

- Uncertain BM 14 elevation … believed by MVN to be suspect/disturbed
- Uncertain BM 14 datum (1951 or ?)
- Settlement (probably < 0.3 ft)

Elevations are referenced to an estimated LMSL (1983-2001 epoch) at Lake Pontchartrain

Preliminary 5 Mar 06—subject to correction

(Not to Scale)

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.

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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.

UMR

Most everyone ended up agreeing on all the major points

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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