Lecture 2

Levee Design Issues in Louisiana

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

Karl F. Hasselmann Chair in Geological Engineering

Missouri University of Science & Technology

for the

First Annual Levee School Symposium

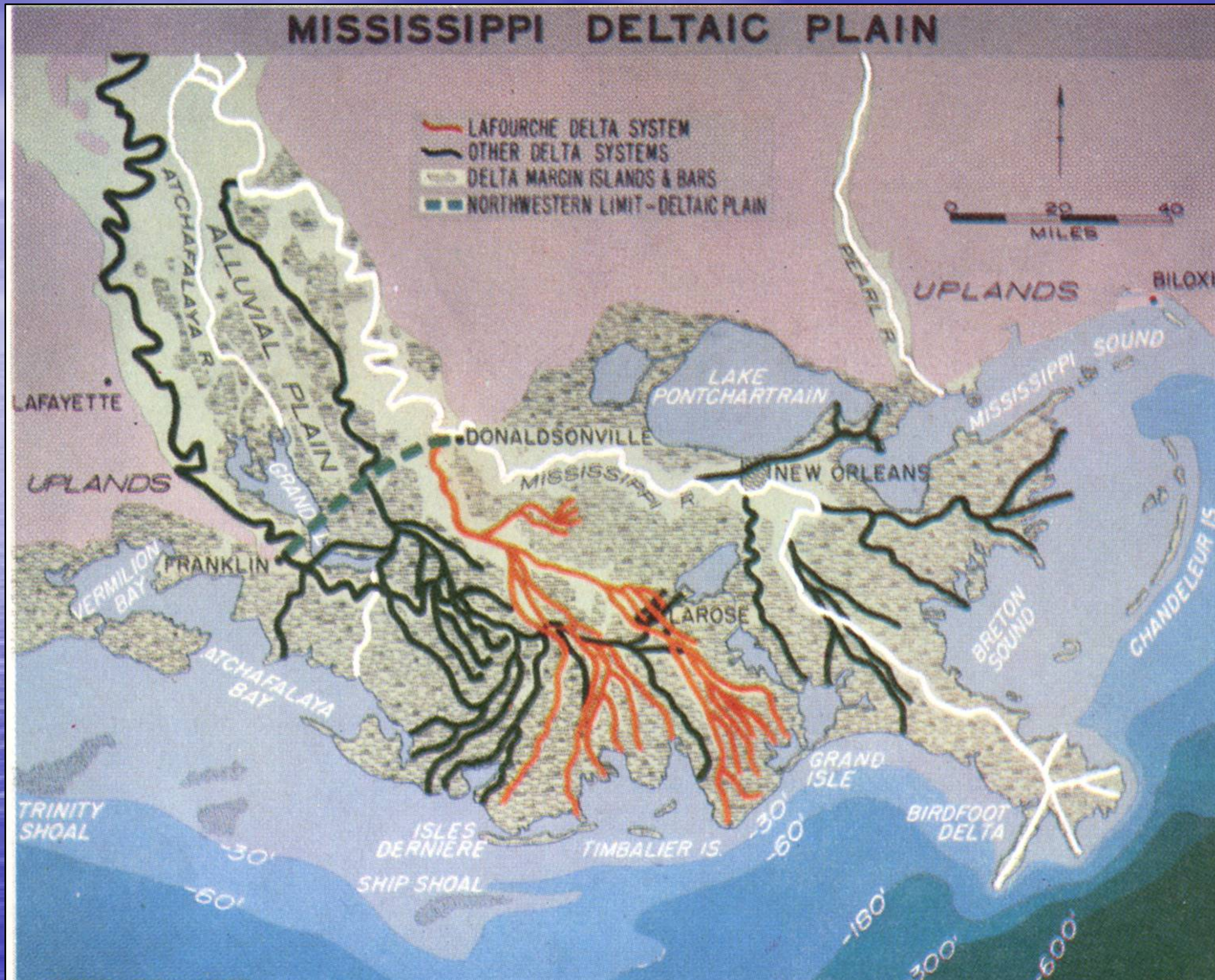
Louisiana State University

Baton Rouge, Louisiana

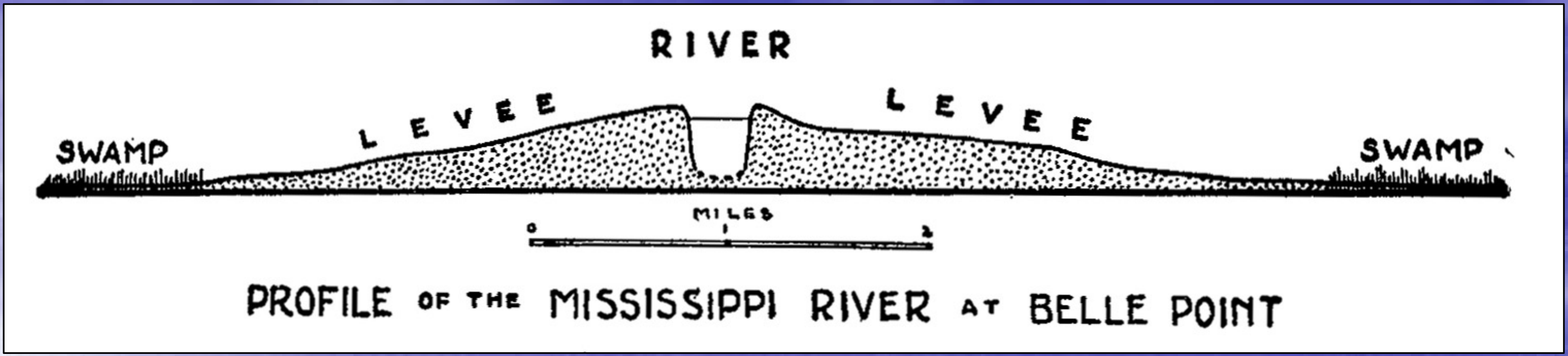
November 28, 2007

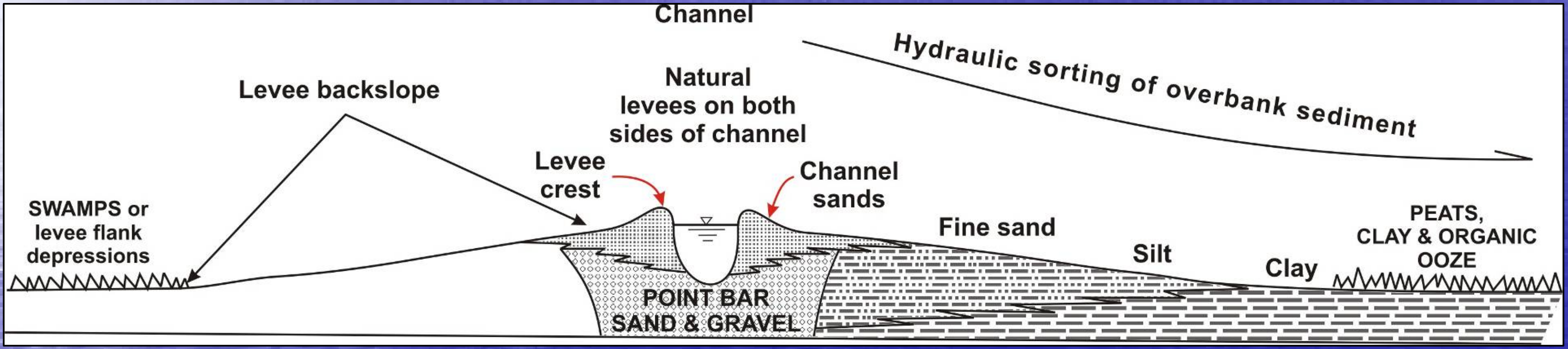
Firm Sand and Gravel Foundations versus Soft and Mushy Backswamp Foundations

Where **you build in the Mississippi Delta influences future performance**

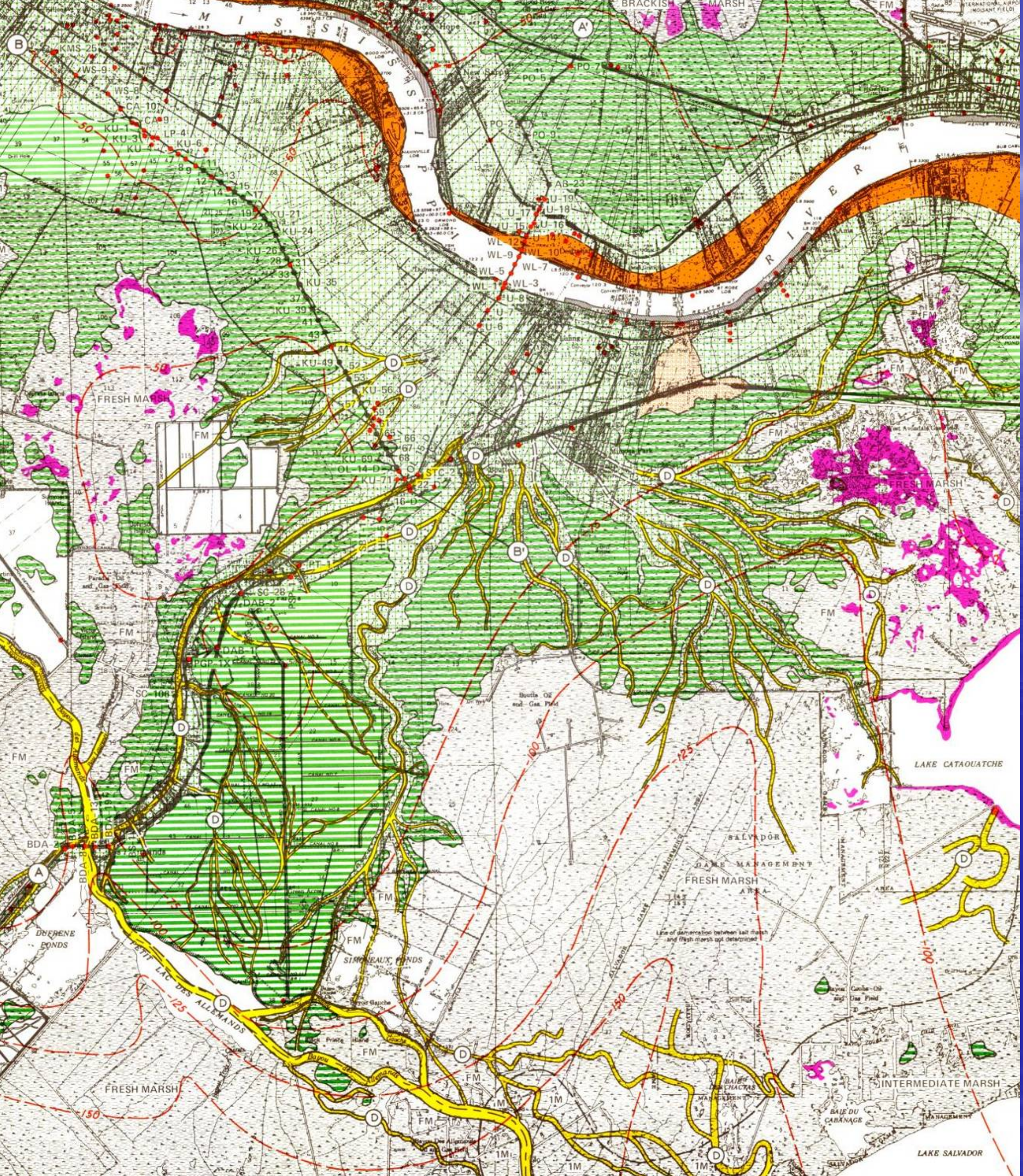


- **The Mississippi Delta has been lain down by an intricate system of distributary channels**



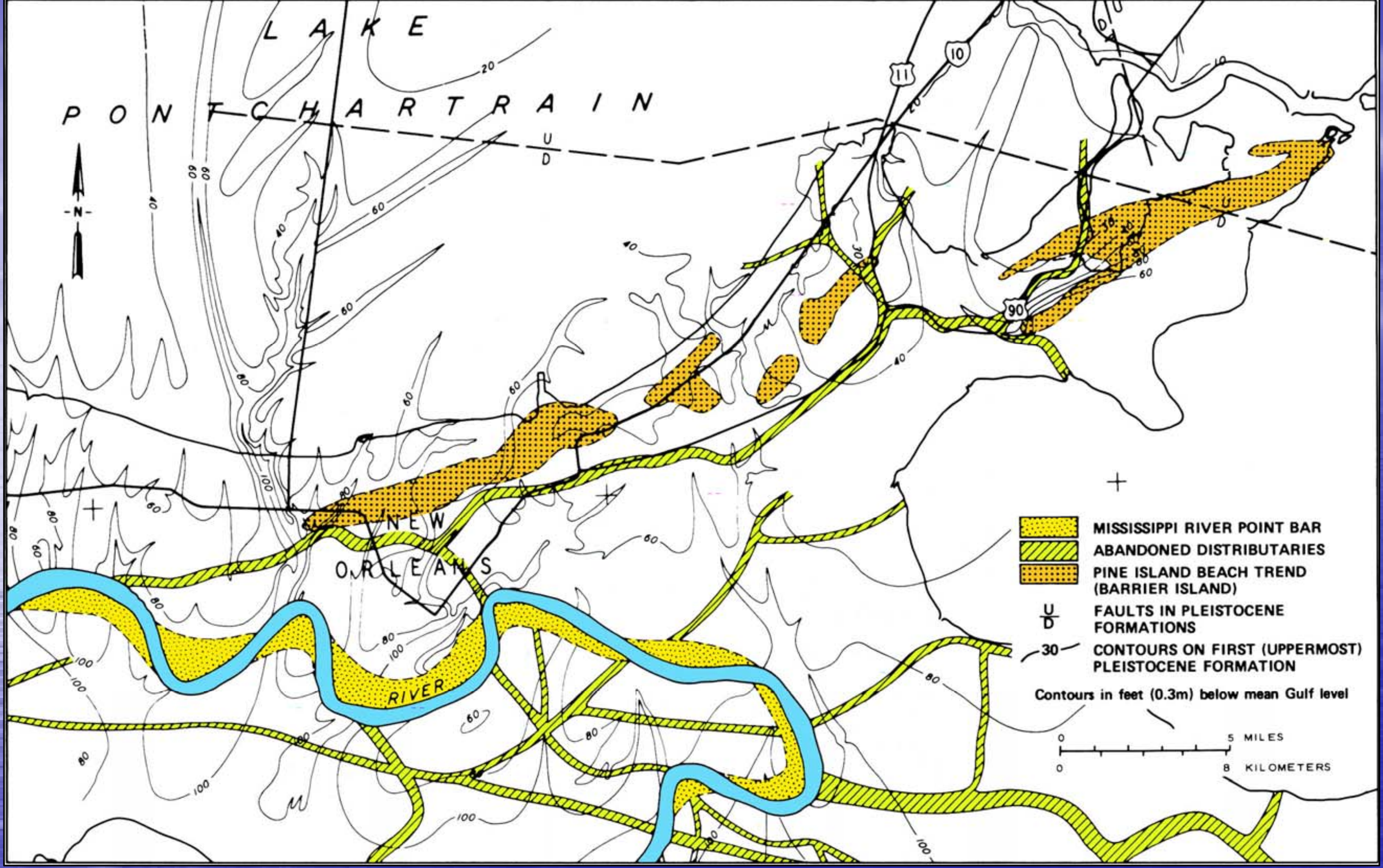


- Typical cross section through the sandy bank levees of the Mississippi River, illustrating how the river's main channel lies above the surrounding flood plain, which were poorly drained swamp lands prior to reclamation.
- There is significant hydraulic sorting of materials deposited on either side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

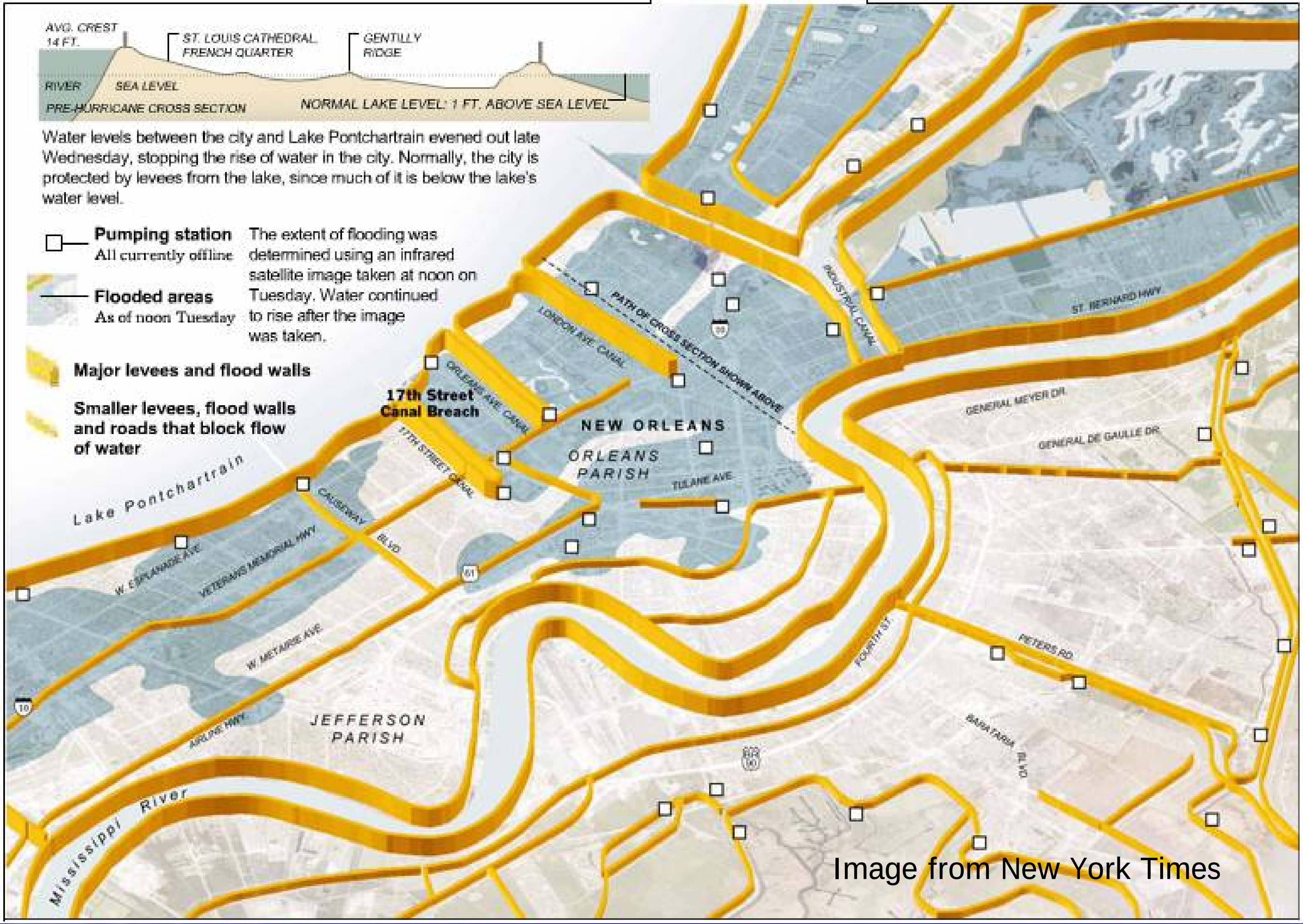


Hahnville is just upstream of New Orleans

- Note classic birdfoot pattern of sand-filled distributary channels, shown in yellow
- Note development

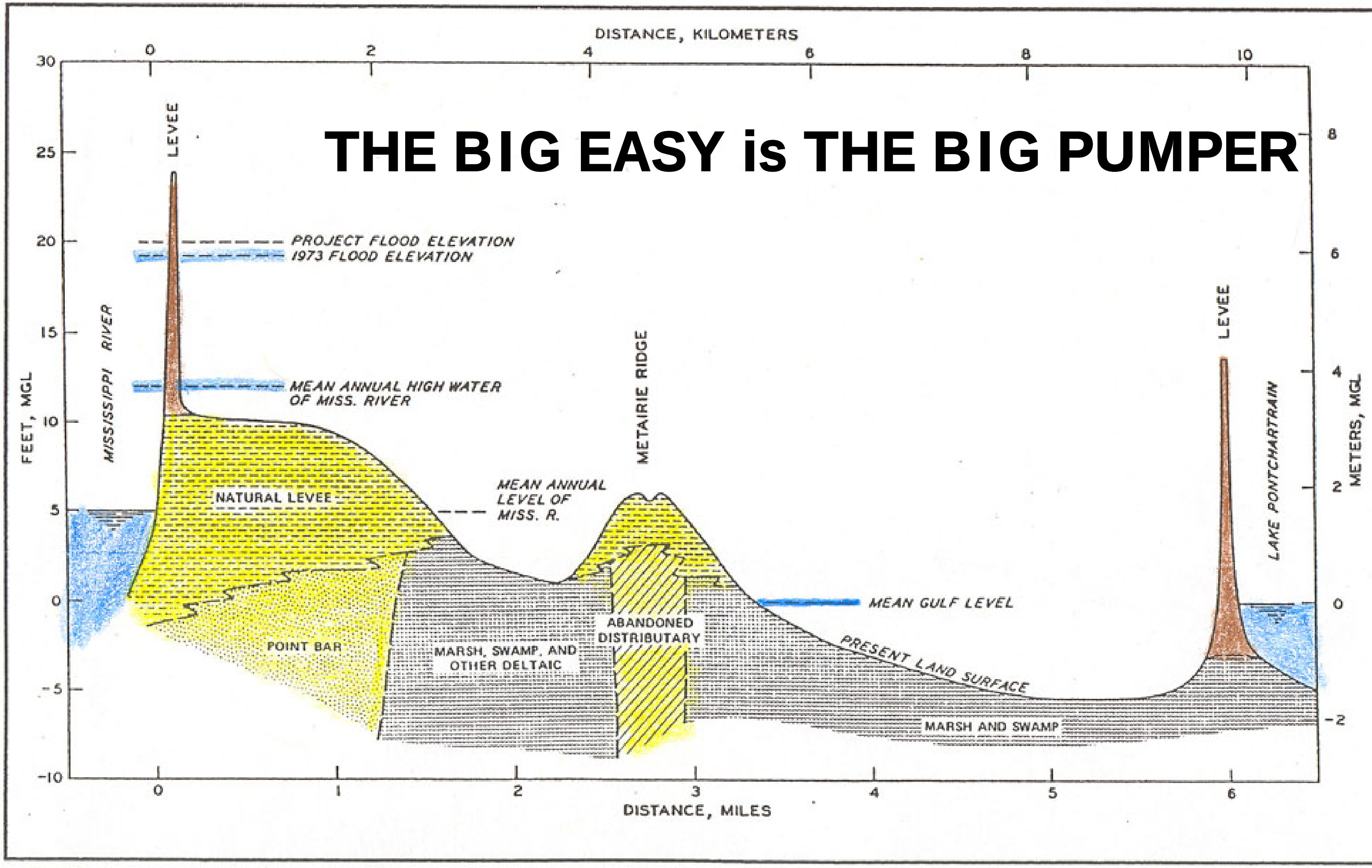


- Pleistocene geologic map of the New Orleans area. The yellow stippled bands are the principal distributory channels of the lower Mississippi during the late Pleistocene, while the present channel is shown in light blue. The Pine Island Beach Trend is shown in the ochre dotted pattern. Depth contours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



A complex network of levees have protected New Orleans from flooding from the Mississippi River since 1859. One of the vexing problems with levees is that it only takes one break at one place to defeat the entire system, if there is a single barrier.

THE BIG EASY is THE BIG PUMPER



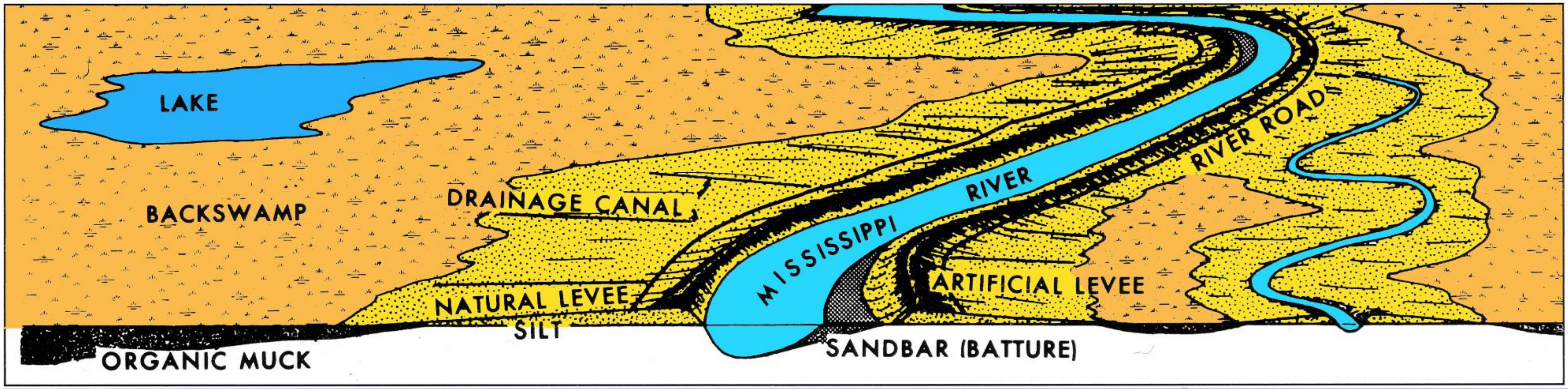
The Mississippi levee crests at 24.5 feet, and the Pontchartrain levee at 13.5 feet. All the major flood incidents that have impacted New Orleans since 1859 have struck the city from Lakes Borgne and Lake Pontchartrain; in 1915, 1947, 1965, 1969, and twice in 2005.

The most treacherous and complex foundation conditions are in Louisiana

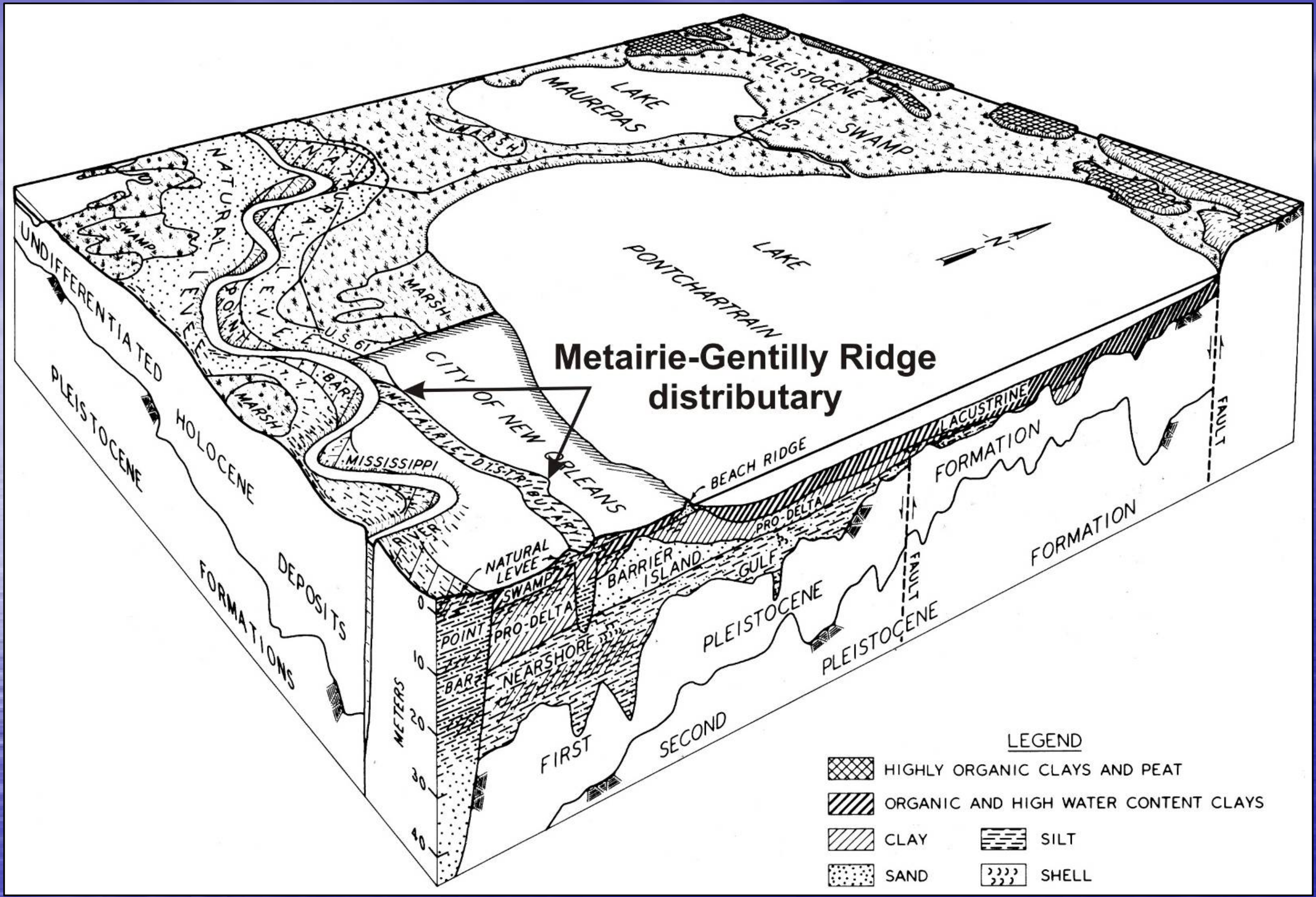
-

Site characterization requires considerable expertise and flexible budgets

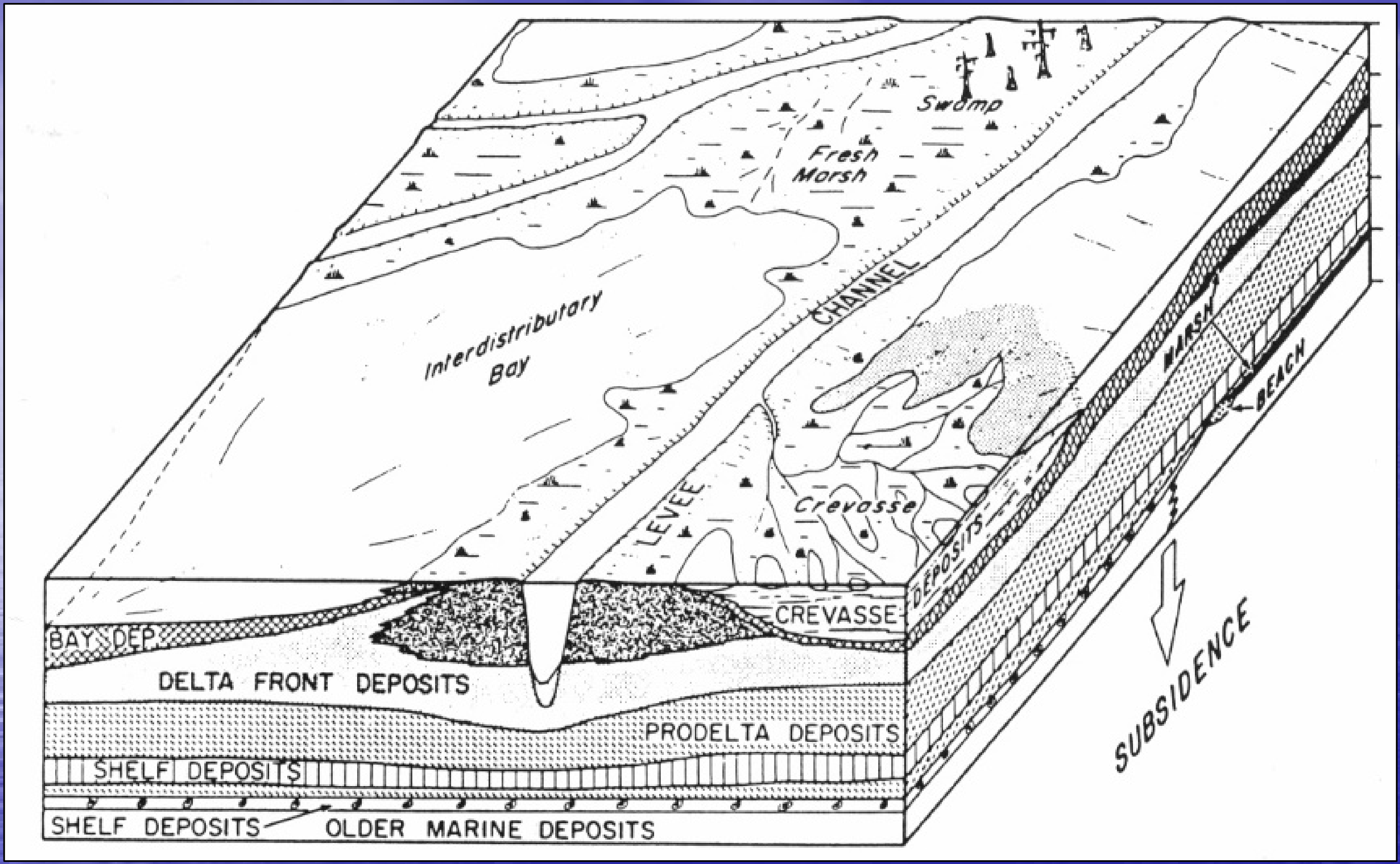
Discontinuous nature of stratigraphy in Mississippi Delta



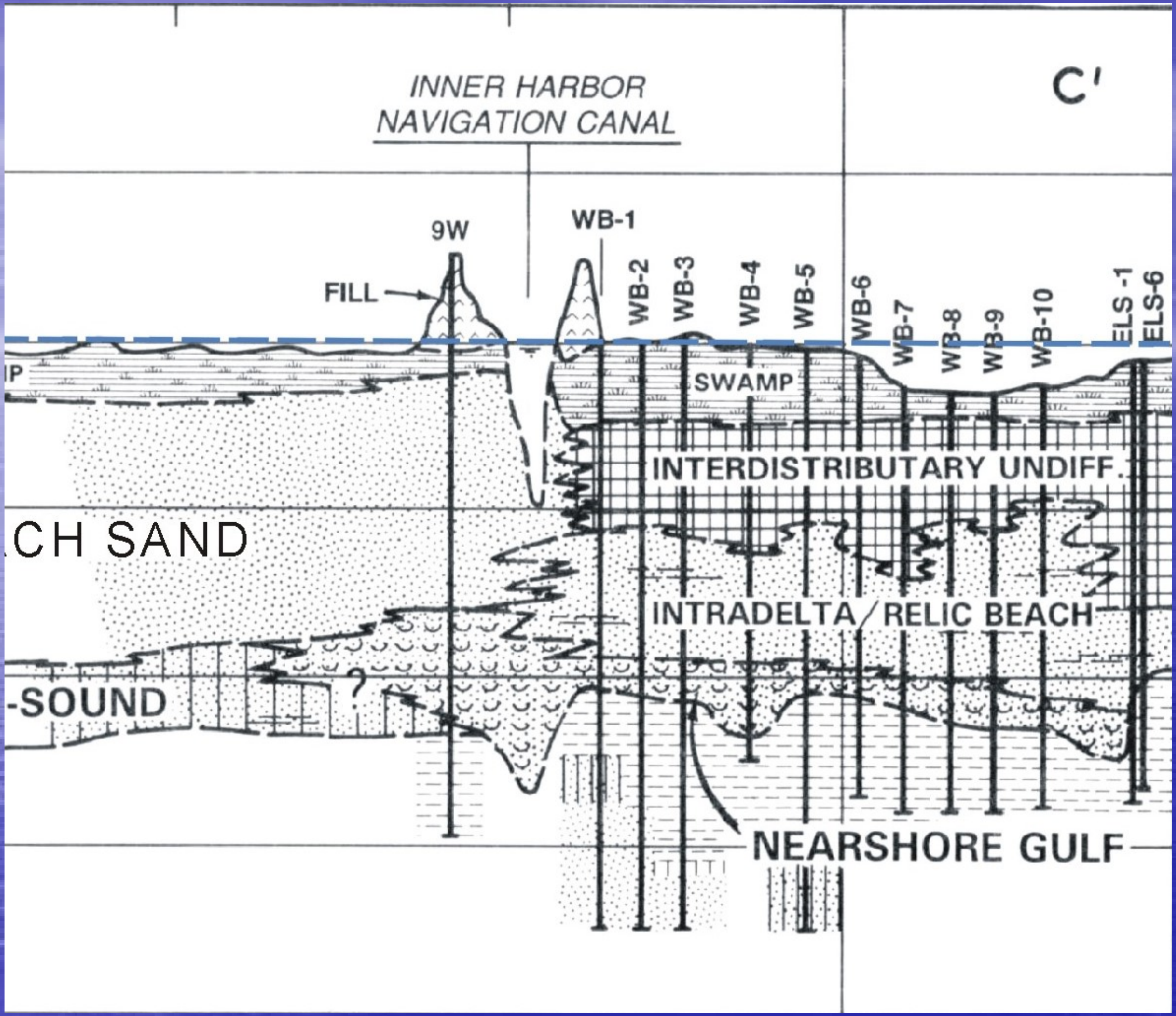
- The stem channels of the Mississippi and its distributaries leave thick sequences of point bar sands adjacent to the river; then historic marshes (lowland backswamp), distributary ridges, and backswamps, like those along large shallow water bodies, like lake Borge and Lake Pontchartrain.



- Block diagram of the geology underlying New Orleans. The principal feature dividing New Orleans is the abandoned Metairie-Gentilly distributary, which extends to a depth of -50 ft MGL and separates geologic regimes on either side.



- Block diagram illustrating relationships between **subaerial and subaqueous deltaic environments** in relation to a single distributary lobe.
- Note fresh water cypress and gum swamps, peat, and interdistributary sediments.



- Typical geologic cross section - through New Orleans Inner Harbor Navigation Channel
- Note how conditions vary on either side of the channel

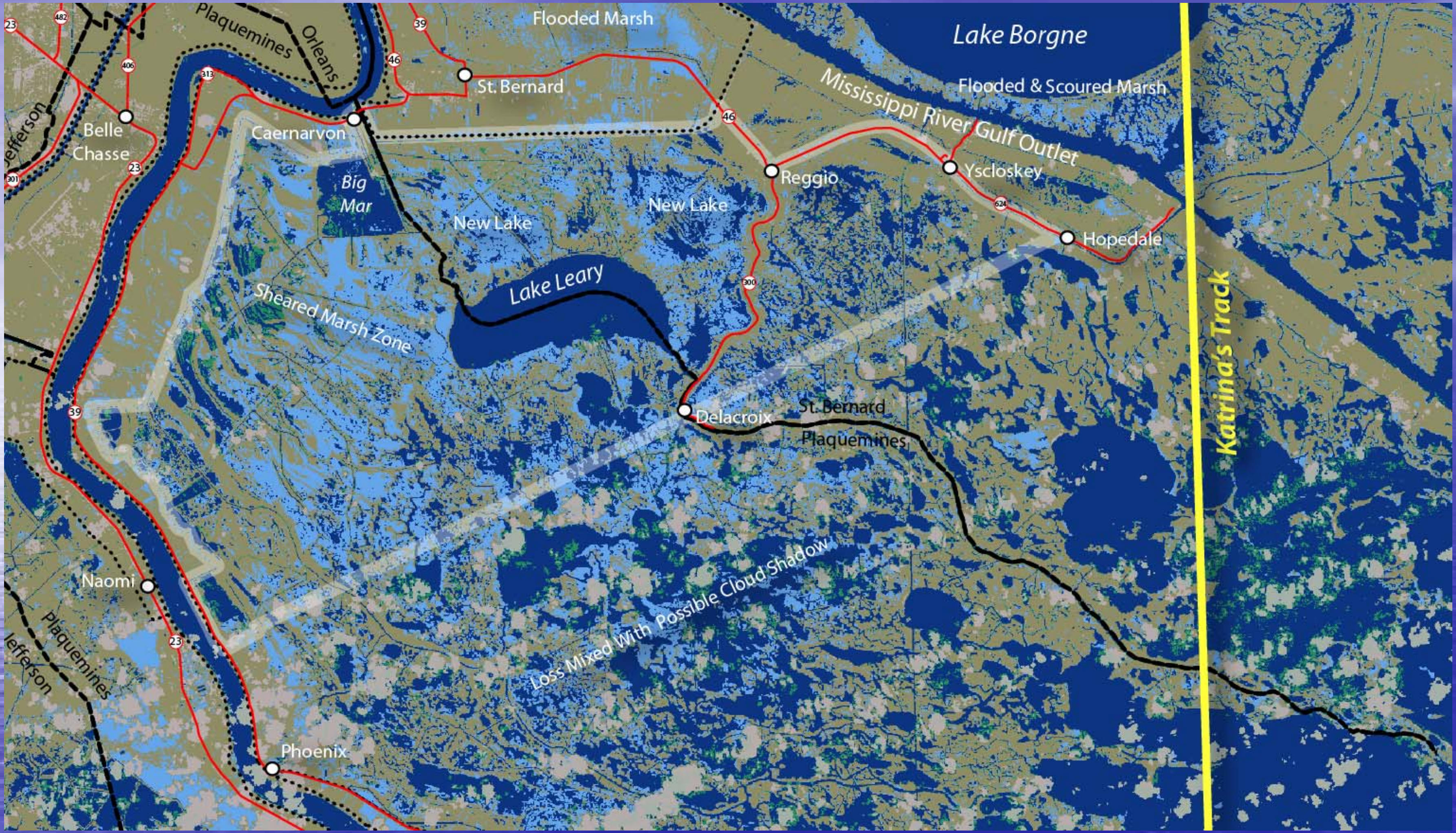
Cypress Swamp die-off

The entire delta is slowly subsiding. If new sources of sediment do not replenish the swamp, the young cypress shoots cannot germinate in water > 2 feet deep; and Cypress forests die off all at once, becoming a treeless, grassy marsh, with a forest of dead tree trunks.

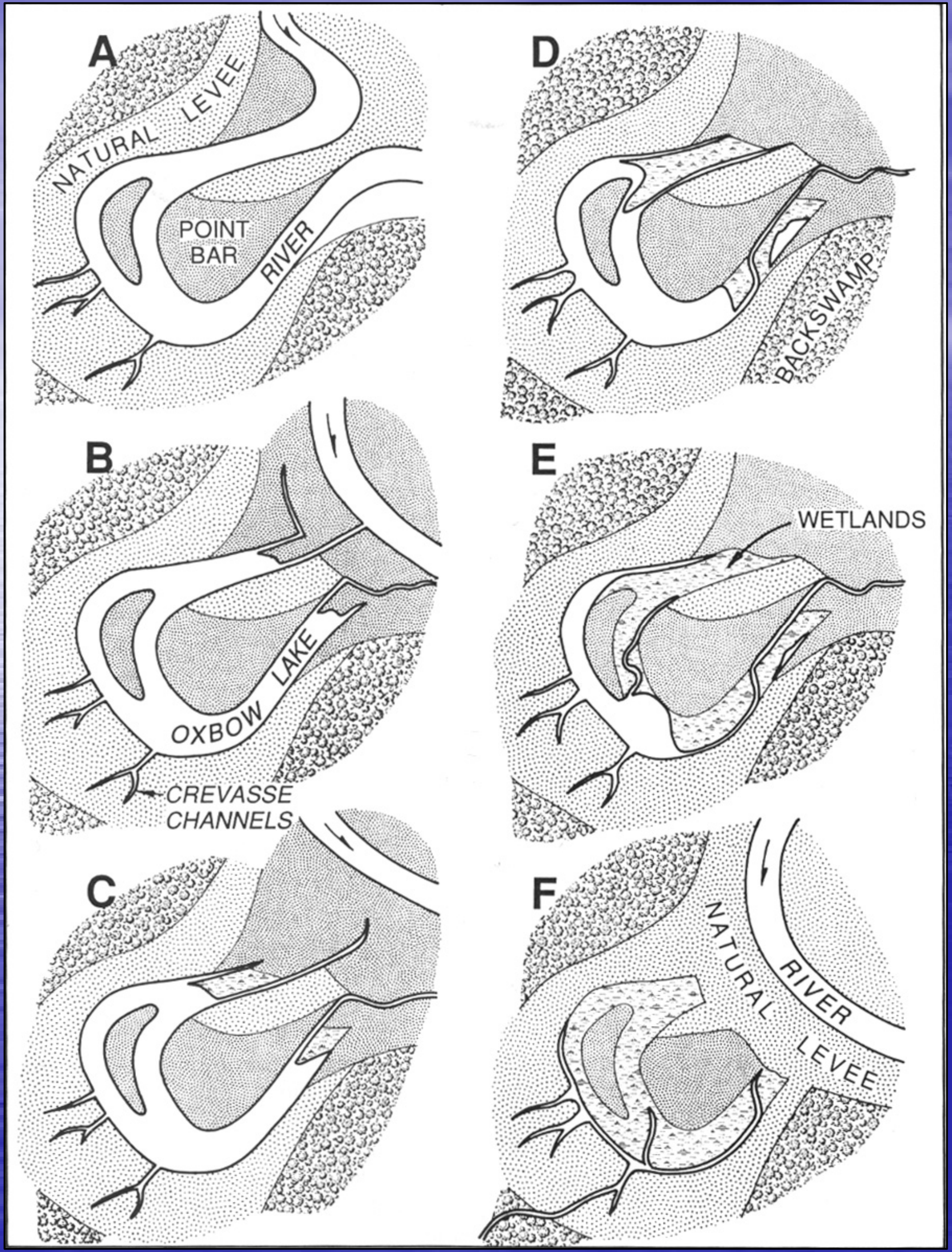
MARSH DEPOSITS OFTEN OVERLIE THE DEAD CYPRESS SWAMPS

Marsh deposits are typified by fibrous peats; from three principal environments: Fresh water marshes; 2) floating marsh – roots and grass sitting on an ooze of fresh water (shown above); and 3) saltwater marshes along the coast. The New Orleans marsh tends to be grassy marsh on a flat area that is "building down", underlain by soft organic clays. Note: smectite clays flocculate during brackish water intrusions.

- **Acute wind shear from Hurricane Katrina stripped off large tracts of floating marsh across the Mississippi Delta (from USGS).** ***How can we construct sustainable levees on these kinds of materials?***



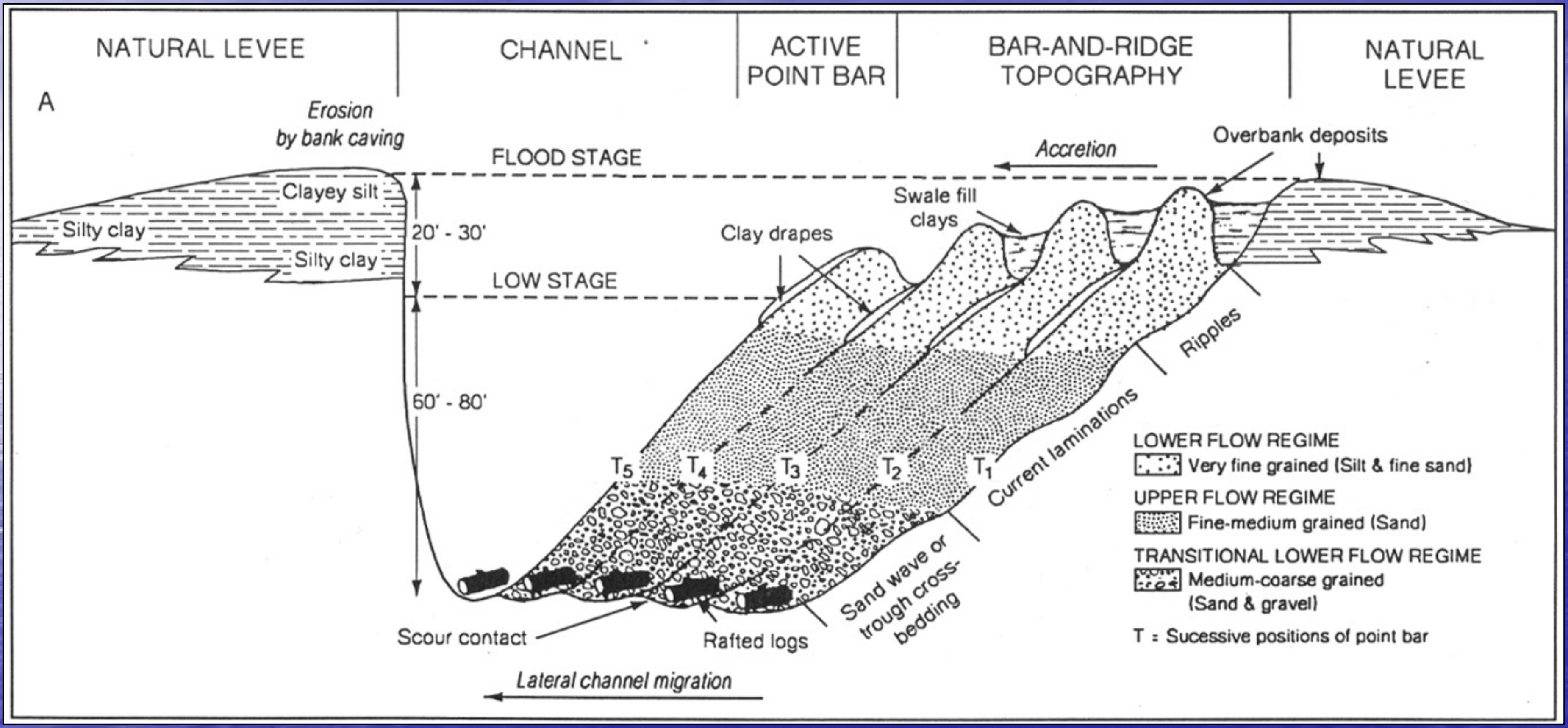
- **"Land loss" in Breton Sound (shown in light blue) after Hurricanes Katrina and Rita in 2005 (from USGS-NWRC).**



Dangers of linearly interpolated stratigraphic correlations

Abandoned meanders result in complex mixtures of channel sands, fat clay, lean clay, fibrous peat, and cypress swamp muck, which can be nearly impossible to correlate ***linearly*** between boreholes.

Clay drapes and pockets

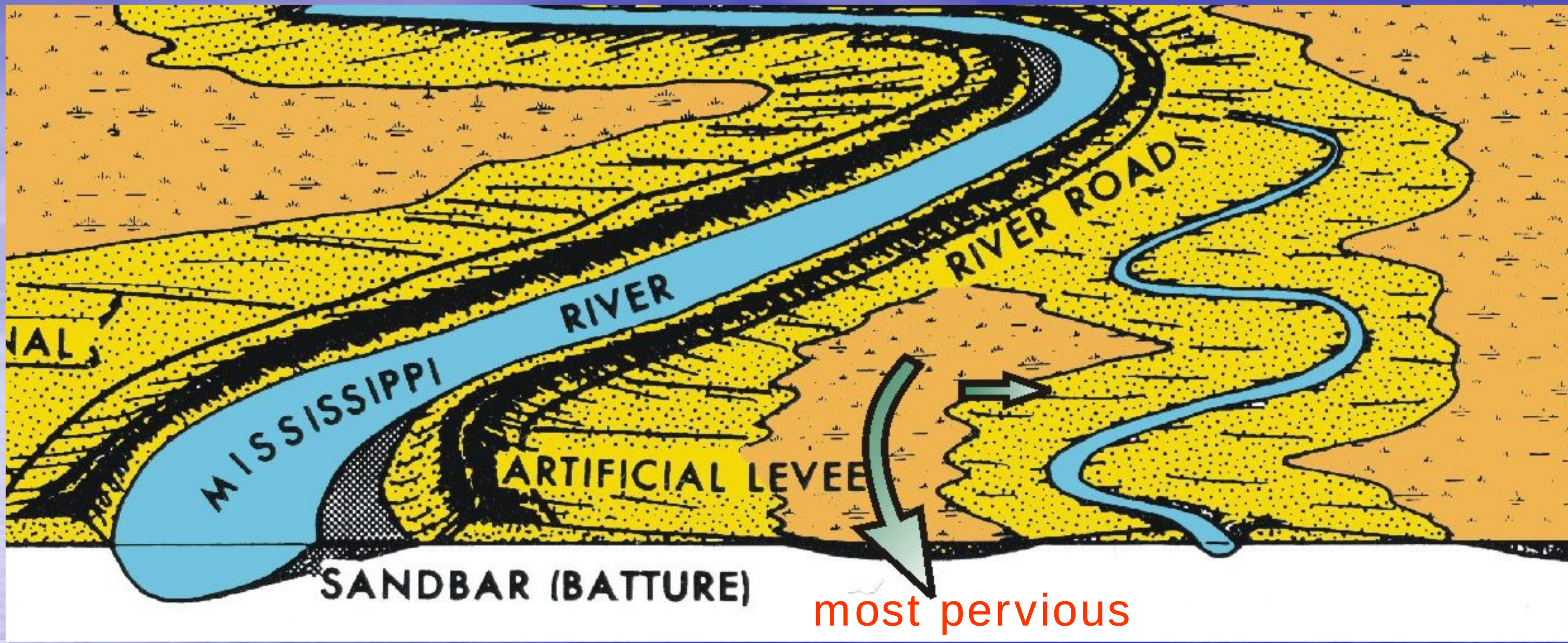


Example showing complex depositional relationships between units in a *distibutary meander belt*. Note discontinuous nature (from Saucier, 1994).

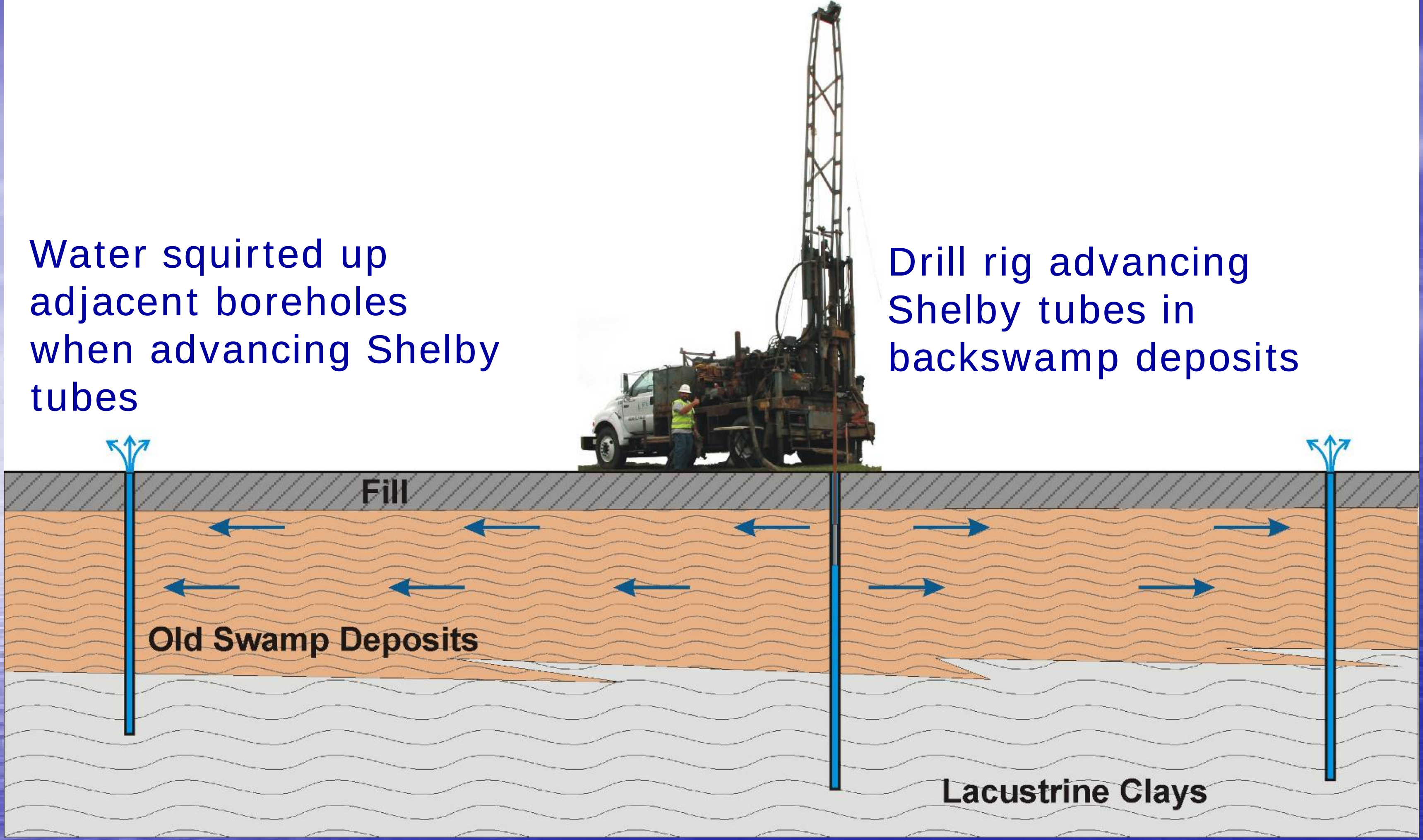
Depositional Environment Keys developed by the Corps of Engineers during the late 1950s

- Cypress wood = fresh water swamp
- Fibrous peaty mtls = marshes
- Fat Clays with organics; usually lacustrine. A pure fat clay has high w/c and consistency of peanut butter
- Interdistributary clays; paludal environments; lakes. Silt lenses when water shallow and wind swept waves
- Lean clays CL LL<50, silty and w/c <60%
- Fat clays CH LL>50 no silt and w/c >70%

Geotechnical Problems Characterizing Levee Foundations for Engineering Analyses

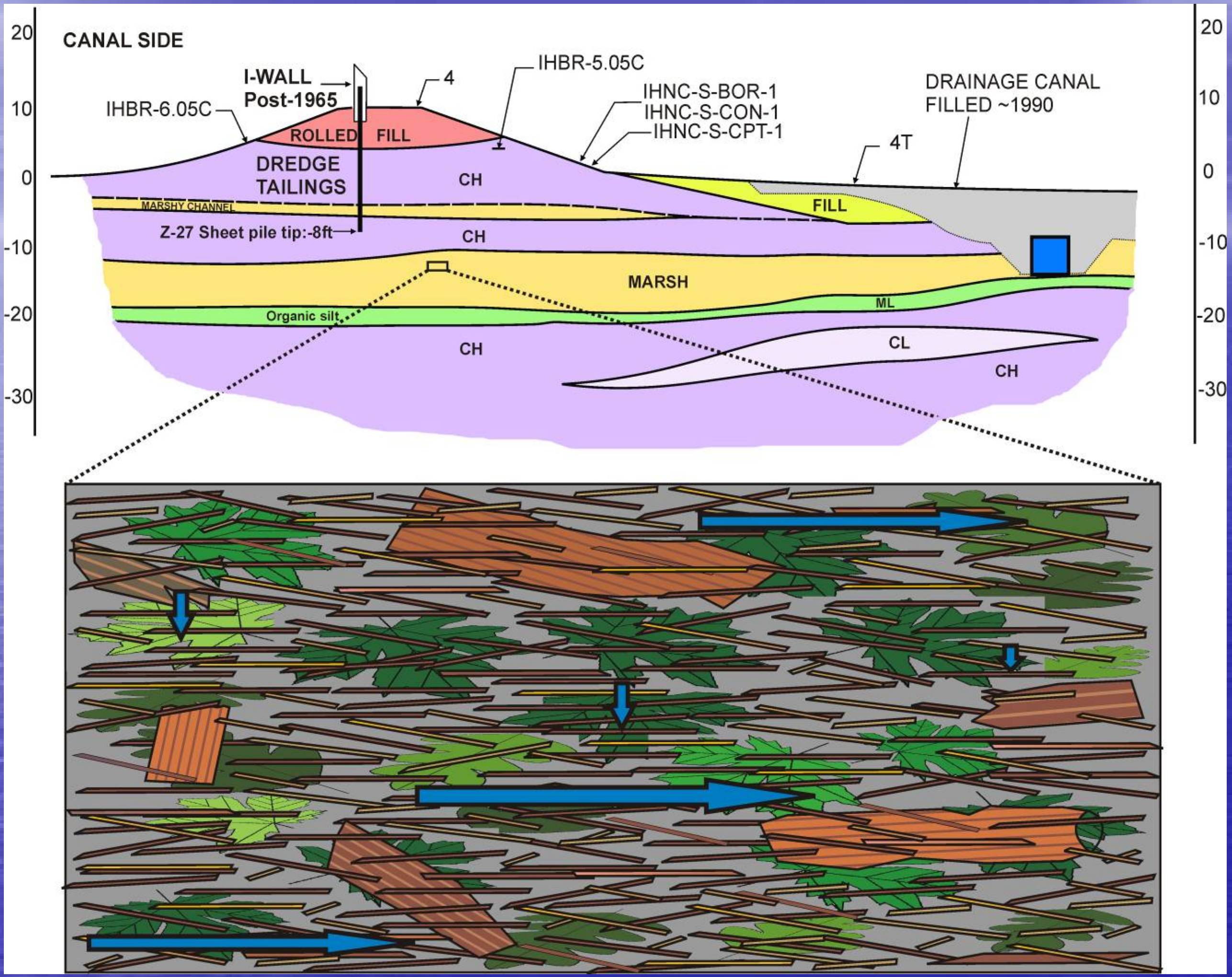


- **Backswamp swales are subject to sieving of fines by occasional higher velocity runoff**
- **This causes *hydraulic conductivity to increase along the runoff path*, as opposed to other seepage paths, within the plane of sedimentation**

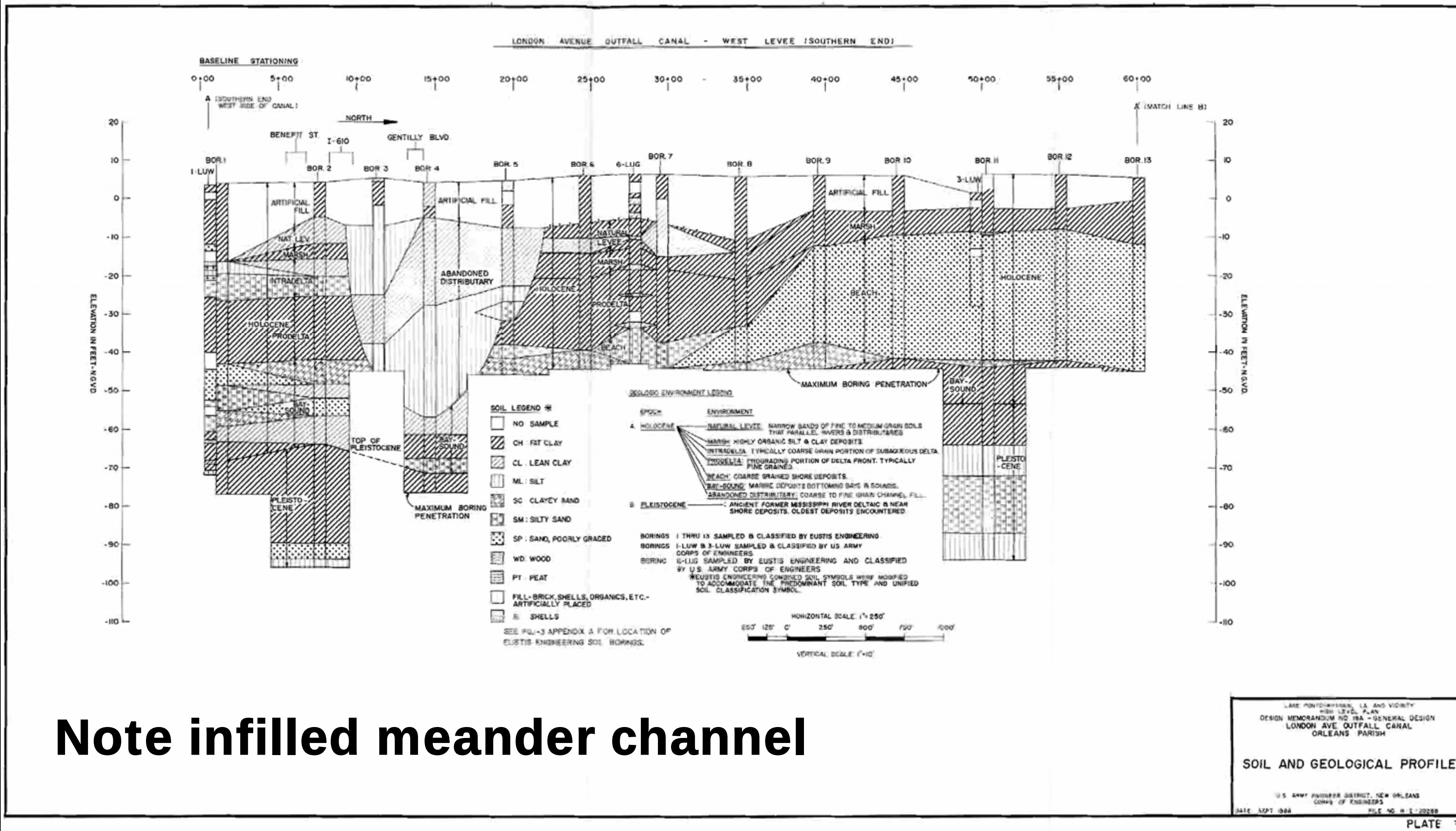


- The porous and highly conductive nature of the backswamp deposits was revealed during post-Katrina drilling and sampling operations.
- Highly conductive in horizontal plane

Anisotropy of backswamp deposits

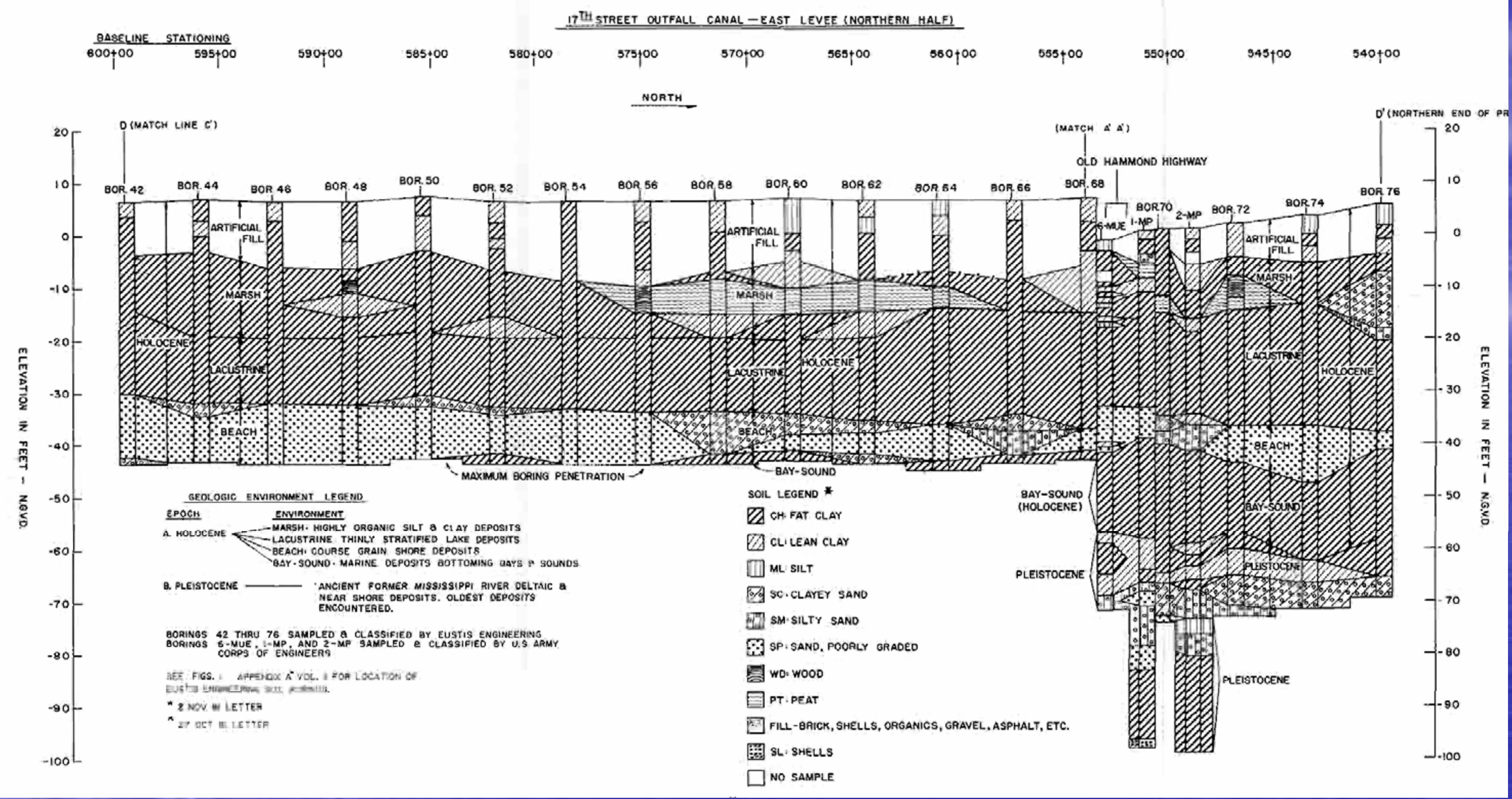


- **Sudden die-off of organics creates highly anisotropic fabric; *preferentially layered***



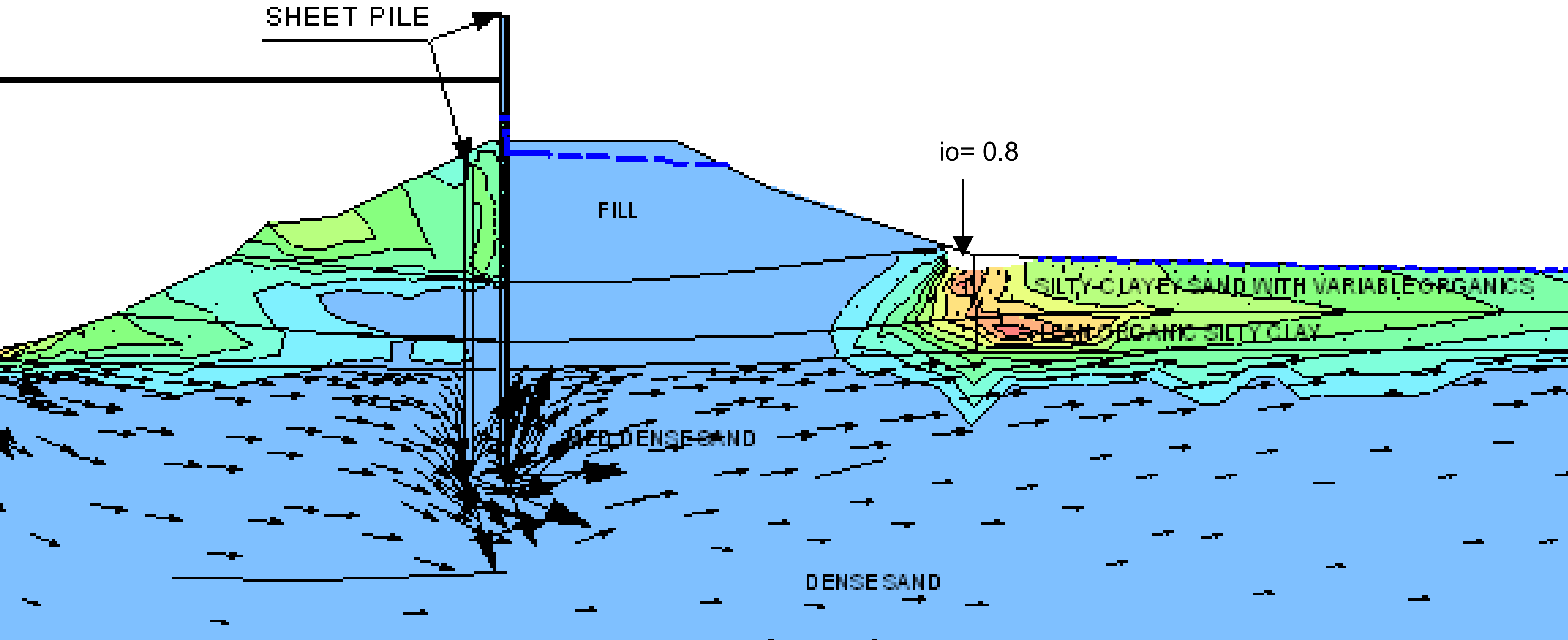
Note infilled meander channel

Geologic section along middle reach of the 17th St. Canal. Note filled meander channel over 50 feet deep.

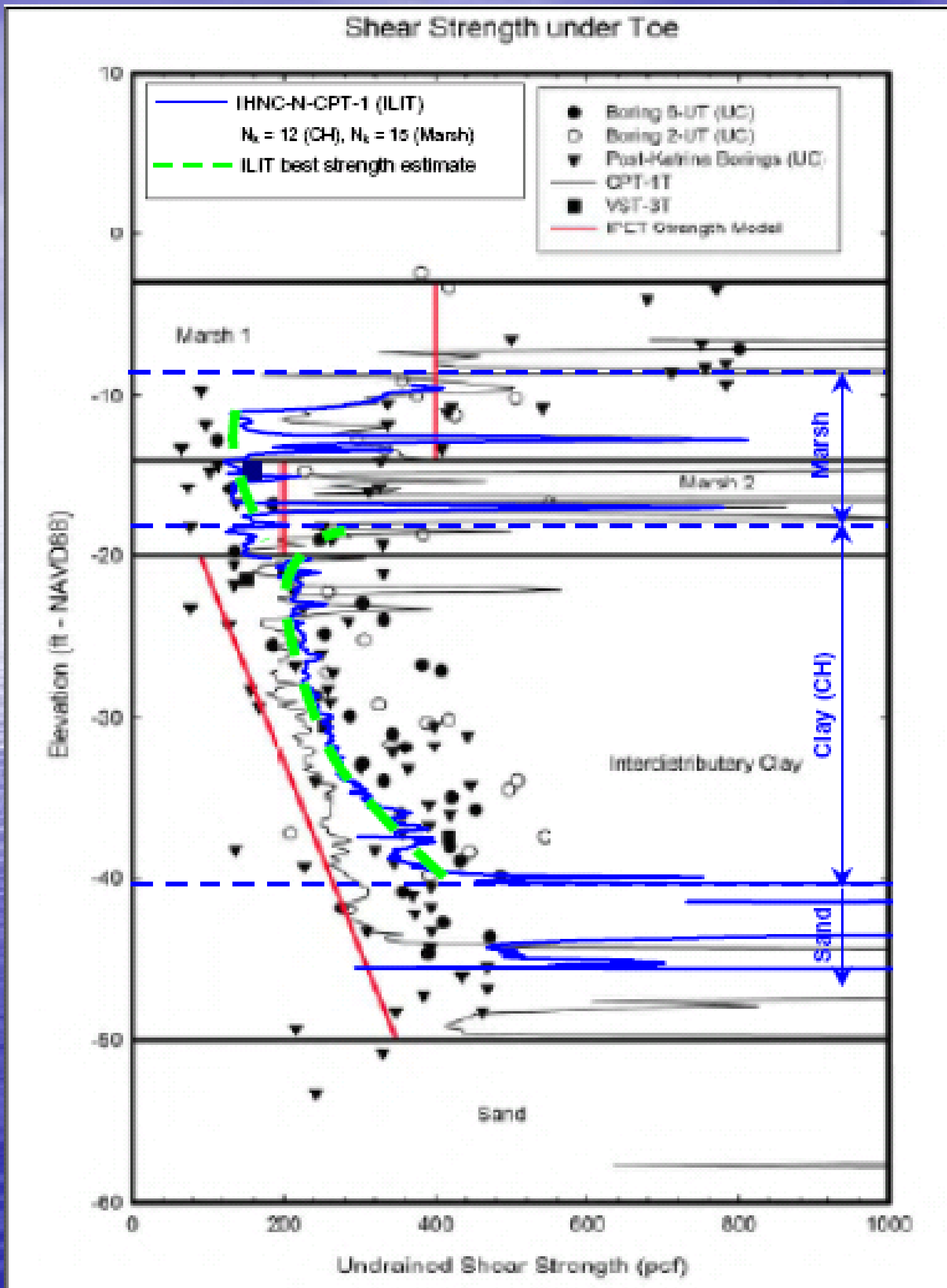


Geologic profile for the 17th St Canal flood wall prepared by Corps' New Orleans District office in 1990. Three of four holes in vicinity of the 2005 failure (spaced 500 ft apart) had zero sample recovery. These contacts were projected and the sheet pile tips designed, accordingly.

Pervious foundation materials most at risk - London Avenue Canal (South Breach)



Very little reliable data exists on horizontal hydraulic conductivity of foundation soils in the Mississippi Delta



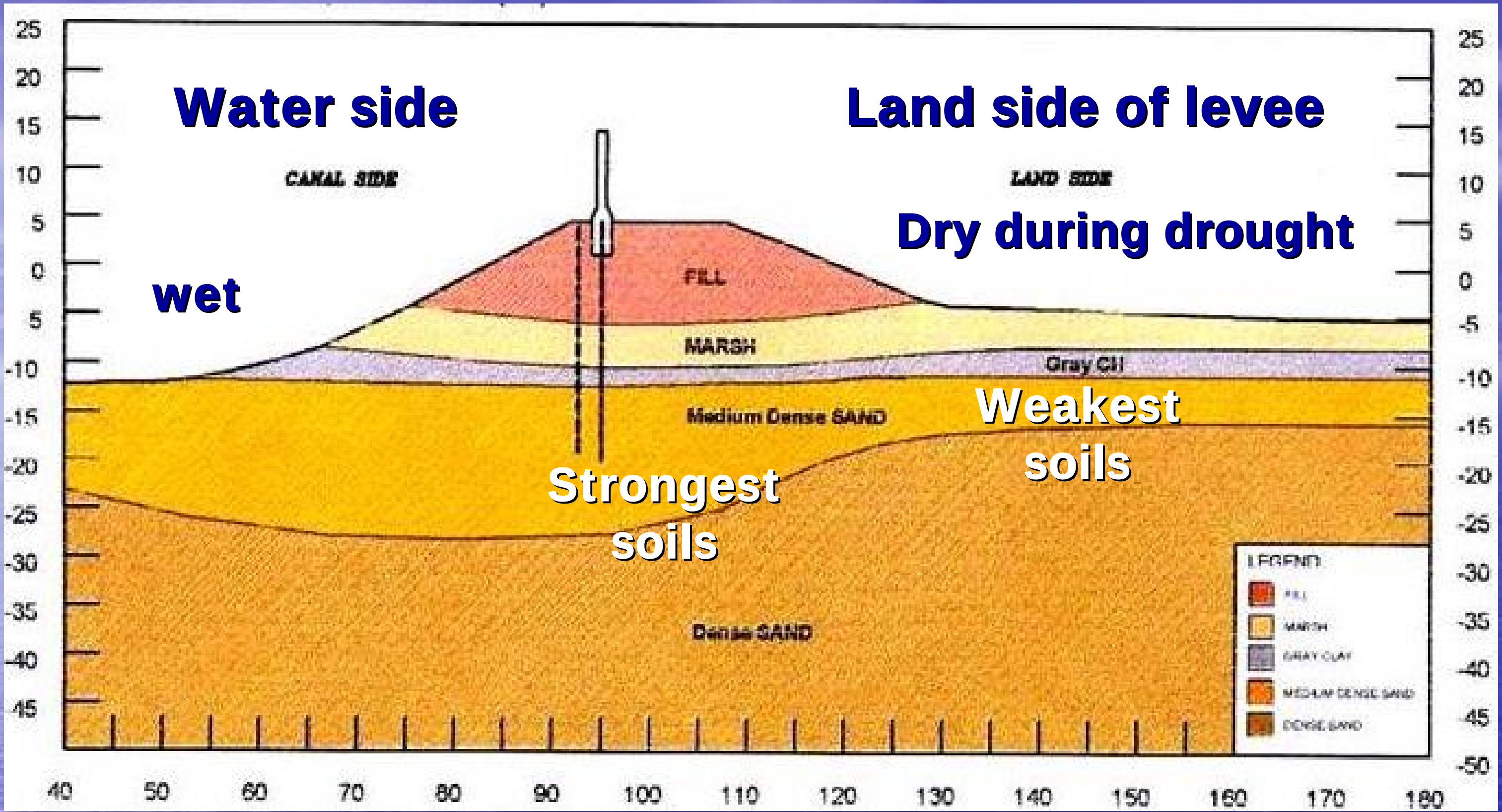
Which soil shear strength should we use?

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

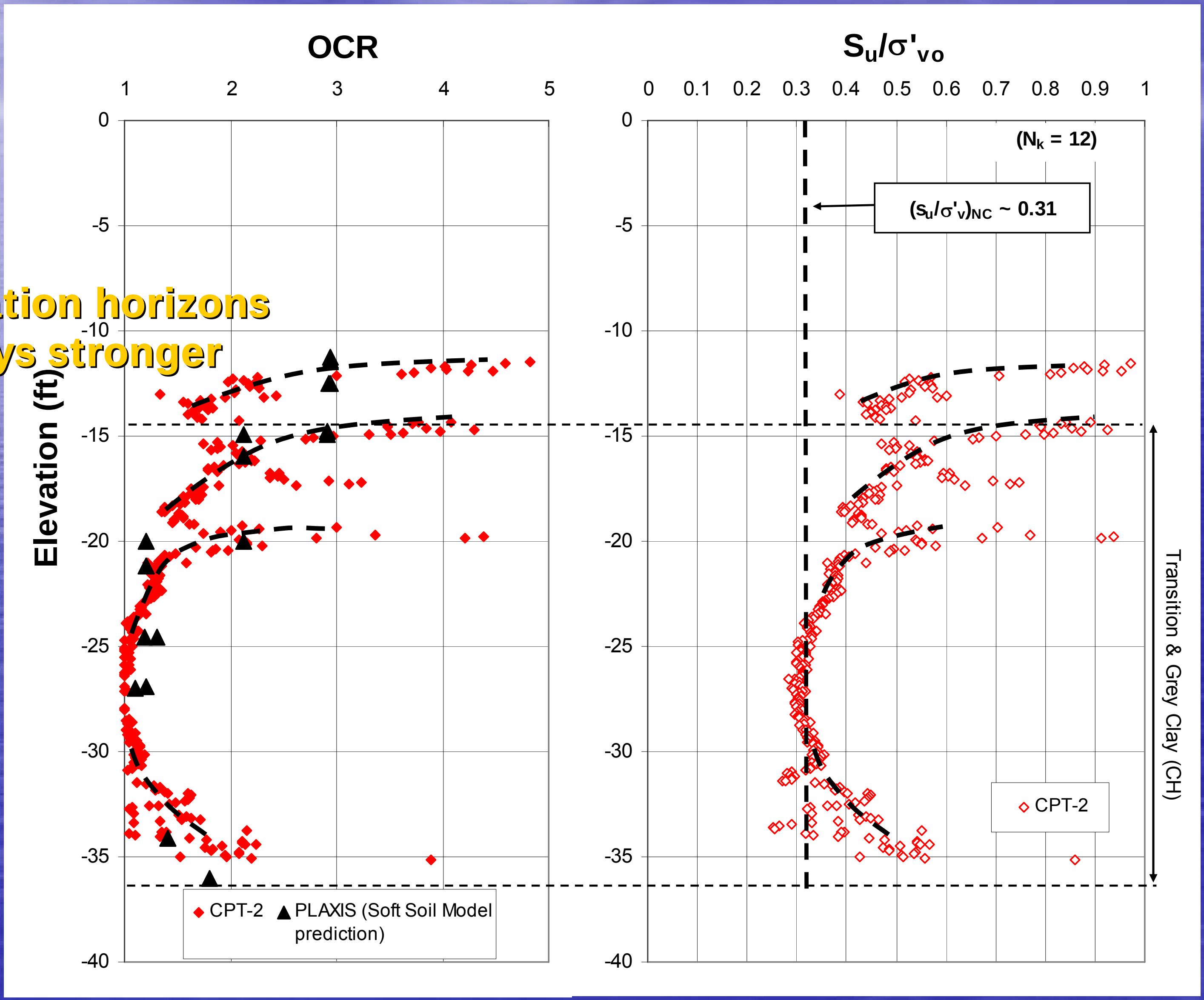
Green line shows strength profile selected by the NSF team

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

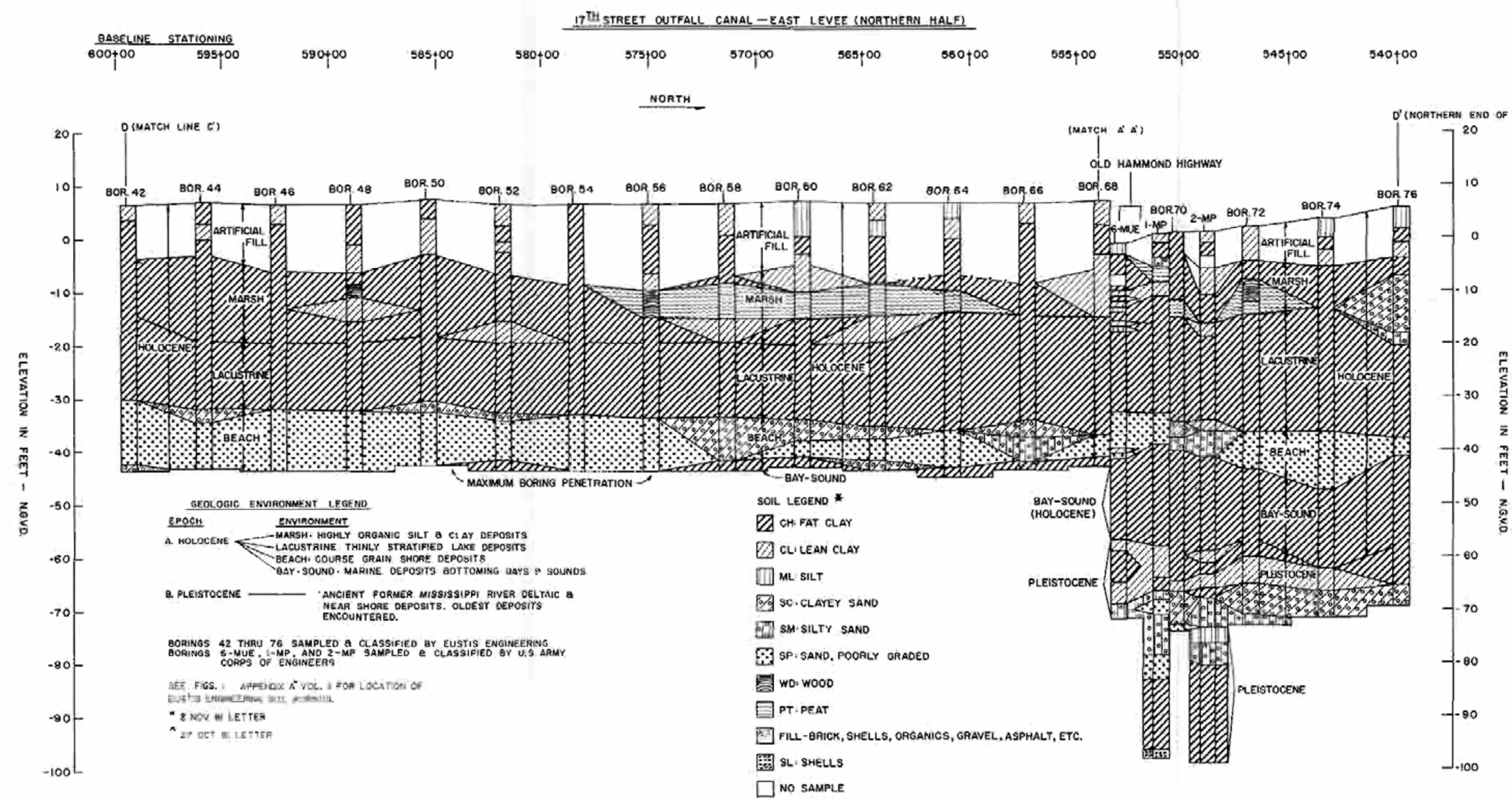


- **Impact of dead load, or the Su versus p' factor.** **The strength of clayey soils increases with increasing confinement created by placement of the earthen dike on natural soils.**
- ***Soil is always strongest beneath centerline of levee*****, where most boreholes get drilled; but weakest beneath flanks. Also dry vs wet side factors.**

17th Street Canal: Soft Gray Clay (CH)
Desiccation Horizons Beneath Levee Toe



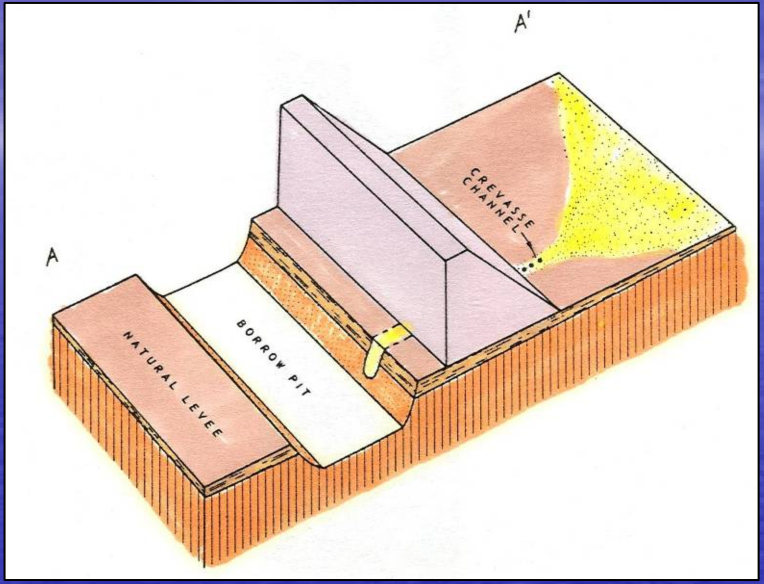
Desiccation horizons always stronger



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 <u>zero sample recovery</u>. These contacts were projected and the sheet pile tips designed, accordingly.

Most Common Levee Failure Mechanisms

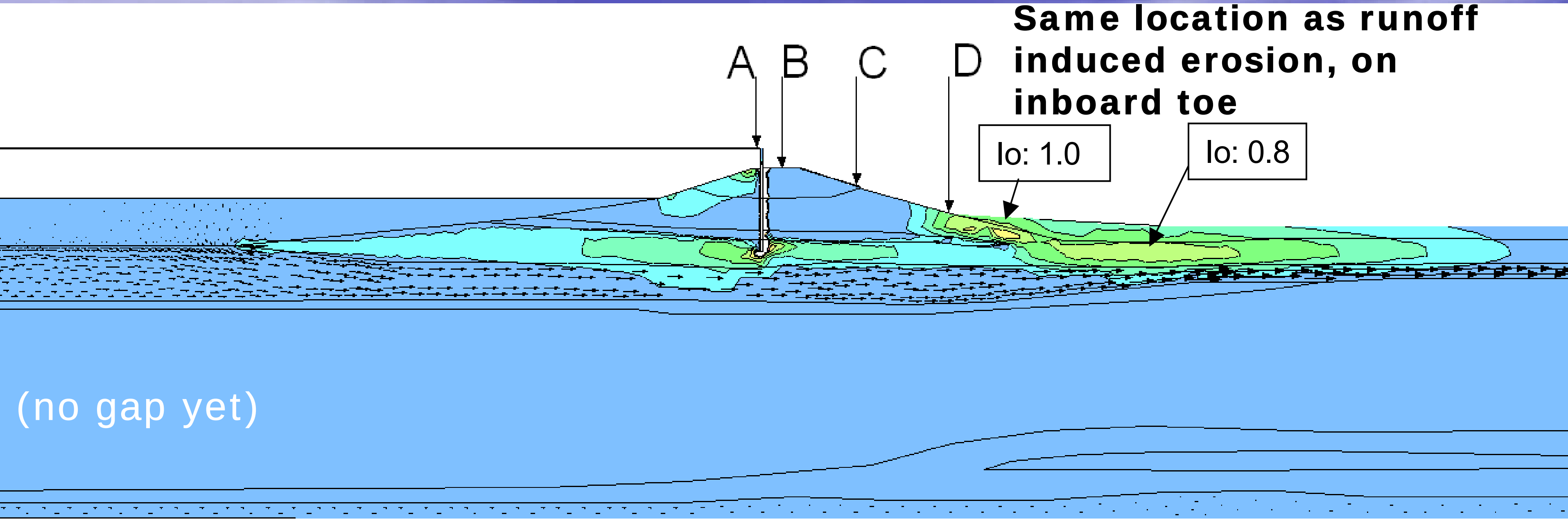
Natural crevasse splays



Crevasses are sand filled distributary channels that form at high flow, and lie beneath earthen levees like ticking time bombs, waiting to explode.

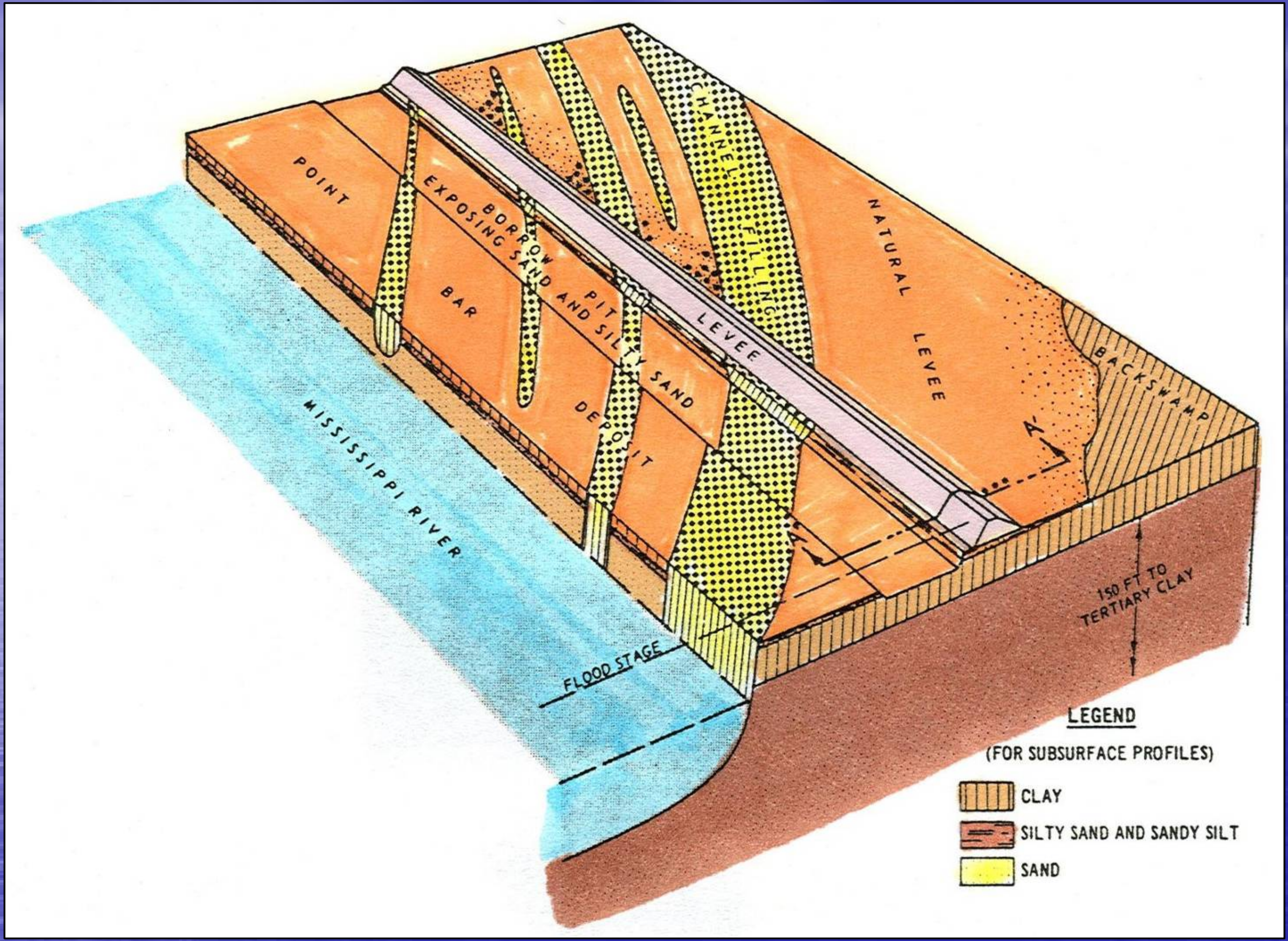
Seepage crevasse exposed at the east levee of the IHNC breach after Hurricanes Katrina and Rita

Hydraulic gradients for piping and uplift

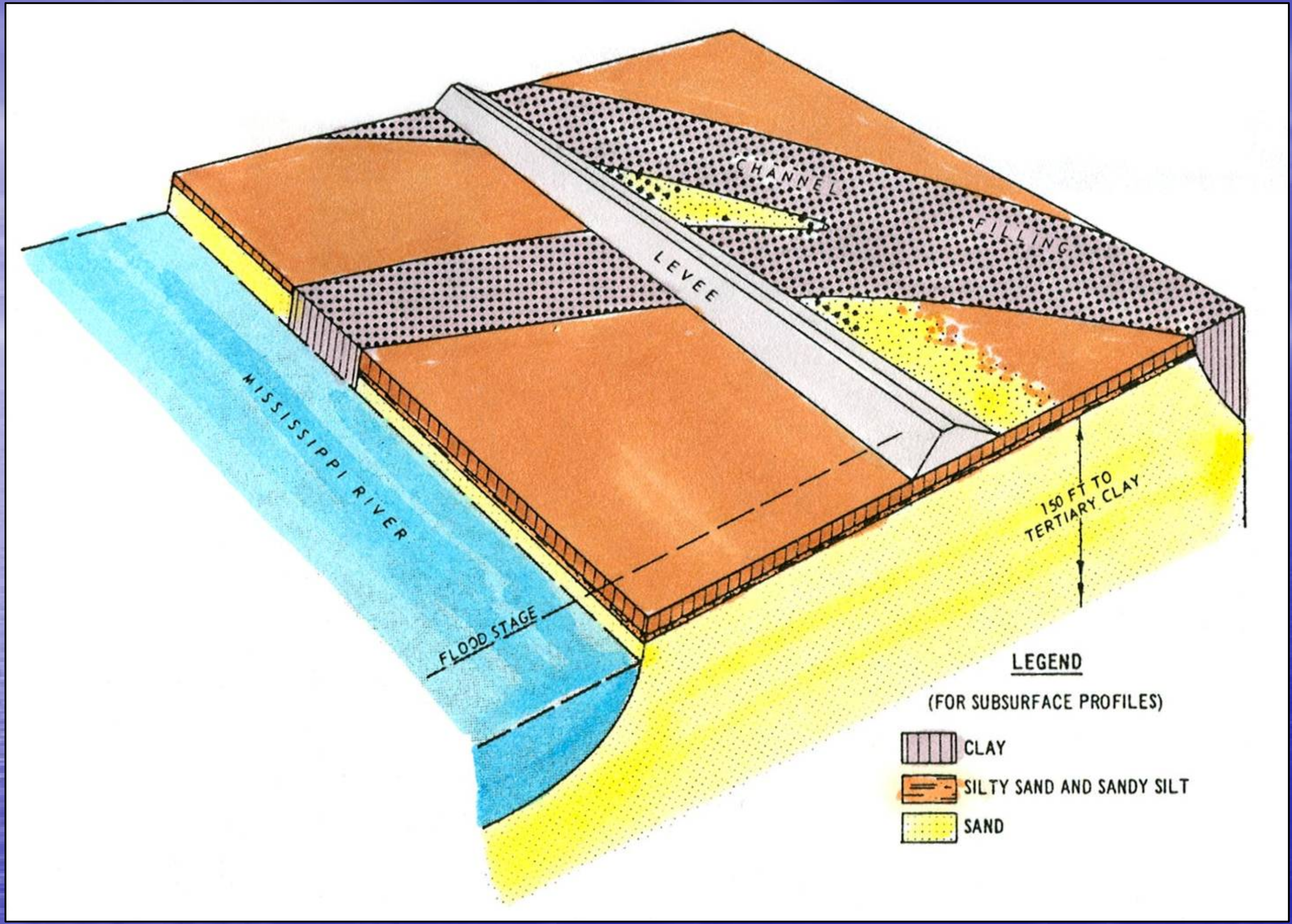


- **Hydraulic gradients for the south breach on IHNC east bank; storm surge at 14.4ft (MSL). Maximum exit gradient at the levee toe is $i_o \approx 0.8$ to 1.0, at threshold for hydraulic piping.**

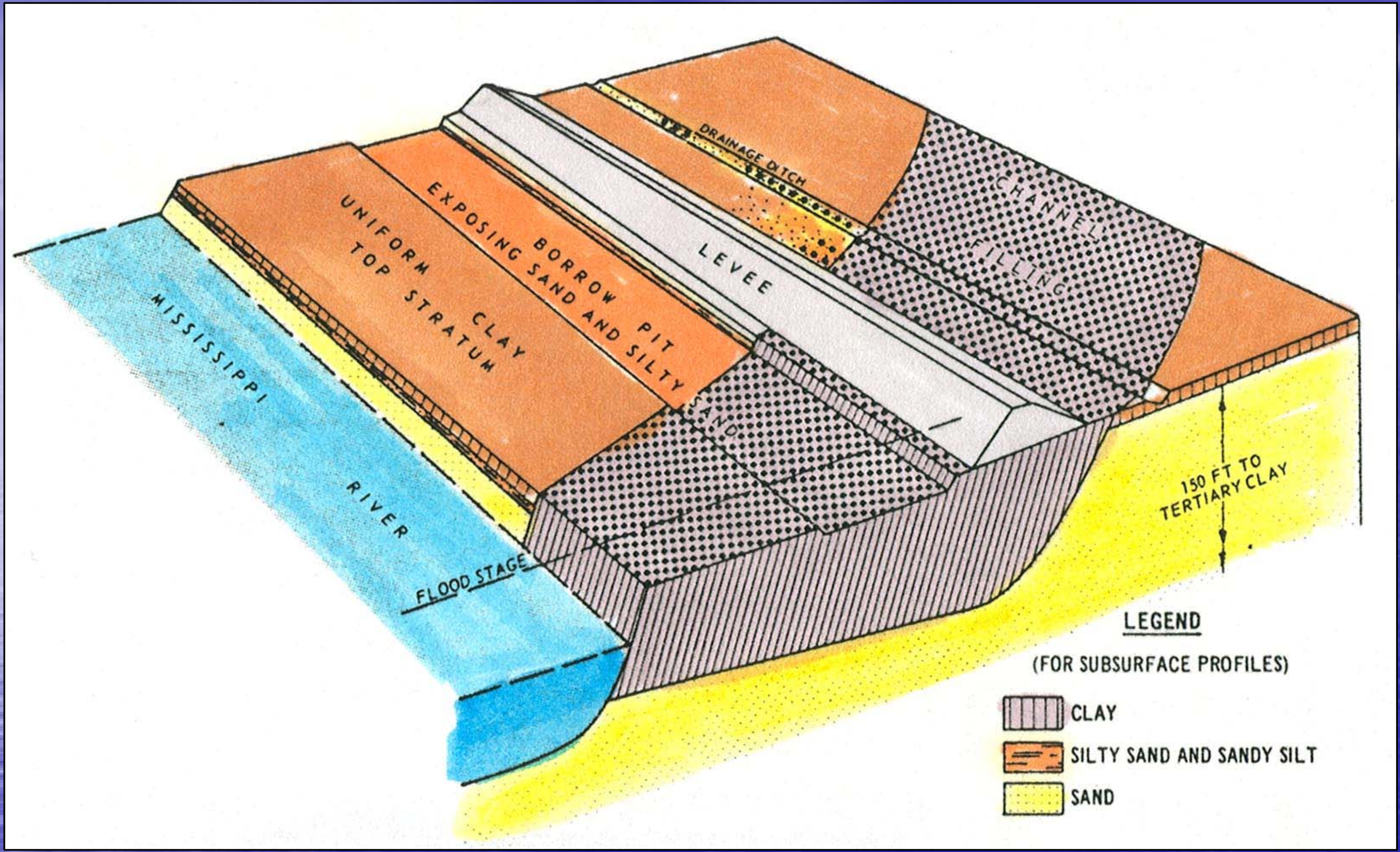
- **This may help to explain the persistent wet spot noted on the backfill of the Jourdan Avenue conduit backfill for weeks afterward.**



- **Permeability contrasts** caused by clay filled oxbows create treacherous and contrasting foundation conditions beneath levees.



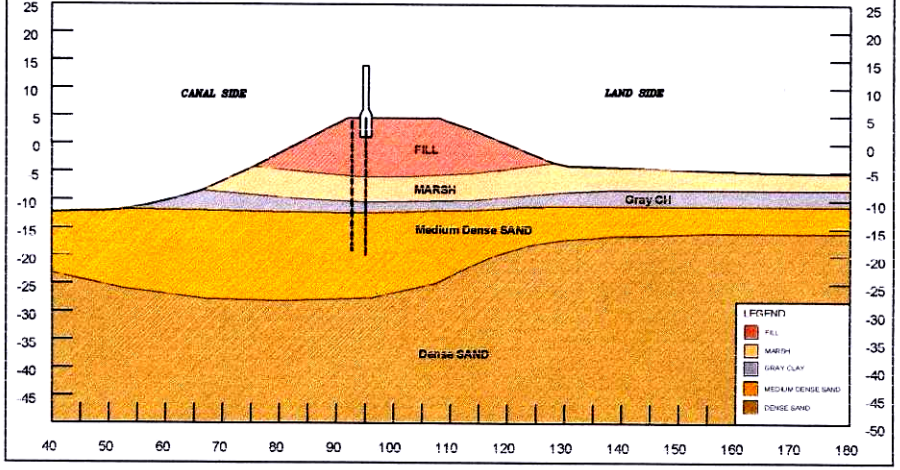
- **The worst combination of foundation conditions is the ‘gore point’ formed between two infilled oxbows, as shown here.**

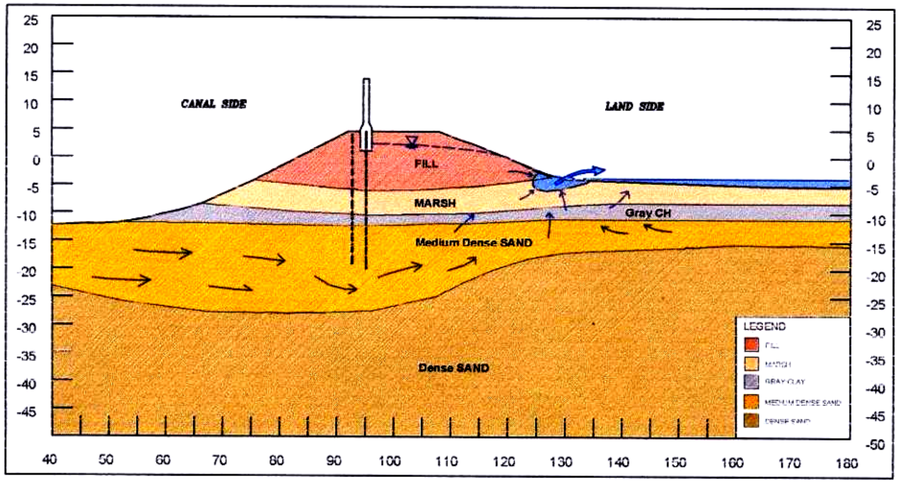


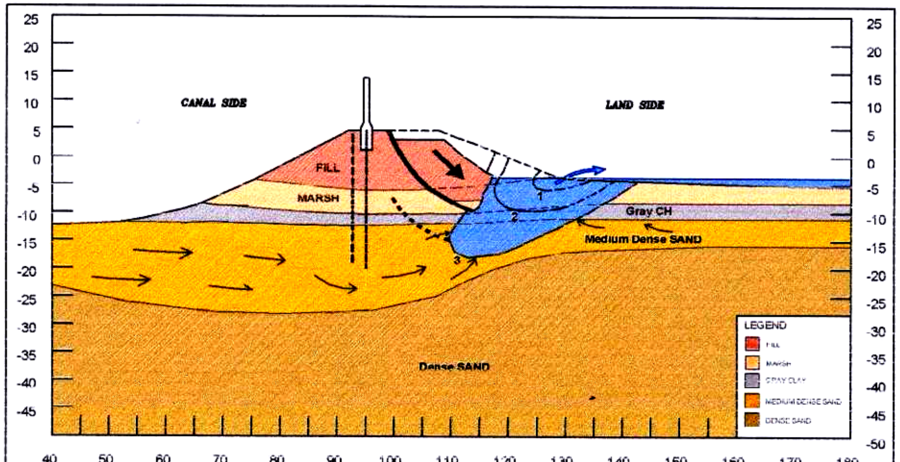
- Clay filled oxbows consolidate under the load imposed by the earthen levees, causing these levees to settle and sink.
- Differential settlement is a major obstacle in maintaining levees.

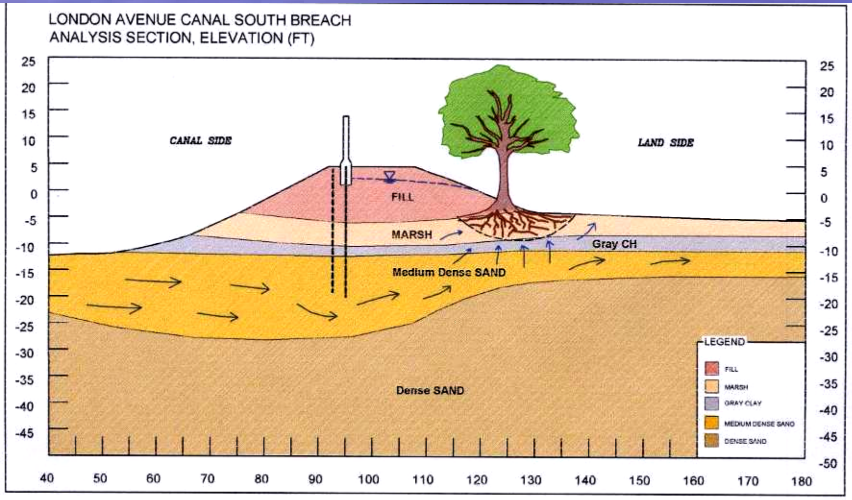

London Ave Canal – Filmore Breach
SEP 7 2005
Photo by Ivor van Heerden

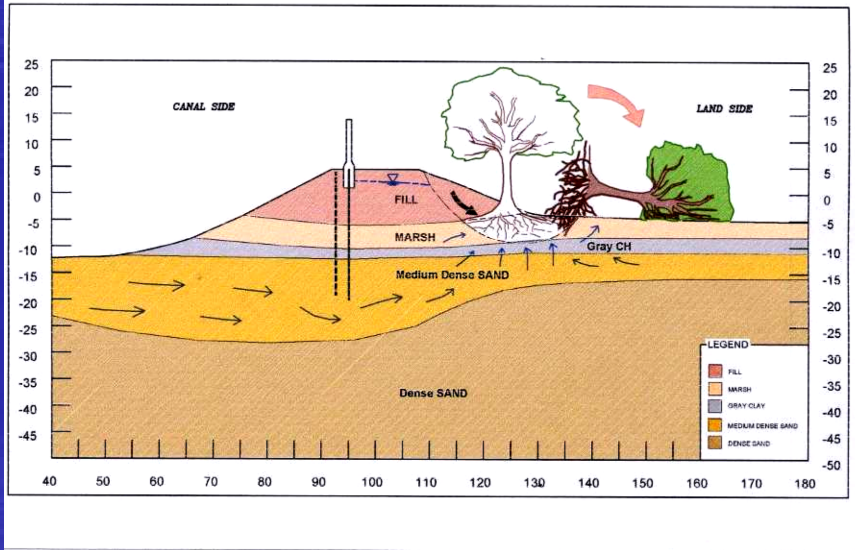
London Ave Canal South Breach precipitated by pervious sands



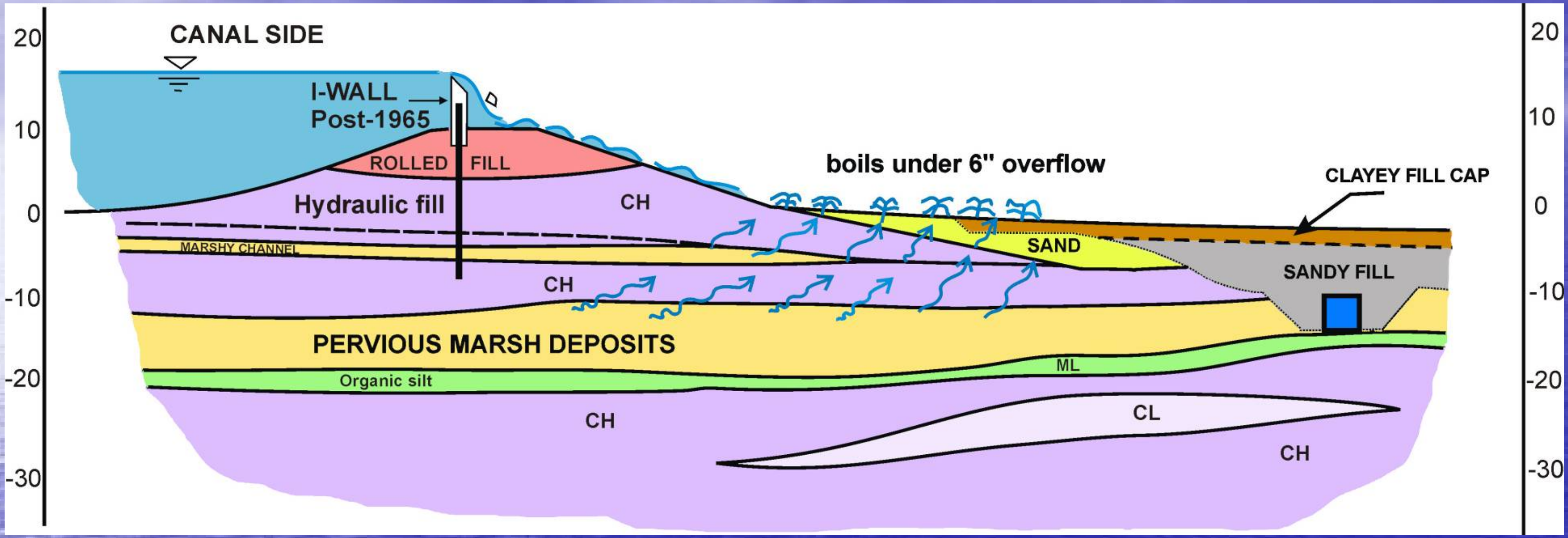






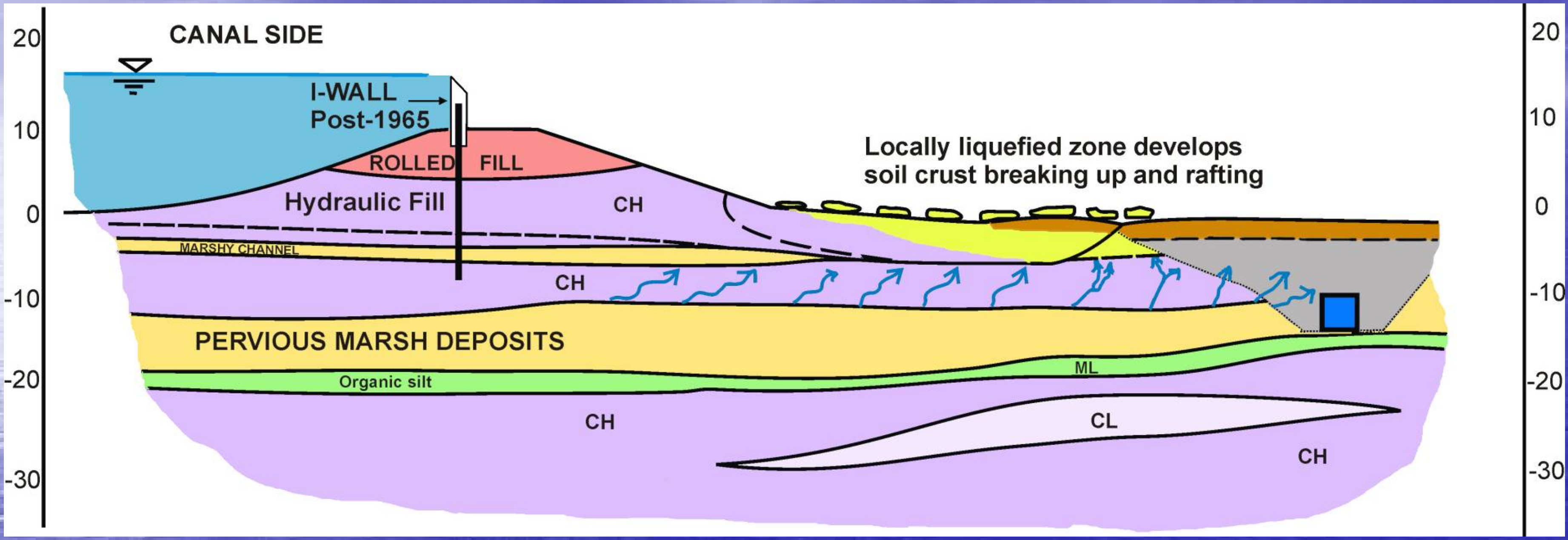


Compound Failure Modes



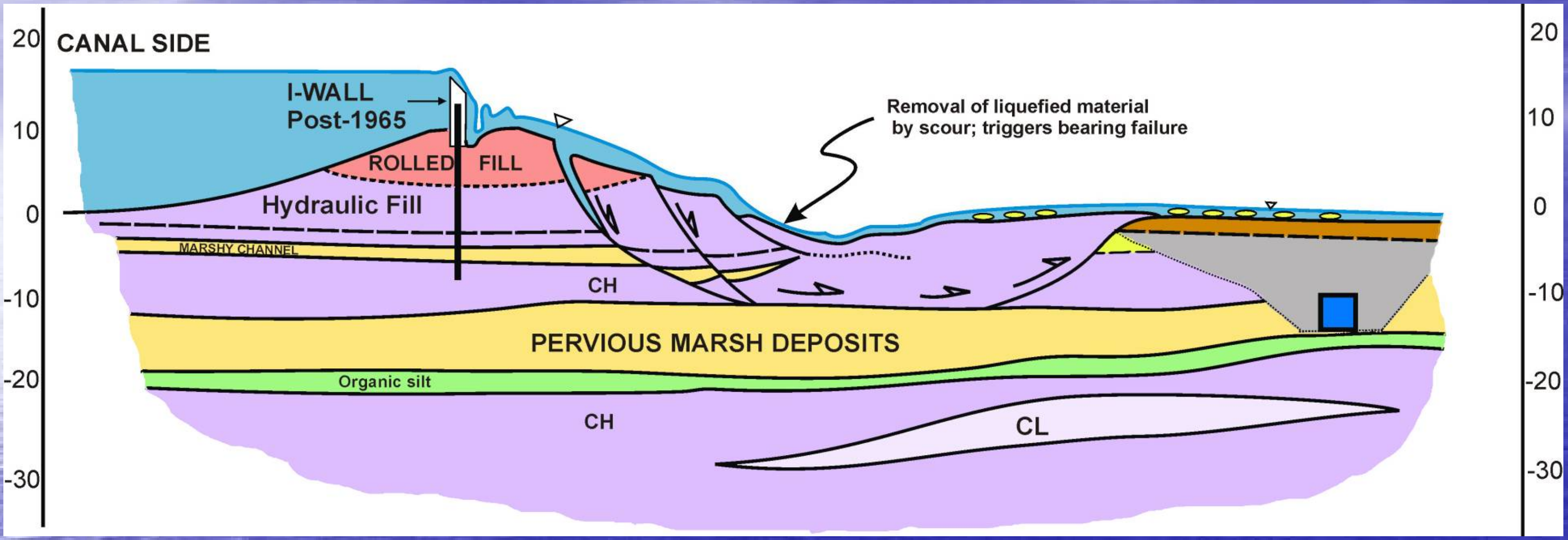
- The two biggest enemies of earthen levees are: 1) **underseepage** (pore water) pressures; and 2) **time** (flood duration).
- Overtopping often obscures seepage-driven levee foundation failures

Seepage-induced liquefaction



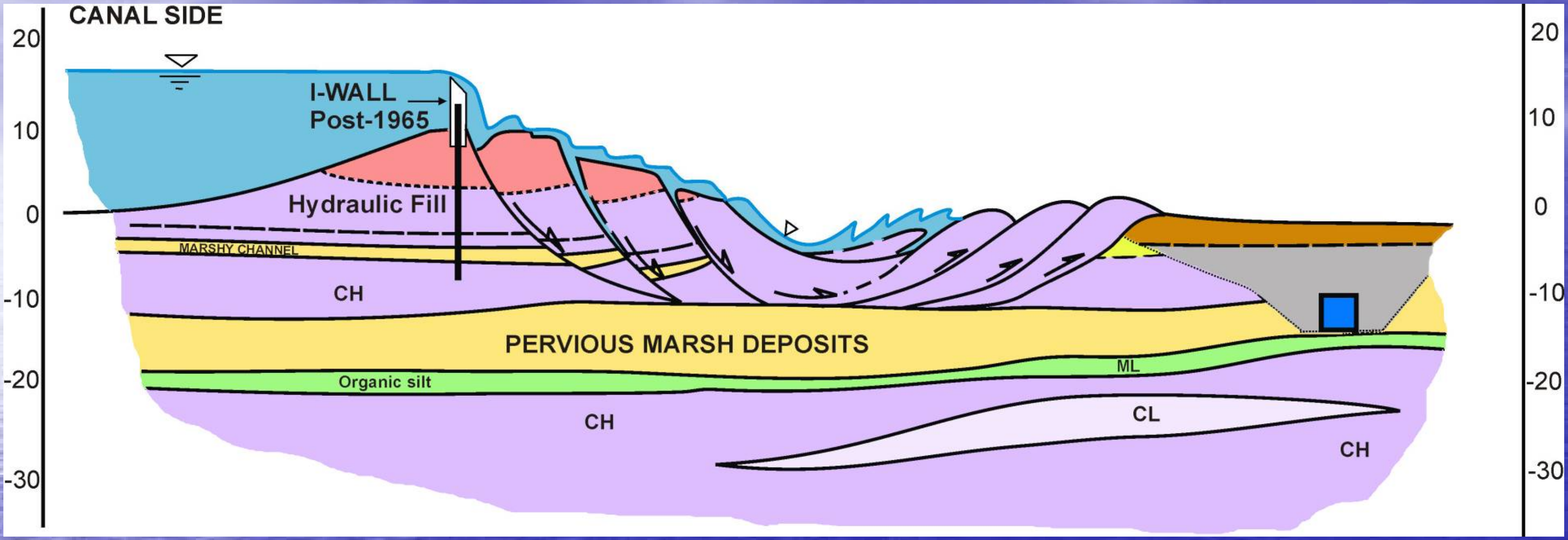
- If the hydraulic gradient exceeds 0.75, the foundation can begin to experience localized liquefaction – which is a failure mechanism common in cohessionless materials

Bearing Capacity Failure



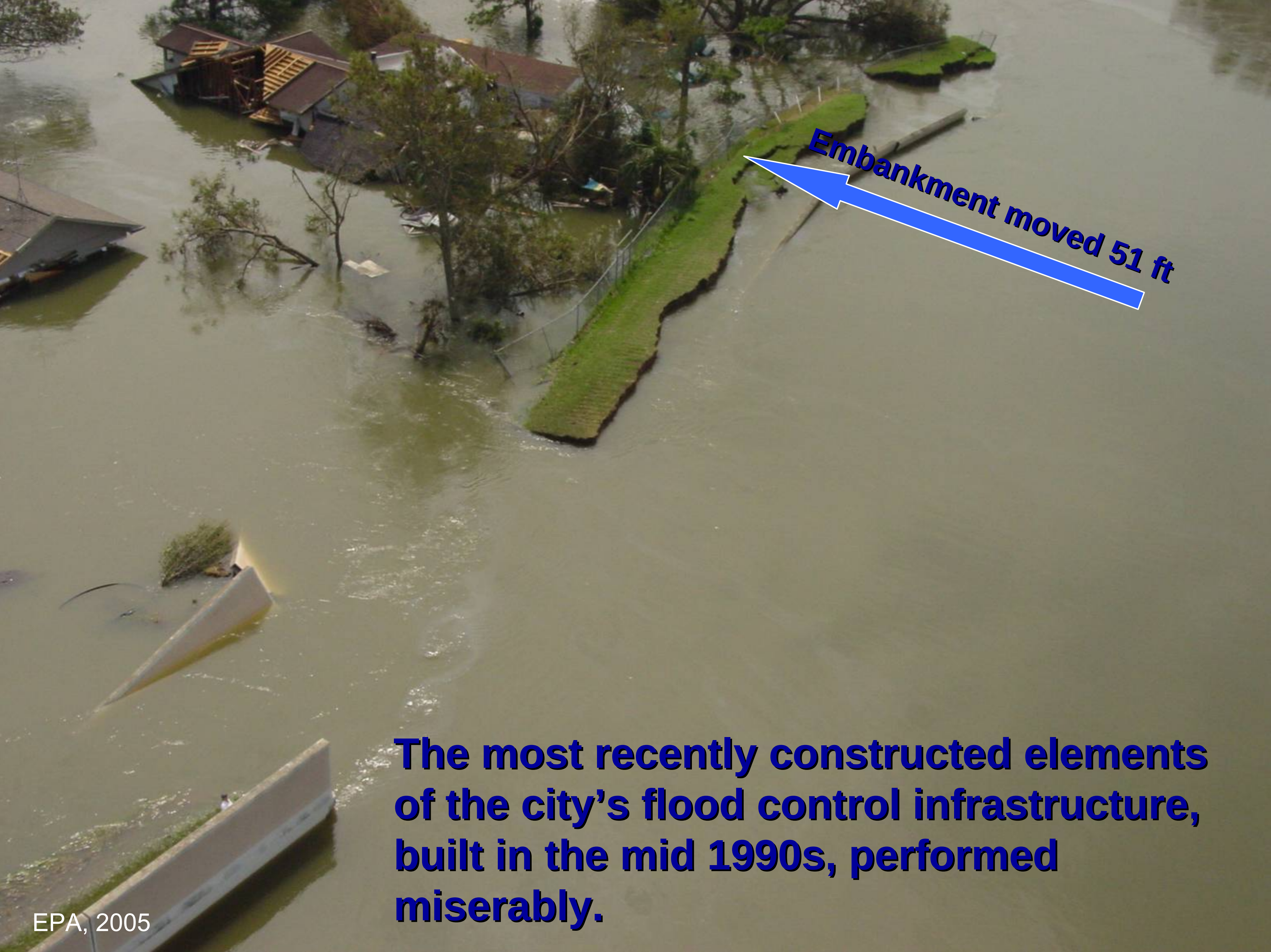
- The loss of soil shear strength in the levee's land side toe area can trigger a massive slope failure on the outboard side of the levee.

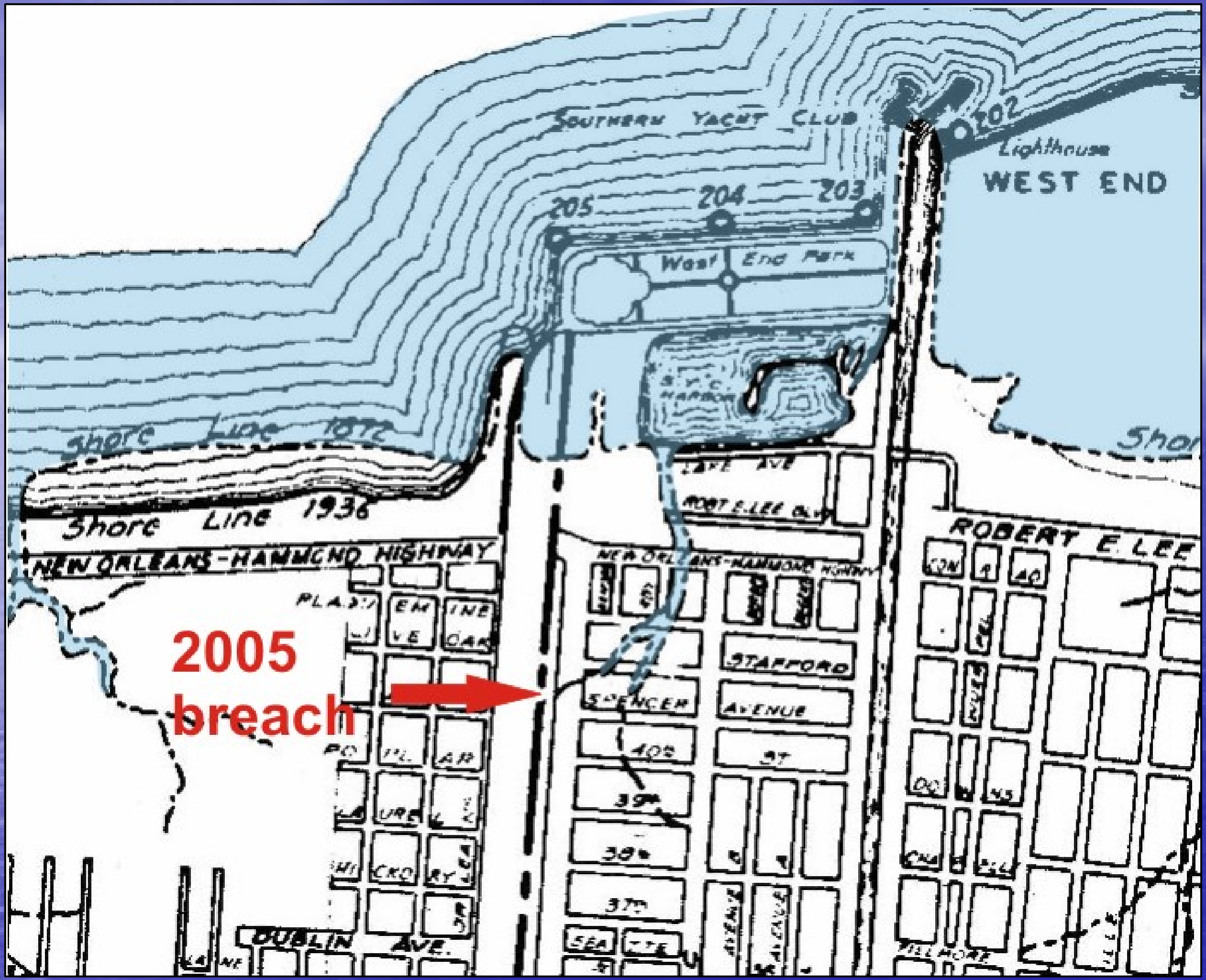
Retrogressive Slope Failure



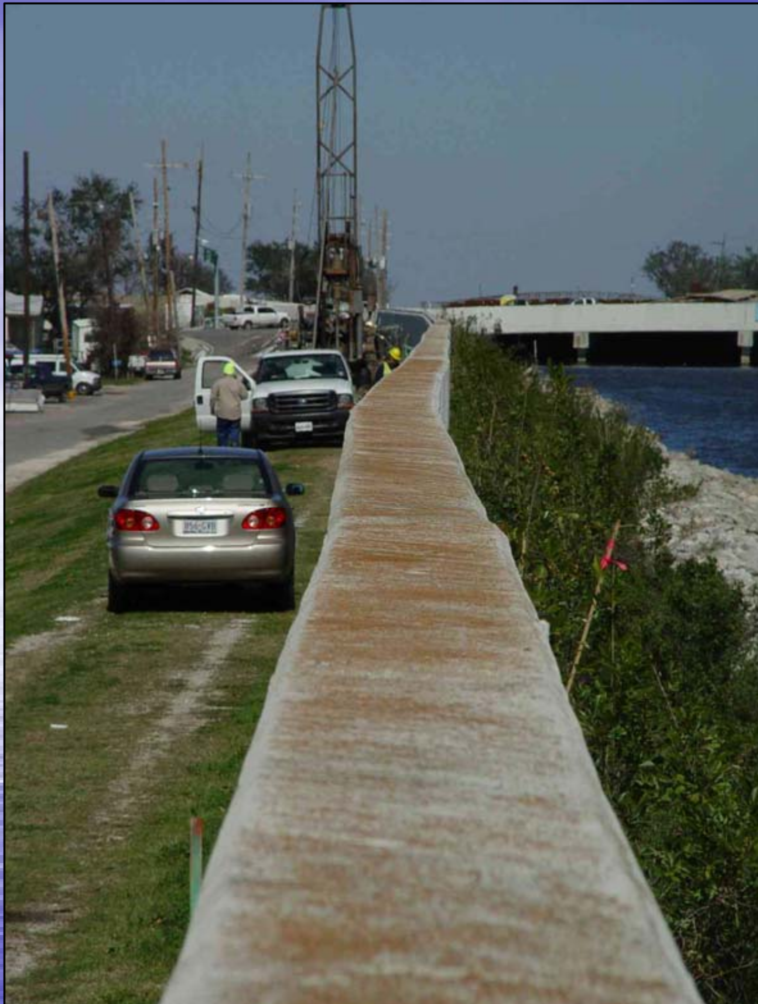
- The loss of foundation bearing capacity can trigger a series of retrogressive slope failures, as sketched here. Four critical mechanisms may occur more or less simultaneously. Analytical programs not currently set up to analyze concurrent failure modes.

- **Aerial oblique view of the 17th Street Canal break, looking east. Note lateral translation of concrete flood wall, between 35 and 50 ft.** **Photo by Ivor van Heerden.**

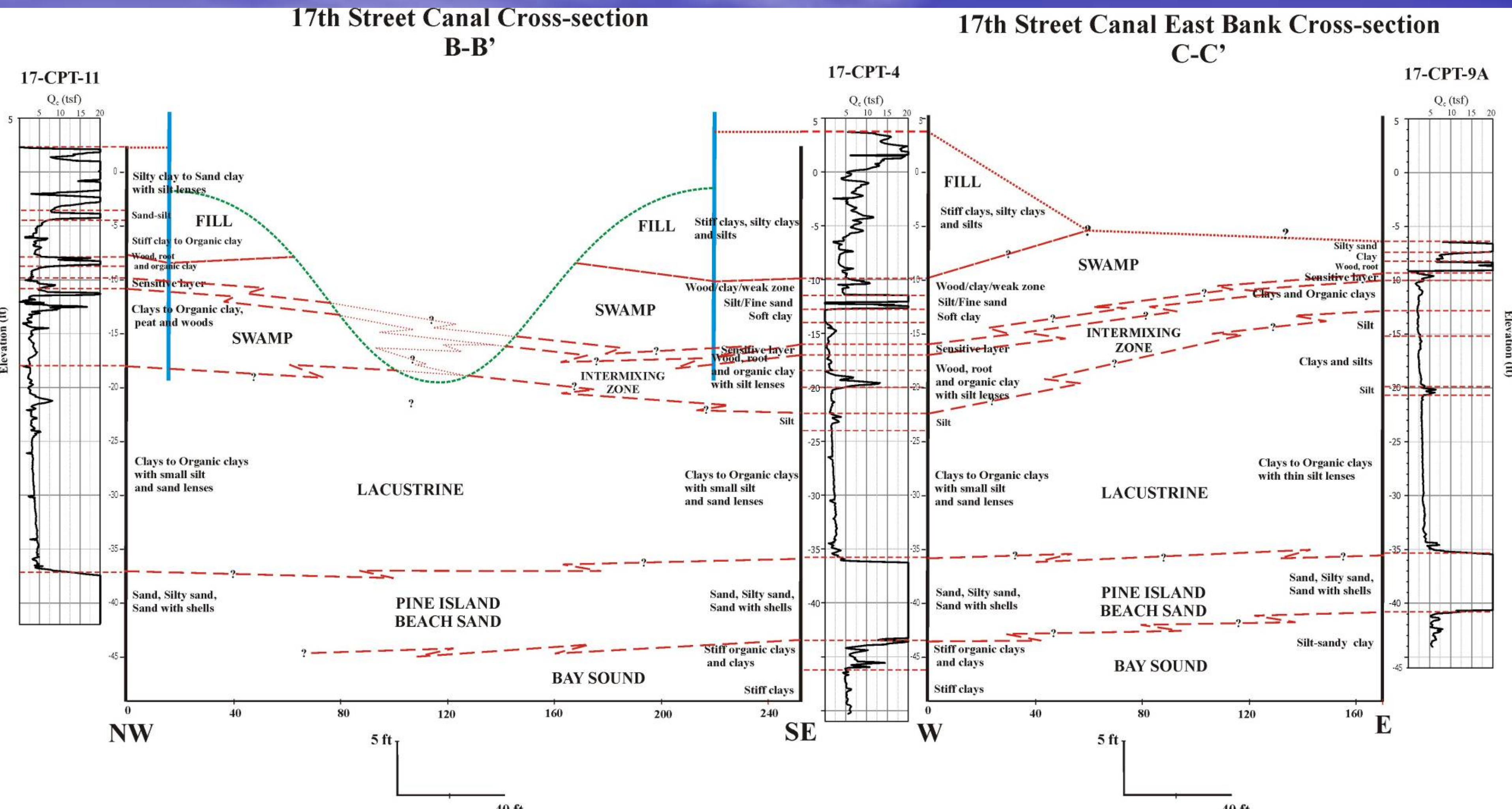

Embankment moved 51 ft
The most recently constructed elements of the city's flood control infrastructure, built in the mid 1990s, performed miserably.
EPA, 2005



- **Overlay of 1872 map by Valery Sulakowski on the WPA-LA (1937) map, showing the 1872 shoreline and sloughs (in blue) along Lake Pontchartrain. Although subdivided, only a limited number of structures had been built in this area prior to 1946. The position of the 2005 breach along the east side of the 17th Street Canal is indicated by the red arrow.**



- Apparent displacement of the 17th Street Canal flood wall on the west (Jeffereson Parish) side, opposite the 17th Street failure.

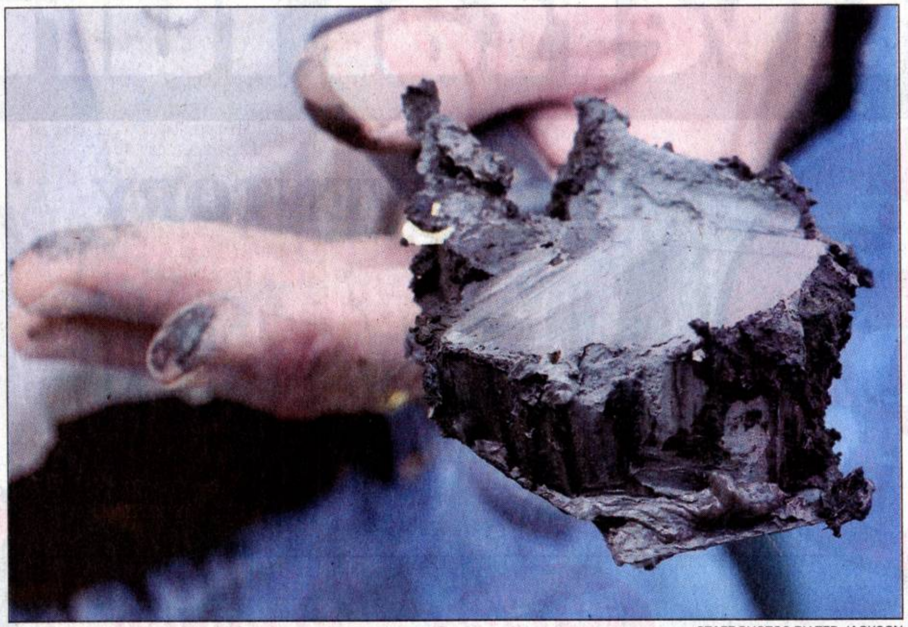


- Stratigraphic interpretations across the 17th Street Canal breach. The swamp much appeared to be thinning northerly, as does the underlying **Pine Island Beach Trend**. The lacustrine clays appear to thicken southward, as shown.
- The approximate positions of the flood walls (light blue) and canal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

The 17th St Canal slip surface

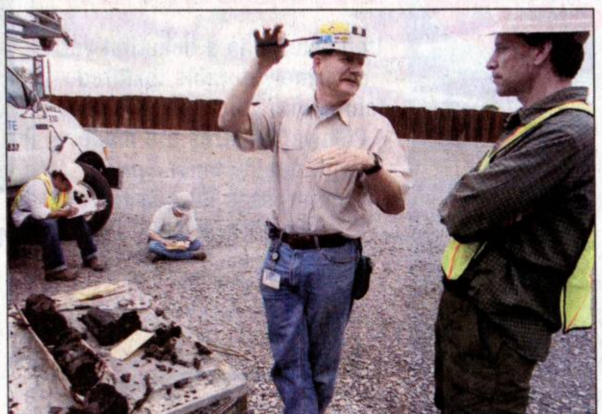
- Sampling the slip surface was only the first hurdle
- Shear testing of this toothpaste consistency paludal clay proved far more difficult
- The results eventually showed a peak shear strength of 50 psf, degrading to zero after a half inch of rotation

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.

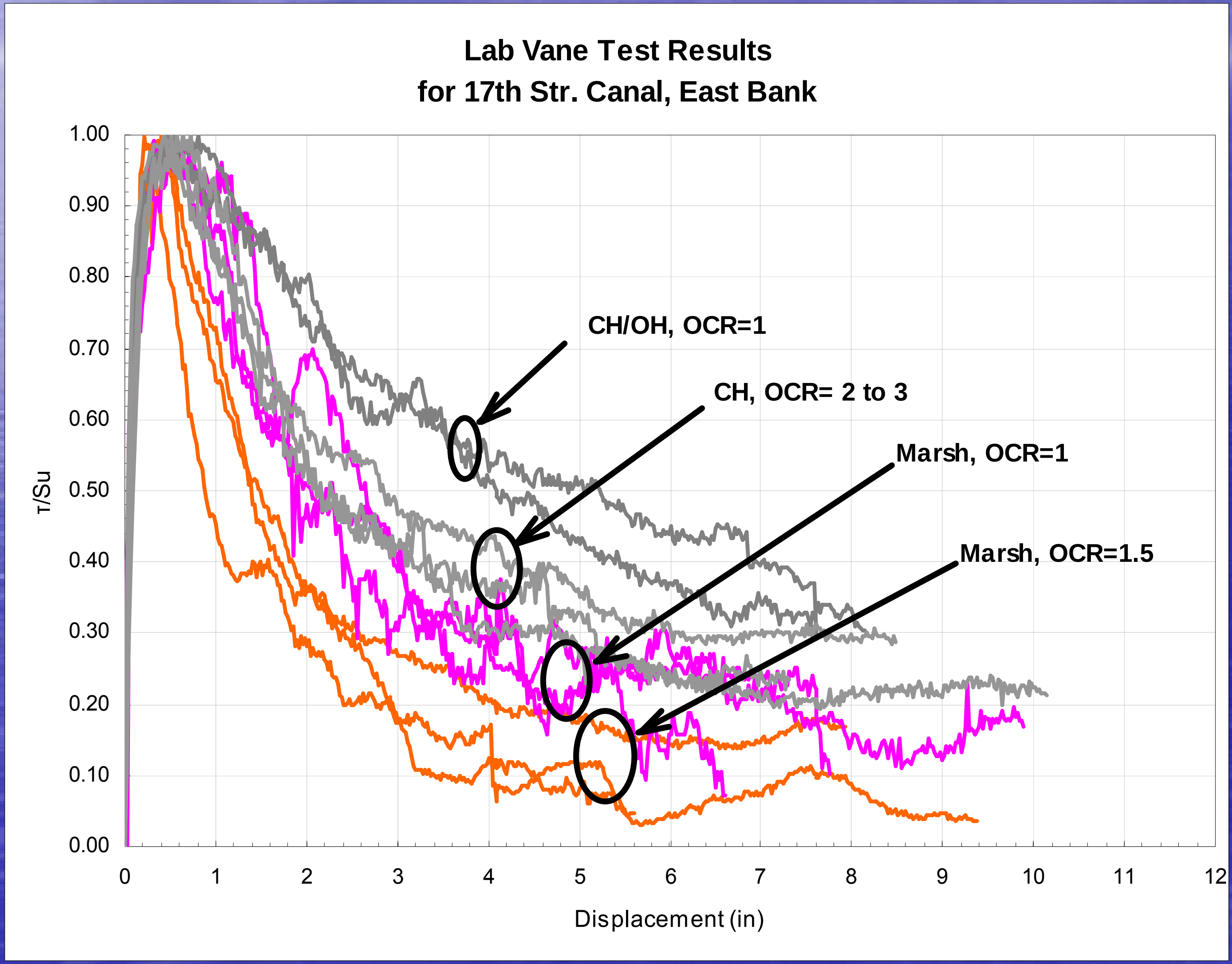
the words "wood" or "shells" written between the lines, indicating a mixture, although the written description of the layers on the log indicates these layers were composed of mostly weak material.

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.

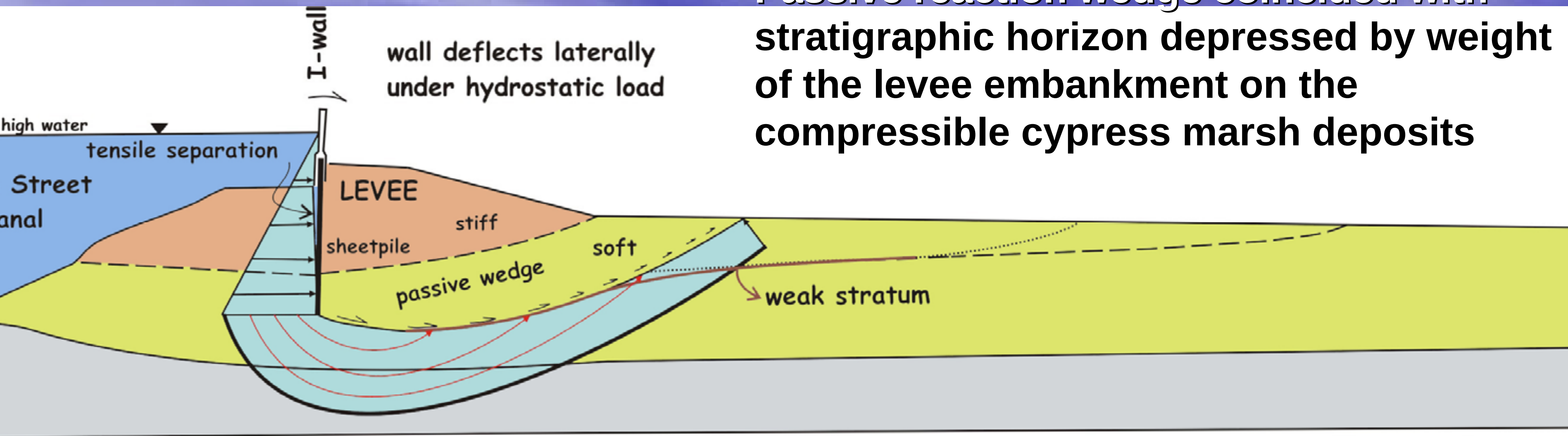
'Significant finding'

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

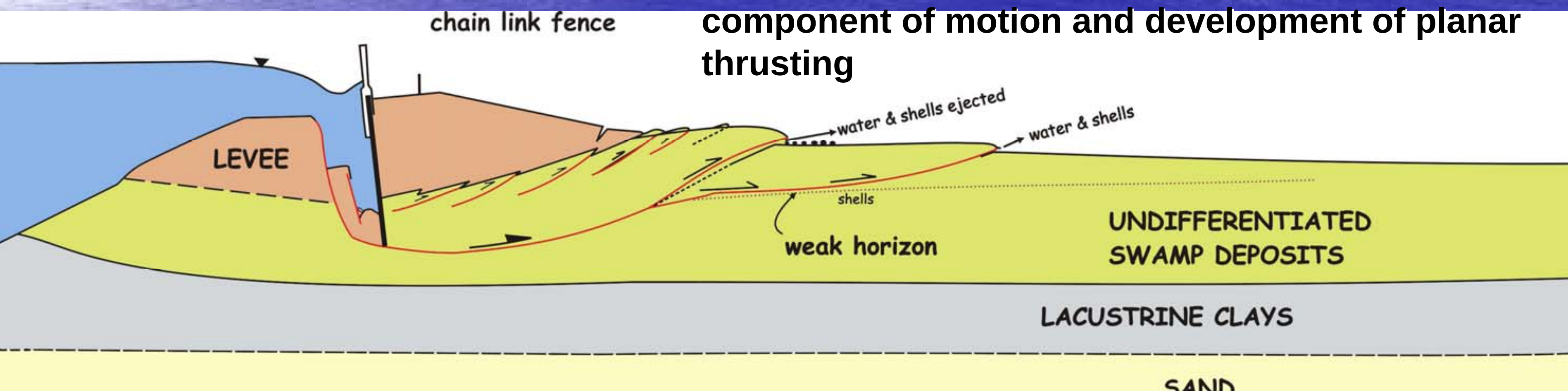
17th Street Canal: Sensitivity of the Sensitive Organic Clay within the Marsh Stratum vs. Sensitivity of the Deeper Gray Clay (CH)



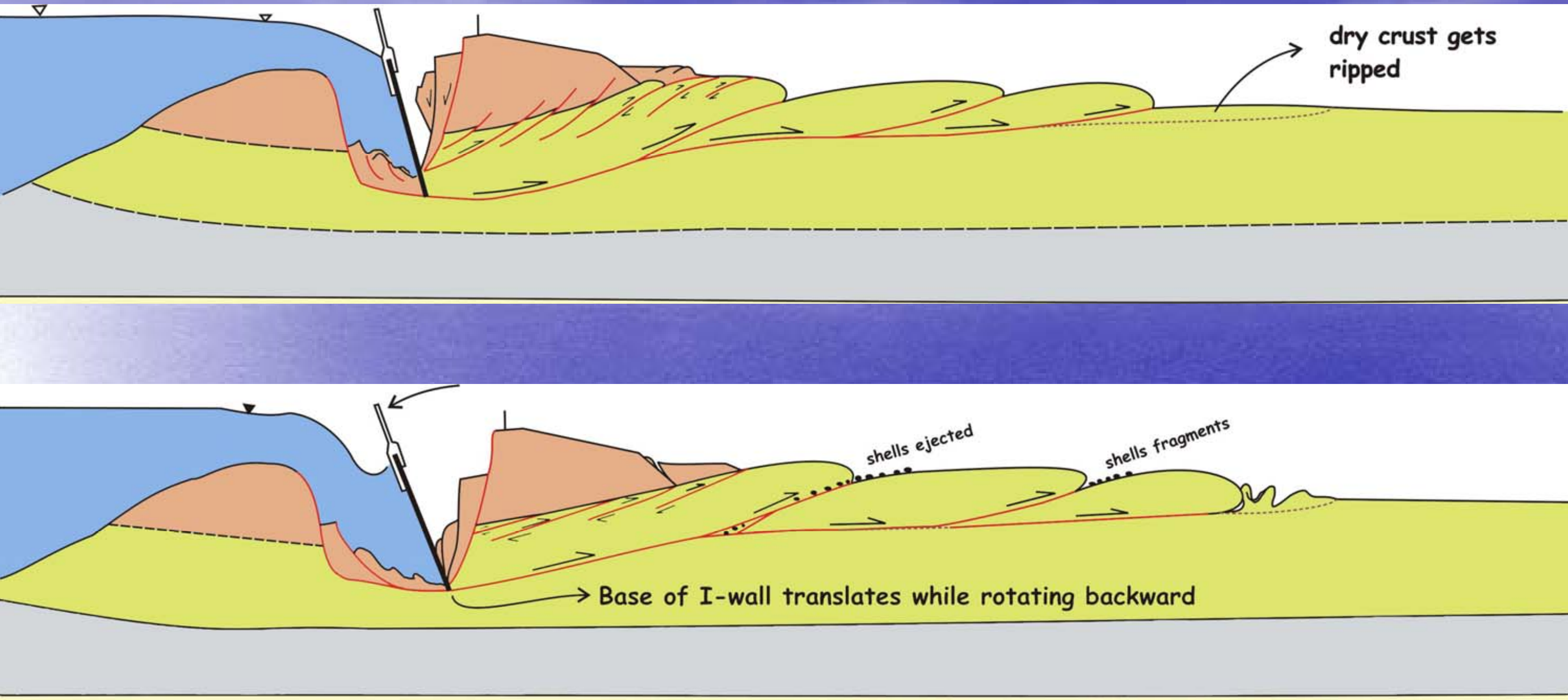
Passive reaction wedge coincided with stratigraphic horizon depressed by weight of the levee embankment on the compressible cypress marsh deposits



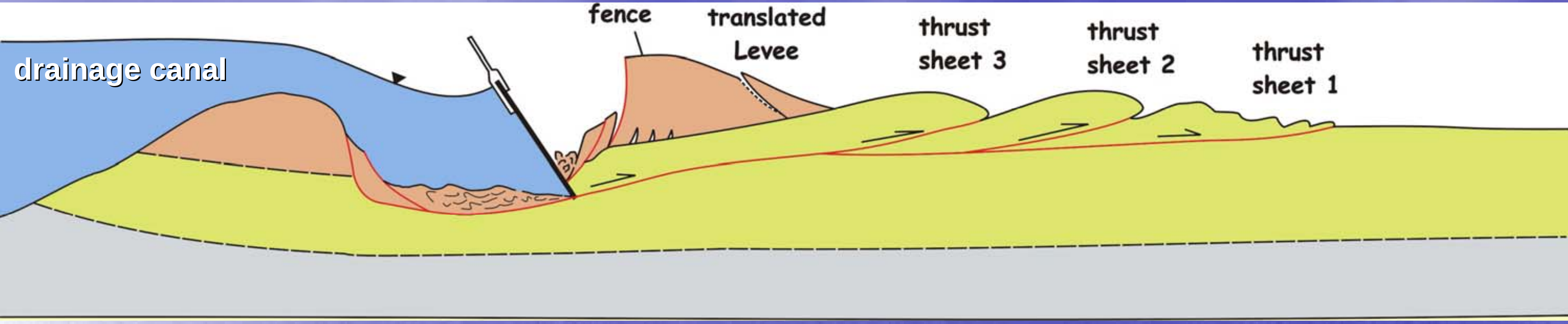
Traction shears noted along base of embankment. Note initial back rotation component of motion and development of planar thrusting



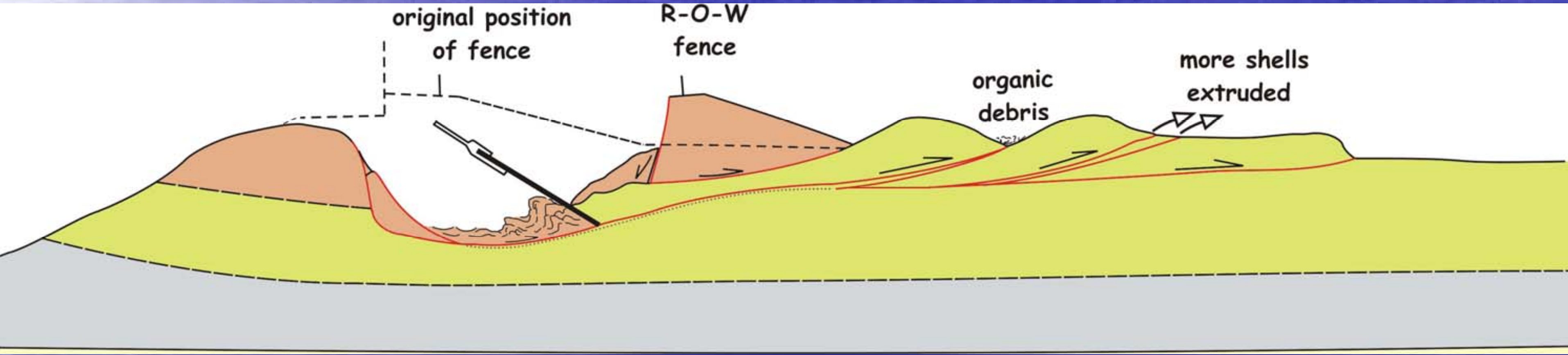
Initial loading conditions. Storm surge rises to within 4 feet of flood wall crest. Hydrostatic pressures on sheetpile supported I-wall highlighted in blue. Translational failure begins.



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.

Aging Factors that should be addressed when designing levees:

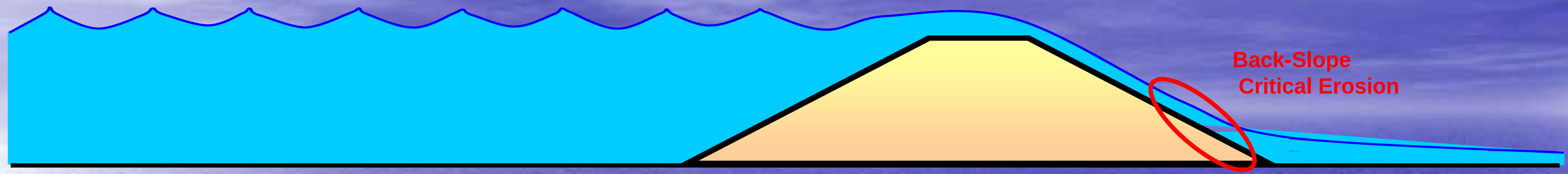
1) Erosion,
2) Settlement, and
3) Changed conditions

Levees are erodible

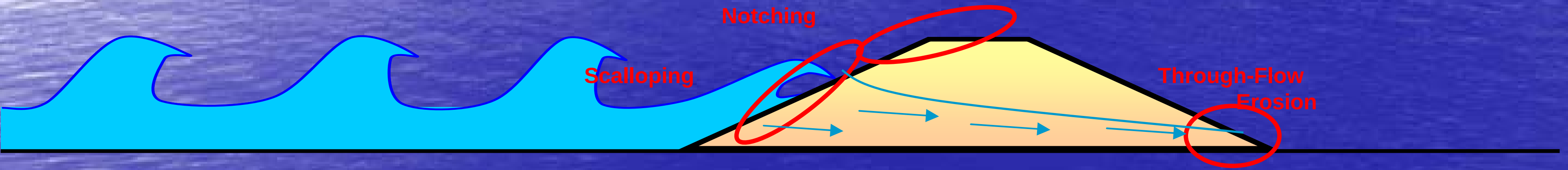
Levees are also susceptible to erosion by overtopping, by edified flow, and by undercutting.

Once flood waters overtop an embankment they quickly scour the land-side toe of the embankment, and deep scour holes develop on either side of the “hydraulic jump” that forms at the point of overflowage, enlarging the breach, as shown here.

Two kinds of overtopping-induced damage



Velocity-induced scour at toe of back slope, at flow transition. Accelerates when vegetation stripped off, depending on cohesion of embankment materials



Scalloping and notching on the fetch side of the levee, due to wave pounding; and piping fomented by emergent seepage at the toe of the back slope

Note: damage at back slope toe looks similar for both modes

MRGO channel

Originally envisioned in 1923 to provide deep draft access to the IHNC.

500 ft wide channel, excavated by dredging in 1960-64

"Funnel feature" at western end of Lake Borgne created by intersection of the GIWW and the MRGO.

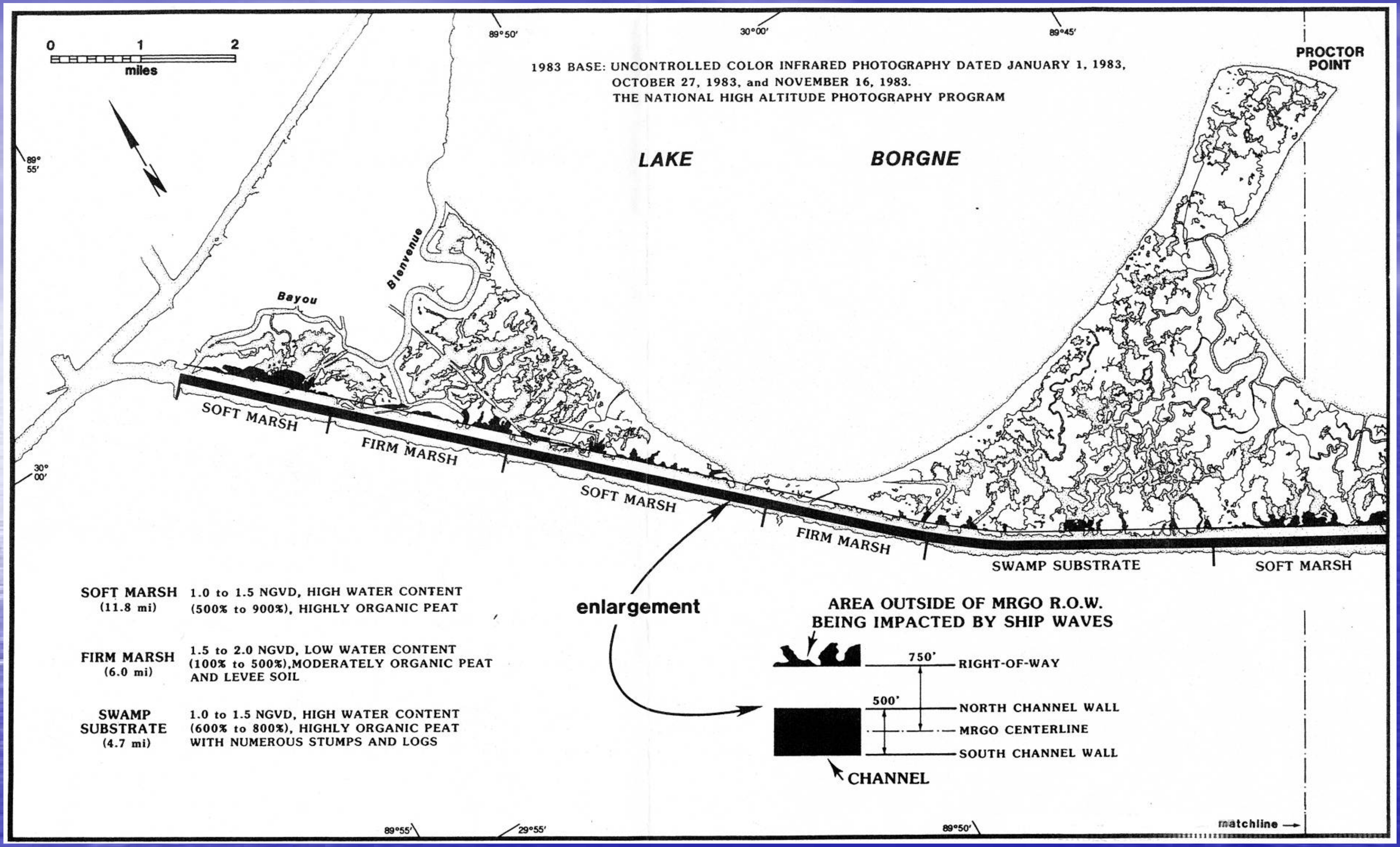
This gore point is 6 miles east of the Inner Harbor Navigation Channel (Industrial Canal)

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

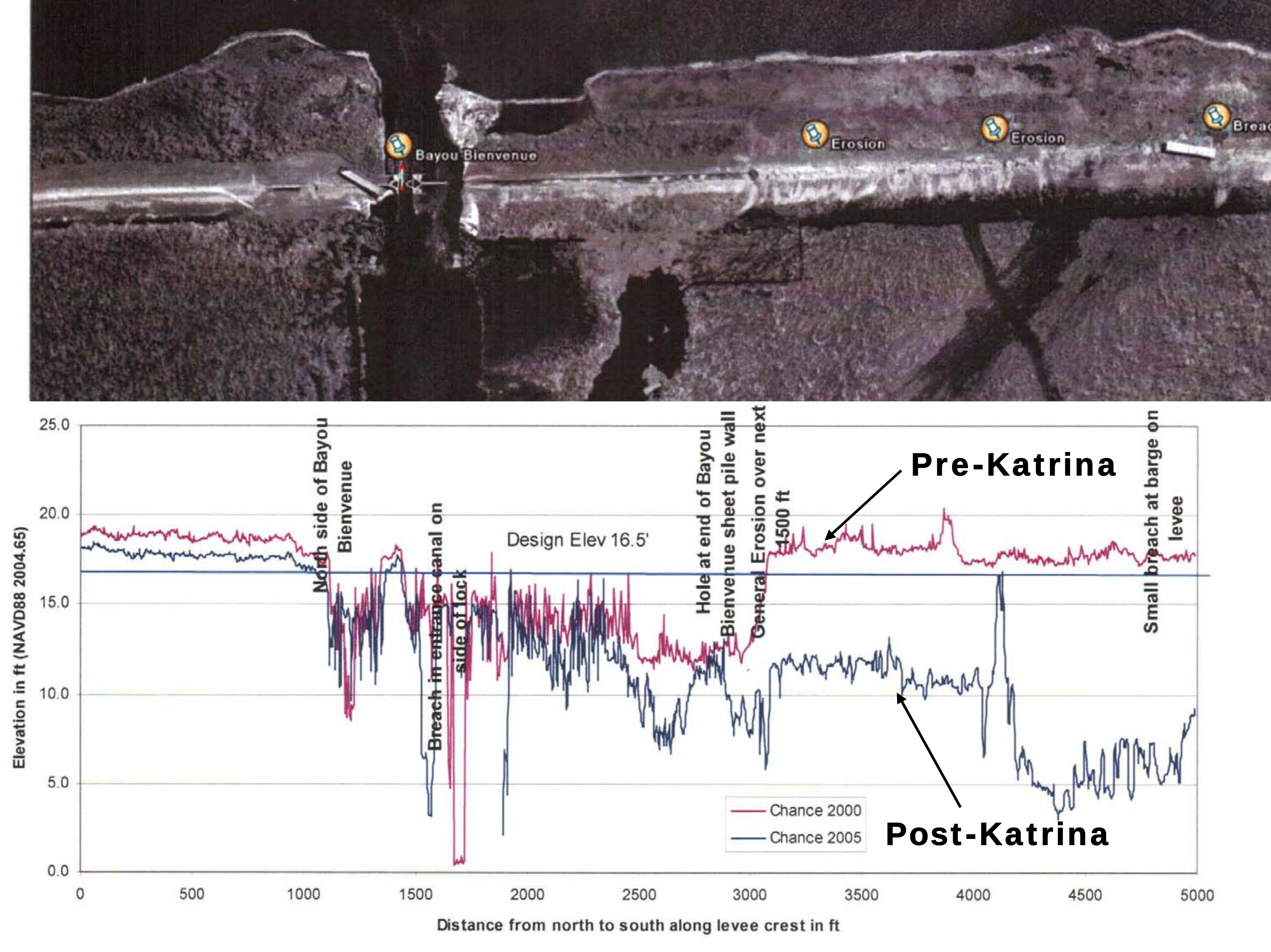

Steel sheetpile cutoff walls along the MRGO
levee were all that remained of the levee after
overtopping erosion from Hurricane Katrina

Cohessionless shell fill erodes like crazy

- Surficial erosion at toe of cut slope in borrow pit adjacent to the reconstructed MRGO channel, illustrating erosion of low cohesion fill materials.



- **Cohesiveness of swamp substrate along the MRGO alignment was viewed as a major design problem in 1958 report by Kolb and van Lopek.**



Bayou Bienvenue
Erosion
Erosion
North side of Bayou Bienvenue
Breach in entrance canal on side of lock
Design Elev 16.5'
Hole at end of Bayou Bienvenue sheet pile wall
General Erosion over next 1500 ft
Pre-Katrina
Small breach at barge on levee
Post-Katrina
Chance 2000
Chance 2005
Elevation in ft (NAVD88 2004.65)
25.0
20.0
15.0
10.0
5.0
0.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance from north to south along levee crest in ft

Conclusions - have to be careful when building on oatmeal

- Levees have allowed development to grow and prosper in coastal margins that are subsiding
- A lot of great work was carried out 40+ years ago that appears to have been all but forgotten
- The three dimensional character of the geology underlying levees needs to considered much more seriously