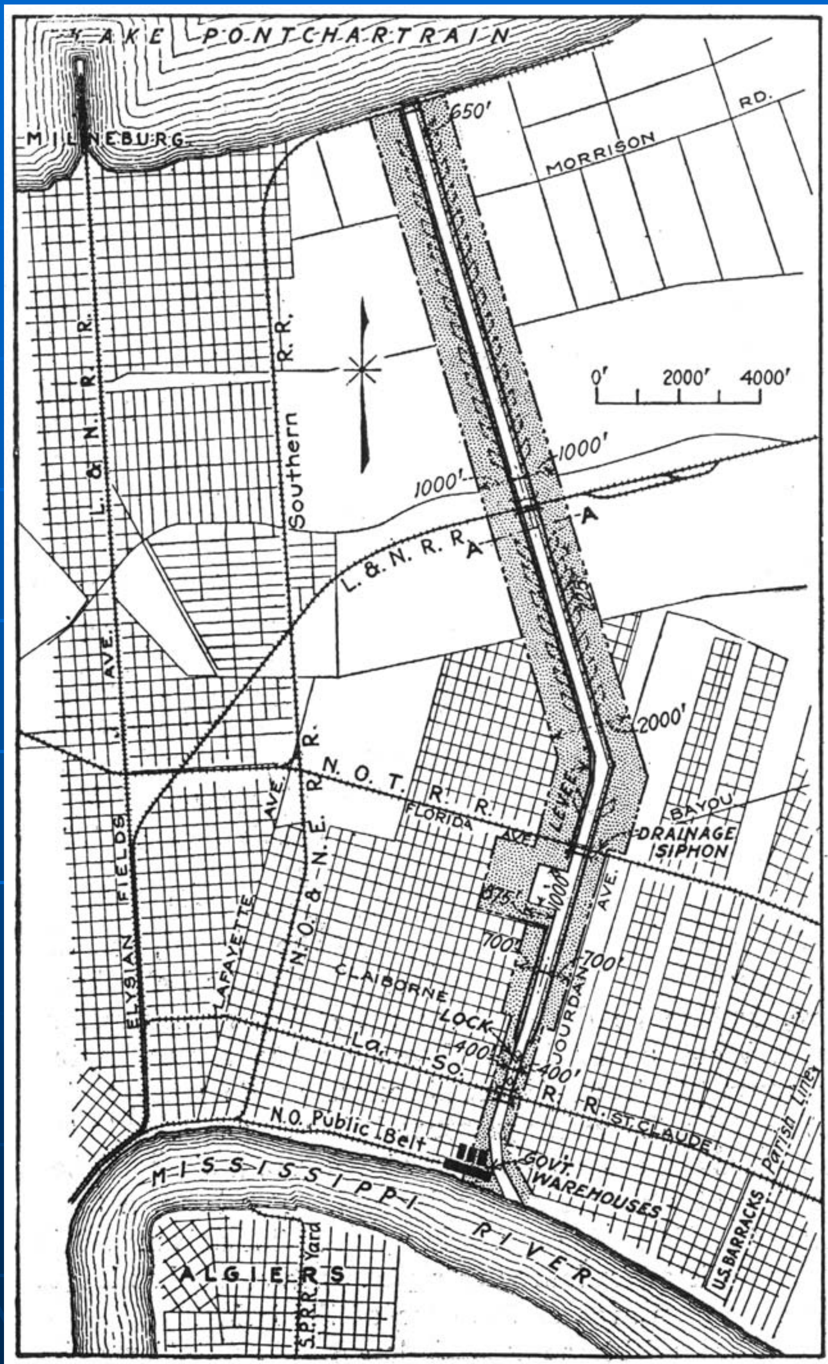
INVESTIGATION OF LEVEE PERFORMANCE IN HURRICANE KATRINA: Levee Failures Along the Inner Harbor Navigation Channel

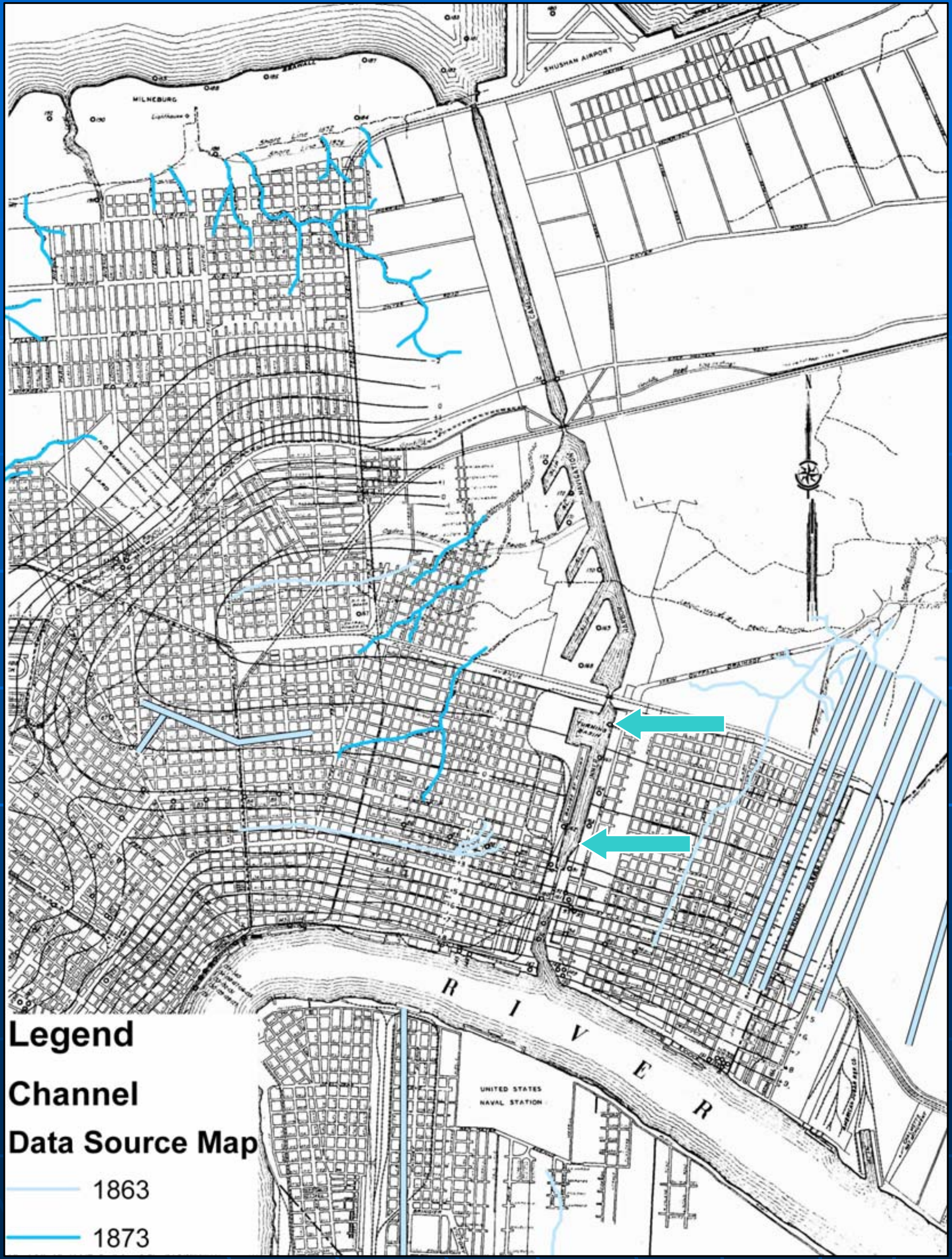
J. David Rogers, Ph.D., P.E., R.G., C.E.G., C.HG.

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

Historic Background
New Orleans
Inner Harbor
Navigation Channel
(Industrial Canal)

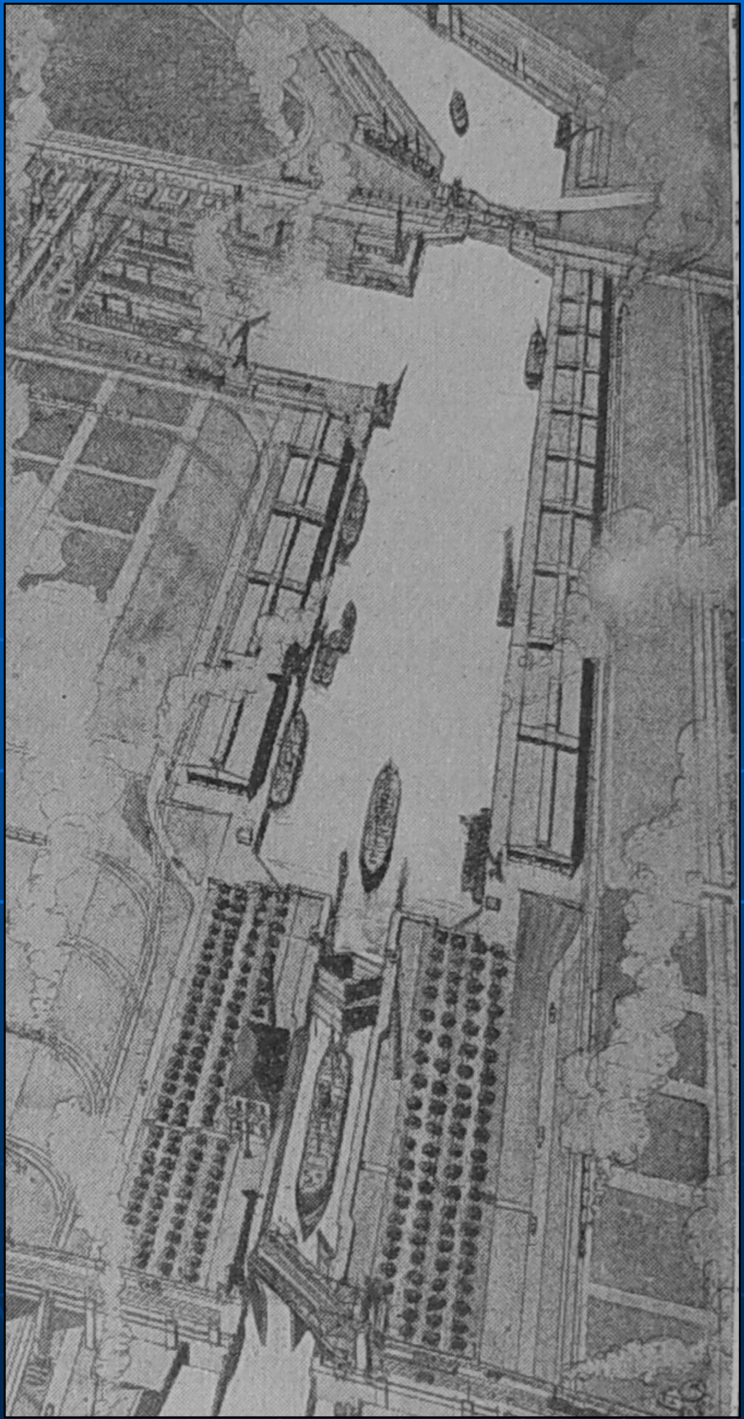


- The 6-mile long **Industrial Canal** runs between the Mississippi River and Lake Pontchartrain
- It was excavated by centrifugal dredges, beginning in May 1918
- Funded by $6 million bond passed in 1914
- Work commenced in May 1918. Berths off the Mississippi River allowed private frontage to be leased for exclusive use of industrial clients
- A series of diagonal slips were envisioned; as was an 18 month construction schedule



Historic drainage channels around the IHNC

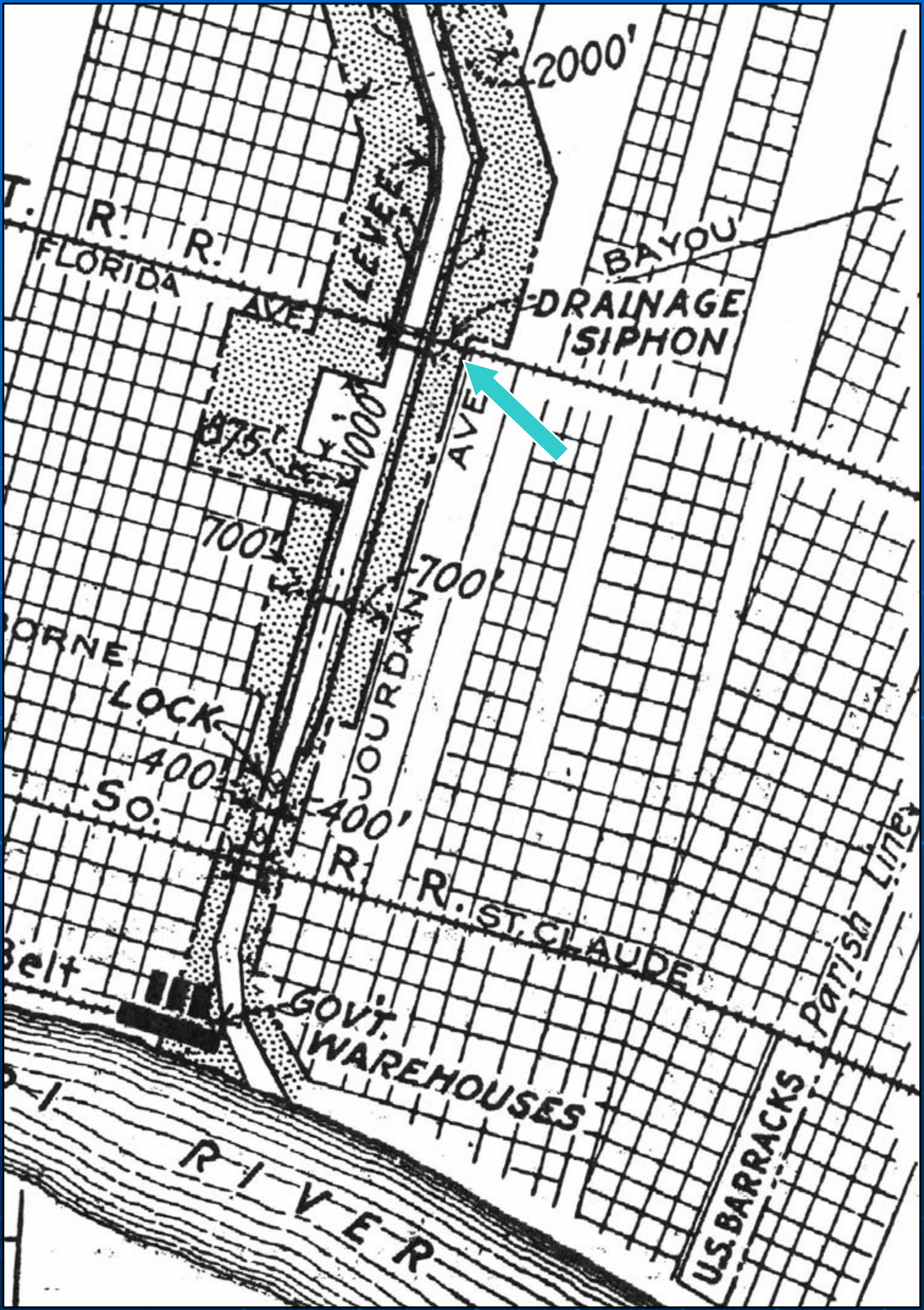
- The IHNC severed open channel flow draining into Bayou Bienvenue
- New drainage canals, siphons, and pumping stations had to be constructed



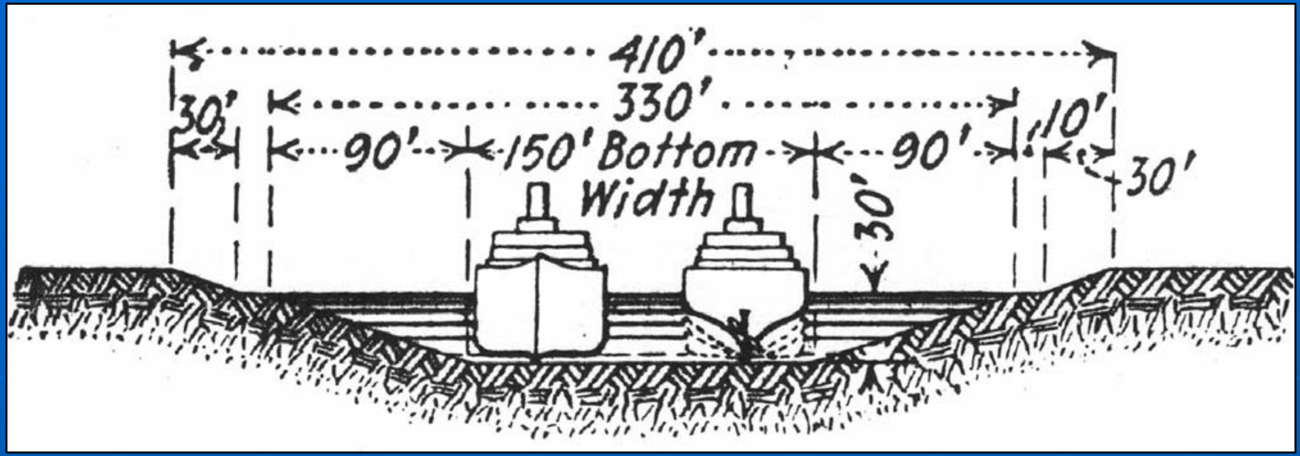
Original Intent

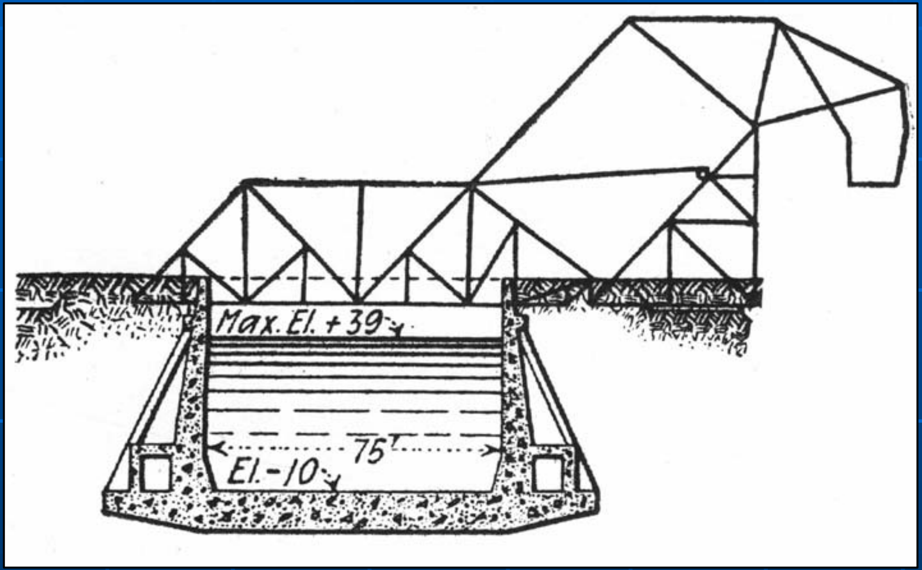
- The lower third of the IHNC was intended to provide private wharf frontage for industrial warehouses, as shown here
- During the first 25 years, only one tenant purchased space, on the west side of the IHNC

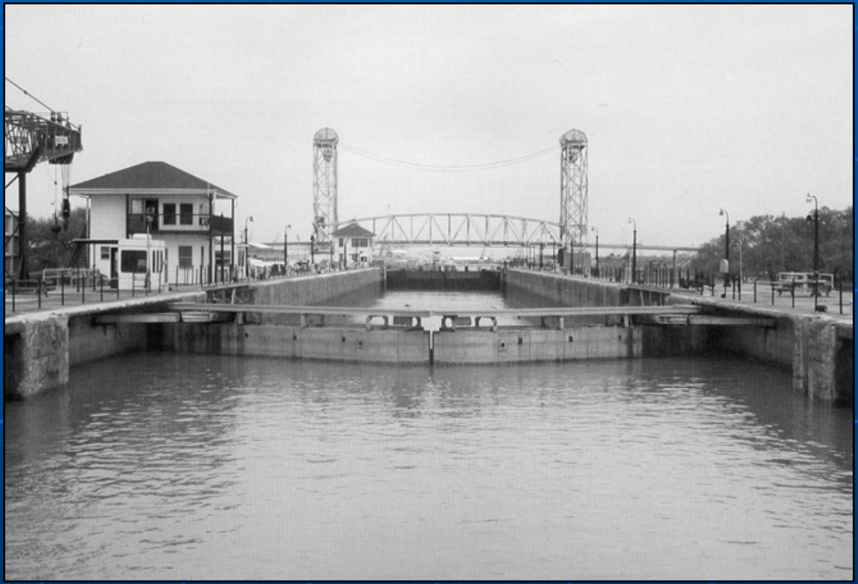
The Big Florida Avenue Siphon



- A reinforced concrete siphon structure capable of conveying 2,000 cfs was constructed beneath the IHNC along Florida Ave. to convey drainage to Bayou Bienvenue
- Stippled areas contain hydraulic fill on "made ground", elevated above surrounding area

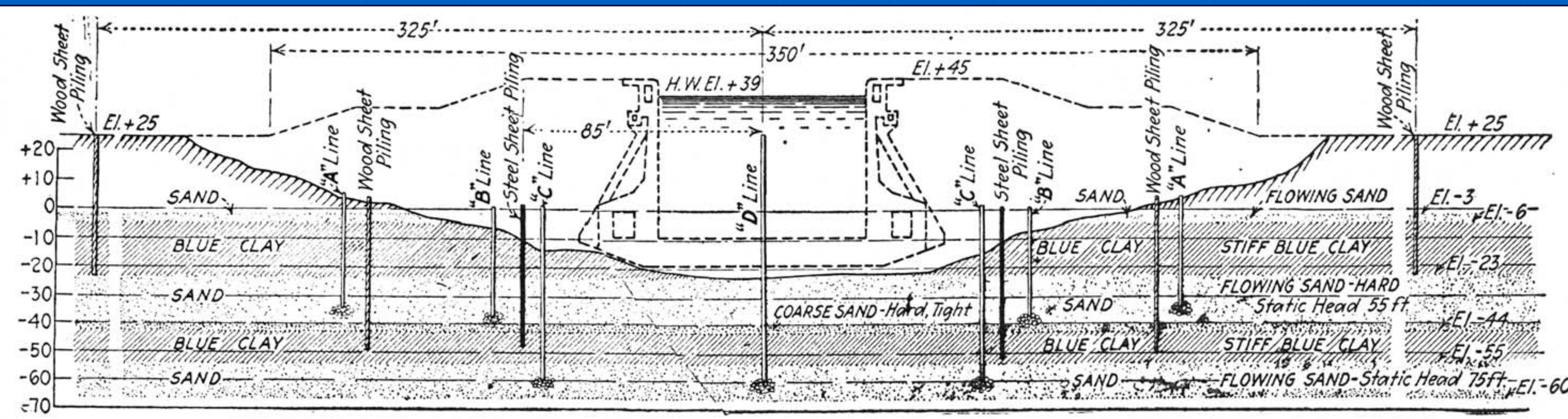






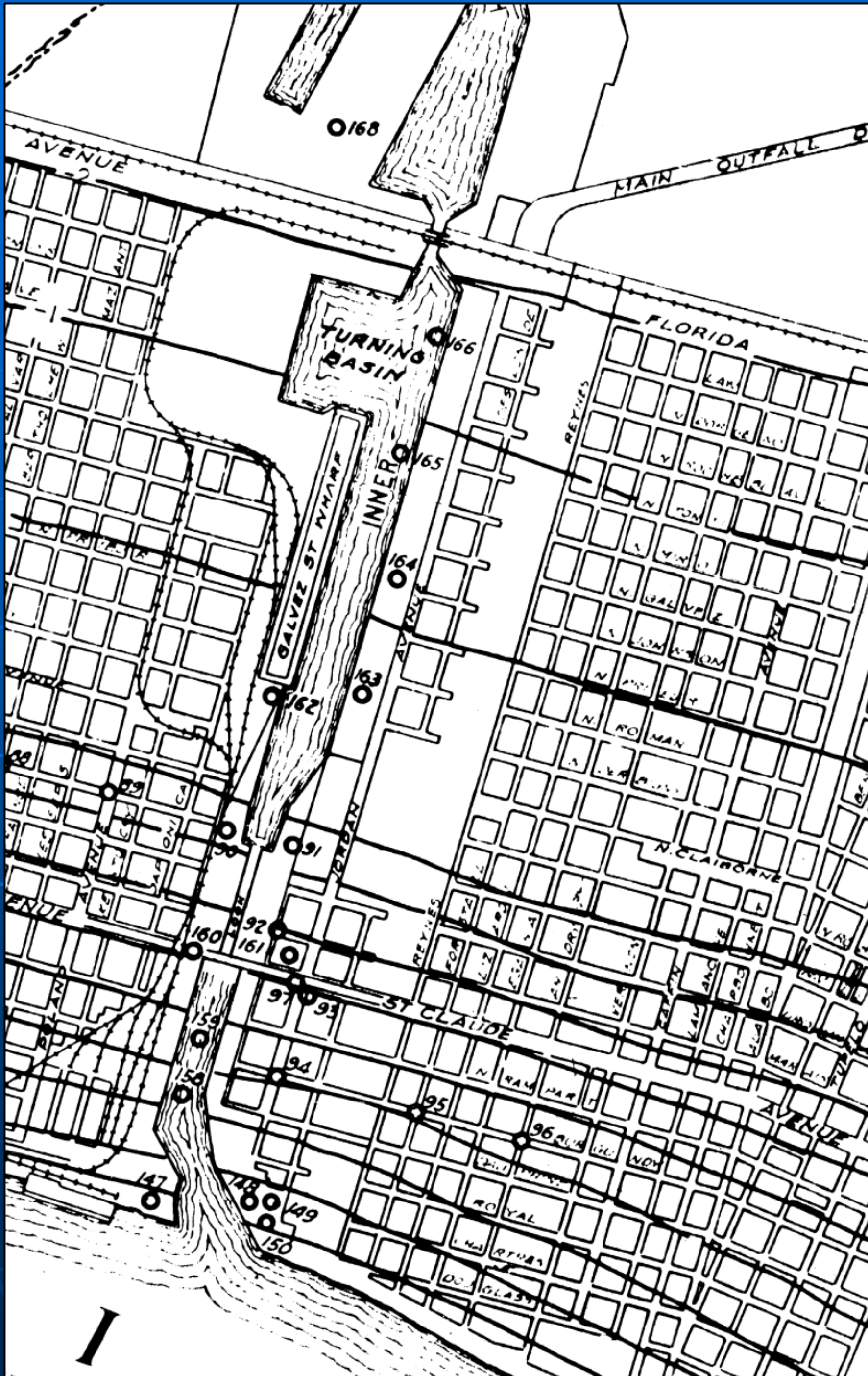
The IHNC was dredged as a trapezoidal channel with a single lock, in two sequences of excavation, undertaken between 1918-23. In Section III the channel was 330 feet wide, with a maximum depth of 30 feet over 150 feet. Side cast hydraulic fill formed levees on either side of the excavation.

Stratigraphy in Vicinity of the IHNC Lock Structure

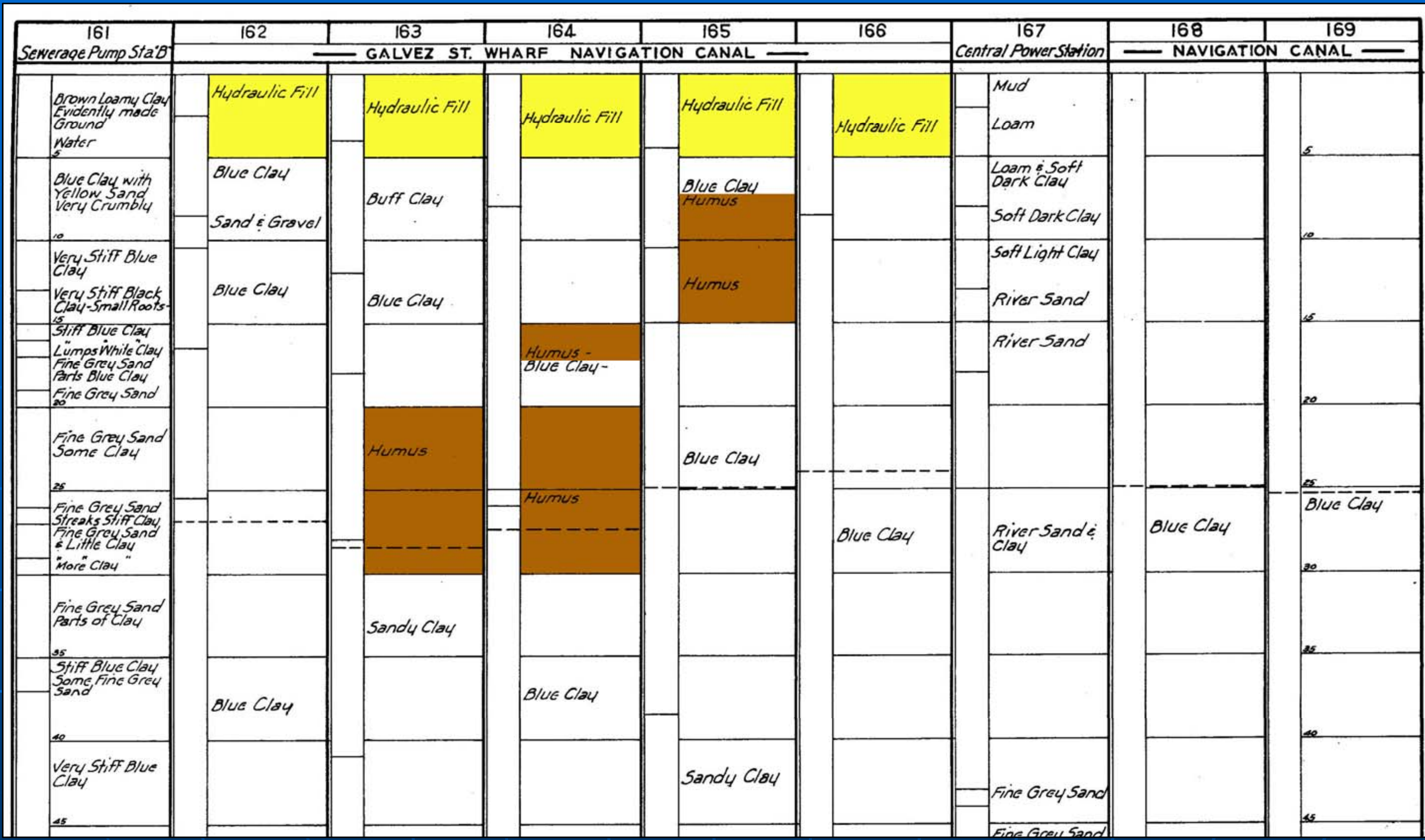


- Construction of the IHNC lock structure in 1919-23 proved troublesome, requiring 6 sheetpile bulkheads with raker braces and 6 rows of dewatering wells, with 5 monitoring wells along the centerline.
- Most of the problems were with two sequences of "running sands"

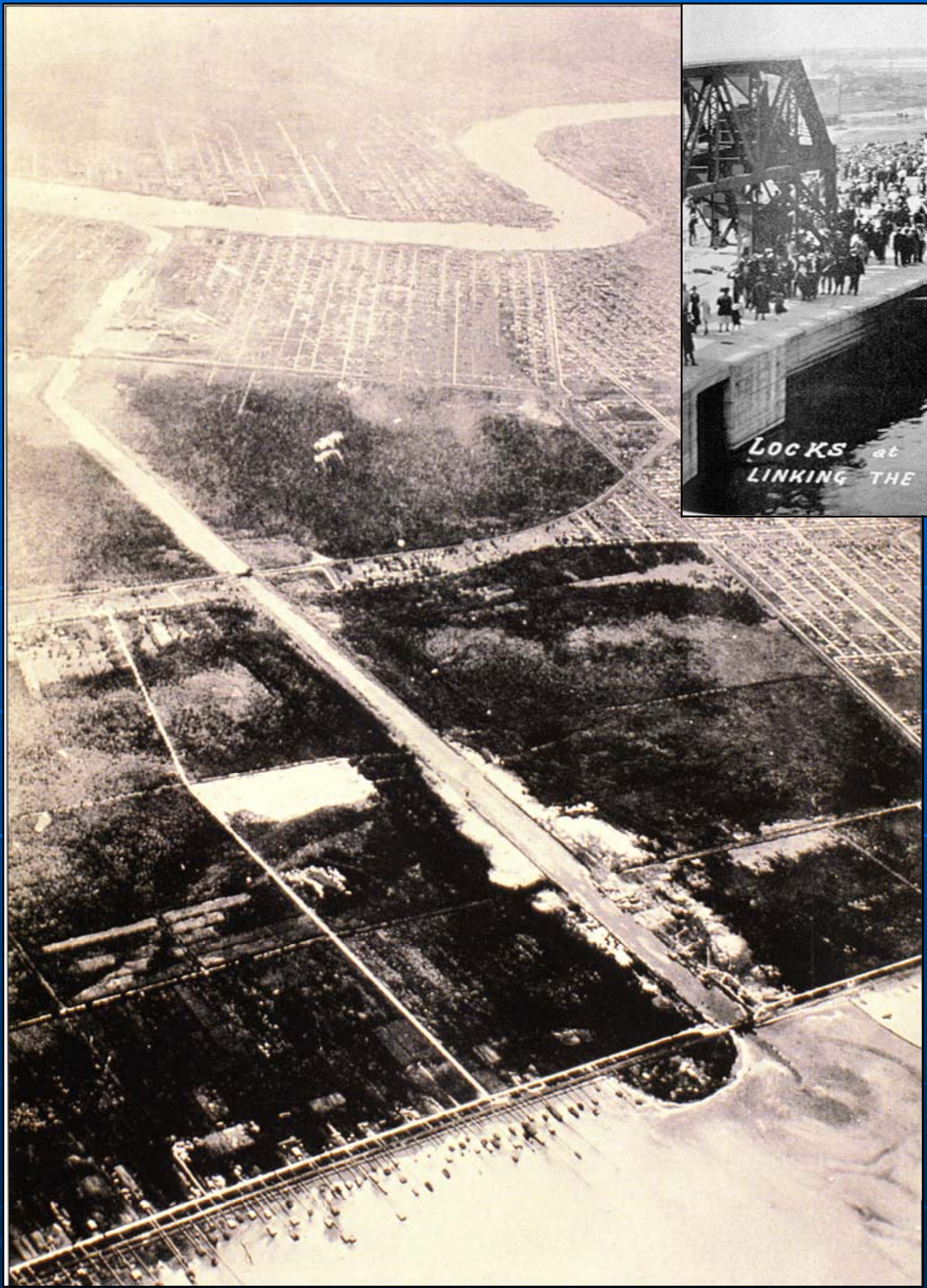
Original Borings for the IHNC



- A series of borings were advanced in vicinity of the newly dredged IHNC using a 10-inch diameter steel pipe driven in 3-foot increments
- This shows locations of those early borings



- **Soundings made in the early 1920s along the eastern side of Section III of the IHNC show hydraulic fill over blue clay over extensive deposits of "humus"** (from ASCE-WPA, 1937)



- After 5 years of construction costing $20 million the IHNC was officially opened on May 5, 1923

GIWW

The GIWW was cut in 1944, during WW2. The excavation of diagonal slips shown here occurred during the mid-1950s, before the MRGO was excavated in 1960-64.

- 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.

MRGO channel

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

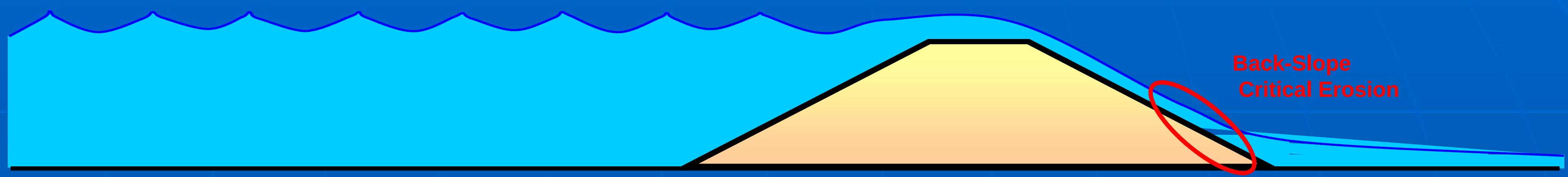
500 ft wide channel, excavated by dredging in 1960-64

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

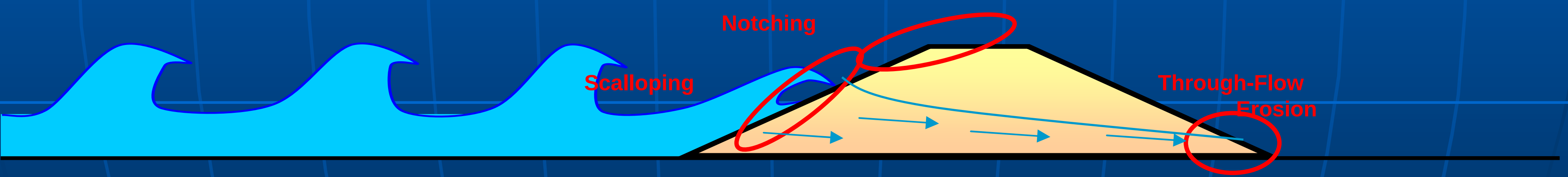
This gore point is 6 miles east of the Inner Harbor Navigation Channel (Industrial Canal)

- Around 6 AM on August 29th the 9 ft storm surge swept into the IGWW-MRGO confluence, engulfing the Entergy Power Plant near the Paris Ave. / I-510 Bridge with waves up to 17 ft high.

Two kinds of overtopping-induced damage



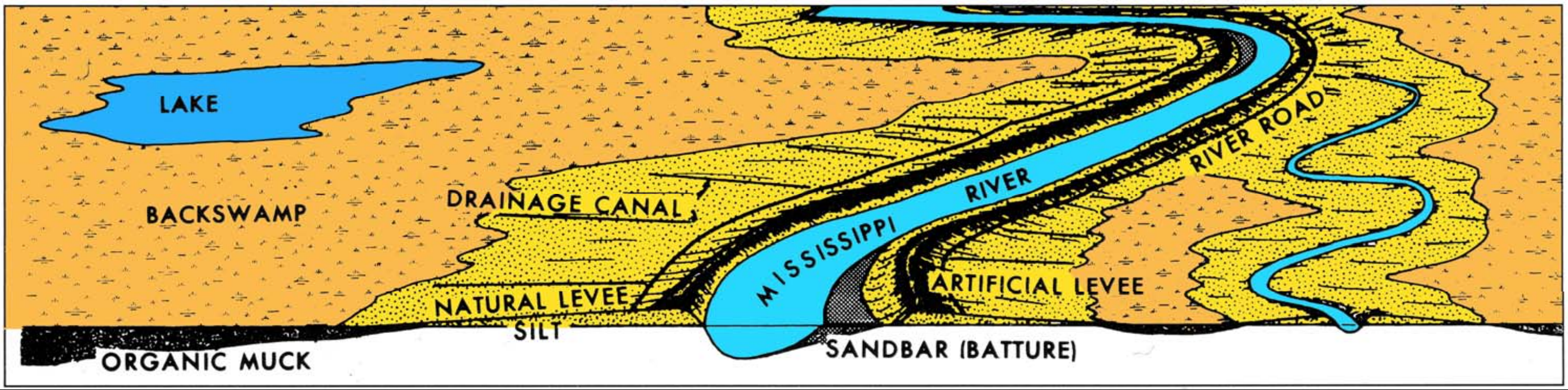
Velocity-induced scour at toe of back slope, at flow transition. Accelerates when vegetation stripped off, depending on cohesion of embankment materials



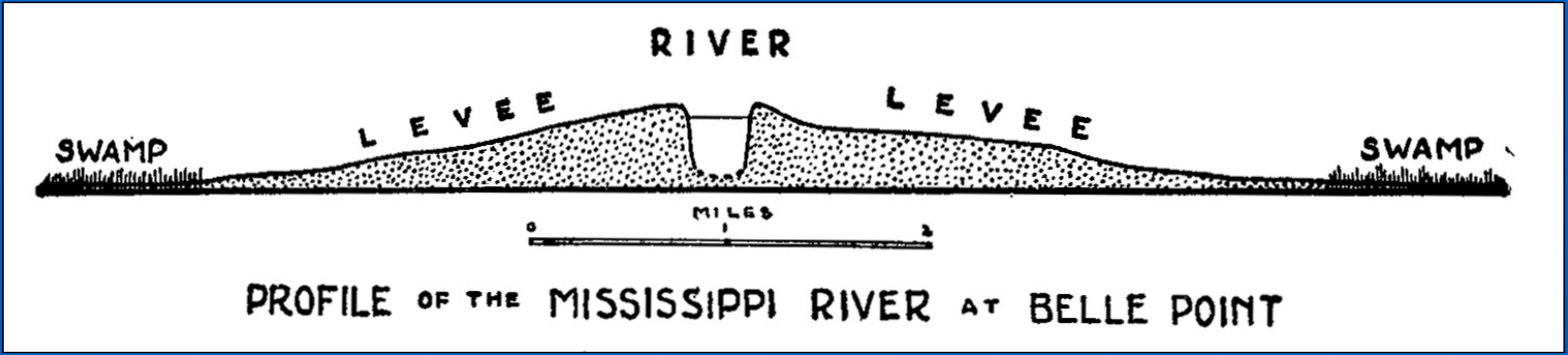
Scalloping and notching on the fetch side of the levee, due to wave pounding; and piping fomented by emergent seepage at the toe of the back slope

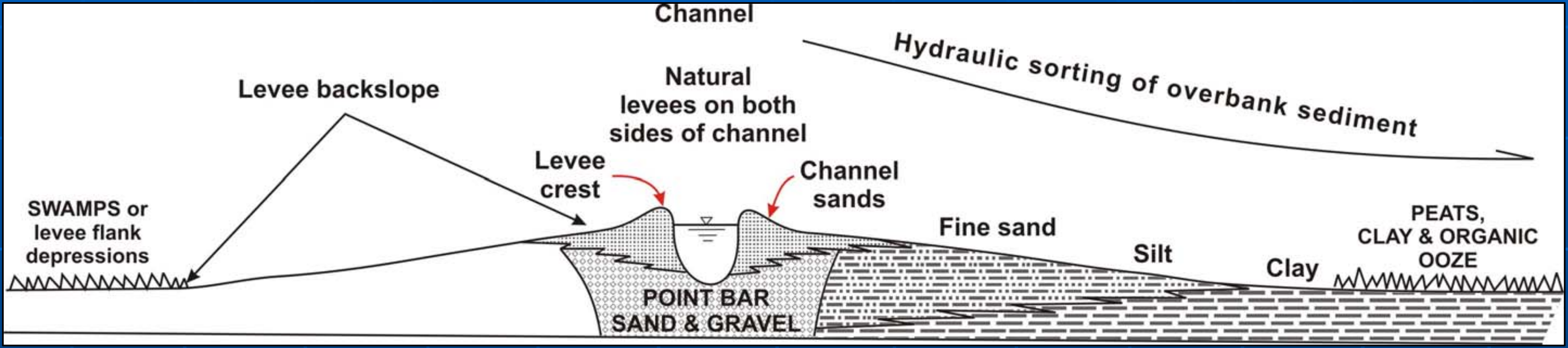
Note: damage at back slope toe looks similar for both modes

Discontinuous nature of stratigraphy underlying New Orleans

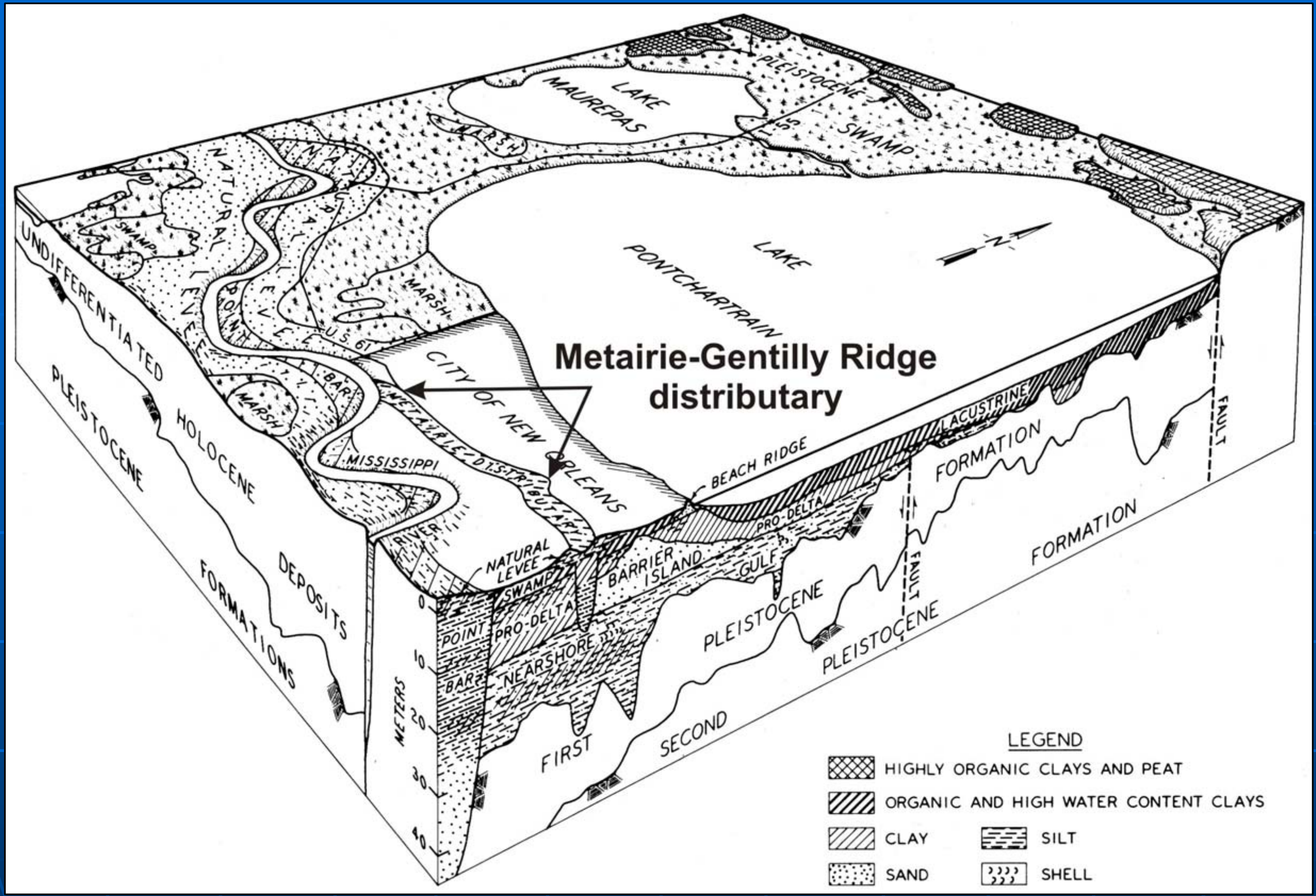


- **The IHNC crossed thick sequences of point bar sands adjacent to the Mississippi River, then historic marshes (lowland backswamp), crossed the Gentilly-Sauvage distributary ridge, and thence into backswamps, before connecting to Lake Pontchartrain.**

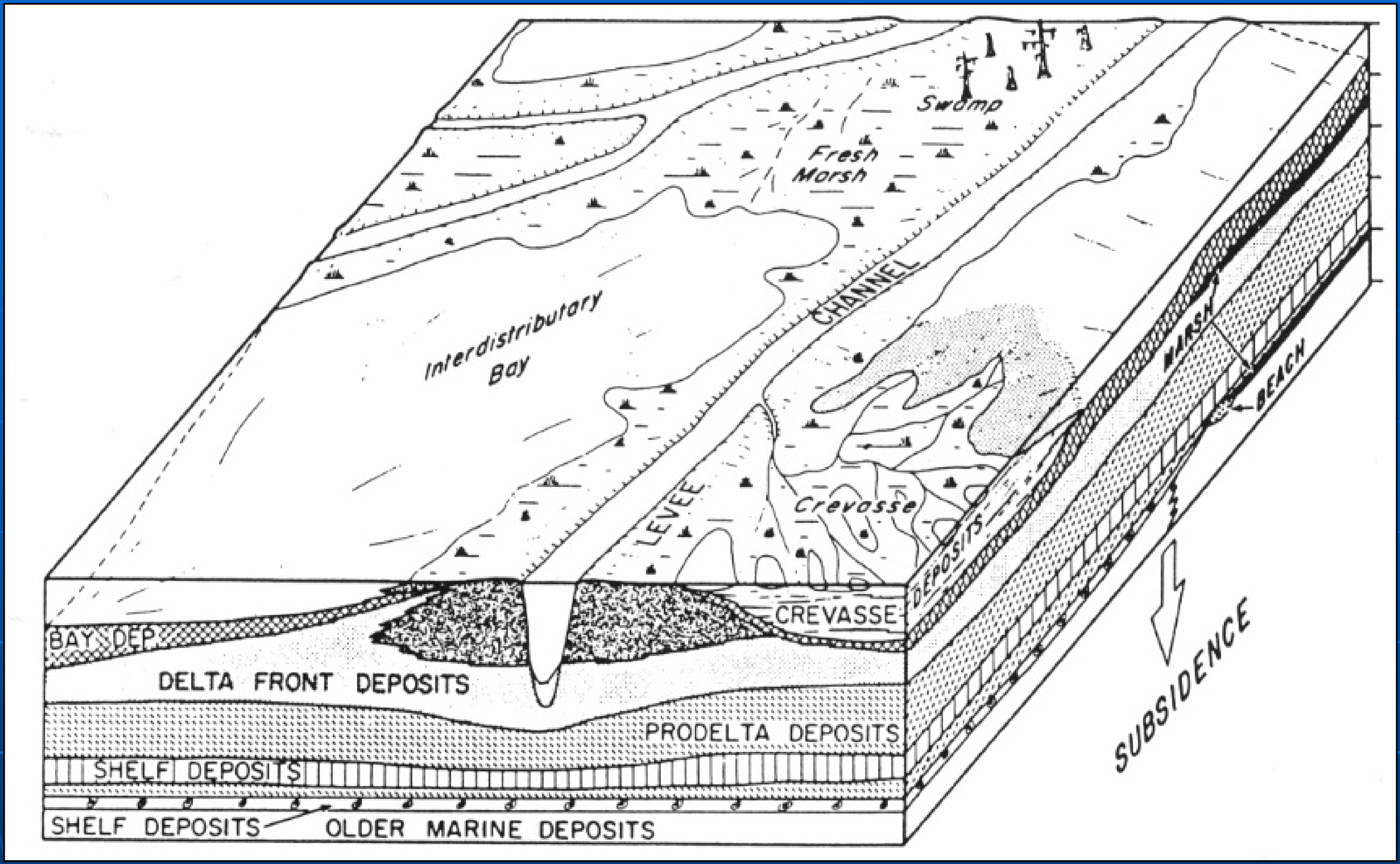




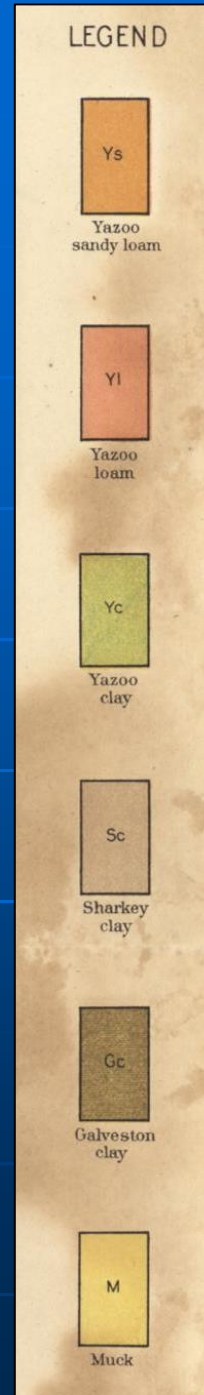
- **Typical cross section through the sandy bank levees of the Mississippi River, illustrating how the river's main channel lies above the surrounding flood plain, which were poorly drained swamp lands prior to reclamation.**
- **There is significant hydraulic sorting of materials deposited on either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



- **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.**



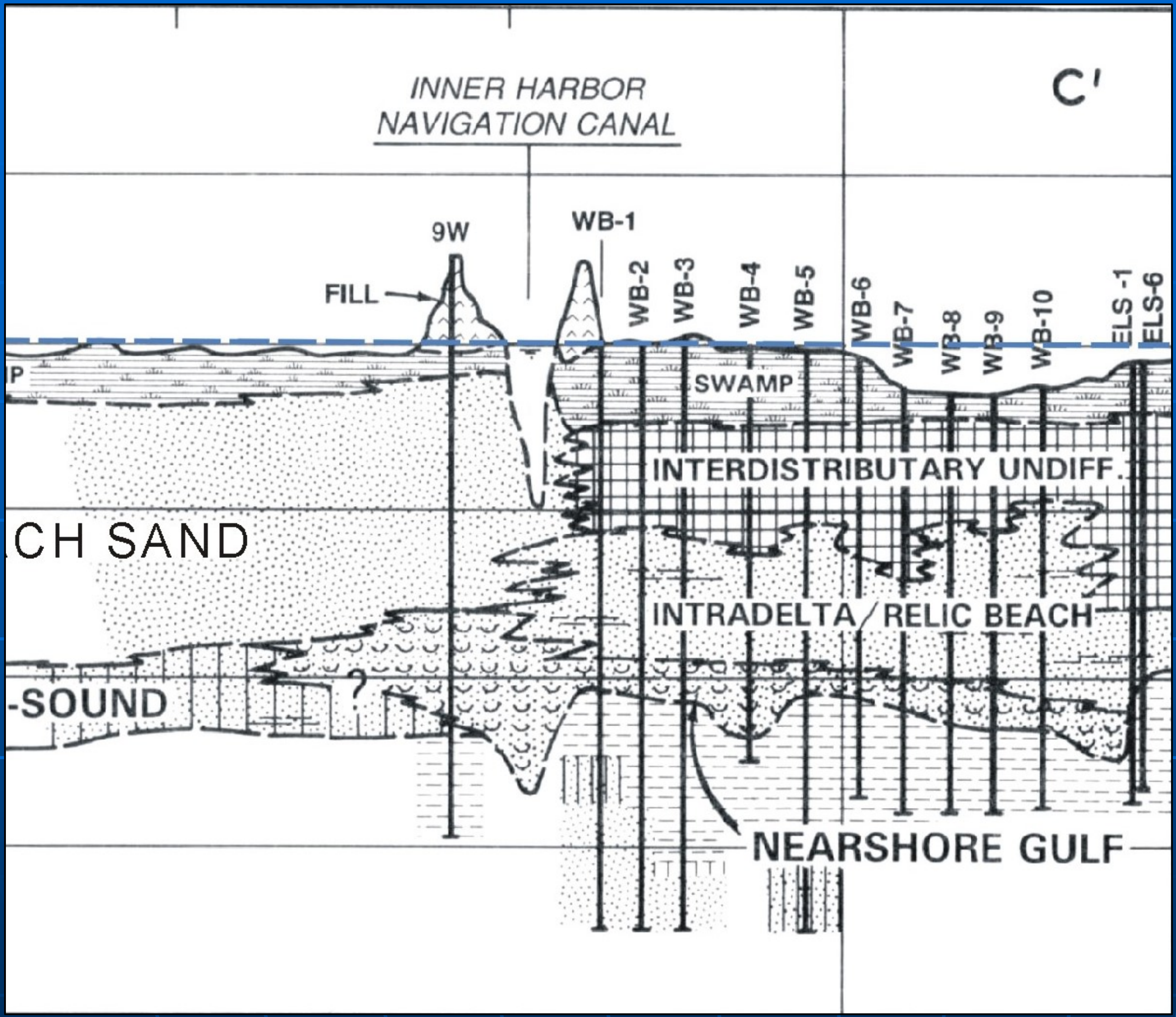
- Block diagram illustrating relationships between **subaerial and subaqueous deltaic environments** in relation to a single distributary lobe.
- The IHNC area of New Orleans is underlain by fresh water cypress swamps, peat, and interdistributary sediments.



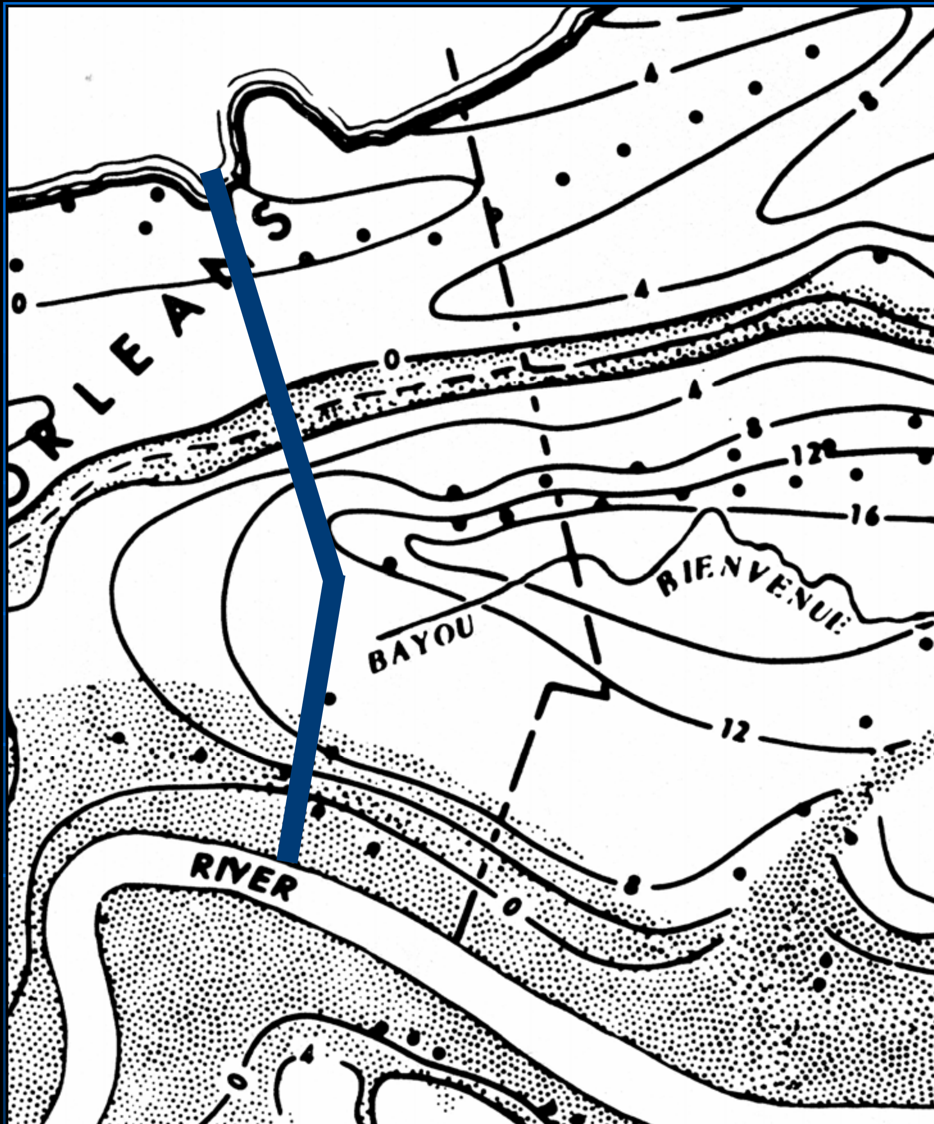
Overlay of 1903 Soils Map and 1937 ASCE Map

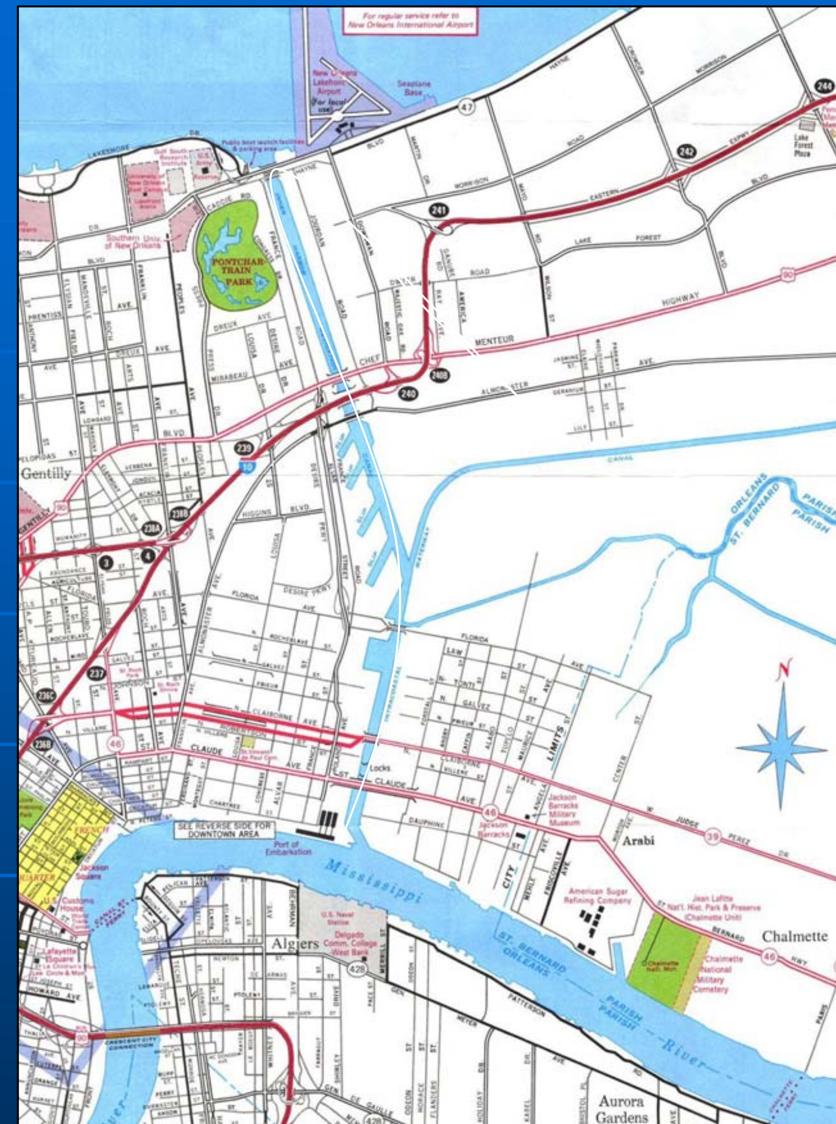
- **The ground surface along the IHNC right-of-way is underlain by Yazoo sandy loam (point bar sands), Yazoo clay, Sharkey clay (swamp), and the Yazoo Loam (distributary ridge)**

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.**

Cypress-Gum 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 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.

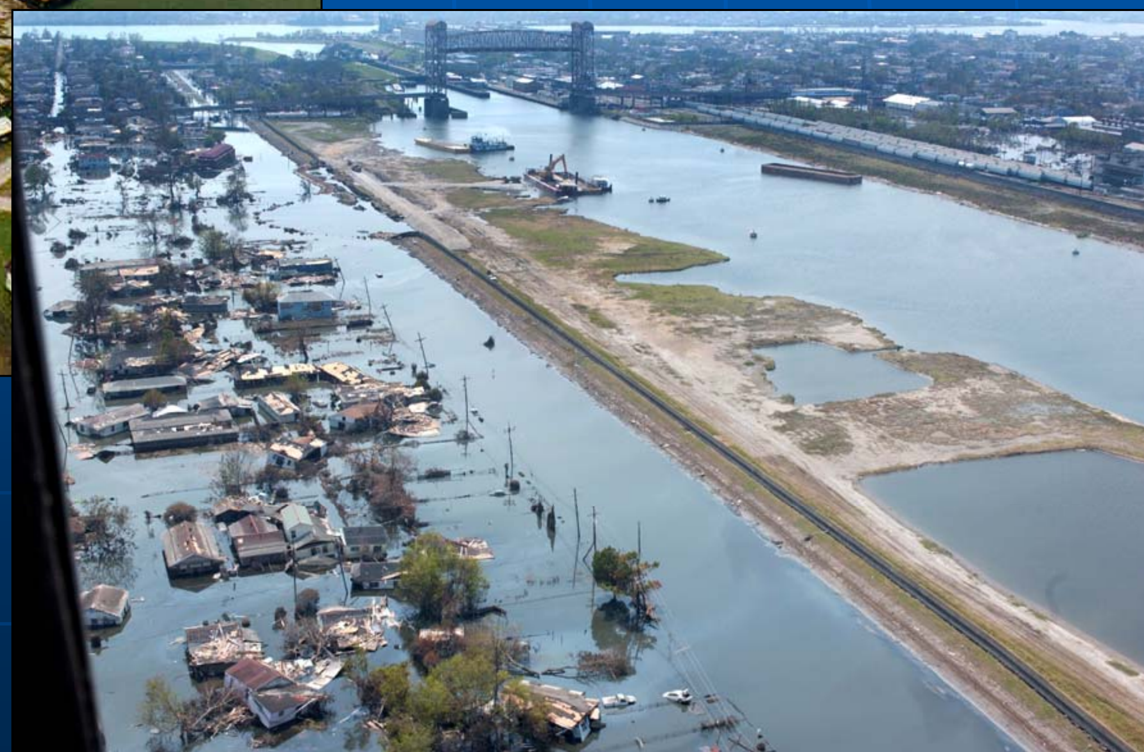
Depositional Environment Keys

- 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%

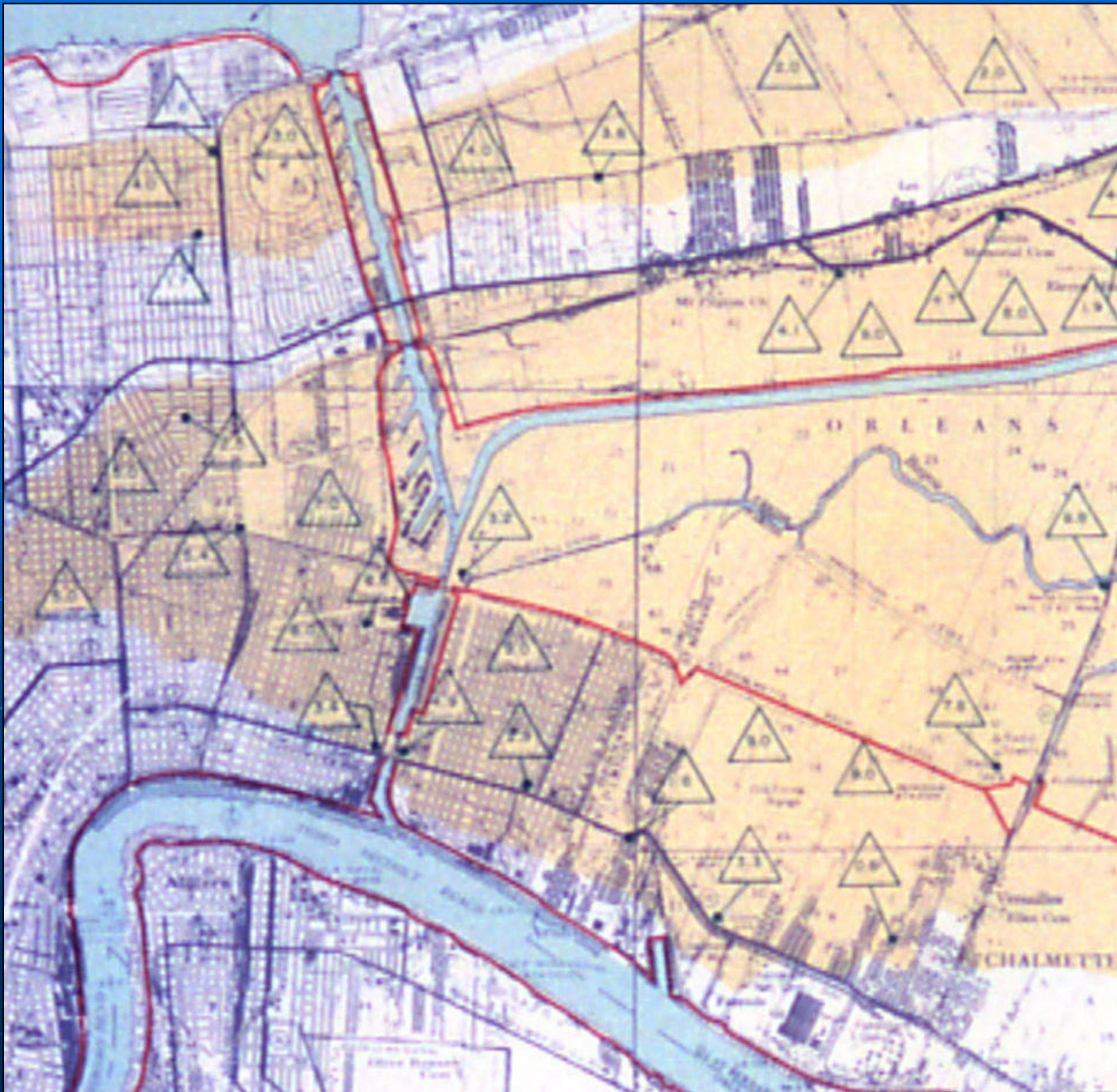
OVERVIEW: East Side IHNC Failures During Hurricane Katrina

East Side IHNC South Breach

Polluted and run-down industrial leases along east side of the IHNC were demolished and cleaned up in 2001-03, leaving exposed shell fill



Same area after re-flooding by Hurricane Rita in late September 2005



1965 flooding

- The Lower Ninth Ward was flooded by overtopping of the levees along the IHNC in 1947 and 1965
- The levee was heightened using rolled fill after both floods
- Sheetpiles added after Hurricane Camille in 1969

- Aerial view of the 900 ft long south breach of the Inner Harbor Navigation Channel (IHNC) in the Lower Ninth Ward. View looking south.

- **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-IGWW 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

- Evidence of sustained overtopping of concrete flood wall along the IHNC in the Lower Ninth Ward. Scour holes usually limited to 1.5X height of the free fall (7.5 ft). This scour trench deepened to the north, as elevations dropped.

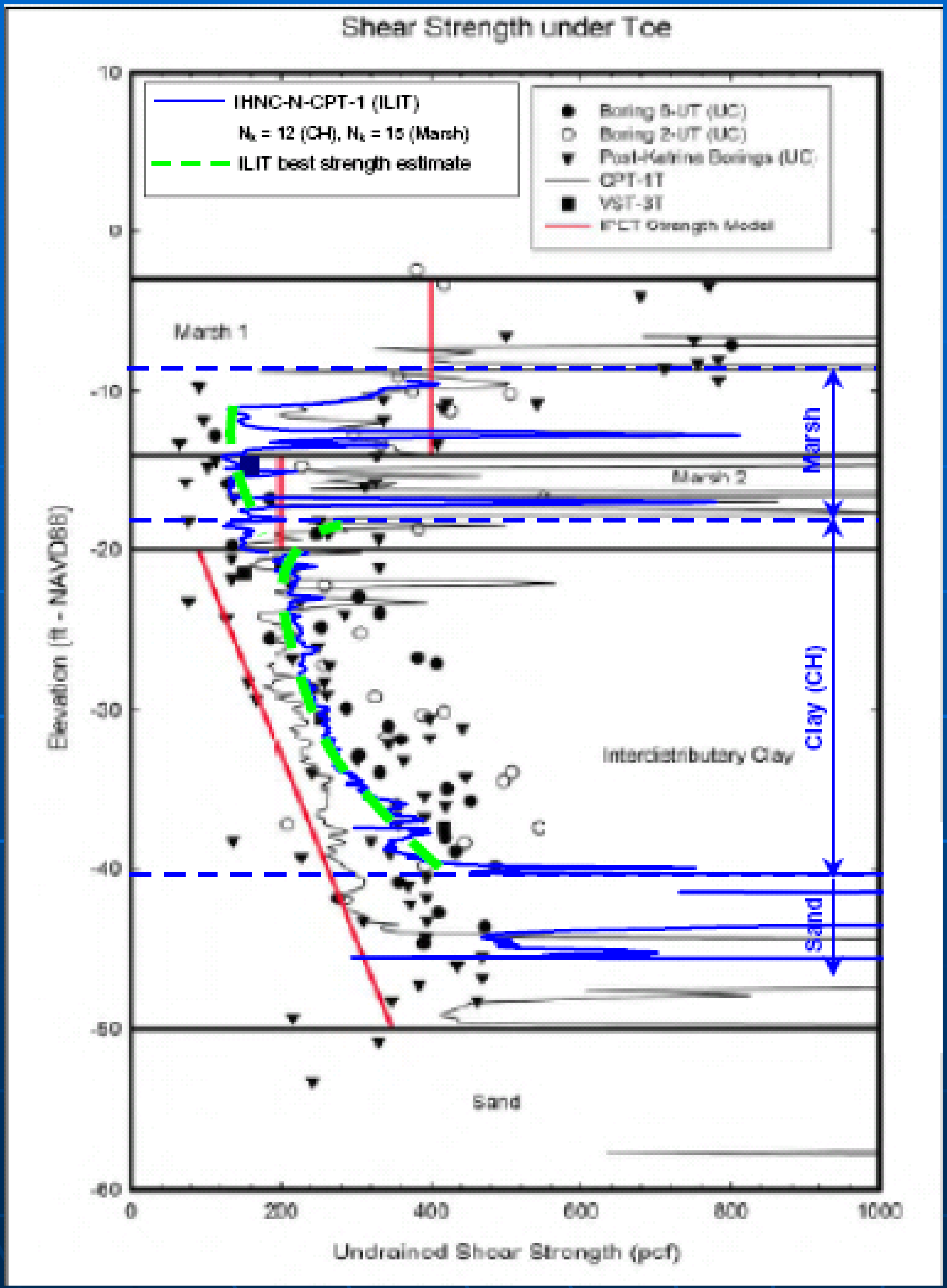
- Overtopping-induced failure of the flood wall on the west side of the IHNC, north of Florida Ave. This breach was only 65 feet wide.

ANALYSES:
East Side IHNC
North Breach

East Side IHNC North Breach

East Side IHNC North Breach, near Florida Ave. bridge and pumping station, during inflow. Note narrow chasm defined by this failure and dramatic flexure of the sheetpiles.

East Side IHNC North Breach, after de-watering.
Note tunnel-like geometry of this narrow breach



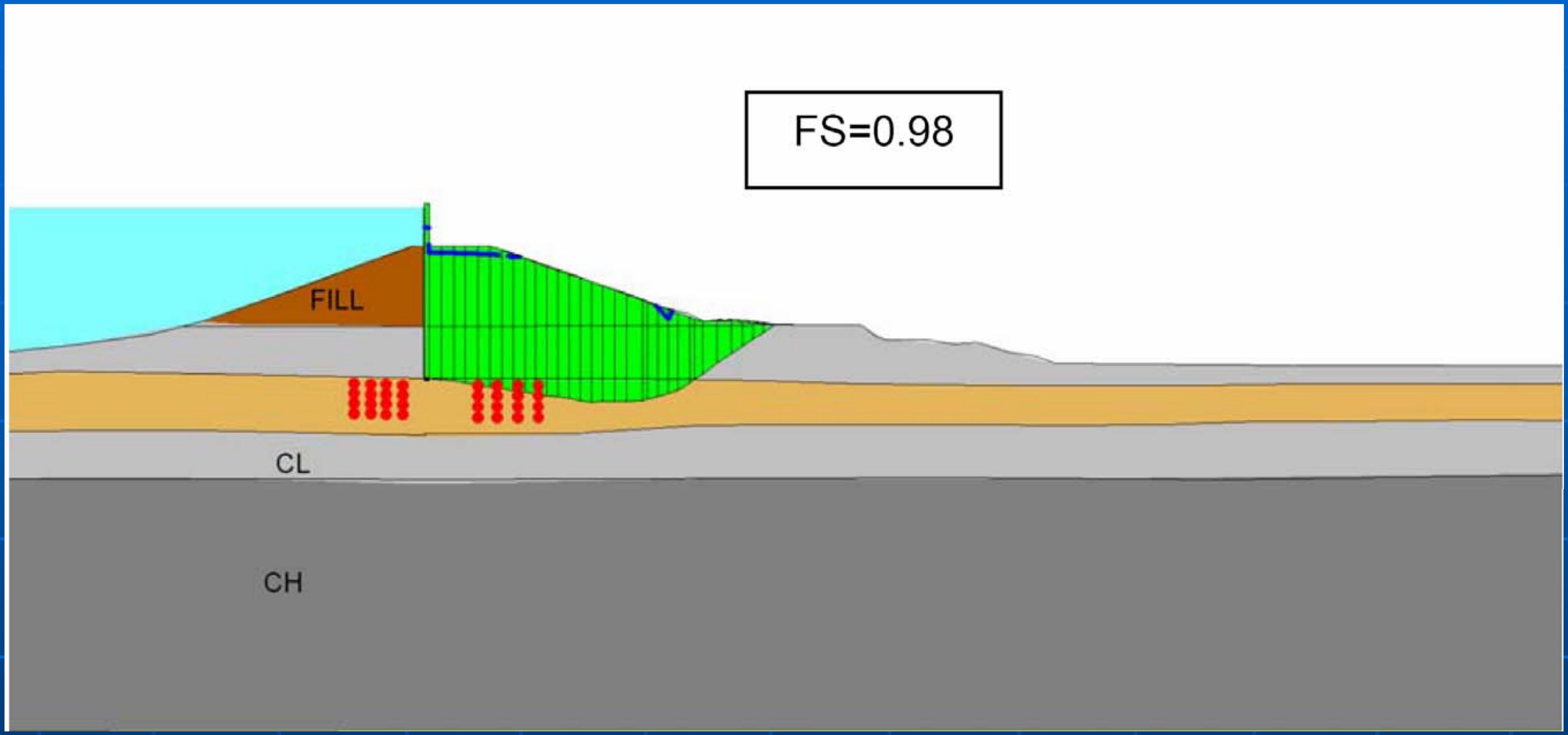
Undrained shear strength vs depth at the East IHNC North Breach

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

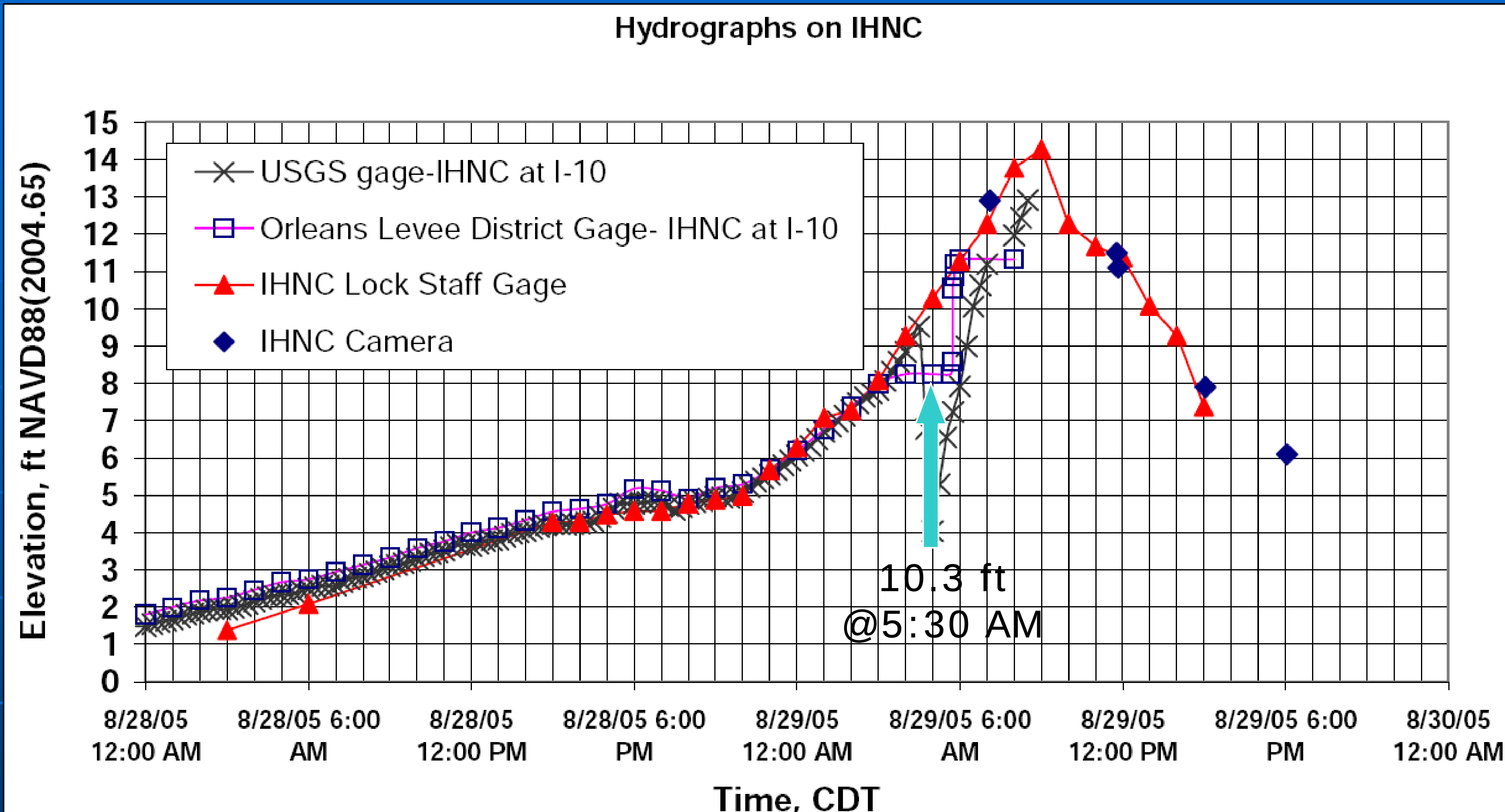
Green line shows strength profile selected by the NSF team

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

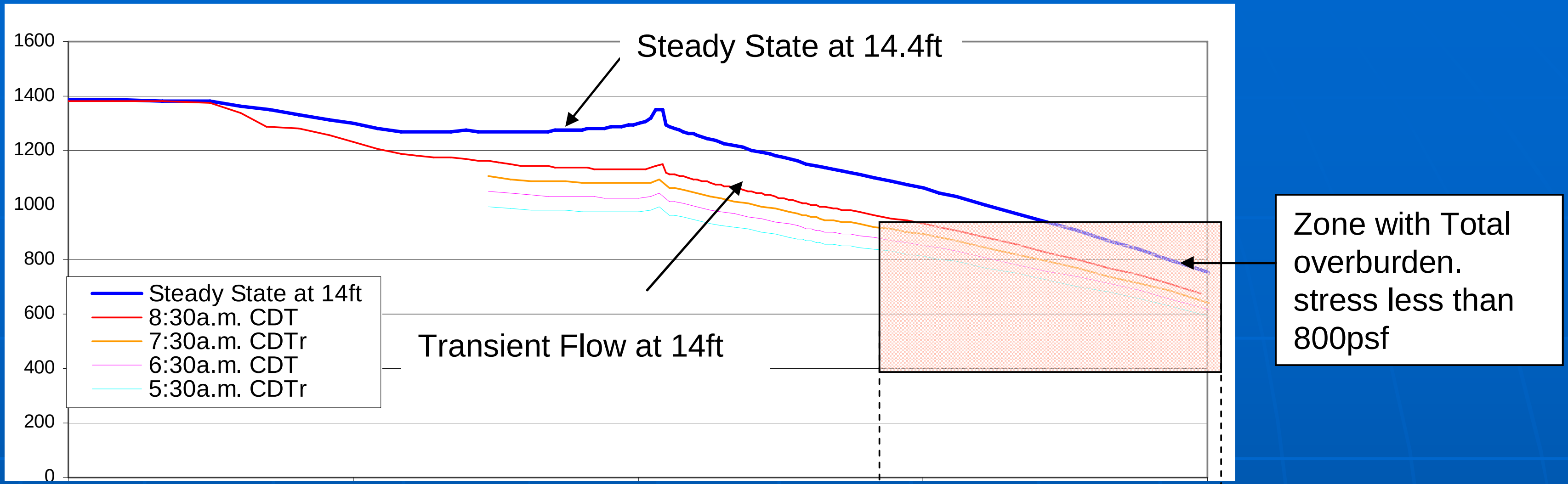
Slope Analysis IHNC North Breach



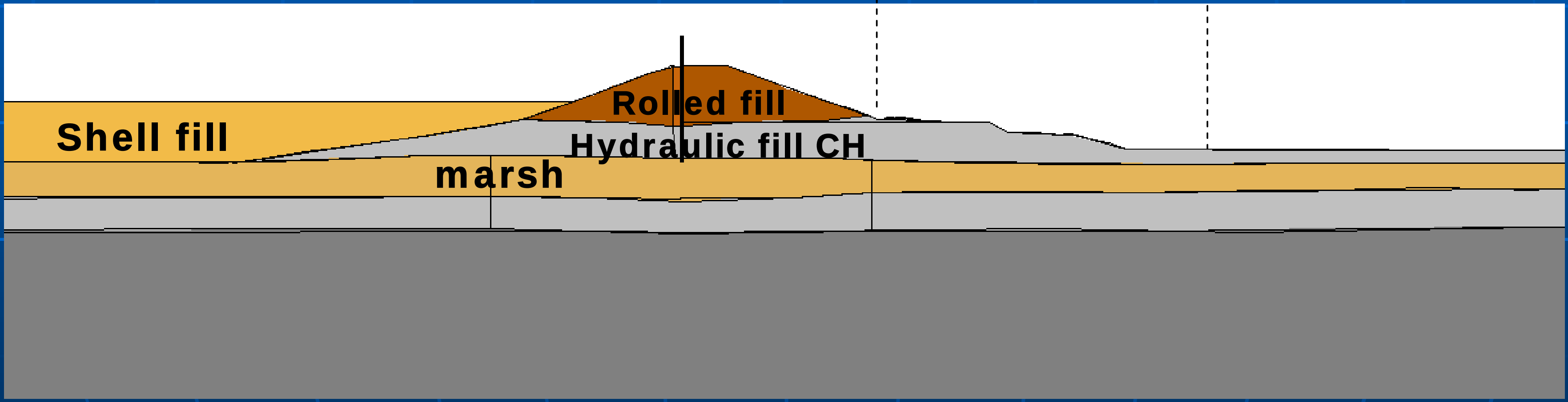
Critical stability conditions for East IHNC North Breach occur when the storm surge reaches +14 feet (MSL), which was not achieved until 9 AM. Note that the presumed failure surface passes through the marsh layer.



The storm surge caused by Katrina began three days before it made landfall, seen here as the gradual increase at left, about 0.32 ft/hr. Around midnight on August 29th, the rate increased 4X, to about 1.2 ft/hr . These rates and levels were used in our seepage analyses.

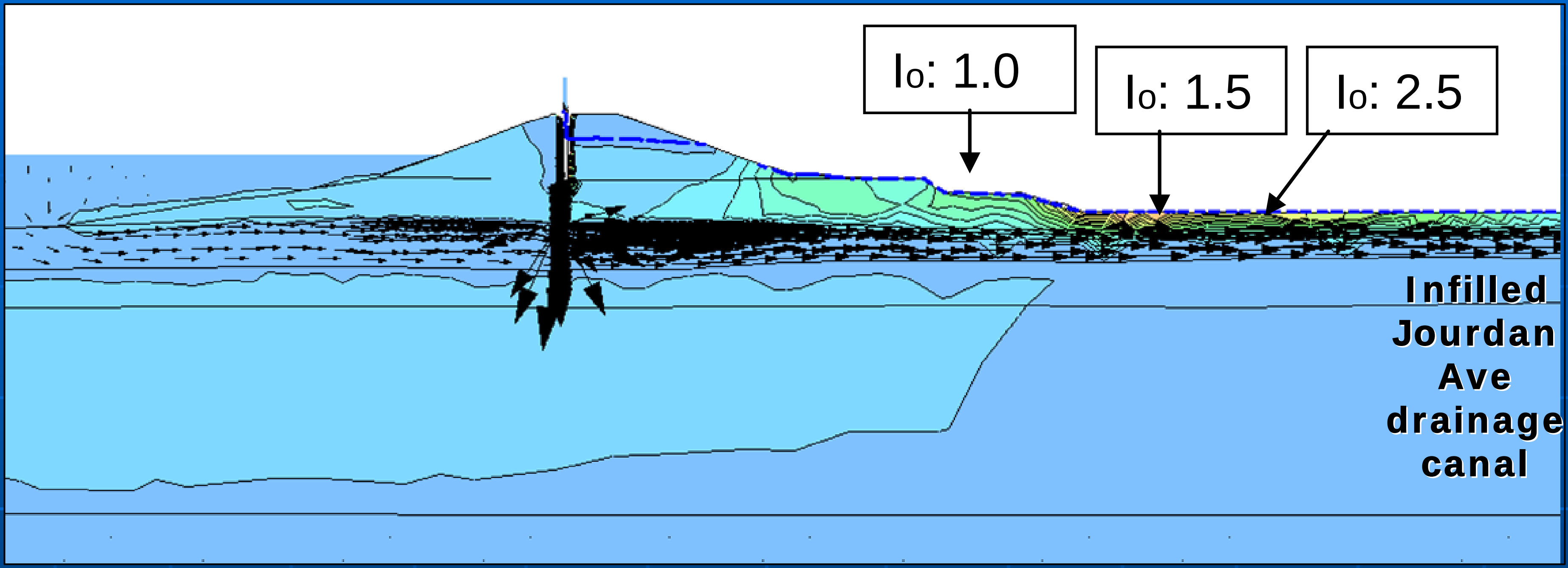


East Bank IHNC North Breach



Cross section used for limit equilibrium and coupled seepage analyses. Upper plot shows pore pressure versus horizontal distance and time for this section.

Severe hydraulic gradients for piping and uplift



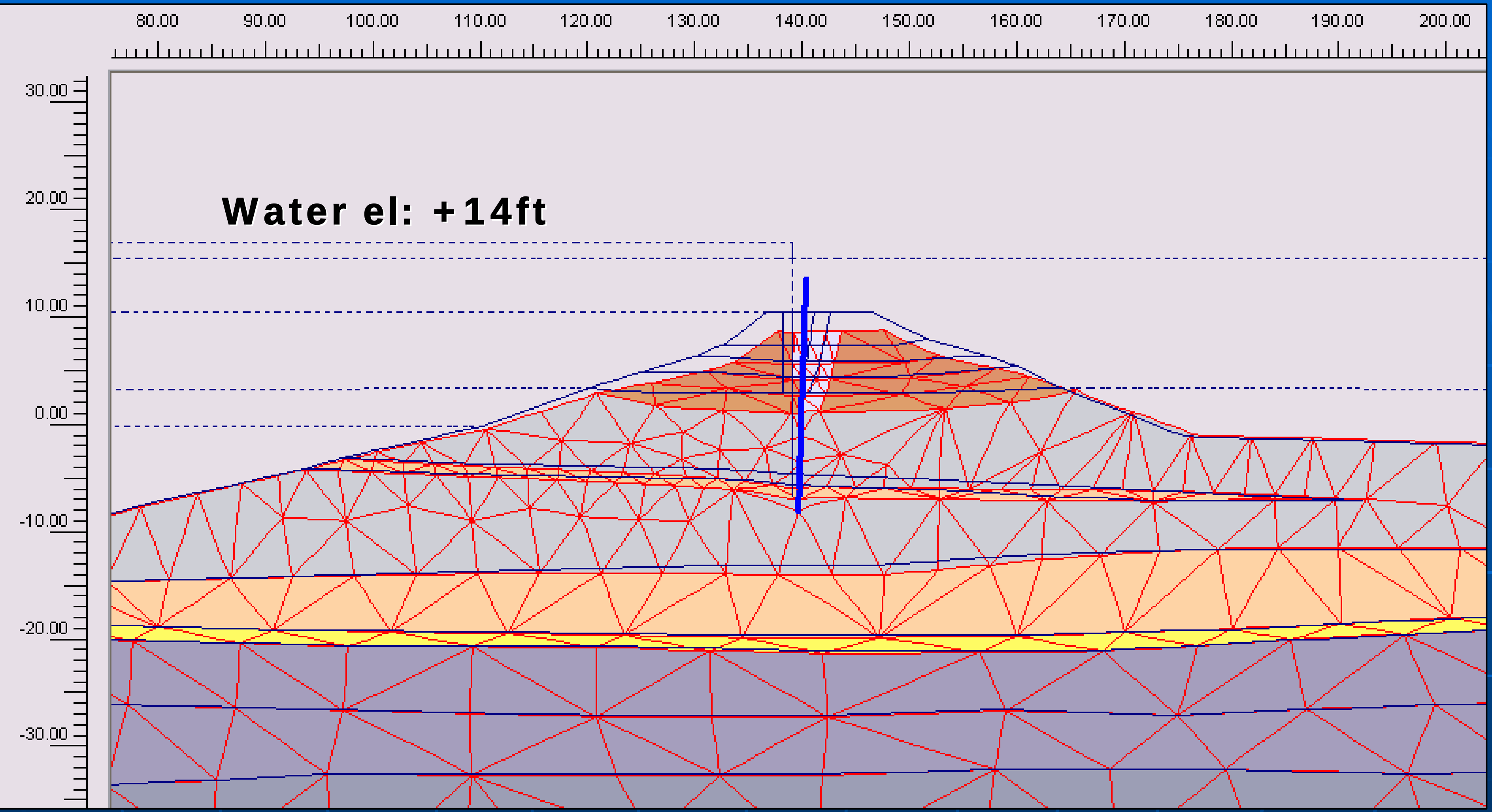
Hydraulic gradients for the north breach on IHNC. Storm surge at +14.4ft (MSL). Maximum exit gradient on the upper levee toe is $i_o \approx 1.0$, and $i_o \approx 1.5$ to 2.5 in the lower toe area. The distal toe value could have been worse, depending on k value of backfill used on Jourdan Ave. drainage canal.

Post Failure Analyses of East Side IHNC South Breach

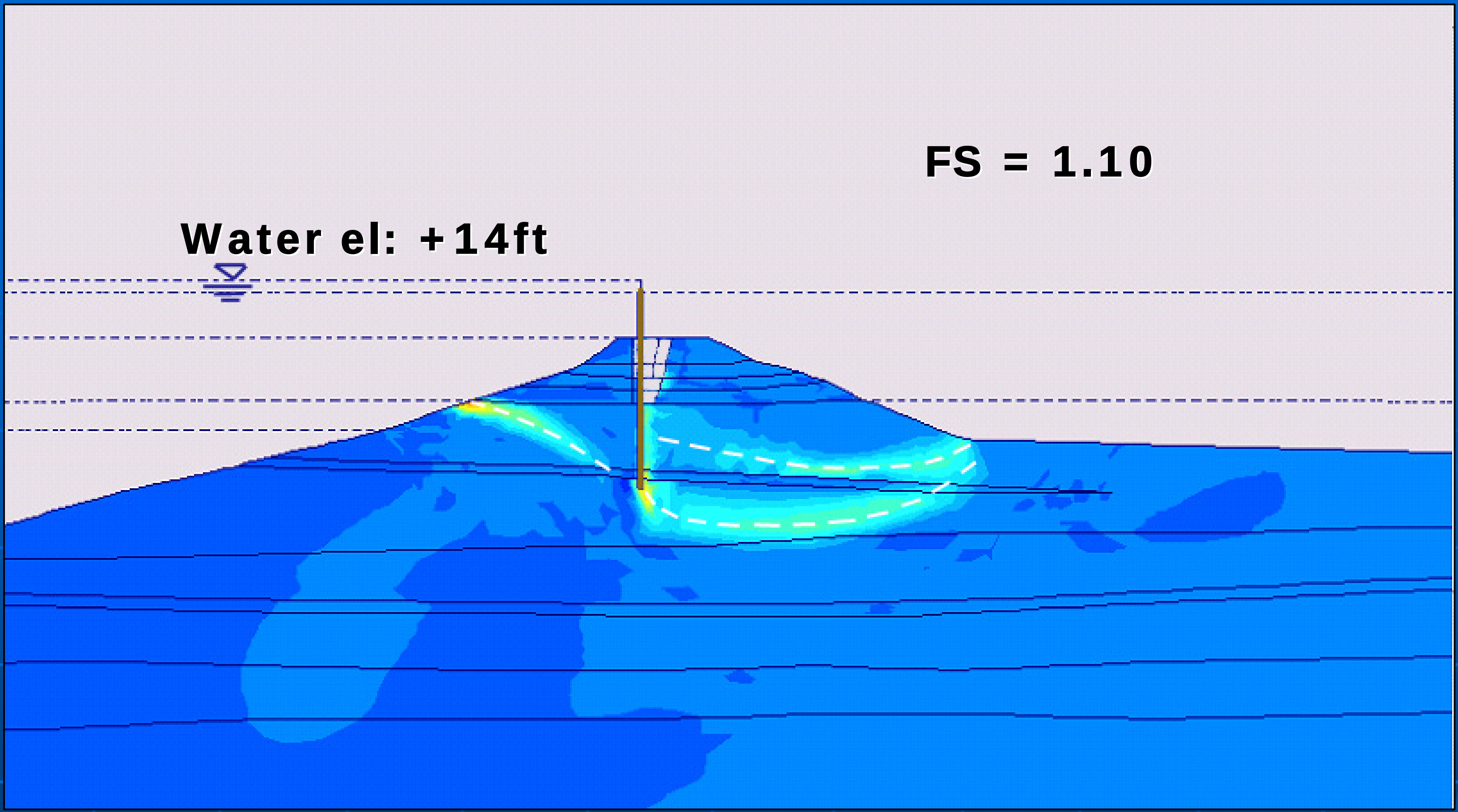
Possible failure modes:

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

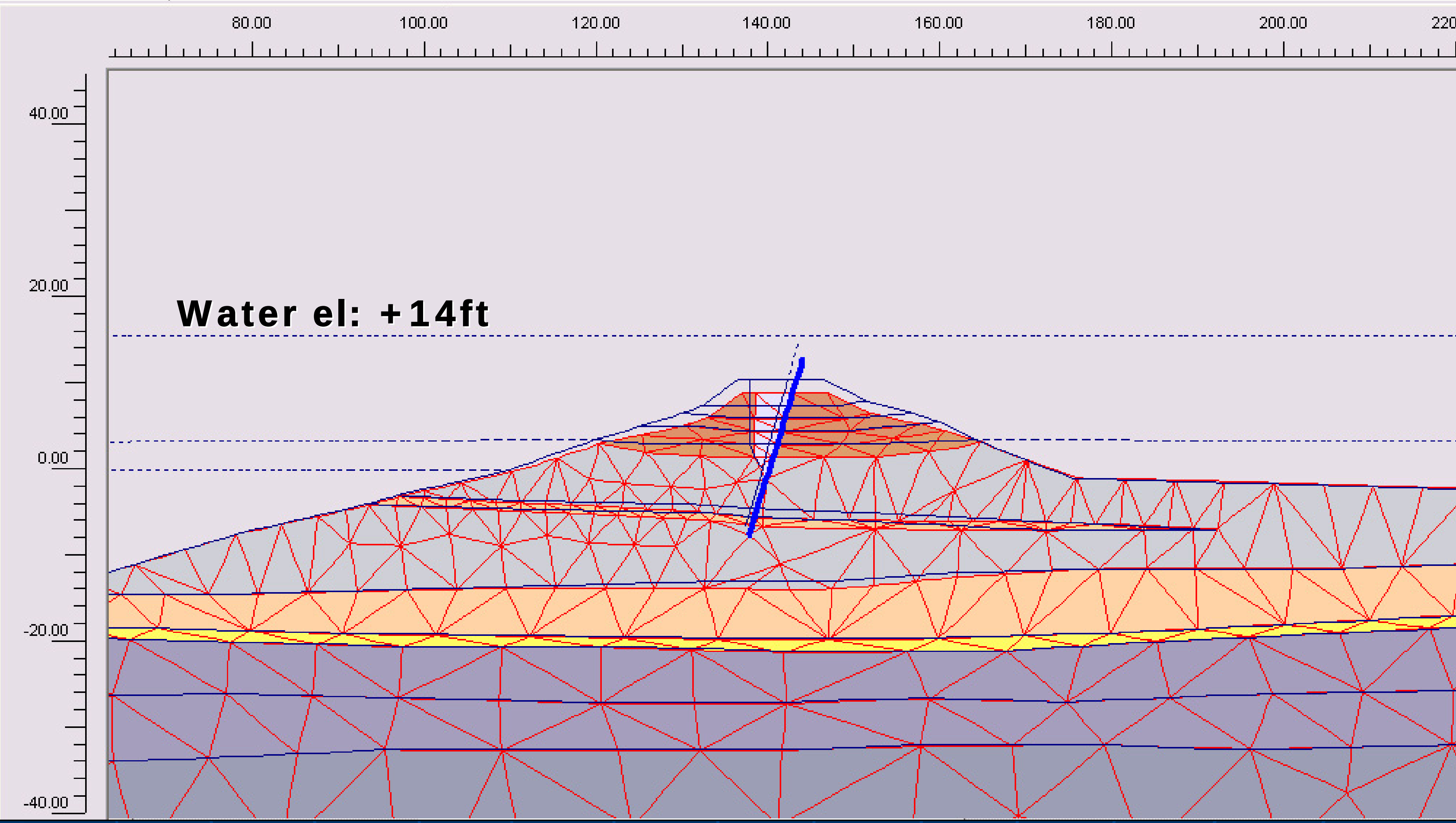
ANALYSES: Stability of Flood Wall East IHNC South Breach



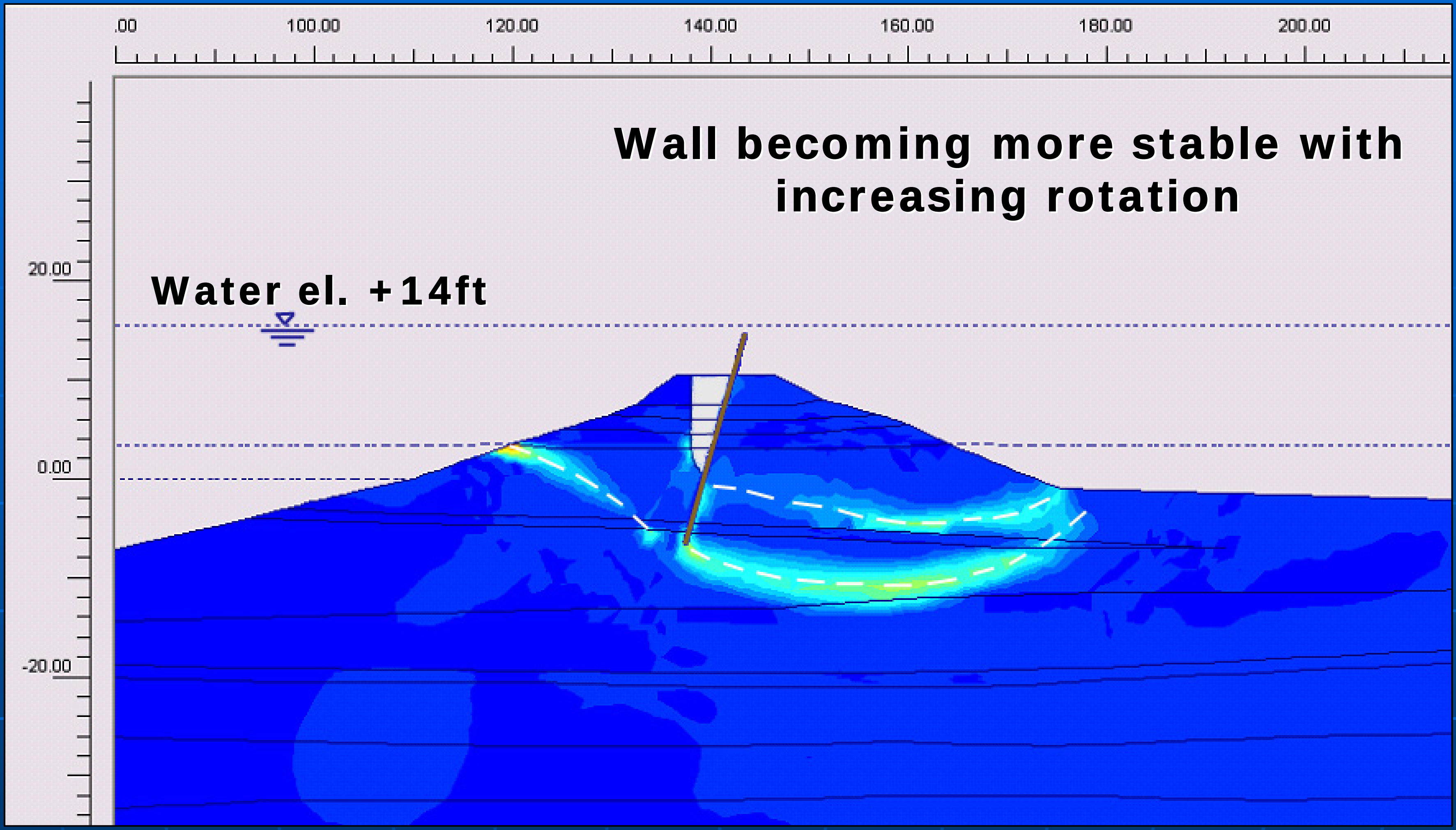
Plaxis soft soil constitutive modeling of 7.5 ft deep scour trench and 4.5 ft gap – deformed mesh – true scale (max displacement of embankment crest = 1.2 ft)



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 phi – Factor of Safety = 1.10. Underseepage-induced pore pressure trapped along base of less pervious clay stratum, overlying the more pervious marsh deposits.



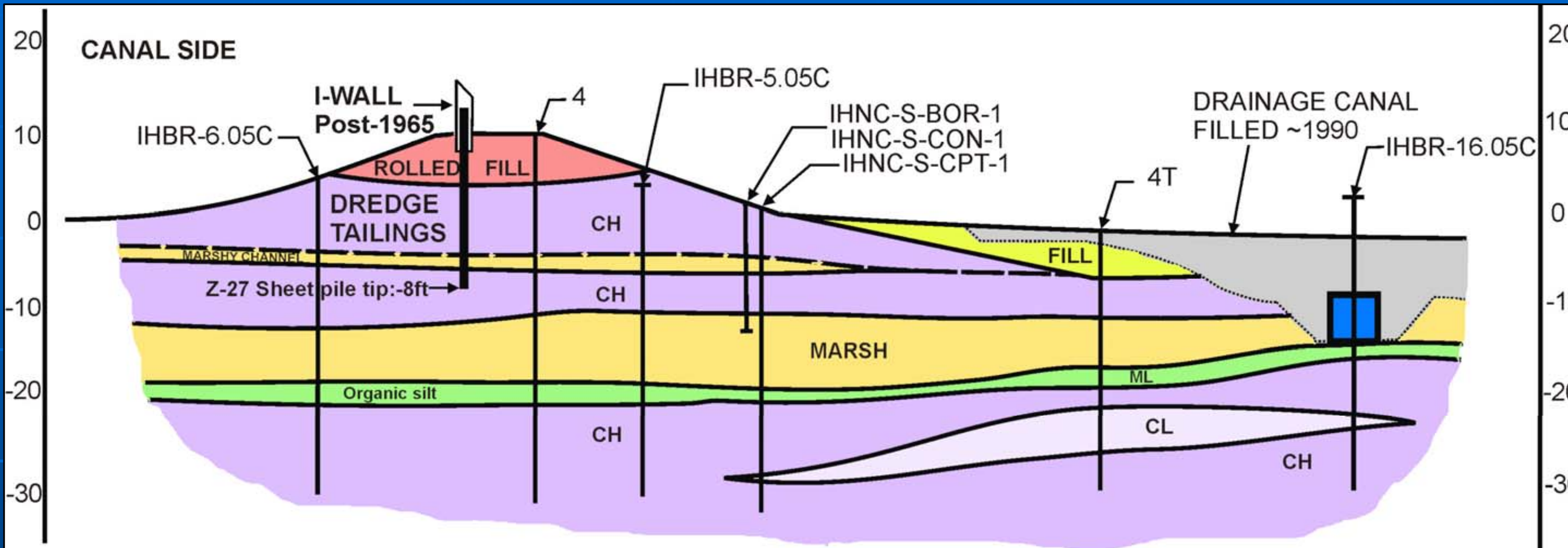
Leaning wall with 8.5 ft of gap – deformed mesh – true scale (max displacement = 1.71 ft)



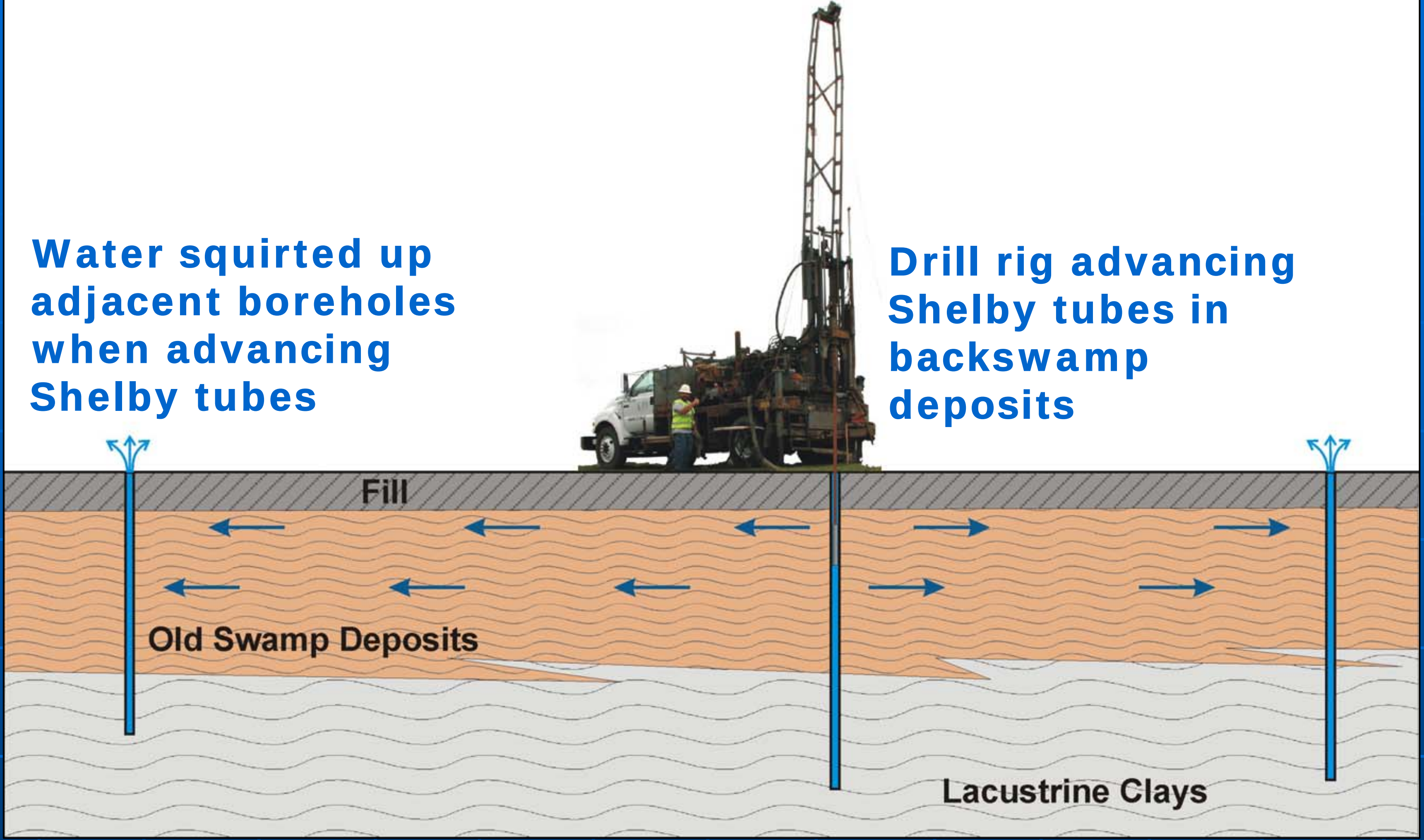
Leaning wall with 8.5 ft of gap. Predicted shear strains using “best estimates” of c and phi. Factor of Safety now = 1.15

Coupled Seepage Analyses of Embankment along East IHNC South Breach

East Bank IHNC South Breach

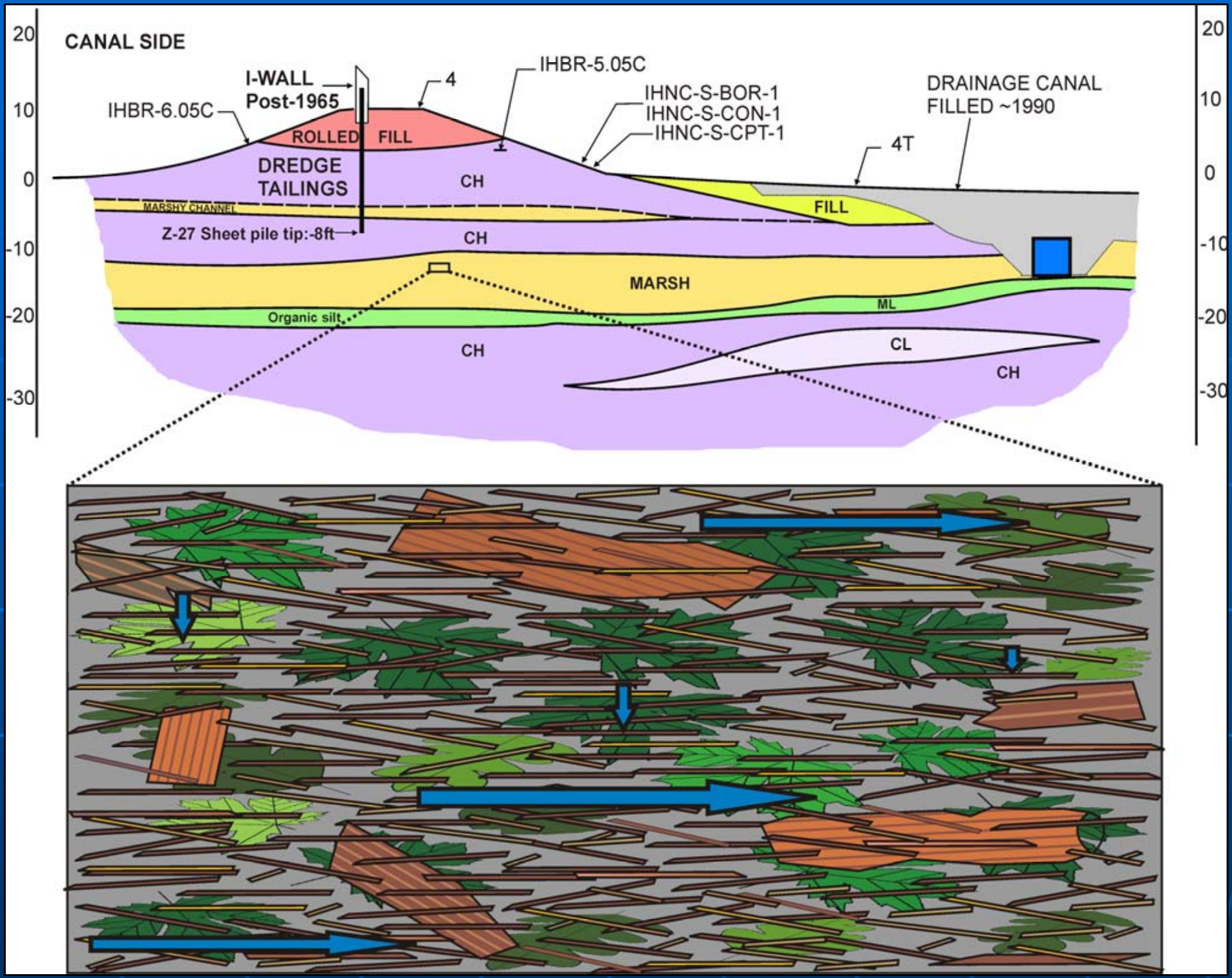


Geologic cross-section showing projections of borings and tentative stratigraphic correlations for the 800 ft long IHNC East Bank-South Breach, adjacent to the Lower Ninth Ward

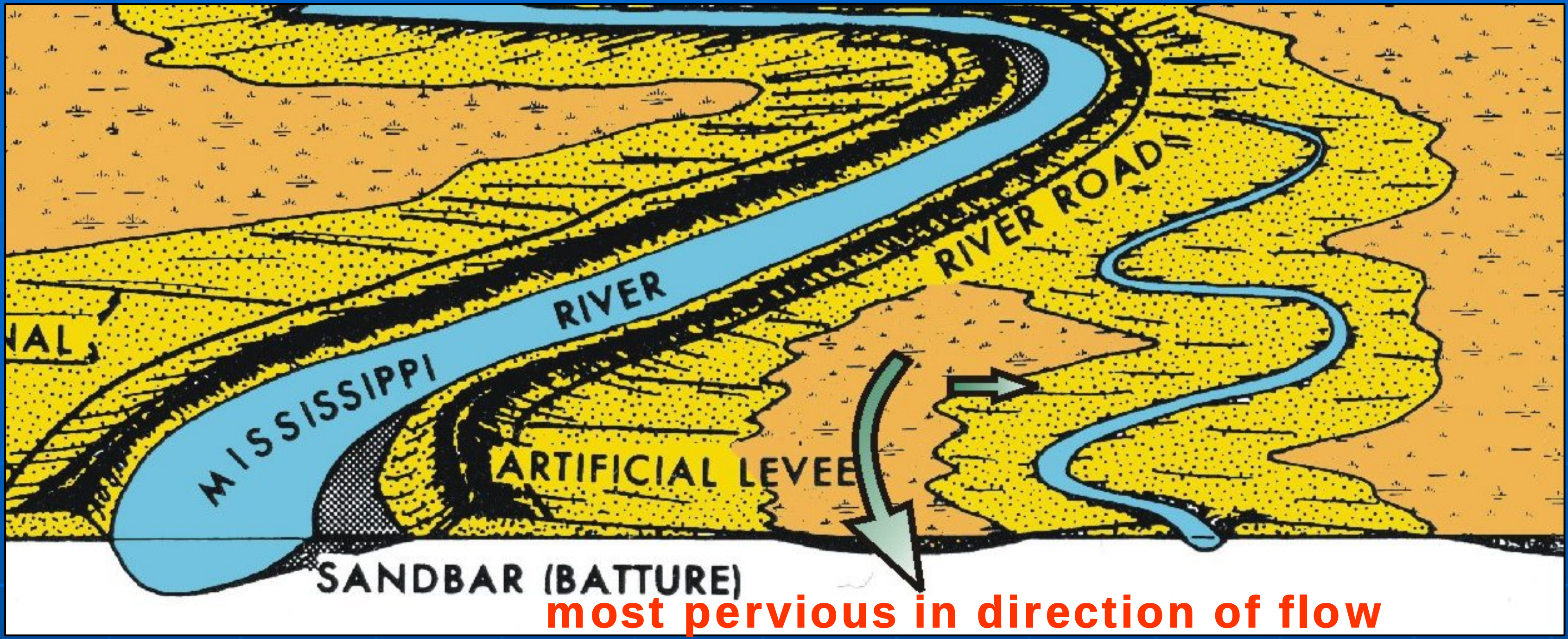


- The porous and highly conductive nature of the backswamp deposits was revealed during post-Katrina drilling and sampling operations.
- Highly conductive in horizontal plane, especially, parallel to original surface drainage.

Anisotropy of backswamp deposits



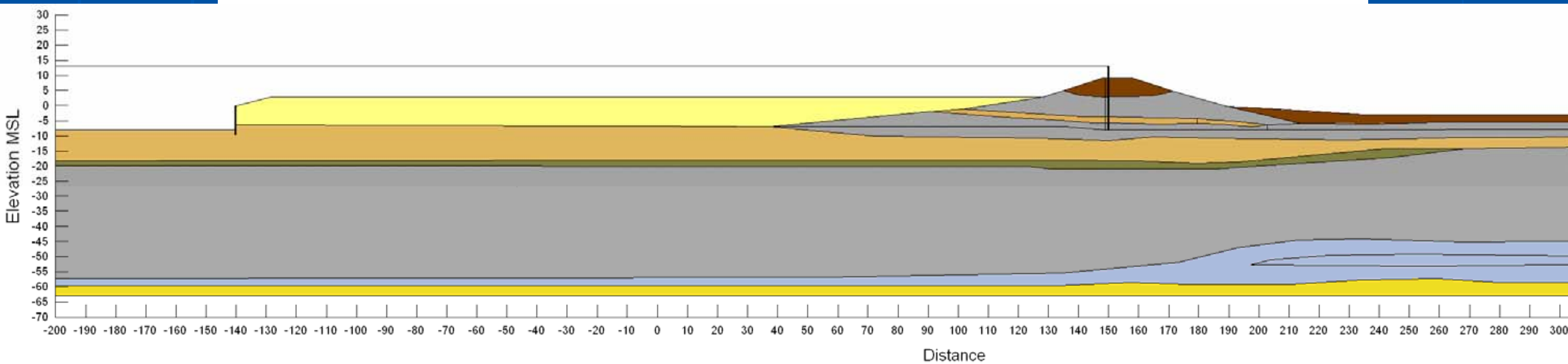
- **Sudden die-off of organics creates highly anisotropic fabric; preferentially layered**



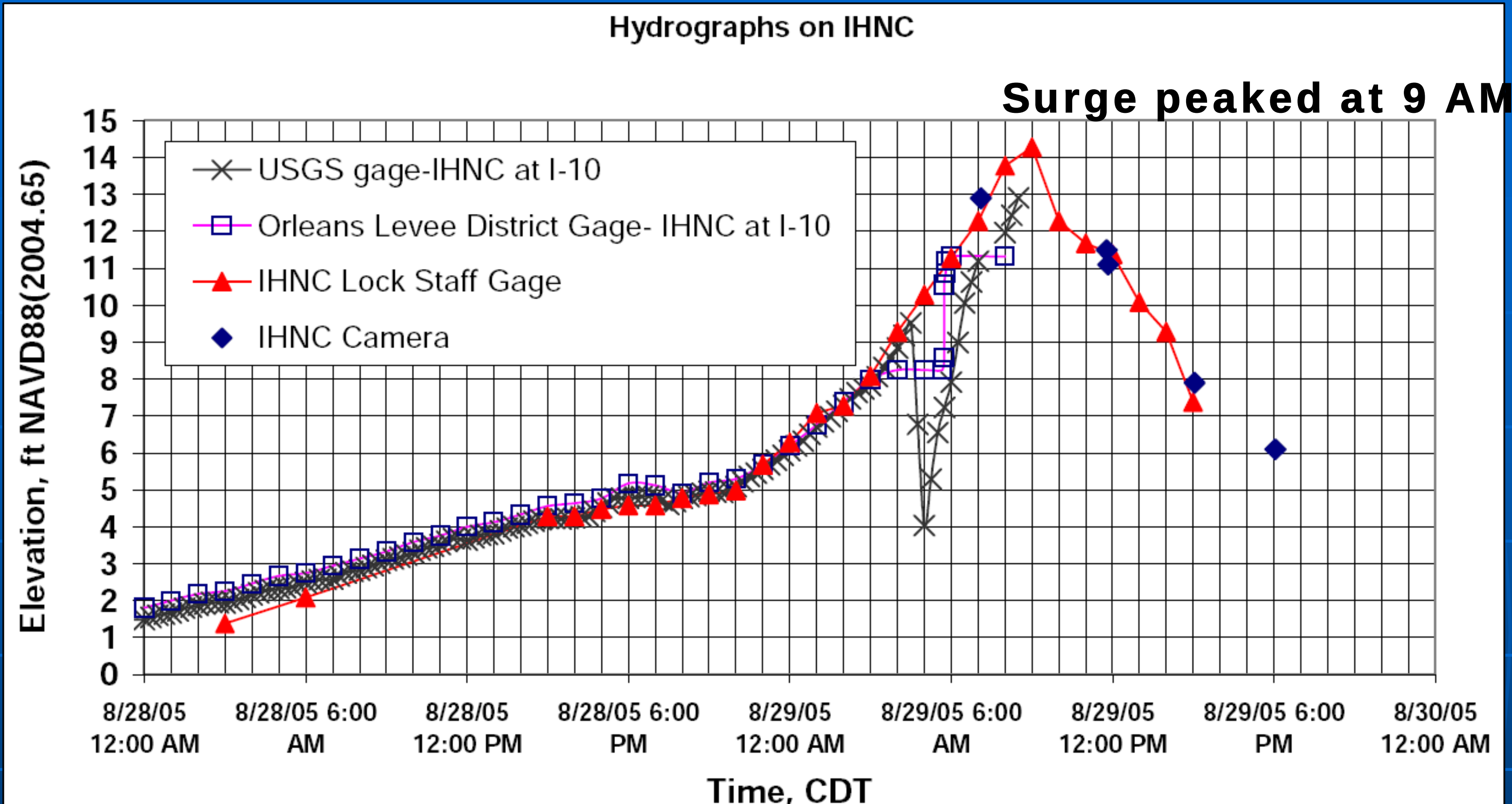
- Drainage swales in the backswamps are subject to sieving of fines by runoff
- This causes hydraulic conductivity to increase along the runoff path, as opposed to other seepage paths, within the plane of sediment accretion

	PARAMETER						
MATERIAL	**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

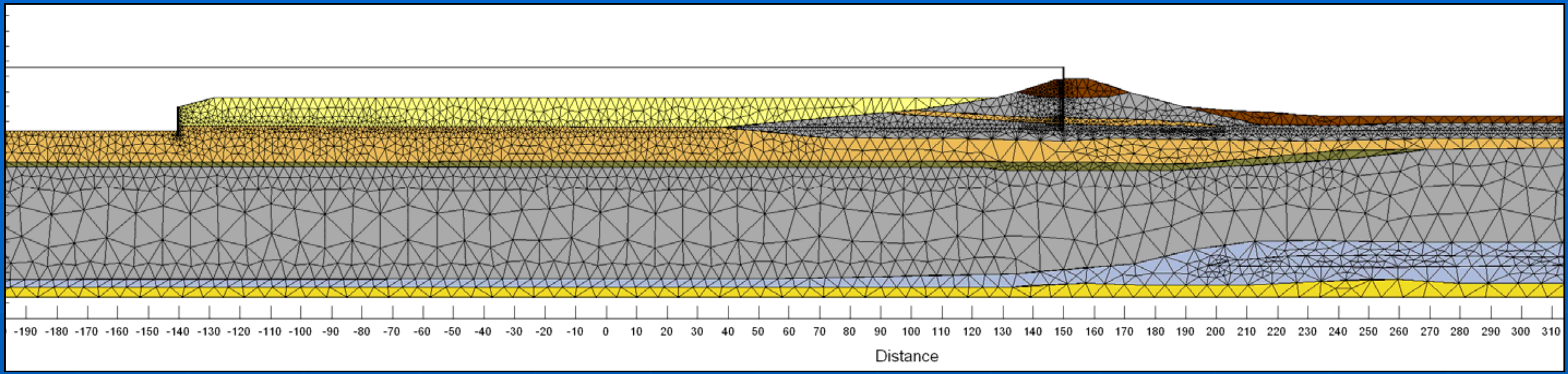
* Fredlund et al, Green and Corey, Van Genuchten



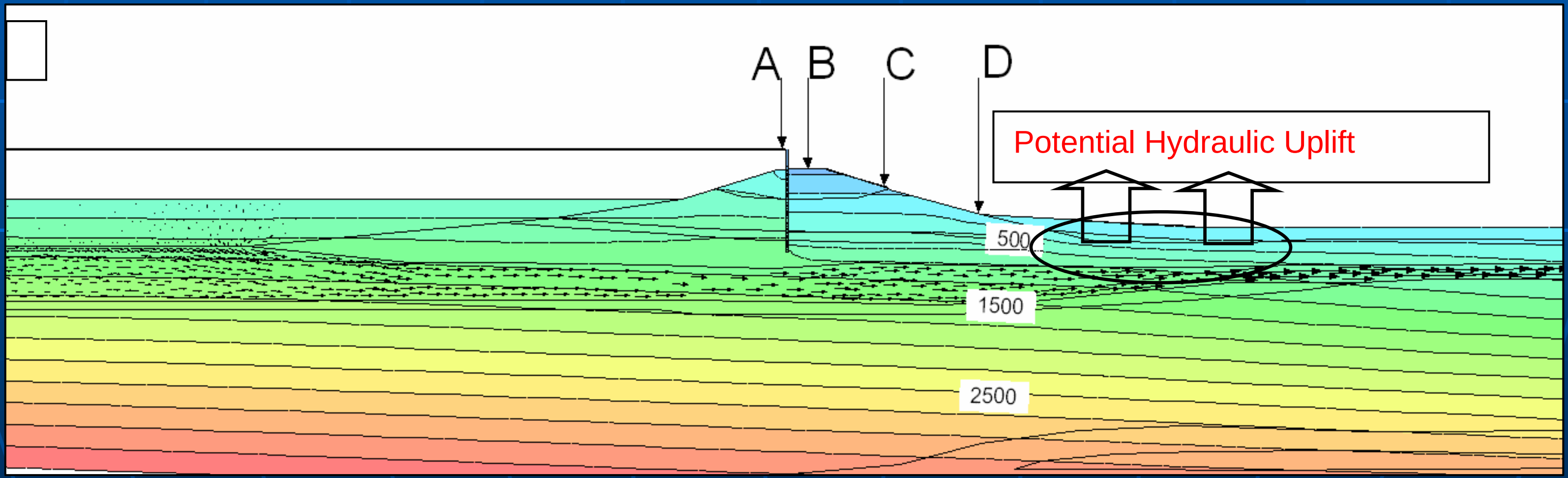
Geotechnical cross-section for conventional limit equilibrium and coupled seepage analyses of the east bank IHNC south breach.



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

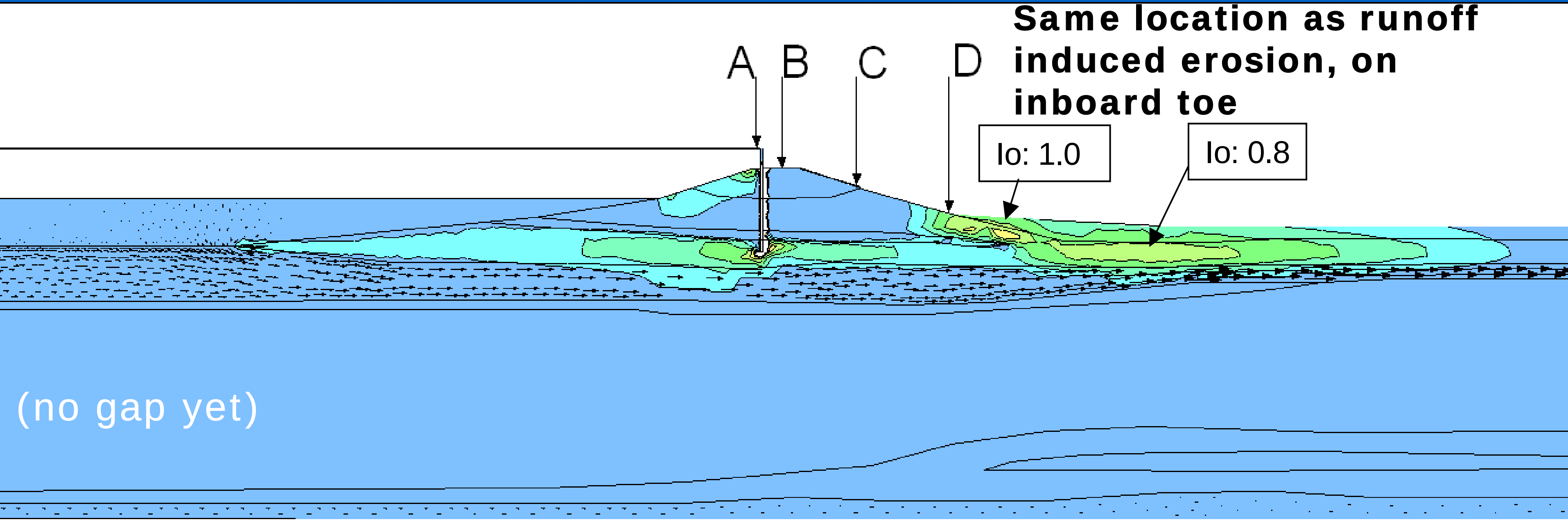


Finite difference mesh for seepage analyses for east bank IHNC south breach.



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.

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]

Slope Stability Analysis of East IHNC South Breach Embankment

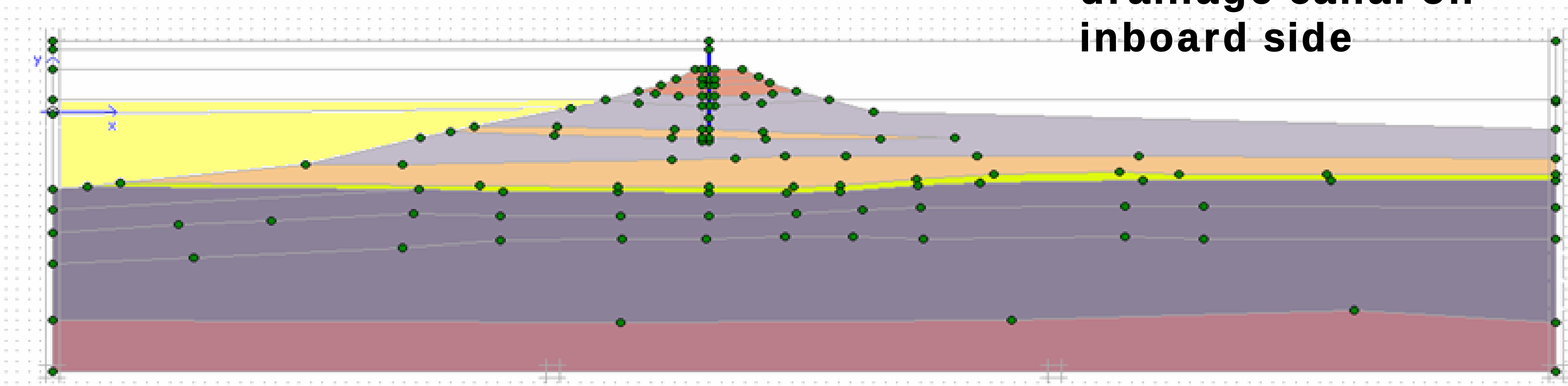
Embankment Stability of East IHNC South Breach

ID	Soil Model	Name	Type	g_unsat [lb/ft^3]	g_sat [lb/ft^3]	k_x [ft/day]	k_y [ft/day]	nu [-]	E_ref [lb/ft^2]	c_ref [lb/ft^2]	phi [°]
CF	Mohr Coulomb	ML-silt (Compacted Fill)	Undrained	105	115	0.0028	0.00028	0.35	234000	900	0.001
Bottom		Gray Clay (bottom)	Undrained	90	90	0.0028	0.0028	0.3	155000	800	0.001

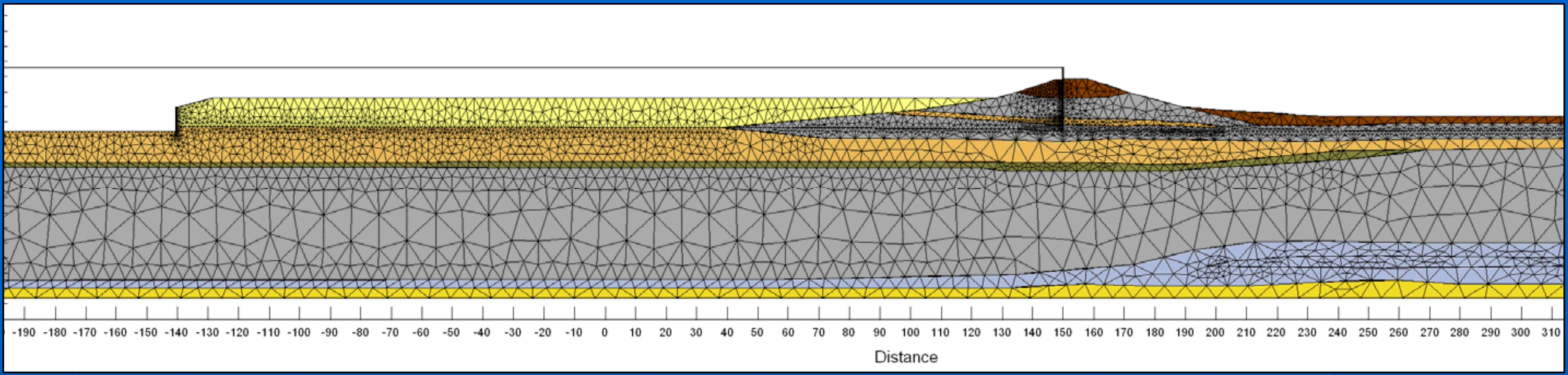
ID	Soil Model	Name	Type	g_unsat [lb/ft^3]	g_sat [lb/ft^3]	k_x [ft/day]	k_y [ft/day]	lambda* [-]	kappa* [-]	n_ur [-]	K0nc [-]	M [-]	c_ref [lb/ft^2]	phi @ pref [°]	OCR
M2	Soft Soil	Marsh 2	Undrained	80	80	28.3	2.8	0.21	0.033	0.15	0.60	1.90	0	36	1.1
M1		upper marsh	Undrained	80	80	28.3	2.8	0.2105	0.033	0.15	0.60	1.90	0.0001	36	2.25
ML		silt	Undrained	85	85	28.32	2.8	0.1	0.02	0.15	0.61	1.27	0.001	23	2
CH2		Gray Clay (CH)	Undrained	90	95	0.00028	0.000028	0.1684	0.03	0.15	0.63	1.24	0.0001	22	2.25-1.70
CH3		Gray Clay (CH)	Undrained	90	95	0.00028	0.000028	0.1684	0.03	0.15	0.63	1.24	0.001	22	1.1

ID	Name	Type	EA [lb/ft]	EI [lbft^2/ft]	w [lb/ft^2]	nu [-]	M_p [lbft/ft]	N_p [lb/ft]
1	I-wall	Elastic	6.32E+08	54290000	150	0.22	1.00E+15	1.00E+15
2	Sheetpile (Z-22)	Elastic	1.87E+08	16400000	22	0.22	1.00E+15	1.00E+15

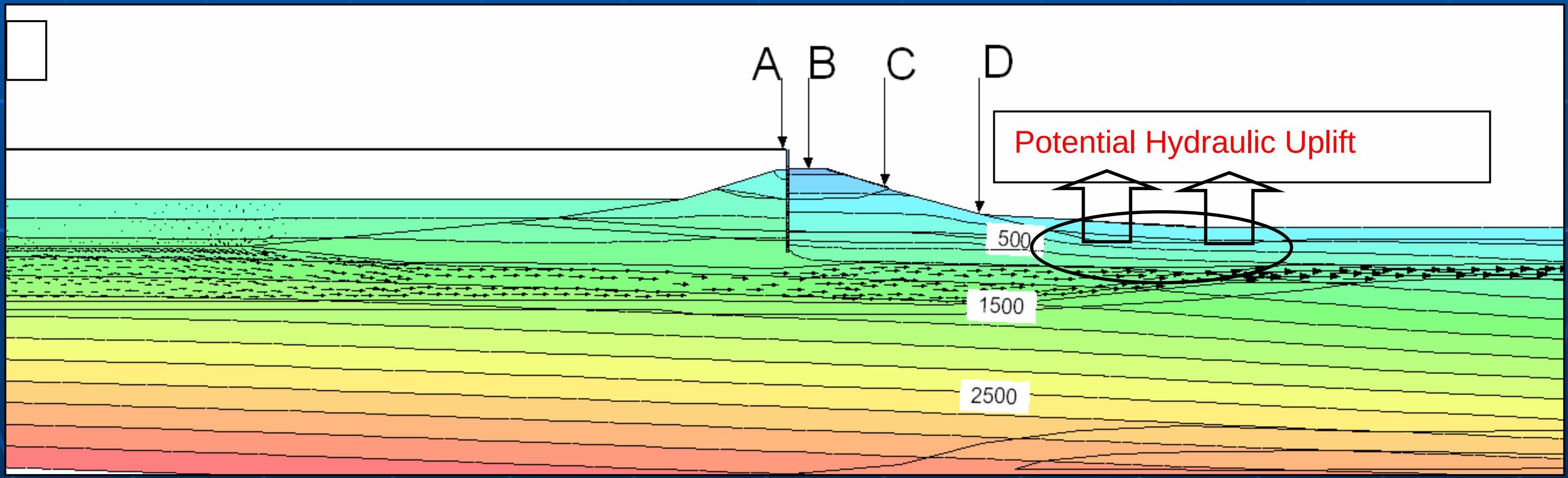
Ignored backfilled drainage canal on inboard side



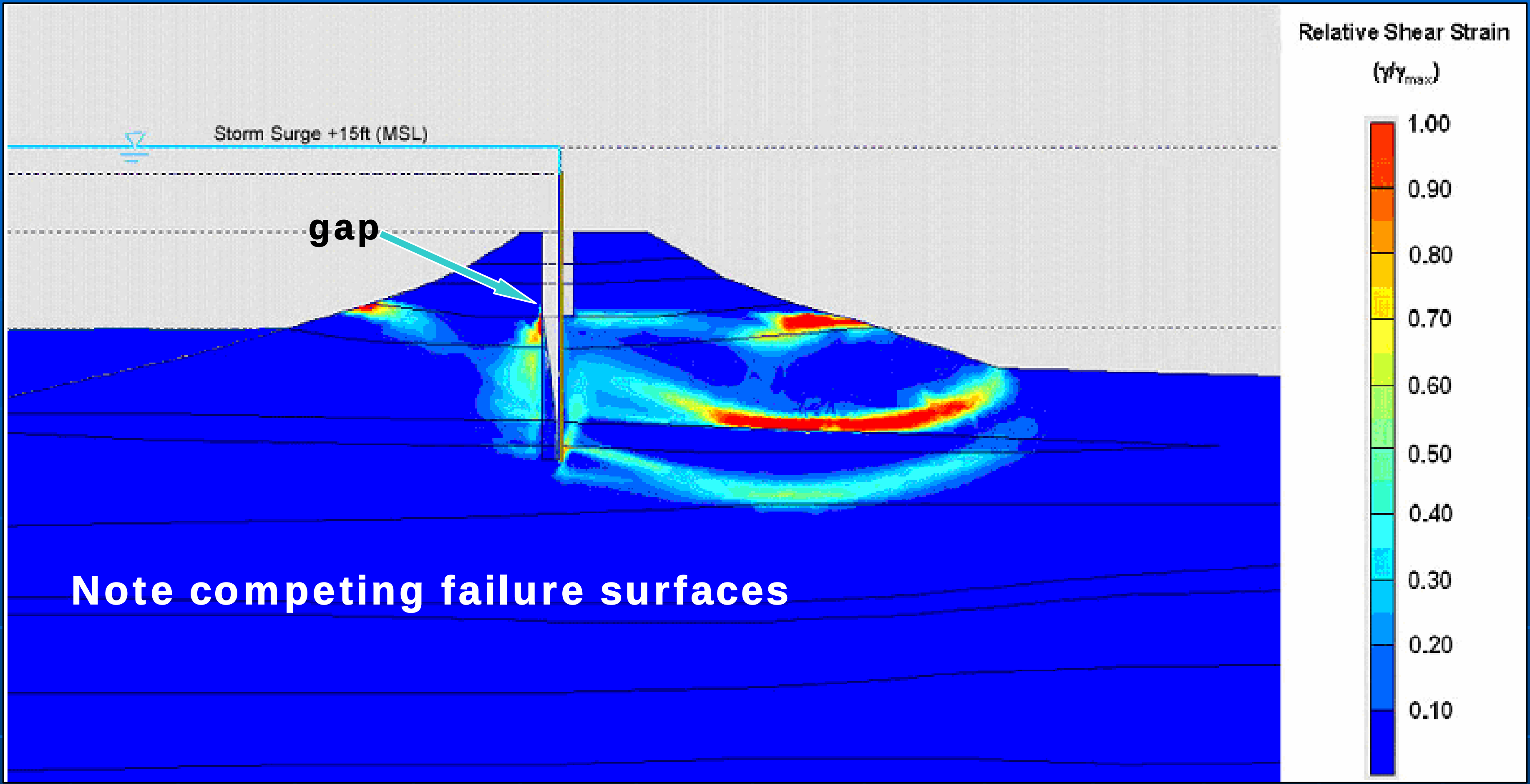
Geometry and input parameters for FEM (PLAXIS) stability analyses for Lower Ninth Ward, IHNC East Bank, South Breach.



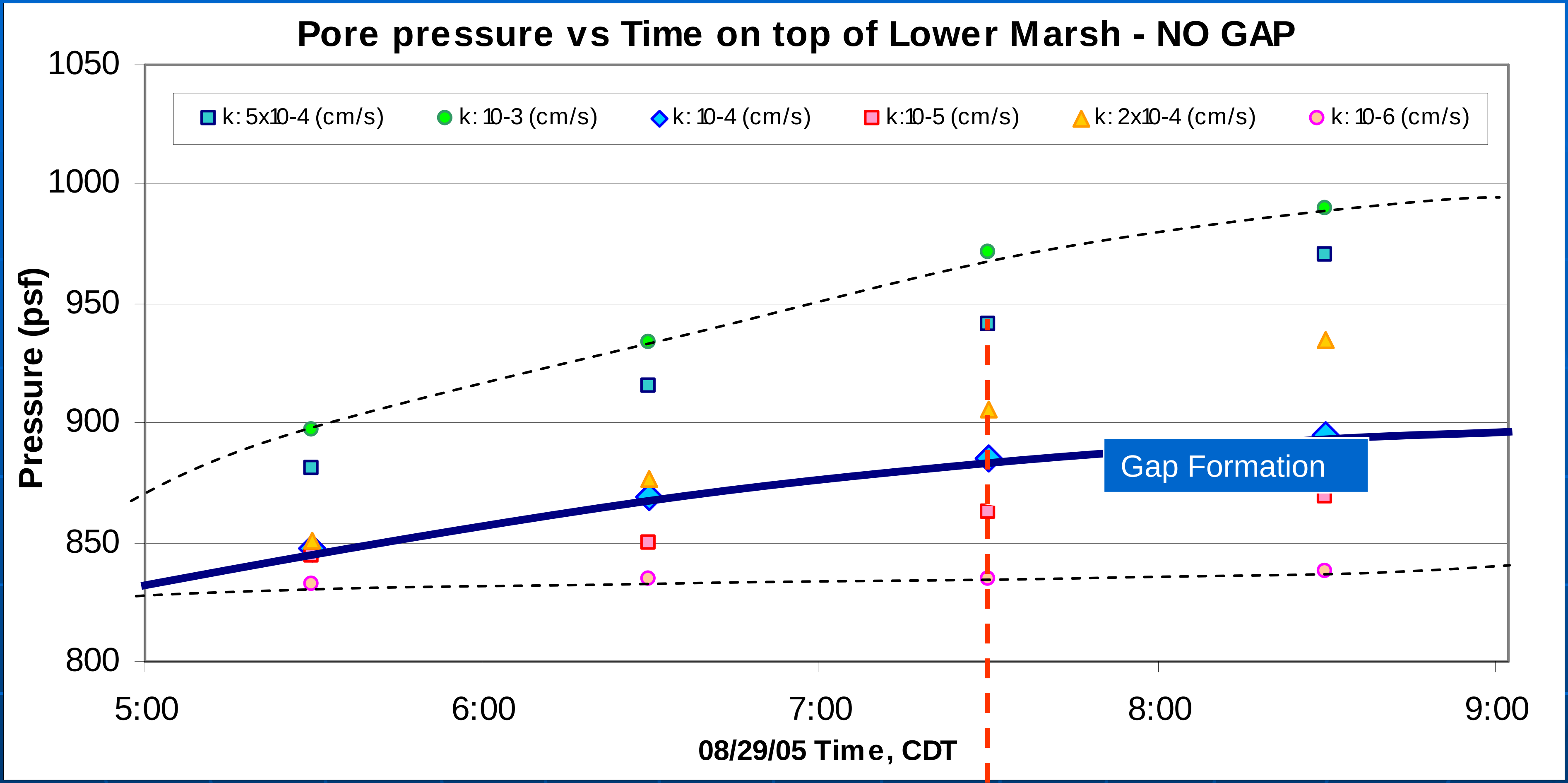
Finite difference mesh for seepage analyses for east bank IHNC south breach.



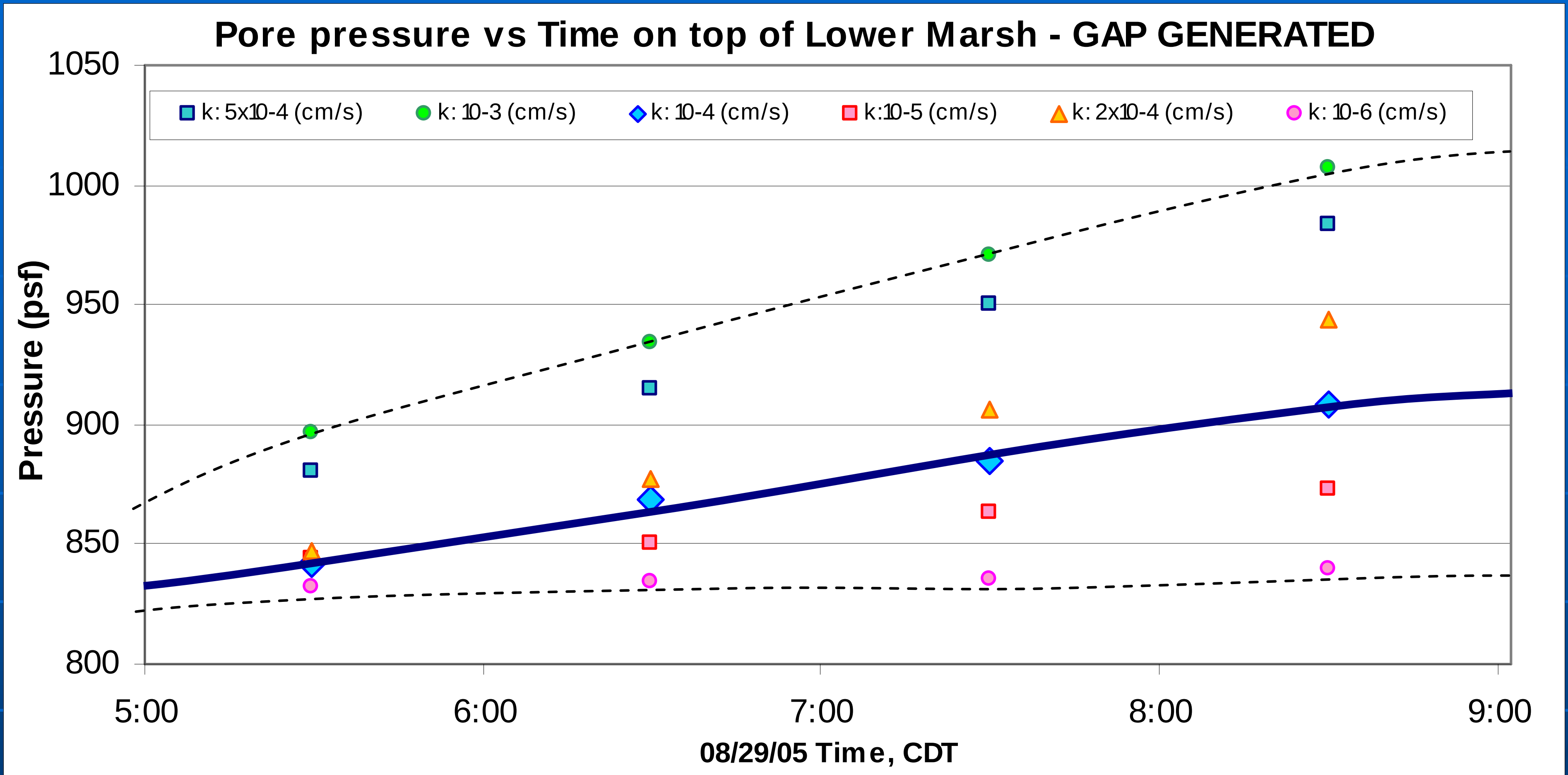
Pressure contours for the south breach on IHNC with storm surge at 14.4ft (MSL).



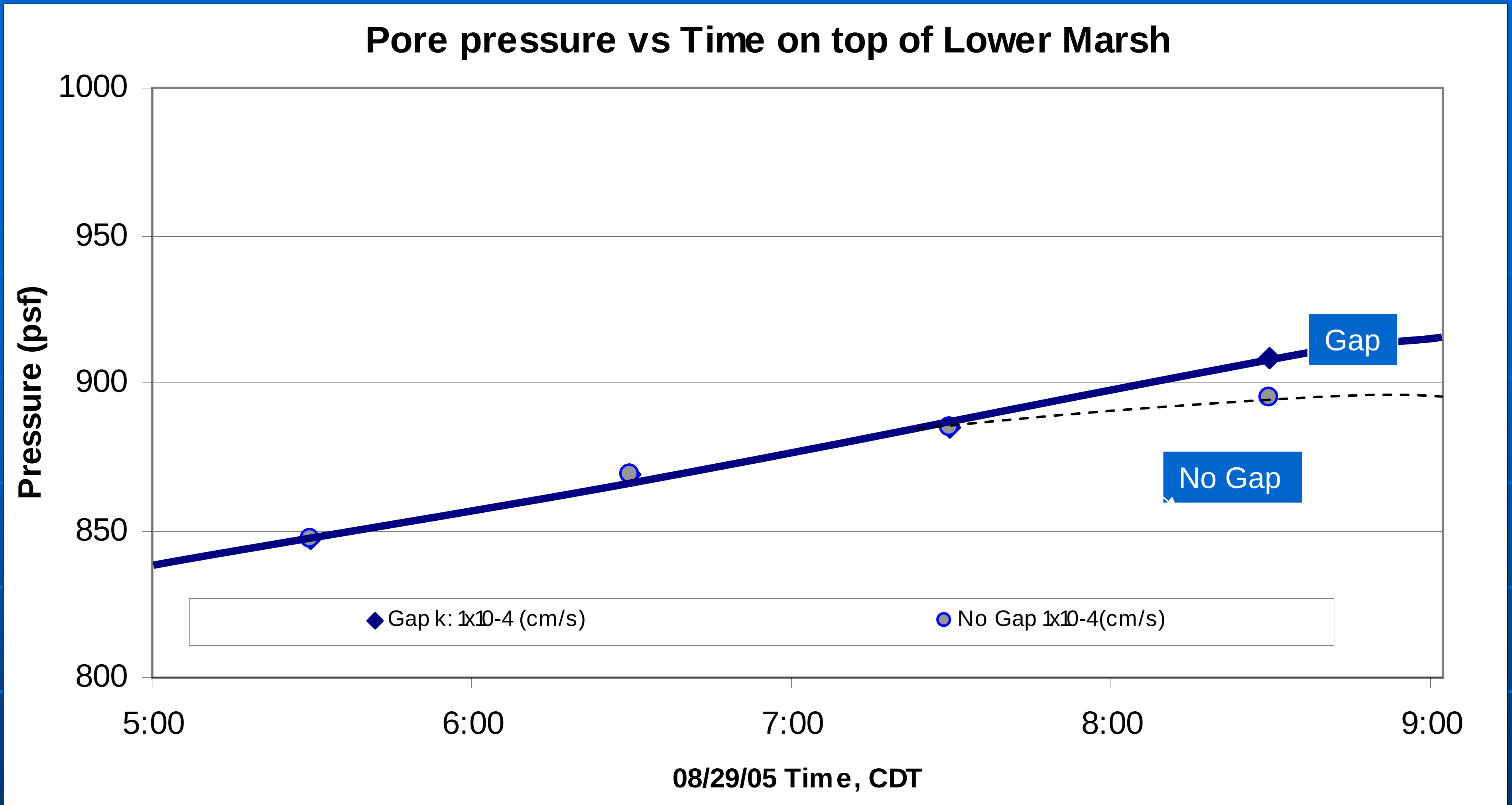
Normalized shear strain contours (shear strain divided by strain to failure) for a storm surge at Elev. + 14 feet (MSL) on the east IHNC south breech; gapping at outboard toe of floodwall is fully developed.



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

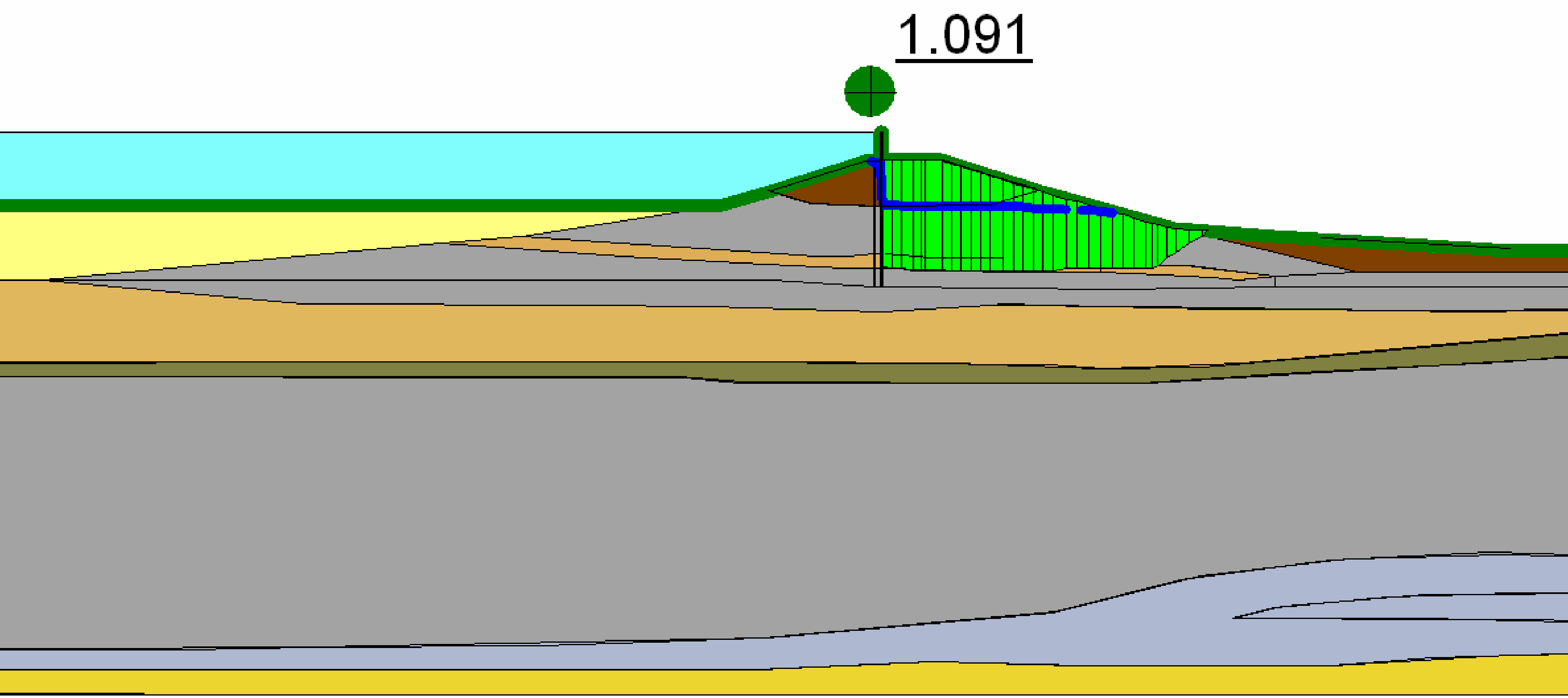


Estimated range in pore pressures at top of lower marsh unit if the flood wall developed a gap; assuming a range of horizontal hydraulic conductivity (k) in the marsh units, varying between 10^{-3} and 10^{-6} cm/sec



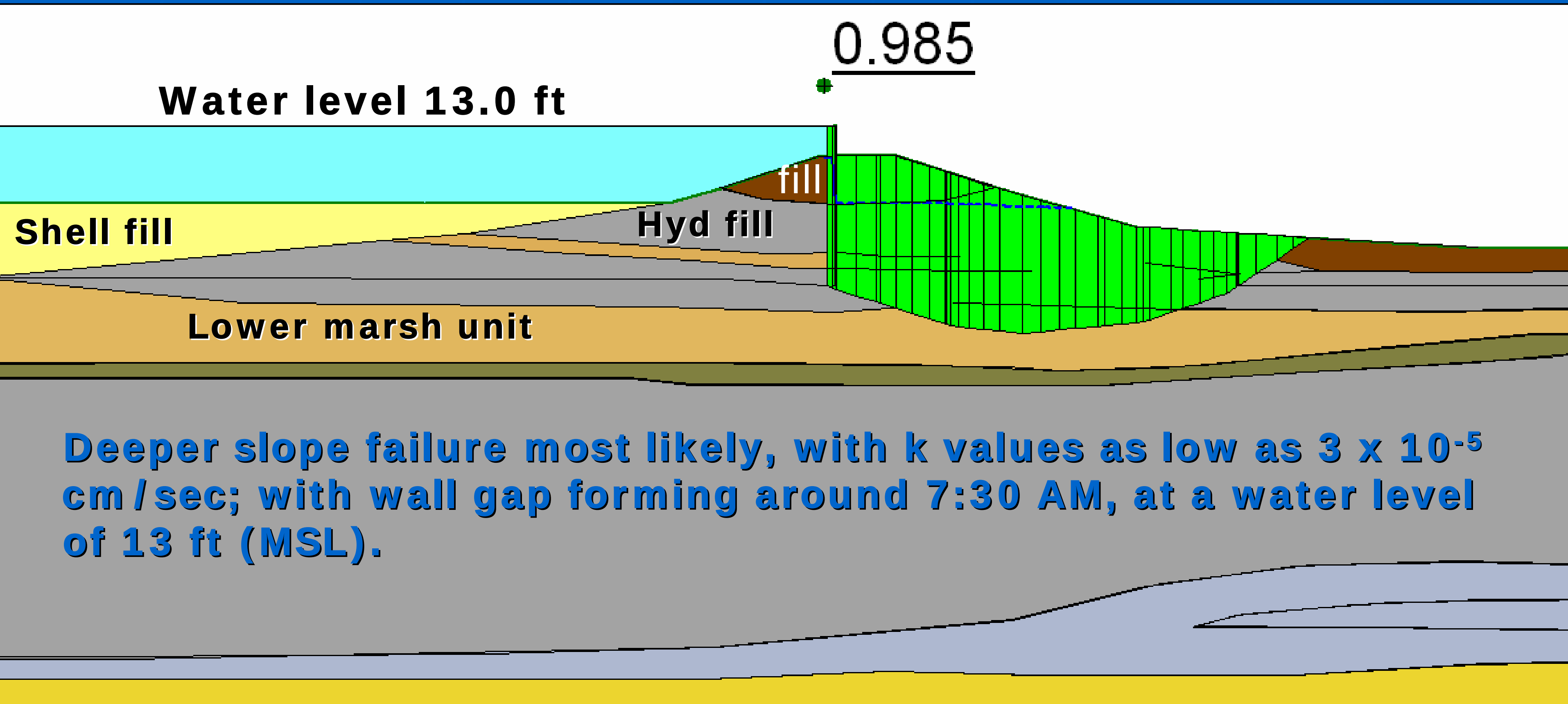
Increase of pore pressure at top of lower marsh unit if the gap on water side of flood wall opened around 7:30 AM. This would have hastened the build-up of pore pressure at this location.

Slope stability – shallow failure mode (in upper marsh) – FS=1.091

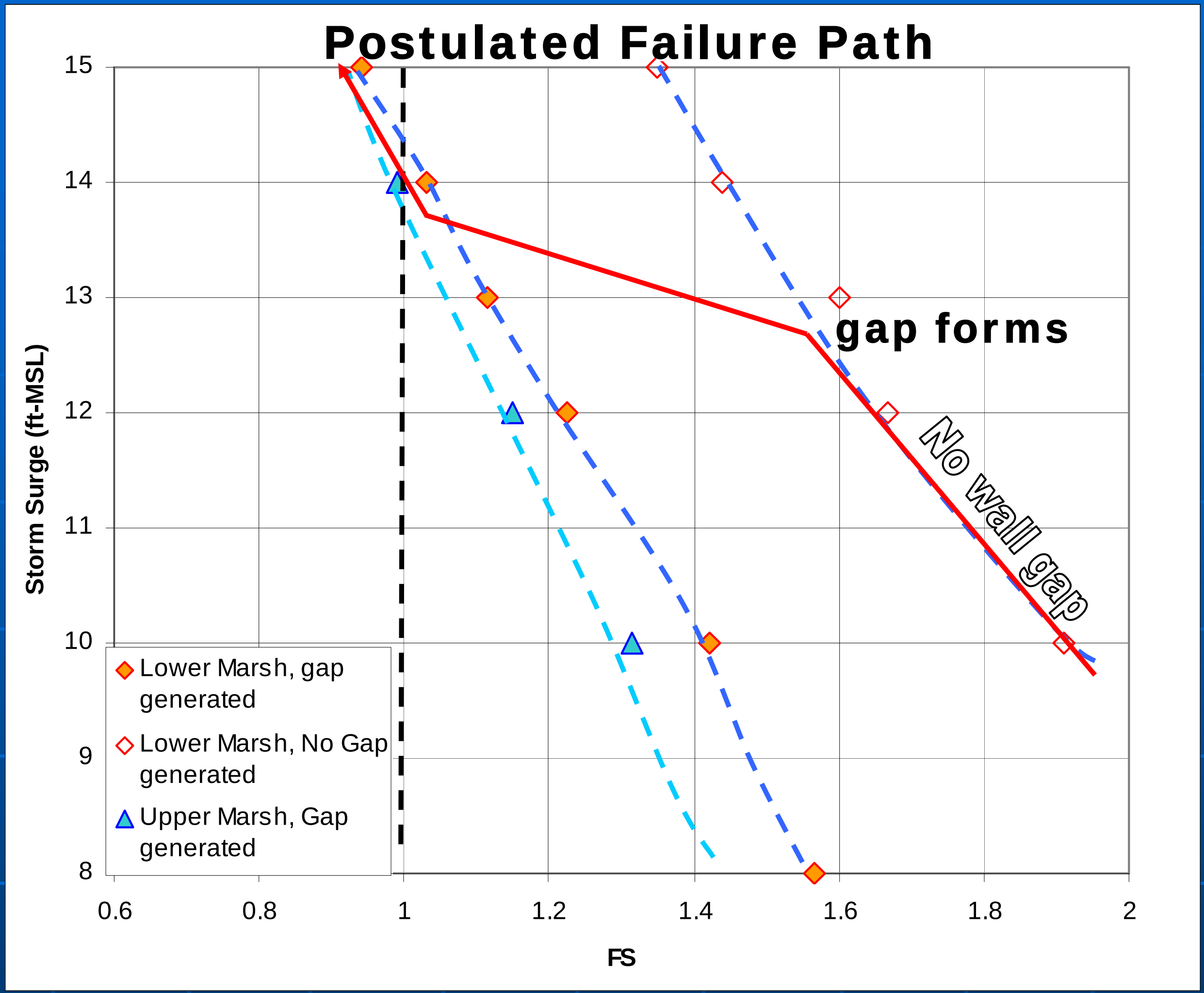


Limit equilibrium analyses

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



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



Calculated Factors of Safety for three modes based on SLOPE/W analyses of the East Bank IHNC South Breach site for various surge levels; showing the best-estimated path to failure.