# Double-Wall Impact Protection Levee Project — Executive Summary

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***Laboratory Experimentation of Hydrodynamic Forcing:*** A physical modeling study was carried out at the Texas A&M University Haynes Coastal Engineering Laboratory to study the conceptual feasibility of a double-wall impact protection levee. Testing used a 1:18 scale model to represent a prototype levee with a crown (crest) height of 18 ft above ground and a prototype crown (crest) width of 10 ft. Two levee configurations were evaluated:

*Test Case 1:* represents an application where the levee is positioned directly on the sea floor (18-ft prototype crown (crest) elevation above the sea floor).

*Test Case 2:* represents an application where the levee is positioned on a natural berm (24-ft prototype crown (crest) elevation above the sea floor).

A range of water depths ($h$, measured from sea floor) and wave conditions (wave height [$H$] and period [$T$]) were evaluated to determine total horizontal force on the double-wall impact levee, where total force is the sum of the hydrostatic (due to static water level) plus dynamic (due to waves) loading. Maximum total load on the levee coincides with the wave crest and acts in the direction of wave propagation. At prototype-scale, test conditions for Test Case 1 ranged from $h$ = 12 to 18 ft and incident $H$ = 3 to 7 ft; test conditions for Test Case 2 ranged from $h$ = 18 to 24 ft and incident $H$ = 5.5 to 9.5 ft. The largest wave height tested at each water depth can be considered depth-limited, meaning that the maximum wave height is dictated by water depth ($H$ = 0.4$h$ as laboratory limit). Surge generation depends on a combination of factors including hurricane intensity (Saffir-Simpson Scale) and spatial extent of tropical-storm-force winds (e.g., Hurricane Surge Index [HSI] of Kantha [2008] and Integrated Kinetic Energy Potential [$S_{DP}$] of Powell and Reinhold 2008) in addition to continental shelf geometry and local geography and topography. It is therefore not practical, and may in fact be misleading, to correlate design surge and wave conditions with the Saffir-Simpson Scale or Integrated Kinetic Energy Potential.

Experimental testing demonstrated that the dynamic loading on the double-wall impact levee can be reliably estimated using the well-accepted Goda (1985) method for estimating horizontal wave force on a structure. At prototype scale, measured total horizontal force for Test Case 1 ranged from 6,800 to 16,500 lb per unit length (ft) of levee; measured total horizontal force for Test Case 2 ranged from 10,100 to 21,200 lb per unit length (ft) of levee. The vertical location of the resulting force depends on the specific hydrodynamic condition. During experimentation on Test Case 1, no overtopping of the levee was recorded when prototype freeboard (crown [crest] elevation — water level) was 6 ft, and low to moderate amounts of overtopping were recorded when prototype freeboard was less than or equal to 3 ft. During Test Case 2 testing, larger wave heights resulted in more overtopping; moderate to high amounts of overtopping were recorded during all tests, even when prototype freeboard was as large as 6 ft.

***Numerical Simulation of Geotechnical Performance:*** The soil profile for the analyses in the report was selected to represent a **"worst-case scenario"** in terms of soil conditions. The final geological cross section for the PLAXIS analyses is assumed as shown in figure 2-4 and figure 2-5. It follows quite closely the soil profile at the west bank of the 17$^{th}$ Street Canal which was used for the Independent Levee Investigation Team (ILIT) analyses. The thickness of the weakest soil (organic clay deposits) at the location of the 17$^{th}$ Street Canal failure was 8 ft. This layer of extremely soft and weak soil was increased to 18.5 ft in the analyses of this report, considerably increasing the overall weakness of the soil profile. See Part II p. 6 and 9 for the profiles and their interpretation. The comparison between the strength profile in the ILIT report and the strength measurements for the test site are shown in Part II p. 10, and show good agreement. Since the information at the test site was limited to soil profile and strength, the material parameters for the finite element analyses were estimated from those reported in the ILIT and Interagency Performance Evaluation Taskforce (IPET) reports for the 17th Street Canal and for the Inner Harbor Navigation Canal (IHNC).

Three different geometries were used in the analyses:

*Scenario 1*: a double-wall levee 18 ft high and 10 ft wide, with sloping ground towards the water and a berm on the land side; the soil profile comprises an 18.5 ft layer of very soft, weak organic clay. Water pressures are those measured in the laboratory for Test Case 1.

*Scenario 2*: a double-wall levee 18 ft high and 10 ft wide, with erosion protection on the water side and a berm on the land side; the soil profile comprises an 18.5 ft layer of very soft, weak organic clay. Water pressures are those measured in the laboratory for Test Case 2.

*Scenario 3*: a double-wall levee 18 ft high and 10 ft wide, with sloping ground towards the water but no berm on the land side. This configuration is referred to as the "stand-alone" double wall levee. The soil profile has an 8 ft layer of soft, weak organic clay. Water pressures are those measured in the laboratory for Test Case 1.

The analyses were divided into 3 parts: (a) construction of the levee and long term static stability; (b) short-term flood loading (water rising); (c) short-term flood loading (with wave overtopping). The analyses in the IPET and ILIT reports only considered short-term loading due to storm surge as represented by rising water. No analysis was carried out in the IPET and ILIT efforts with any additional dynamic pressure due to waves overtopping the levee. This must be considered in interpreting the results summarized below.

(a) Construction and long term static stability

The simulation of construction was not meant to be realistic, since its function was to give the state of stress in static conditions. Therefore, consolidation was allowed to take place until all excess pore pressures would be dissipated. In actual conditions, this may not be an option for a reasonable construction schedule. In addition, the effect of settlements in the soft clay layers were not considered. At the end of construction, after the dissipation of all excess pore pressure, the factor of safety (FS) were estimated to be:

*Scenario 1*: **1.64**

*Scenario 2*: **1.60**

*Scenario 3*: **3.44** This factor of safety is likely much larger than the previous ones because of the absence of the berm which increases the load on the soft and weak soils.

(b) Short-term flood loading (water rising)

*Scenario 1*: As the water elevation rises, the factor of safety reaches **1.5** with the water elevation between EL 166 (FS=1.53) and EL 167 (FS=1.46), or between 16 ft and 17 ft of water acting on the double wall levee. When water level reaches the height of the levee, EL 168 or 18 ft, the factor of safety is 1.38.

*Scenario 2*: As the water elevation rises, the factor of safety reaches **1.5** with the water elevation between EL 163 (FS=1.51), or 7 ft of water acting on the double wall levee. When water level reaches the height of the levee, EL 174 or 24 ft, the factor of safety is 1.08. Since the water depth is much higher (24 ft) in this scenario, the hydrostatic force acting on the levee is also higher, leading to a smaller factor of safety than in the previous case.

*Scenario 3*: The factor of safety for water elevation at the top of the levee (18 ft) was estimated to be **1.54**. Better soil conditions, although still as weak as in the case of the 17th Street Canal failure, result in a fully satisfactory factor of safety with water at the level of the levee height. Increasing the width of the "stand alone" double wall levee to 15 ft increases the factor of safety to **1.59**.

(c) Short-term flood loading (with wave overtopping). This case was **not** considered in the IPET and ILIT analyses.

*Scenario 1*: When the dynamic pressure due to waves is added to the water level rising to the top of the levee (18 ft), an additional, almost uniform pressure ranging from 338 psf to 368 psf is applied to the levee. The factor of safety is 1.16.

*Scenario 2*: In this scenario, the dynamic pressure due to waves is also higher than in the previous scenario, resulting in an almost uniform pressure ranging from 521 psf to 600 psf applied to the levee, in addition to the static pressure due to a water level of 24 ft. The factor of safety decreases to 0.96. In this scenario, the geometry of the levee should be evaluated. Extending the front sheet pile wall will provide additional resistance to lateral forces.

*Scenario 3*: When the dynamic pressure due to waves is added to the water level rising to the top of the levee (18 ft), an additional, almost uniform pressure ranging from 338 psf to 368 psf is applied to the levee. The dynamic force decreases the factor of safety to 1.28. Increasing the width of the "stand alone" double wall levee to 15 ft increases the factor of safety to 1.33.

The stability of the "stand-alone" double wall levee without the earth berm on the land side, for the soil profile of scenario 1, with 18.5 ft of weak organic clay, was also evaluated. This is essentially scenario 1 without the berm on the land side. In the scenario of the very thick layer (18.5 ft) of organic clay, the stand-alone option is less stable than the option with the earth berm, because the fill helps resist the horizontal forces.

In all scenarios, the factor of safety can be improved during the design process by evaluating the geometry of the double wall levee to maximize its resistance. Longer sheet pile walls, taking advantage of more favorable soil conditions, for example by extending the walls into stronger soil layers, widening the double wall levee, considering a smaller berm on the land side for erosion protection and additional resistance to lateral forces are all possible improvements, which can increase the factor of safety to the required level of 1.5 or greater.

***Design and Construction Considerations***: The above experimental setup evaluated the conceptual feasibility of the double-wall impact levee design. For field-scale design and construction, a number of additional design and construction aspects should be considered. First, since the double-wall levee design maximizes the geotechnical capacity of the soil, the exact design of the levee will be highly site-specific, depending on both soil conditions and design water level and wave conditions. Specifically, the penetration depth of both vertical walls and the structure crown (crest) width must be carefully designed based on soil conditions at the site. Second, careful attention should be given to designing scour protection at the toe of the levee and behind the levee, to protect against overtopping-induced erosion, to ensure integrity of the geotechnical design. Third, constructability considerations of the levee will strongly depend on specific site characteristics, and therefore should receive attention during design of each application. Fourth, additional detailed geotechnical analyses must be performed 1) to fully evaluate the levee performance when subjected to horizontal point impact loading, such as that by heavy debris or barges, 2) to evaluate vertical wave impact loading in the case of wave breaking on the levee crown (crest), and 3) to evaluate levee performance when subjected to a moving vertical load on the crown.

The report provides the evaluation of a limited number of test cases, in which soil conditions were assumed based on a worst-case scenario and levee dimensions were fixed. The test scenarios were analyzed here to evaluate the functional viability of the double-wall levee design. Therefore, the test scenarios shown here do not necessarily provide the best geometry for the specified conditions; rather, they should be considered a starting point for design. The analyses in the report were aimed at evaluating whether the double wall levee concept can be a viable solution for situations in which a traditional design may not be the preferred solution. **The analyses presented here clearly demonstrate the viability of the double-wall levee design concept.** The analyses in the report show that the test scenarios examined led to stable configurations in static conditions and average daily water levels, but these configurations may not be the most effective. Most of the test scenarios were also stable with rising water and additional dynamic forces. However, in order to obtain the desired factor of safety of 1.5 for a double wall levee under any of the loading combinations considered, it will be necessary to evaluate the geometry of the levee, together with the specific soil conditions to develop the most effective site-specific design.