Design and Analyses of the Hurricane Protection Floodwall in South Louisiana

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Abstract. This paper presents a comprehensive review on the finite element analyses for the performance-based design of the Floodwall, an important component of hurricane storm surge barrier for New Orleans, Louisiana. The finite element models are calibrated and verified with a lateral pile load test, and they are used to derive the design hurricane storm surging loads on the Floodwall. Such storm surging loads are used to determine the seepage cut-off depth of the wall based on design seepage criteria. The settlement of the Floodwall during its design life is estimated by the finite element consolidation analysis with considering soil-pile-interaction. Finally, a brief discussion is given to the finite element stability analysis for an effective remediation design of the submerged rock dike of the Floodwall using a soil cut-off structures at the dike toe.

1 Introduction

In 2005, Hurricane Katrina hit the city of New Orleans, Louisiana, and the storm surge overwhelmed the existing levee system of the Inner Harbor Navigation Canal (IHNC), resulting in a devastated flooding of the city (Duncan et al. 2008; IPET 2007). In order to protect the city from future hurricanes, the U.S. Army Corps of Engineers decided to build a storm surge barrier across Lake Borgne on the east of New Orleans between the Mississippi River-Gulf Outlet (MRGO) and the Gulf Intercoastal Water Way (GIWW). An important component of the surge barrier is the 3.2-km long Floodwall (Huntsman 2011; Reid 2013). The general soil profile at the construction site consists of Holocene age mash and soft clay overlying Pleistocene deposits. Due to the deep soft ground condition, the Floodwall was designed as a laterally braced piled wall, with a submerged rock dike over the MRGO channel. The high storm surge loading combined with the very deep soft soils created significant design challenges for the Floodwall. These design challenges include determining the appropriate hurricane storm surge loads on the wall, estimating the settlement of the wall during its design life, and evaluating the global stability of the wall under design storm surge loading. A safe and cost-effective design of the Floodwall "floating" in soft-medium-stiff clays required a thorough understanding of the soil-pile-interaction to satisfy design requirements for structural strength and serviceability. For this purpose, finite element Soil-Structure-Interaction (SSI) analysis models were developed to assess the performance of the Floodwall under the design hurricane surge condition (Dong and Schwanz 2011; Dong 2016).

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This paper presents a comprehensive review on finite element model analyses that were used to assess the performance of the Floodwall under storm surging loads, with respect to several important geotechnical aspects, including soil-pile interaction, seepage, settlement and rock dike stability. First, the general condition of the subsurface profile at the site and the details of the Floodwall are presented. Next, the finite element SSI model are briefly described. Then, the calibration and verification of the soil input parameters and finite element model with the results of a lateral pile load test are discussed. The finite element SSI seepage analyses are used for deriving the appropriate hurricane storm surge loads on the wall, which are used to determine the seepage cut-off of the wall. Next, the finite element settlement analysis that is used to estimate the consolidation of the Floodwall over the MRGO channel with a submerged rock berm is described. Finally, a brief discussion is given to the finite element stability analysis for the effective remediation design of the submerged rock dike of the Floodwall using a soil cut-off structures at the toe.

2 General Subsurface Profile

The general subsurface profile at the construction site include a very soft organic surficial clay (or Marsh) layer underlain by the Interdistributary and Prodelta soft clay deposits. The soft clay is underlain by Pleistocene medium and stiff clay, with an intrusion layer of nearshore gulf (Interdelta) sand in some areas. Both soil borings and field Cone Penetrometer Tests (CPT) were made at several locations to determine the soil profile and shear strengths along the structure alignment. The soil profile and design soil shear strengths for a typical Floodwall design ranch are shown in Table 1 (EUSTIS 2009). In Table 1, γ_{sat}, s_u, ϕ, $Nu_u k_h$ and k_v represent the saturated unit weight, shear strength, internal friction angle, undrained Poisson ratio, horizontal and vertical hydraulic conductivities of soil layers. The soil hydraulic conductivities were estimated based on the design manual DIVR-1110-1-400 (USACE 1998).

Table 1. General soil profile and design parameters

Elevation (m)	Soil Type (USCS)	γ_{sat} (kN/m^3)	s_u (kPa)	Φ (deg)	ν_u	k_h/k_v (10^{-3} m/day)
0 to −3.7	PT	10.8	4.8		0.4	1.7/0.5
−3.7 to −6.1	CH	16.5	5.0		0.4	1.7/0.5
−6.1 to −15.2	CH	15.7	5.0 –21.7		0.4	1.7/0.5
−15.2 to −18.3	CH	17.3	25.2 –32.3		0.4	1.7/0.5
−18.3 to −21.3	SM	19.7		30	0.4	73.5/37.0
−21.3 to −35.1	CH	18.1	37.3–60.0		0.42	1.7/0.5
−35.1 to −51.8	CL	17.4	52.3–91.9		0.45	1.7/0.5
Below −51.8	CL	17.4	52.3–103.9		0.45	1.7/0.5

3 Floodwall

The Floodwall is built over the Lake Borgne and MRGO at the east of New Orleans, South Louisiana, with a total length of about 3.2 km. Along with a sector gate over the GIWW, the Floodwall creates a surge barrier to prevent future storm surges from entering the City of New Orleans during hurricane seasons. The typical Floodwall is composed of vertical precast post-tensioned cylindrical concrete piles with an outside diameter of 1.7 m and a thickness of 15.2 cm. These large diameter cylindrical concrete piles are driven closely and braced by steel-pipe batter piles with a batter angle of 34° (or a slope of 1 H:1.5 V). The embedment length of the plumb piles of the Floodwall is about 35 m from the mudline at EL-4.6 m, and their center-to-center spacing is 1.8 m. The steel batter piles have a wall thickness of 1.9 cm above EL-8.2 m and 1.3 cm below and were driven into the ground to EL-58 m with a center-to-center spacing of 3.6 m. The interstitial space between plumb cylindrical piles of the Floodwall was closed by the irregular pentagonal closure piles with jet grout applied to seal the gap between the closure and cylindrical piles. The Floodwall provides a flood protection to El + 7.6 m with wave deflectors to El + 7.9 m. Figure 1 shows a photograph of the Floodwall during construction. The soft clay foundation conditions and large storm surge loading combined to create design challenges of the Floodwall. A safe and cost-effective design of the Floodwall "floating" in soft-medium-stiff clayey soils required a thorough understanding of soil-pile-interaction to satisfy design requirements for structural strength and serviceability. For this purpose, soil-structure-interaction finite element model analyses were conducted to assess the performance of the Floodwall under design hurricane surge loading conditions.

Fig. 1. Floodwall with batter piles during construction

4 Finite Element Model

4.1 Model Configurations

The finite element SSI model of the Floodwall were developed using a commercial geotechnical computational program PLAXIS 2D (Brinkgreve 2002). In the 2D finite element model, the elasto-plastic plate (or beam) elements were used for both vertical and batter piles. The structural properties (e.g. axial stiffness and flexural rigidity) of elements were determined by dividing pile properties by the pile center-to-center spacing. This smearing approach was also applied to define unit weights of beam elements. The connection of the vertical pile to the cap beam is fixed, but a pinned connection was used for the batter pile to cap beam. The advanced hardening soil model was used in the finite element analyses to describe the nonlinear soil reaction behavior to pile deformation (Brinkgreve 2002; Duncan and Chang 1970). The computational domain was discretized using high order (6-node) triangular elements. To save the computational time, a finer mesh was used in the soil wedges adjacent to vertical piles while the coarser mesh was used in the region far from the Floodwall structure. Sensitivity analyses have been performed to verify the accuracy of such selected finite element mesh. Based on the soil shear strength characteristics, an average strength reduction factor of 0.67 was applied to the soil-structure interface elements to simulate the soil adhesion to piles. The standard fixity boundary conditions were used in the finite element model, i.e. fixed in horizontal direction on the vertical boundaries and fixed in both horizontal and vertical directions on the bottom of the model. A close boundary condition was also set on the bottom of the model during the groundwater seepage calculations. Figure 2 shows the finite element model configuration. The calculation phases were created in the finite element modeling for major construction sequences such as construction of the dredged channel, installation of piles and the placement of scour stone layer. Additional calculation phases were also created for different design loads cases, including hurricane loading case. Based on the evaluation of geological and hurricane condition, the long-period surging load to the top of wall is considered critical for the design of the Floodwall, and it is modeled as the hydrostatic water load in the finite element analyses.

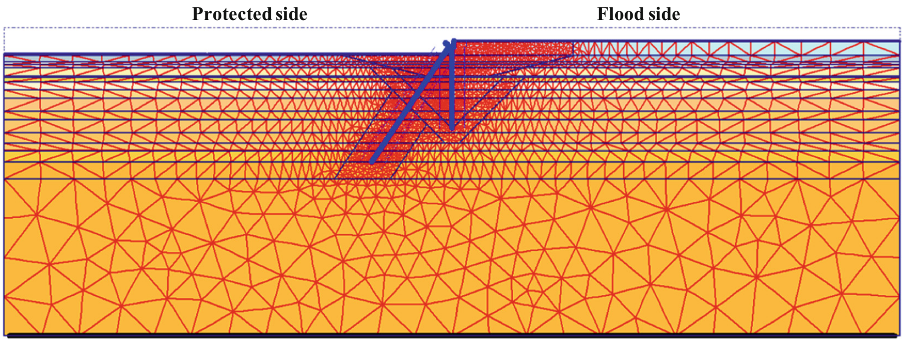
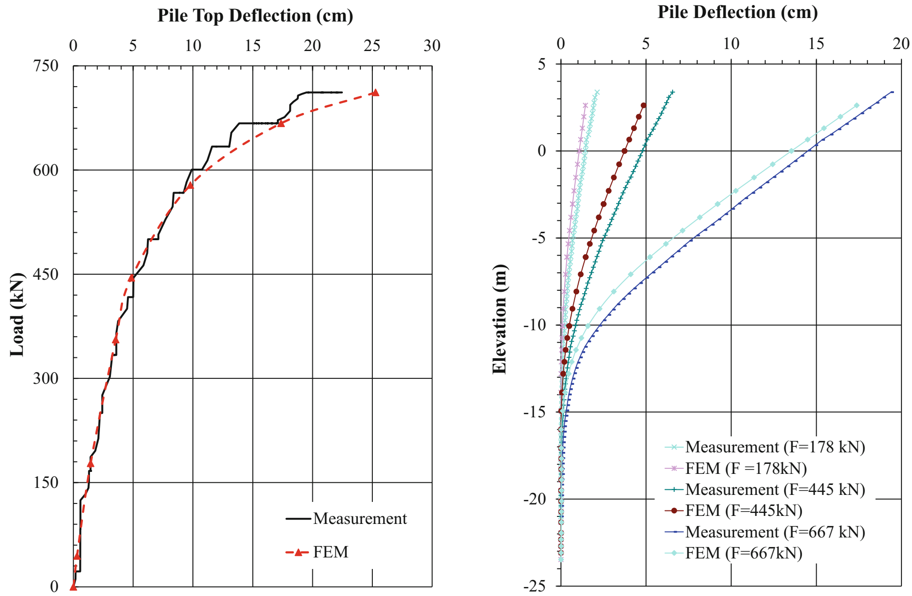


Fig. 2. Finite element model configuration of the Floodwall

4.2 Lateral Pile Load Test

To better model the soil-pile-interaction behavior in the 2D finite element SSI analysis, the lateral resistance of local soft clays to laterally loaded large-diameter piles were calibrated by the results of a lateral pile load test. The lateral pile load test was performed on a



(a) Pile top deflections (b) Pile deflections

Fig. 3. Field measurements and numerical predictions of load-deflection behavior of the test pile

prototype cylindrical precast post-tensioned concrete pile of the Floodwall (Reese 2009). Using the revised Matlock approach (Matlock 1970; Lee and Gilbert 1979; Dong and Schwanz 2011), the in-situ stiffness's of soft clay under the single pile deformation were derived and they are used in 2D finite element models to reflect 3D pile-soil-interaction. Figure 3 shows the comparison of the numerical predictions and field measurements on the deformation of tested pile under different test loads. The good agreement of numerical predictions with field measurements supports the reconciliation of soil stiffness's with the *p-y* interpretation from the lateral pile load test and the rigorousness of the finite element modelling for the soil-pile interaction.

5 Soil Structure Interaction

5.1 Pile-Soil Interaction

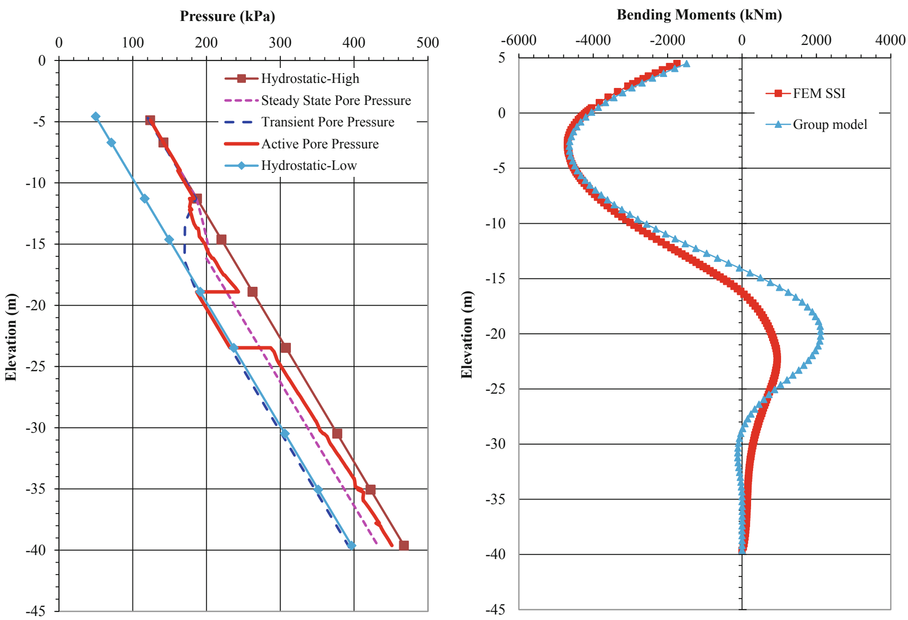
The plumb piles of the Floodwall were installed closely, resulting in the overlapping of the activated passive soil wedges of laterally loaded adjacent piles. Such overlapping would result in an increase in the soil stress level within the interfered passive wedges of the pile, and consequently leading to an increase in soil strain based on the stress-strain relationship of the soils. In order to take into account this pile group interaction effect, soil wedges from pile tips to mudline are introduced in the 2D finite element models in the vicinity of the plumb pile wall (see Fig. 1). Using the soil wedge concept, the group effect of closely spaced vertical cylinder piles of the Floodwall was taken into consideration in the soil finite element model by reducing soil strength and stiffness parameters by a group reduction factor (Ashour et al. 1998; 2004; Dong and Schwanz 2011).

5.2 Active Pore Pressures

First, the finite element model was used to investigate the storm surging loads on the Floodwall under design hurricane conditions, which would induce a high-water level at EL 7.5 m at flood side and a low-water level at EL 0.5 m at the protected side, respectively. The corresponding hydrostatic water pressures on the wall to this high and low water level are shown Fig. 4(a). Both steady-state and transient seepage analyses were performed using soil hydraulic conductivity as shown in Table 1, and corresponding steady-state and transient pore water pressures on the Floodwall in the soil layers are also shown in Fig. 4(a). The steady-state pore pressures correspond to the long-term ultimate stage of the subsurface flow under storm surging condition, which would only be achieved in a relatively long period in the clayey soil materials. The transient pore water pressures, on the other hand, correspond to the short-term subsurface flow state under storm surging condition, which only takes place in the shallow soil layers during one-day surging period due to low permeability of soils. However, both long-term steady state and short-term transient pore water pressures do not include the water surcharge effect on foundation soft soils under the storm surging condition. During one-day storm surging period, the foundation clay layers can be considered to have undrained behaviors, and therefore, excess pore water pressures would develop under the water volume surcharge on the flood side. Such excess pore pressures also include the effect of soil volume change due to the SSI effects of the Floodwall with adjacent soils. Thus, the active pore pressures on the Floodwall under storm surge loading condition consists of the transient pore pressures and the excess pore pressures due to the undrained behavior of the clay layers (Dong, 2016). Such active pore pressures are captured by the finite element SSI analysis, and they are shown in Fig. 4(a) as well.

5.3 Model Results

With the verification of the finite element model with lateral pile load tests and comprehension on storm surging loads on the wall, the finite element SSI models were used to assess the performance of the Floodwall under design hurricane loading condition. Figure 4(b) shows the computational results of the unfactored bending moment distribution along the vertical pile corresponding to critical design load case including high storm surge water pressures on the flood side. Figure 4(b) also includes numerical results from a *p-y* curve-based GROUP model analyses (Reese et al. 2010). In GROUP model analyses, the storm surge induced net unbalanced pressures on the vertical pile wall below the mudline were derived from the finite element SSI analysis. A very good agreement of the design bending forces on the vertical pile was observed between the finite element analysis and GROUP model as shown in Fig. 4(b). The discrepancy in the numerical results in pile bending moment below EL-15 m mainly attributes to the fact that the finite element model analysis indicate the soil movements in the vicinity of piles, which would release the restrains on piles and reduce the bending demands on piles. Such soil movements were not included in the GROUP analysis.



(a) Pressure distributions (b) Bending moments of plumb piles

Fig. 4. Outputs of finite element SSI analyses of the Floodwall

6 Seepage Cutoff

As stated previously, closure piles with grout soil columns were installed between the cylindrical piles to provide a seal to reduce leakage. The depth of the grouted soil column for seepage cutoff was determined based on three seepage criteria as required by Hurricane and Storm Risk Reduction System Design Guide (HSDRRS) (USACE 2012) including exit gradient, Terzaghi piping and heave criteria (Terzaghi 1995; Dong 2012). The exit gradient criterion requires that the critical hydraulic gradient of subsurface flows be greater than the exit gradient, to avoid zero effective stress condition. Terzaghi piping criterion requires that the buoyant weight of overlying soils be greater than the upward seepage force at seepage cut-off tip, to avoid an effective heave phenomenon that a mass of soil may be lifted initially then followed by piping. The heave criterion is like Terzaghi piping criterion but is based on total stress approach. Using these design criteria and the active pore water pressures obtained from finite element SSI analyses, as presented in Fig. 3(a), the distributions of safety factors for seepage cut-off along the Floodwall in one design reach per different design criteria are calculated and shown in Fig. 5. The dashed red lines in Fig. 5 represent the minimum factors of safety required by the HSDRRS for each seepage criterion. Based on these minimum factors of safety, the required seepage cut-off depth of the Floodwall for each criterion can be easily obtained from these safety factor distributions.

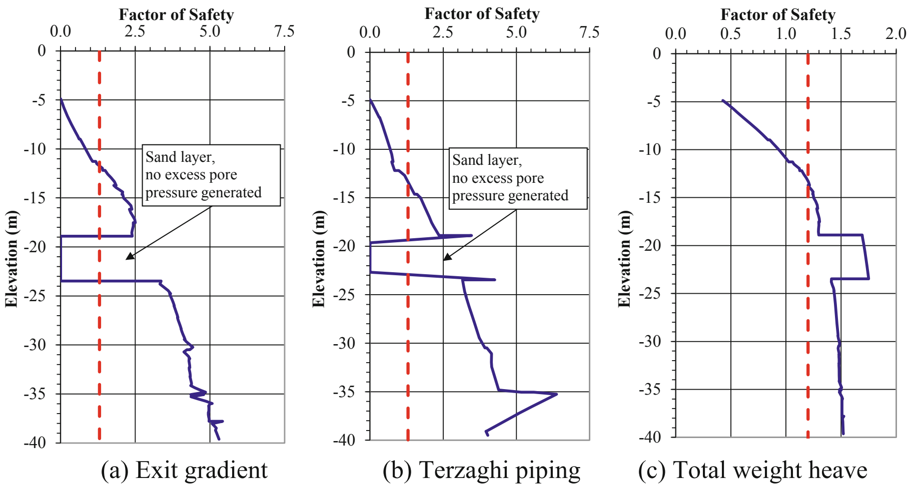


Fig. 5. Distributions of safety factors based on design seepage cutoff criteria

7 Settlement Analyses

7.1 Consolidation Model

The southern portion of the Floodwall was built across the MRGO channel that has a maximum depth of about 12.8 m below mean sea level at the EL + 0.0. This portion of Floodwall is referred as the MRGO Closure, and it requires a submerged rock berm with a top elevation to EL-4.5 m over the outlet channel to provide lateral supports to the wall. The berm consists of two rock dikes on both sides of the wall with a side slope of 1 V:9 H and a sand core in between to facilitate driving of the piles. A final 6-feet rip rap stone layer with a side slope of 1 V:3 H was placed atop of the sand core for scour protection. The max length of the berms along the channel at top and bottom are about 49 and 175 m, respectively. The placement of the rock berm with a maximum thickness of about 8.2 m induces a significant consolidation of the soft soils beneath. Such settlement had to be addressed in the design of the MRGO Closure. For this purpose, a finite element soft soil creep (SSC) model (Brinkgreve 2002) was created to estimate the consolidation of the MRGO Closure during its 50-year design life. Figure 6 shows the cross section of the MRGO Closure at the center of outlet channel with a mudline at EL-12.8 m.

7.2 Consolidation Calculations

First, the consolidation of the rock berm along the central line of the outlet channel (with a thickness of about 8.2 m) with a 50-year design life was investigated using

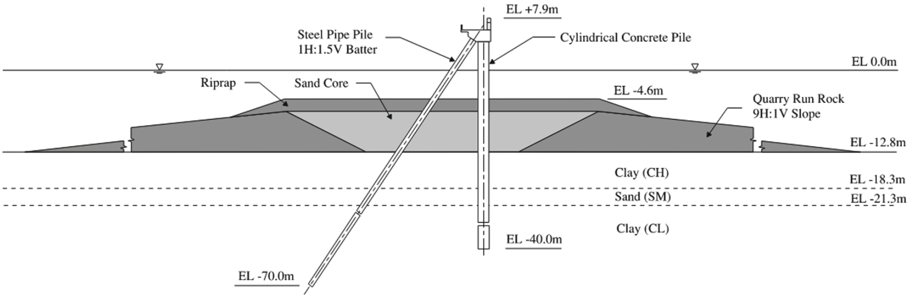


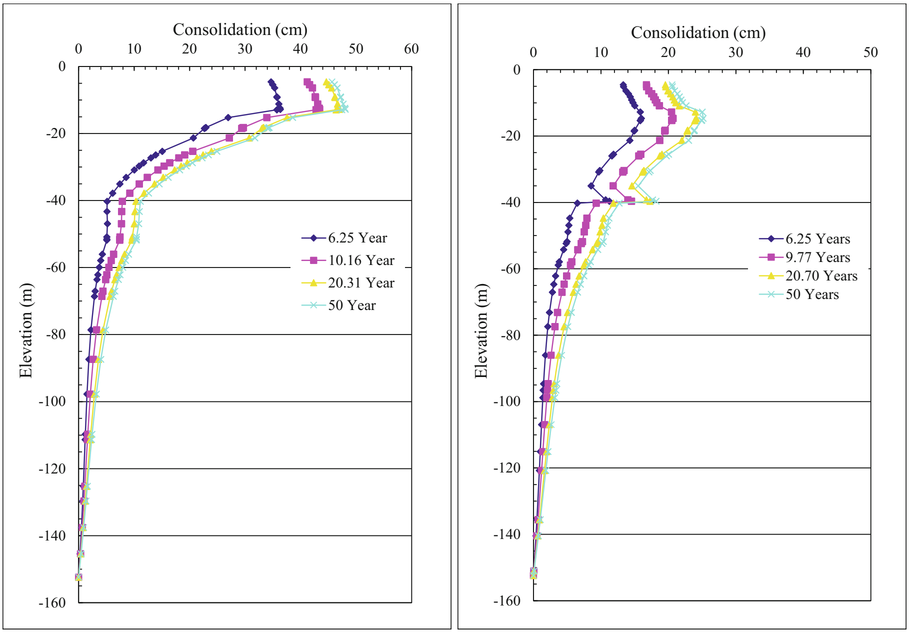
Fig. 6. Cross section of the MRGO Closure with rock berm at the outlet channel center (mudline at EL-12.8 m)

the 2D finite element SSC model. The corresponding settlement profiles corresponding to different time spans, obtained from the finite element consolidation analyses, are shown in Fig. 7(a). These numerical predictions indicated a settlement of about 45 cm for the MRGO berm along its center line in 50 years. However, these consolidation calculations are only for the rock berm and they do not consider the influence of the Floodwall structures built through it. To estimate the settlement of the MRGO Closure during its design life, the finite element model was rerun again with the Floodwall pile structures. The equivalent structural properties of the vertical and batter piles in the 2D finite element model were determined by considering the spacing of vertical pile and batter pile. The unit weight of vertical pile includes the weight of closure piles, jet grout around pile and buoyance effects. The corresponding settlement profile along the center line of the berm, obtained from the finite element analyses, is shown in Fig. 7(b). It can be seen by comparing Figs. 7(a) and 7(b) that the less consolidation of the berm can be expected due to the interaction between pile and soils. With the pile structures installed, the adjacent settling soil under surcharge will create down-drag forces on the piles, and thus the surcharge loads are transferred to deeper more competent soils. The settlement of the MRGO Closure in 50 years is approximately equal to the soil settlement of about 20 cm at the vertical pile tip elevation of EL-40 m (see Fig. 7(b)).

8 Stability of Rock Berm

8.1 Deep-Seated Soil Failure Below Rock Dike.

During the construction of the rock berm of the MRGO Closure, field observations indicated rotational displacements of the rock berm and implied a global slip movement of the soft soils beneath the rock dike on the flood side. Bathymetric surveys identified mud waves at toe of the rock dike on the flood side, accompanying a displacement of the sand core and the upper portion of rock dike. This deep-seated soil failure beneath the rock dike was successfully captured by the finite element stability analysis (Dong et al. 2012). The ϕ-c reduction approach was used in the finite element stability analysis.



(a) without the Floodwall (b) with the Floodwall

Fig. 7. Finite element settlement estimates of the MRGO Berm

The analysis showed a safety factor of 1.1 for the as-built condition of the rock dike, indicating a marginally stable conditions of the rock dike as observed. This deep-seated slip failure in the weak soil layer created displacement of dick crest and a mud wave at the rock dike toe as shown in Fig. 8(a).

8.2 Soil Cut-Off Structures

In order to increase the stability of the rock berm, the rock dike on the flood side was redesigned with a sheet-pile soil cut-off structure at its toe. The penetration depth and grade of the sheet-piles were determined based on the finite element SSI stability analysis with a minimum target safety factor of 1.5. Figure 8(b) shows the corresponding critical failure surface with a safety factor equal to 1.51, obtained from finite stability analysis with a sheet pile embedment of 13 m. With such embedment length, the sheet pile cut-off structure penetrated through the weak soil layer and embedded into the stronger soils below. It can be seen from the Fig. 8(b) that the slip failure surface and mud wave that occurred previously in the weak soil layer were successfully cut-off by the sheet pile wall.

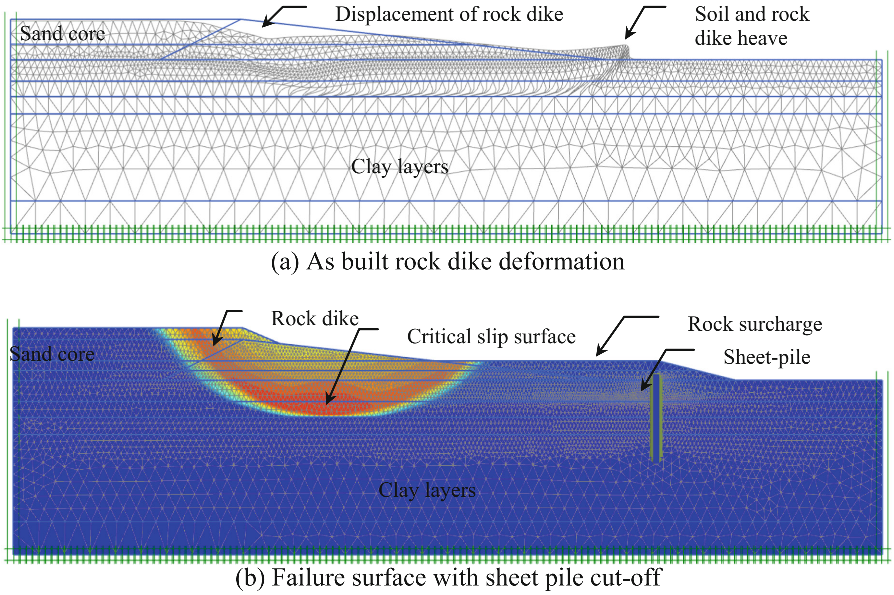


Fig. 8. Finite element stability analysis results of rock dike

9 Conclusions

Finite element model analyses have been successfully used for the performance-based design of the Floodwall that was built in the soft soil foundation to satisfy the design requirements for hurricane storm surge barrier system. The soil input parameters and the finite element models are calibrated and verified by the results of a lateral pile load test. The finite element SSI analyses are used to address several important design challenges including determining appropriate hurricane storm surge loads on the wall and the seepage cut-off depth of the wall, predicting the settlement of the wall during its design life, and the effective remediation design of the rock berm of the MRGO Closure. With the aid of the finite element modeling analyses, the Floodwall was designed safely and economically.

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