Investigations of Stability Improvements for Submerged Berm on Soft Clay in South Louisiana

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ABSTRACT

Rotational deformation of the submerged rock berm of the hurricane protection Floodwall over the Mississippi River Gulf Outlet in South Louisiana was observed during its construction. The deep seated slip surface profile of soft soil beneath the rock berm was investigated based on stability back analyses and bathymetric surveys. Remolded strengths of soft clays under the deformed rock dike were determined by field CPTs and vane shear tests, and they were verified with the back analysis as mentioned above. In order to restore the stability requirement of the submerged rock berm for the Floodwall, several remediation approaches were studied using finite element and limit equilibrium stability analyses. These stability analyses indicated that both rock surcharge and soil cut-off structure should be used to stabilize submerged berm on the soft soil during its further construction. Such soil cut-off structures can be constructed by means of stone trench fill or sheet-pile. The later option was finally adopted based on the constructability and cost estimate.

INTRODUCTION

The Inner Harbor Navigation Canal (IHNC) Lake Borgne Barrier Floodwall is an important component of the Hurricane and Storm Damage Risk Reduction System (HSDRRS) in New Orleans, Louisiana. The Floodwall is comprised of large diameter cylindrical pre-stressed concrete piles driven closely together and braced by steel-pipe batter piles on the soft clay. The southern portion of the Floodwall was built across the Mississippi River Gulf Outlet (MRGO). The maximum depth of the MRGO channel is about 42 feet below mean sea level at datum of about 0.0 ft. The Floodwall across the outlet channel requires a submerged rock berm to provide lateral stability support. The berm consists of two rock dikes on both sides of the Floodwall and a sand core in between facilitating driving of the Floodwall pilings. A final 6-feet rip rap stone layer was placed atop of the sand core for scour protection. The borings and

CPTs at the site indicate a soft peaty clay layer about 10 feet thick directly beneath the rock berm.

During the construction of the rock berm, bathymetric surveys were performed and they 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. Field observations indicated rotational displacements of the rock berm and implied a global slip movement of the soft soil beneath the rock dike on the flood side. Mud waves that occurred due to soil slip movement mechanism generated both lateral and vertical heave of the surrounding soil, and therefore would have impact on the subsequent construction of overlying scour stones and potentially the stability of the Floodwall. Therefore, appropriate remediation measures were required to obtain satisfactory stability of the submerged rock/sand berm. To identify most suitable remediation methods, the as-built soil conditions were investigated based on filed Vane Shear Tests (VST) and CPTs. The global stability back analysis indicated the necessity to use rock surcharge and soil cut-off structure for the remediation. The outline of the paper is summarized as below.

First, bathymetric surveying observations of the mud wave at the rock toe on the flood side and sand core displacement were briefly described, which indicated a rotational movement of the rock dike. Then, a brief discussion on remolded soil strengths of soft clay layers under the deformed rock dike was provided based on field VSTs and CPTs on the site. The remolded soil strengths at the site under soil slip movement were verified by stability back analyses using field observations. Based on the as-built stability status of the submerged rock dike, several remediation approaches were proposed and evaluated. The design requirements of the selected approach were determined based on corresponding stability analyses and constructability. Finally, a summary and conclusions on proposed remediation plans were presented at the end of the paper.

BACKGROUND AND SURVEYING OBSERVATIONS

The submerged MRGO rock berm consists of rock dikes on both sides of the Floodwall and a sand core in between with a rip rap layer on the top. The rock dikes were first built from channel bottom to the elevation of -21 feet; then the sand fill were placed for the construction of the Floodwall; finally a 6-foot rip rap layer were placed atop of the sand core for the purpose of scour protection. Bathymetric surveys were performed during the placement of the sand fill. Surveying observations indicated mud waves with a height of up to 10 feet that developed near the toe of rock dike in several locations on the flood side during the construction of the sand core. In addition, the sand core and the crest of the rock dike on the flood side displaced downward and the rock dike toe moved upward (See Figure 1). Such soil heave at the rock dike toe and the displacement of the sand core indicated a rotational displacement of the rock dike and implied a global slip movement of underlying soft soils. After the construction at this stage, the rock dike on the flood side of the Floodwall proved to be marginally stable, i.e. factor of safety is close to the unity. Further placement of the rip rap layer on the top of sand core may induce the further instability of the rock dike. Therefore, engineering remediation of the rock dike on the flood side was required to maintain the stability during the subsequent construction of the berm.

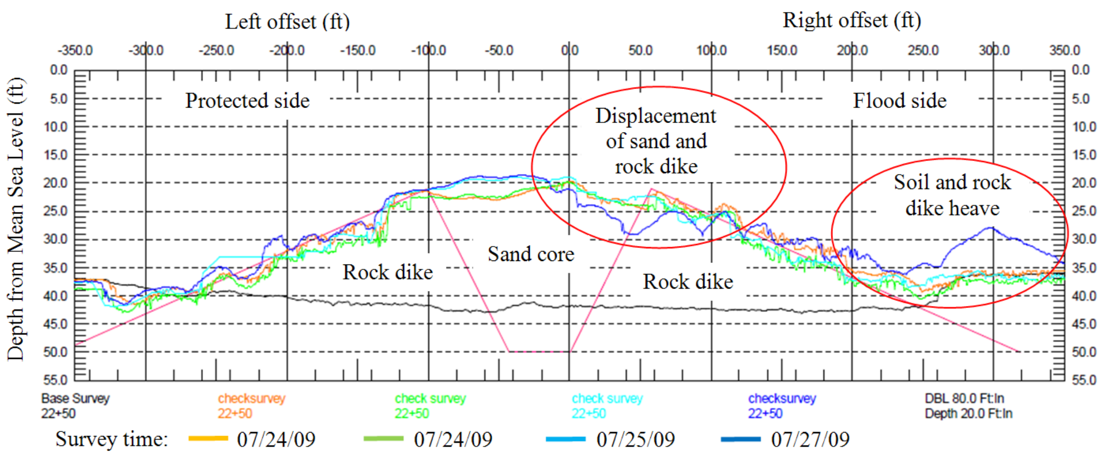


Figure 1. Bathymetric surveys of as-built cross section of MRGO Berm at STA 22+50

SOIL STRENGTH PARAMETERS

CPT correlations

Soil profile at the construction site in general consists of a peat layer up to 10 feet below mudline at the elevation of -42 feet, underlain by normally consolidated clays down to the elevation of approximate -100 feet. Based on local experience and the correlation with borings, the undrained shear strength S_u on the site was estimated from adjacent soil borings and CPTs as listed in Table 1. However, soft clays under the deformed rock dike on the flood side were remolded, and therefore, their resistance should be represented by remolded shear strengths due to the movement of the foundation soil. The remolded shear strength $(S_u)_r$ of the peaty clay layer and underlying clay layers are related to undisturbed undrained shear strength S_u and the soil sensitivity S_t (Lunne et al, 1997). Table 1 lists basic soil profile until the depth of interest and key parameters, including unit weights, undrained and remolded shear strengths of clay layers, which are estimated from CPT correlations.

Additional field testings

In addition to CPT correlations, the in-situ strength characteristics of clay layers on the site under the deformed rock dike were also investigated using additional four field VSTs and CPTs. The locations of these additional field tests are indicated in Figure 2. The corresponding field VST and CPT results are shown in Figure 3. Based on the evaluation of these field testing results and the HSDRRS design guidance (USACE 2007), the in-situ soil shear strengthline on the flood side were modified as shown in Figure 3. Soil shear strength above the elevation of -53 feet was proposed to follow additional CPT3 strengthline. Below the elevation of -53 feet and above the elevation of -61 feet, additional CPT3 strengthline was shift to the left such that 2/3 peak strengths obtained from VSTs are above the modified strengthline. Since no VSTs were performed below the elevation of -61 feet, CPT correlated remolded shear strength as discussed in the previous section was adopted during stability analyses. Below the elevation of -70 feet, original design soil undrained shear strength and unit weights were adopted.

Table 1. Key soil parameters for stability analyses

Elevation (feet)		Soil Type	γ' (pcf)	S_u (psf)	$(S_u)_r$ (psf)	$(S_u)_r$ (psf) (field testings)		
From	To					Top	Ave	Bot
-42	-53	Peat	10	140	75	100	142.5	185
-53	-61	Clay	47	600	220	120	140	160
-61	-70	Clay	62.5	630	315	-	315	-
…	…							

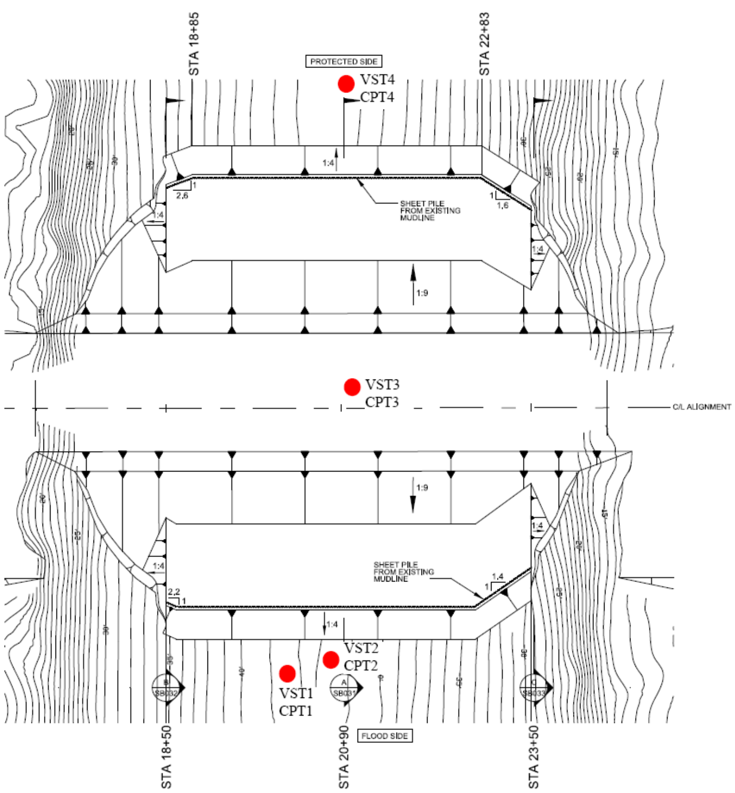


Figure 2. Plane view of MRGO berm and lay-out of additional field testings

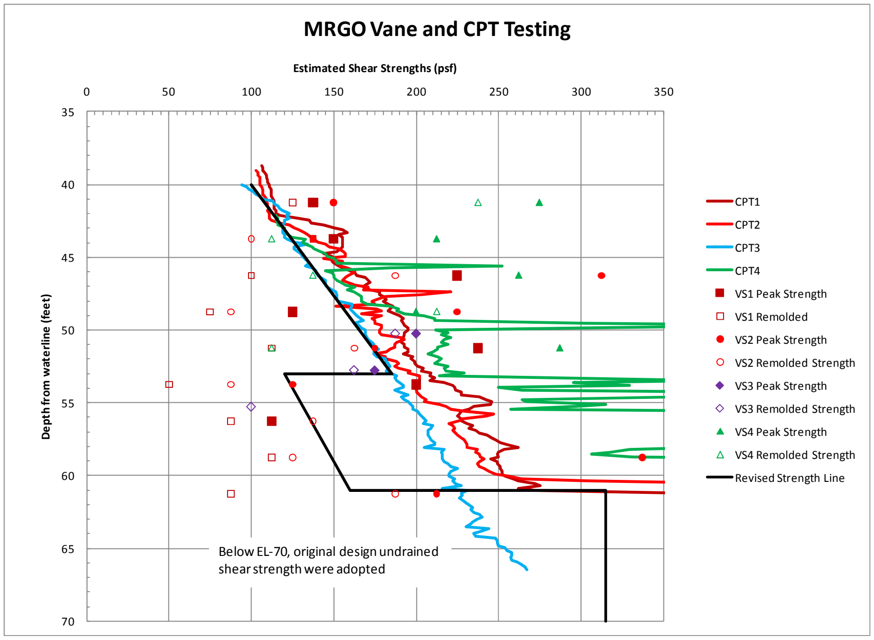


Figure 3. Additional field testing results and revised soil strengthline

STABILITY BACK ANALYSES OF AS-BUILT CONDITION

As mentioned at the beginning, the rock dike on the flood side after the placement of sand fill core was marginally stable with the remolded soft soil underneath. Such as-built global stability of the rock dike on the flood side was investigated with limit equilibrium analysis and finite element modeling. The limit equilibrium stability analyses were performed using Slope/W with Spencer method and the total stress approach. The remolded soil shear strengths for top three soft clay layers were used in the computation. The corresponding Slope/W stability analysis results of critical slip movement surface beneath the submerged rock dike on the flood side were shown in Figure 4. The block specified slip surface option was used in Slope/W analyses to capture the deep seated slip surface beneath the rock dike as shown in Figure 4. The corresponding Factor of Safety (FS) is 1.153. This indicated that the rock dike was just marginally stable as expected. Such calculation conclusions were confirmed with finite element stability analyses using PLAXIS with φ-c reduction approach. Figure 5(a) shows PLAXIS result of the critical slip movement surface beneath the rock dike with a FS equal to 1.099, which matched very well with the Slope/W result. Figure 5(b) shows PLAXIS result of soil movement characteristics beneath the rock dike, which indicated a potential downward displacement of the upper portion of rock dike, upward deformation of the lower portion of the rock dike, as well as soil heave at the toe during the soil slip movement with the soft soil layer underneath the rock dike.

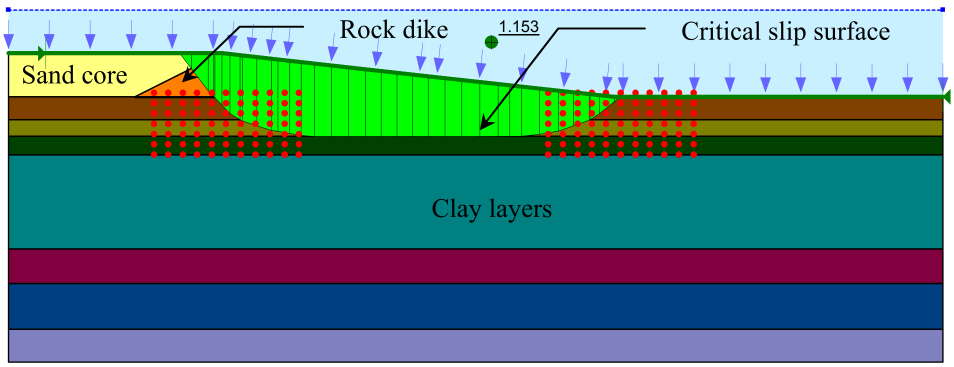
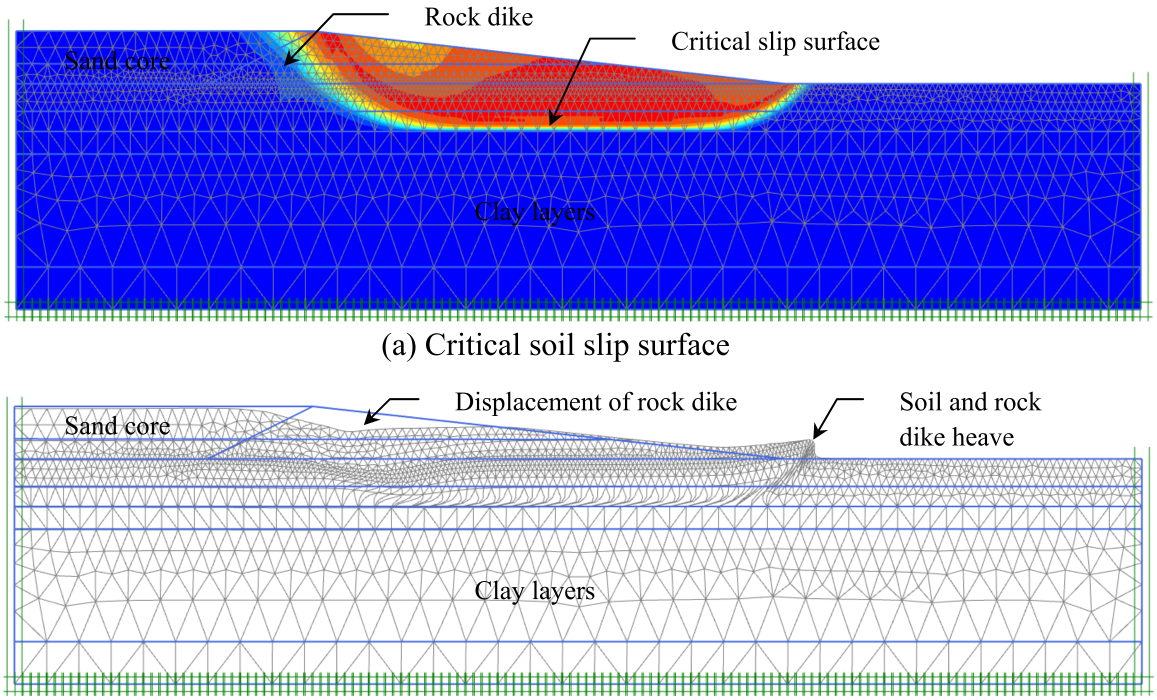


Figure 4. Slope/W stability analysis result of the critical slip surface for the as-built condition under the rock dike



(a) Critical soil slip surface

(b) Potential deformation characteristics of the rock dike and soil heave

Figure 5. PLAXIS stability analysis results of the critical slip surface for the as-built condition under the rock dike

REMEDIATION APPROACHES

The stability back analysis of as-built rock dike with remolded soft soil foundation indicated the necessity of remediation to achieve the berm stability with a required safety factor of 1.5.

Rock surcharge at toe

Based on the finite element stability analysis of the as-built rock dike on the flood side, as presented in Figure 5(b), an initial remediation approach was proposed to place additional rock surcharge from lower portion of the rock dike slope to a distance beyond the rock dike toe as illustrated in Figure 6. The rock surcharge layer is proposed to extend 28 feet beyond the toe of the existing rock dike with a height of 10 feet from the design mudline at the rock dike toe, and then it slopes down to the mudline with a slope of 4H:1V. The global stability of this rock surcharge remediation approach (with the final rip rap layer atop the sand core) was investigated with a Slope/W analysis. Figure 6 shows the corresponding critical slip surface with a FS just slightly greater than unity. This indicates that rock surcharge would not be sufficient to achieve the required FS of 1.5. Therefore, a soil cut-off structure is necessary to prevent the potential slip movement of the soft soils beneath the rock dike and rock surcharge as indicated in Figure 6. Two soil cut-off options, using rock fill trench and sheet pile respectively, were proposed and evaluated in the ensuing sections.

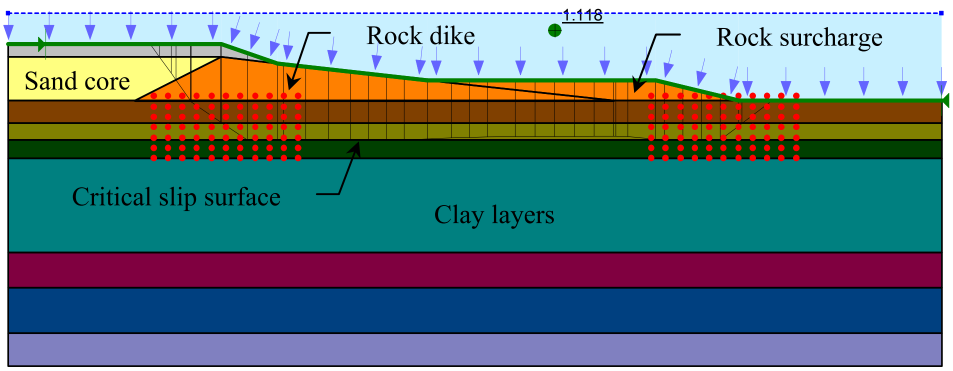


Figure 6. Slope/W stability analysis result of the critical slip surface beneath the rock dike and rock surcharge

Rock surcharge with rock fill trench soil cut-off

In the rock fill trench soil cut-off option, a trench with rock fill was considered as cut-off of soft clays beneath the rock dike. Two geometries of the rock trench option were investigated: one with a shallow depth to the elevation of -53 feet and the other with a deep depth to the elevation of -63 feet, as illustrated in Figures 7 and 8 respectively. With the shallow depth, the FS of 1.5 was hardly reached even with much wider rock trench due to the soft soil layer beneath. Figure 7 shows Slope/W stability analysis results with a FS=1.491 for the geometry with the shallow rock fill trench that is 170 feet in width at the bottom of rock surcharge. The trench slope on both sides was proposed to be 3H:1V. It is implied by this stability analysis that the rock fill trench should be built deeper to cut-off the soft soil layer beneath. In the second scenario, therefore, the rock fill trench was proposed to penetrate to the elevation of -63 feet, 2 feet below the second soft soil layer, with a width of 6 feet at the bottom. Figure 8 shows the Slope/W stability analysis result with a FS of 1.829

for this scenario. Therefore, the deep rock fill trench geometry was considered to be a feasible remediation option to achieve the stability requirement for submerged rock berm of the Floodwall.

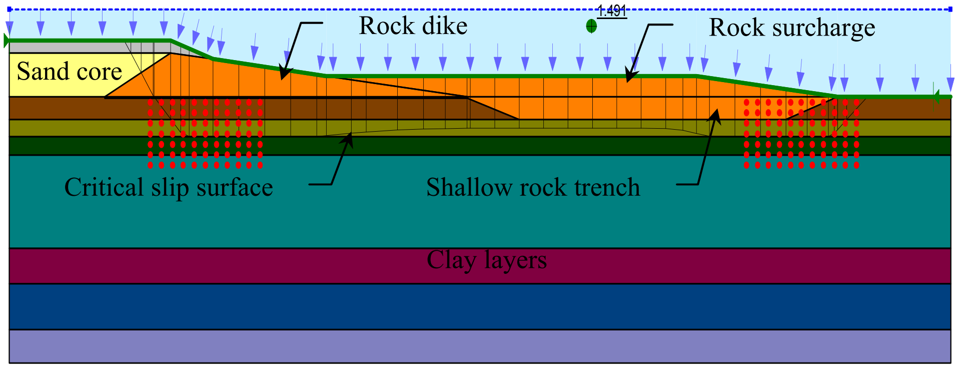


Figure 7. Slope/W stability analysis results for the shallow rock fill trench with the bottom at elevation of -53 feet

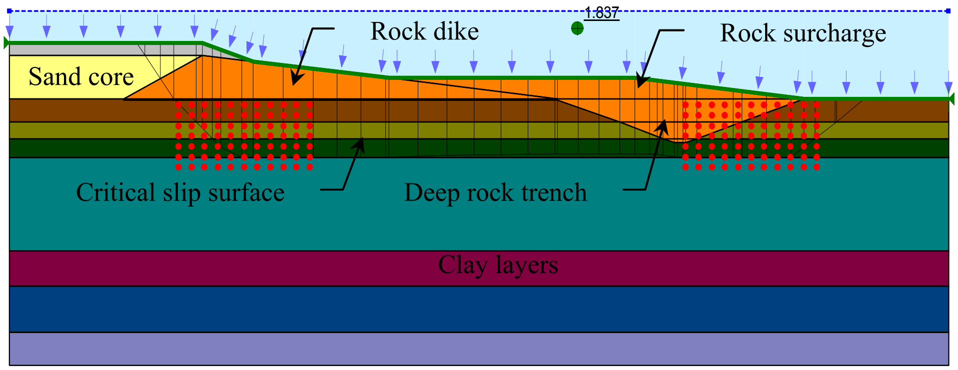


Figure 8. Slope/W stability analysis results for the deep rock fill trench with the bottom at elevation of -63 feet

Rock surcharge with sheet-pile soil cut-off

In the sheet-pile soil cut-off option, the sheet-pile was proposed to be installed below the rock surcharge to cut-off underlying soft soils. The penetration depth and grade of the sheet-pile were determined based on an unbalanced load that was derived from the global stability analysis of the rock dike using Spencer method based on HSDRRS design guidance (USACE 2007). Compared to Figure 6 in the previous section, which shows a FS close to unity for the geometry with the rock surcharge only at the toe of the rock dike, Figure 9 shows a FS greater than 1.5 for the geometry with a line load of 15kips/ft applied at EL-46ft, 4ft below the mud-line, under the rock surcharge. Such line load represents the unbalanced load that sheet-pile should provide to achieve a stability condition of the rock dike with the FS as shown in Figure 9. With such unbalanced load, the penetration depth and section modulus of the sheet-pile was determined by sheet-pile stability calculation (USS, 1984). In this sheet-pile stability calculation, the line load as mentioned above was transferred to a distributed load of 1.875 ksf on the top of the sheet pile from the elevation of -42 feet to elevation of -50 feet to represent the unbalance load. Stability calculations indicated a minimum embedment of 43 feet and a minimum section modulus of 66.4 in^3/ft of the sheet-pile. The stability of such remediation approach with rock surcharge plus sheet-pile soil cut-off underneath was also checked with finite element φ-c reduction modelling using PLAXIS. Figure 10 shows corresponding PLAXIS stability analysis result with a FS equal to 1.51. Factors of safety obtained from both limit equilibrium and finite element stability analyses match very well to each other. And they are all greater than 1.5, which ensured the feasibility of such remediation option.

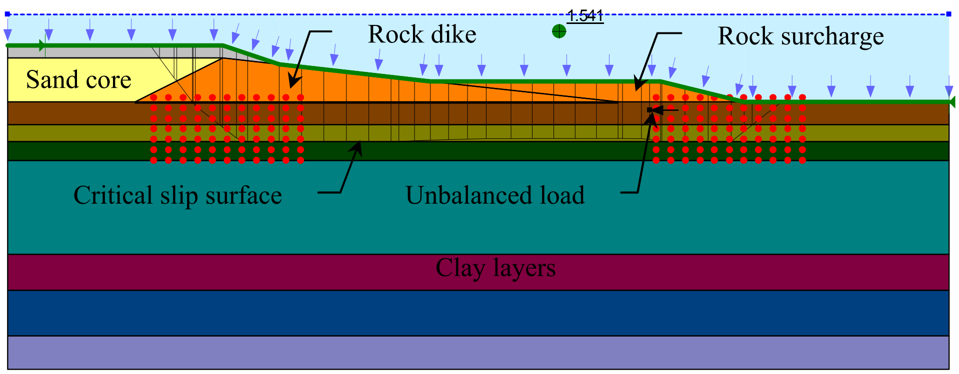


Figure 9. Slope/W stability analysis results of rock surcharge with an unbalanced load of 15 kips/ft at the elevation of -44 feet

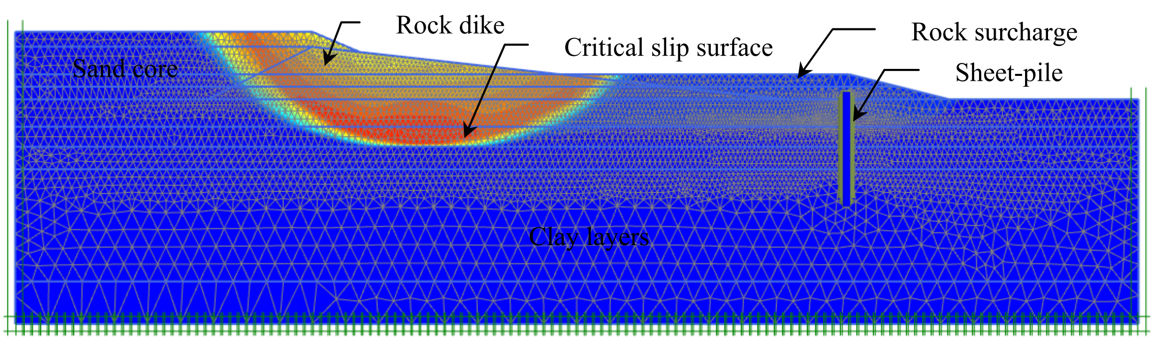


Figure 10. PLAXIS stability analysis result of rock surcharge with sheet-pile soil cut-off

CONCLUSIONS

Two remediation options were proposed to enhance the submerged rock/sand berm of the Floodwall over MRGO in South Louisiana to restore the design stability requirement. The as-built condition of soft clays beneath the deformed rock dike on the flood side was investigated based on field VSTs and CPTs as well as stability back analyses. Such as-built soil conditions were used to evaluate proposed remediation approaches. Limit equilibrium and finite element stability analyses showed that rock surcharge only on the downstream of the rock dike is not sufficient to stabilize the underlying soft clay during the final construction of the submerged rock berm, and therefore soil cut-off structures are necessary. In this case, two soil cut-off options were proposed using rock fill trench or sheet pile, respectively. Design requirements for each soil cut-off option were investigated based on the global and structure stabilities. The proposed soil cut-off solutions for the soft soil improvement beneath the submerged rock berm were evaluated from the view point of global stability of the soil foundation. The final choice of the remediation solution with rock surcharge and sheet-pile soil cut-off was selected based on the considerations of constructability and cost estimate.

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