Finite Element Seepage Analysis of the Floodwall in South Louisiana

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Abstract

Seepage analysis is an important design aspect of the floodwall in South Louisiana for assessing its hydraulic stability. Estimating subsurface flow through the floodwall requires a thorough understanding of pore pressure characteristics in foundation soils under hurricane storm surge condition. During a surge period, the seepage flow is far from the steady-state due to the low permeability of the local soft soil foundation and is influenced by the surge-induced water surcharge load on the flood side of the floodwall. The active pore pressures on the floodwall under surge conditions result from both the transient flow and excess pore pressure resulting from soil volume changes induced by the water surcharge and structural deformation. Prediction of such subsurface flow is beyond the capability of conventional seepage analyses. This paper presents a finite element seepage analysis to investigate active pore pressures on the floodwall with the consideration of soil-structure interaction effects. The results of the finite element seepage analysis are used to evaluate the gap formation and the seepage cut-off of the floodwall based on seepage design criteria.

INTRODUCTION

Hurricane Katrina in 2005 caused catastrophic damage to the City of New Orleans and surrounding areas. The storm surge that entered via the Gulf Intracoastal Waterway (GIWW) and Mississippi River Gulf Outlet (MRGO) converged at the Inner Harbor Navigation Canal (IHNC), creating multiple breaches along the levees and concrete floodwalls atop of it (Brandon et al, 2008; Duncan et al, 2008; Seed et al, 2008; IPET, 2007). To prevent future storm surges from entering the IHNC, a nearly two-mile-long surge barrier, comprised of a floodwall and two gate structures, was built in Lake Borgne across the GIWW and MRGO (Huntsman, 2011; Reid, 2013). The floodwall provides flood protection to El+25 with wave deflectors to El+26, and consists of closely-spaced large diameter pre-stressed concrete cylindrical piles braced by steel-pipe batter piles. The interstitial space between plumb cylindrical piles throughout the water column was closed using irregular pentagonal closure piles installed down to EL-90. Jet grout was applied to seal the gap between the closure piles and cylindrical piles of the floodwall. The depth of the grouted soil column was determined based on the seepage criteria required by the Hurricane and Storm Risk Reduction System Design Guide (HSDRRS) (USACE, 2012).

Seepage analysis is therefore an important aspect of the floodwall design in order to determine the penetration depth of the jet grout seepage cut-off column required to maintain stability of the earth and wall. Conventional seepage analyses usually assume steady-state subsurface flows within soils. Steady-state seepage flows can be reached either in a relatively short time period in soils of high permeability (i.e., granular materials) or over a longer time period in soils with low permeability (i.e., clays or silts). For the clays encountered in the foundation of the floodwall, hydraulic conductivities are very low. In addition, the surge duration would be relatively short from the viewpoint of the seepage flow in the clay layers; therefore, the pore pressure distribution in the soft soil layers would not be able to reach a steady state. On the other hand, pore pressure distributions obtained from pure transient seepage analyses do not include the effect of Soil-Structure Interaction (SSI) (Dong and Schwanz, 2011). During a storm period, the soft clays are surcharged by high surge water and can be considered to undergo undrained behavior due to their low permeability. Excess pore water pressures would thus develop in the clays on the flood side of the floodwall. Thus, the active pore pressures in these clay layers include hydrostatic pressures plus excess pore pressures generated during surging. Such active pore pressure distribution is a much more realistic scenario compared to either steady-state or transient pore pressure distribution, and it should be used with piping and/or heave design criteria to determine seepage cut-off of the floodwall. The active pore pressures on the floodwall are also important for investigating the development of a water-filled gap behind the wall (Brandon et al., 2008; Duncan et al., 2008).

This paper presents a finite element seepage analysis for determining the active pore pressures on the floodwall under storm surge condition, which are then used to investigate the gap formation and seepage cut-off penetration depth. The content of the paper is outlined as follows. First, the seepage analysis approaches that are considered in the floodwall design are briefly described as a reference. Next, the design water levels and subsurface profile that are considered in the seepage analysis are presented. With the soil profile and hydraulic boundary conditions, a finite element model is then created using a geotechnical computational program PLAXIS, and this is used to determine the active pore pressures on the floodwall under surge conditions. The active pore pressures are then compared with soil pressures, hydrostatic, steady-state and transient pore pressures in the following section. Finally, the computed active pressures are used to determine the seepage cut-off at the floodwall cross-section being considered, based on the design seepage criteria.

SEEPAGE ANALYSIS APPROACHES

Exit gradient

The seepage force f_s per unit volume of water is defined as

$$f_s = \gamma_w \frac{\Delta h}{L} = i\gamma_w \qquad (1)$$

where γ_w is the water unit weight, $\Delta h = h_t - h_d$ is the pore pressure head difference between the seepage cut-off tip (h_t) and seepage flow downstream (h_d). The definitions of h_t and h_d are illustrated in Figure 1. Using (1), the differential pore pressure Δp from seepage cut-off tip to seepage flow downstream can be calculated as

$$\Delta p = \gamma_w (h_t - h_d) = f_s dL = \gamma_w \Delta h \tag{2}$$

This upward seepage pressure is resisted by the effective weight of soil overburden above the seepage cut-off tip. In this respect, therefore, a factor of safety of seepage cut-off can be evaluated as below (USACE, 1986),

$$F_S = \frac{\sigma'_v}{\Delta p} = \frac{D\gamma'_s}{\Delta h \gamma_w} = \frac{i_{cr}}{i_e} \tag{3}$$

where γ'_s is the soil effective unit weight, D and $\sigma'_v = D\gamma'_s$ are the soil thickness and effective soil overburden pressure above the seepage cut-off tip, $i_{cr} = \gamma'_s / \gamma_w$ represents the critical hydraulic gradient, and $i_e = \Delta h / D$ represents the exit gradient (Freeze and Cherry, 1979). The case of $i_e \geq i_{cr}$ corresponds to a zero effective stress condition. In order to avoid such a situation, the critical hydraulic gradient of subsurface flows should be greater than the exit gradient, i.e., $F_S = i_{cr} / i_e > 1$.

Terzaghi piping analysis

The exit gradient approach is equivalent to the conventional Terzaghi piping analysis (Terzaghi et al, 1996; USACE, 1993). Using model tests of seepage beneath the sheet pile, Terzaghi (1922) found that the rise of the sand occurs within a distance of about $D/2$ from the sheet piles, where D is the penetration depth of seepage cut-off. The failure, therefore, starts within a prism of sand with a depth D and a width $D/2$. Failure by piping occurs as soon as the uplift seepage force U becomes equal to the effective weight W' of the sand prism above the seepage cut-off tip (see Figure 1). Therefore, the factor of safety with respect to piping is calculated as

$$F_S = \frac{W'}{U} = \frac{D \times \gamma'_s \times (D/2) \times 1}{\Delta h_a \times \gamma_w \times (D/2) \times 1} = \frac{D\gamma'_s}{\Delta h_a \gamma_w} \tag{4}$$

where Δh_a is the average differential pore pressure head on the bottom of the sand prism as determined from seepage analysis, $W' = D \times \gamma'_s \times (D/2) \times 1$ is the effective weight of the soil blocked by D and $D/2$, $U = \Delta h_a \times \gamma_w \times (D/2) \times 1$ is the average uplift seepage force below the soil block as shown in Figure 1. The Terzaghi piping criterion (4) reveals an effective heave phenomenon that a mass of soil may be lifted initially, followed by piping, when the upward seepage force at the seepage cut-off tip is greater than the buoyant weight of overlying soils.

Heave analysis

In addition to the effective stress seepage analysis approaches as discussed above, a heave analysis based on total stress is also required by the HSDRRS design guide (USACE, 1986) for the evaluation of tension crack and seepage cut-off of the floodwall. For this case, the pore water pressure force at the seepage cut-off tip is compared with the total weight of soil overburden, and the corresponding factor of safety can be defined as

$$F_S = \frac{W}{U_t} = \frac{D \times \gamma_{sat} \times (D/2) \times 1}{h_t \times \gamma_w \times (D/2) \times 1} = \frac{D\gamma_{sat}}{h_t \gamma_w} \tag{5}$$

where $W = D \times \gamma_{sat} \times (D/2) \times 1$ is the total weight of soil overburden, γ_{sat} is the saturated unit weight of the soil, $U_t = h_t \times \gamma_w \times (D/2) \times 1$ is the pore water pressure force at the seepage cut-off tip, and all other symbols were defined earlier.

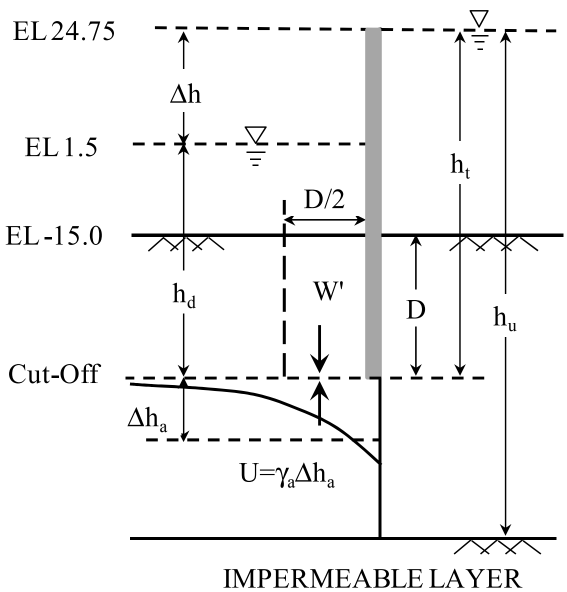


Figure 1. Schematic diagram of seepage analysis.

FINITE ELEMENT SEEPAGE ANALYSIS MODEL

Design water levels

As can be seen from the above discussions, all seepage analysis approaches require accurate estimates of the pore water pressures on the floodwall under design storm surge water levels. According to the design basis, the floodwall should provide a minimum flood surge protection elevation at EL+24 in the year 2057. To offset the effect of settlement, one-foot high infill planks will be added to retain the required surge protection elevation in the future. The consolidation analysis shows an approximate 3.0-inch settlement of the floodwall at one design reach during its 50-year design life. Therefore, the design water level at the Top of the Wall (TOW) is chosen as EL+24.75. According to the HSDRRS design guide, the water elevations for seepage analysis should be "water to TOW" on the flood side and EL+1.5 on the protected side of the floodwall.

Subsurface profile and hydraulic properties

The subsurface profile at the typical floodwall cross-section under consideration is shown in Table 1. This soil profile includes a soft organic clay (Marsh) at the top overlaying Interdistributary and Prodelta (Holocene) soft clay. The soft clay is underlain by Pleistocene medium and stiff clay, with an intrusion layer of nearshore gulf (Interdelta) sand. Table 1 also lists the mechanical and hydraulic properties of the clay and sand layers of such a subsurface profile. The soil mechanical properties were determined based on laboratory and in-situ cone penetration tests; the soil hydraulic conductivities were estimated based on the DIVR-1110-1-400 (USACE, 1998). In Table 1, γ_{sat}, s_u, ϕ, k_h and k_v represent the saturated unit weight, shear strength, effective friction angle, horizontal and vertical hydraulic conductivities of the soil layers, respectively. The hydraulic conductivity of a rip rap layer placed on the top of the mudline as wave overtopping scour protection, is assumed to be the same as that for the sand layer.

Table 1. Soil Profile and Properties.

Elevation (*ft*)	*Soil Type* (*USCS*)	γ_{sat} (*pcf*)	s_u (*psf*)	ϕ (*deg*)	k_h (*ft/day*)	k_v (*ft/day*)
-12 ~ -20	PT	101	100		5.67×10^{-3}	1.70×10^{-3}
-20 ~ -62	CH	105	100~674		5.67×10^{-3}	1.70×10^{-3}
-62 ~ -77	SM	125.5		30	2.41×10^{1}	1.22×10^{1}
-77 ~ -100	CH	114	780~1075		5.67×10^{-3}	1.70×10^{-3}
-100 ~ -190	CL	110	1075~2170		5.67×10^{-3}	1.70×10^{-3}

Finite element model

Based on the soil profile and properties as listed in Table 1, a finite element seepage analysis model was developed to predict the soil and pore pressures on the floodwall under storm surge conditions at a typical cross-section under consideration. The finite element model was created with the aid of the geotechnical computational program PLAXIS and its add-on seepage module PlaxFlow. The mesh configuration of the finite element model is shown in Figure 2. The computational domain had a width of 1600 ft and depth of 500 ft. The design water levels as discussed in the previous section were applied on the flood side at the right and the protected side at the left, respectively. The differential water head from both sides drives the subsurface flow through the floodwall. Since the horizontal and vertical flow paths are more than 15 and 10 times the proposed seepage cut-off length of the floodwall, the flow near the bottom boundary of the domain is close to horizontal. Therefore, a homogeneous Neumann (wall) boundary condition was applied on the bottom of the computational domain for an assumed impervious boundary condition there.

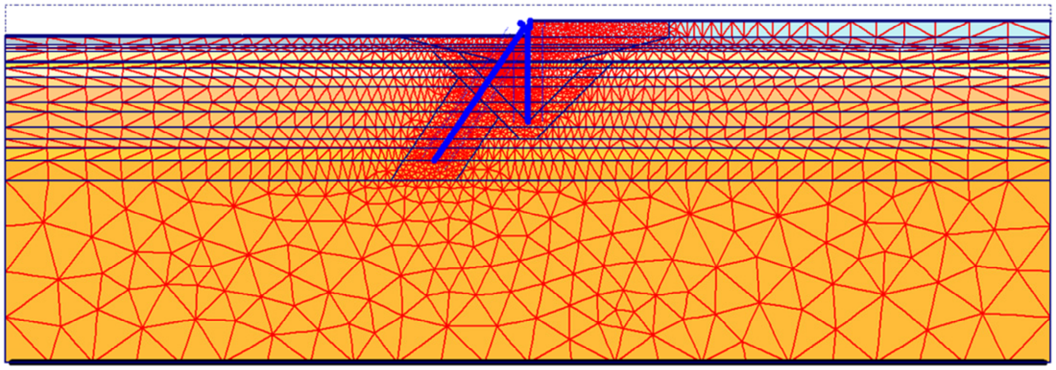


Figure 2. Mesh configuration for finite element seepage analysis.

PORE WATER PRESSURES UNDER SURGE CONDITIONS

Steady-state and transient subsurface flows

The steady-state pore water pressures on the floodwall in the soil layers correspond to the long term ultimate stage of the subsurface flow under storm surging conditions. Such steady-state seepage flow in soils with low permeability can only be achieved over a reasonably long time period. Thus, the subsurface flow in the clay layers with a hydraulic conductivity of 5.6×10^{-3} ft/day does not attain a steady state in a one-day period of storm surging. On the other hand, the transient pore water pressures on the floodwall in the soil layers correspond to the short term subsurface flow state (without considering the water surcharge effect) during storm surges. Figure 3 shows the PlaxFlow results of a pore pressure head distribution of the transient subsurface flow state during a one day surge. It can be seen that due to the low permeability of the clay layers, the seepage only takes place in the shallow soil layers on the flood side during such one-day surging.

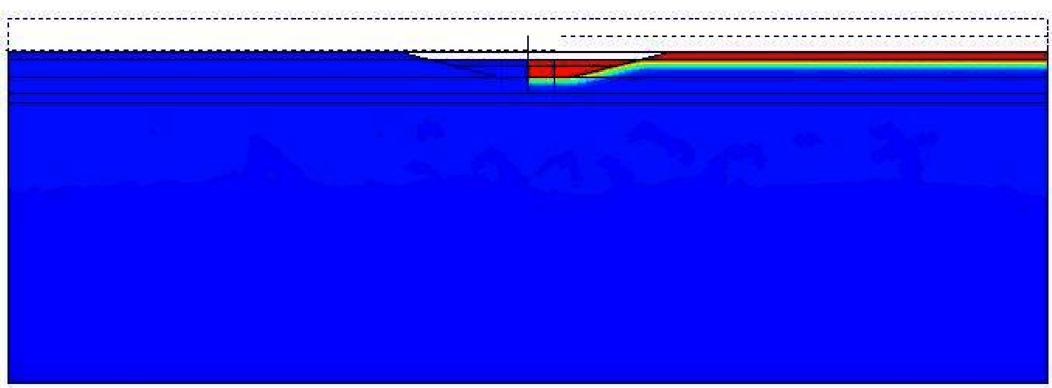


Figure 3. Transient pore pressure head distribution.

Active pore pressures

The transient pore pressure head distribution as shown in Figure 3 does not include the SSI effect of the floodwall with the soil foundation. During a storm surge, the water level increases from mean sea level to the TOW, resulting to a water surcharge over the marsh on the flood side. During a one-day storm surging period, the foundation clay layers can be considered to exhibit undrained behavior, and therefore excess pore water pressures would develop under the water surcharge on the flood side. Such excess pore pressures also include the effect of soil volume changes due to SSI effects. Thus, the active pore pressures on the floodwall under storm surge loading consists of the transient pore pressures and the excess pore pressures due to the undrained behavior of the clay layers. Such active pore pressures can be determined using the finite element seepage analysis as discussed previously with a consideration of the SSI effect. Figure 4 shows the active pore pressures on the floodwall under storm surge conditions, as well as the pore pressures obtained from the steady state and transient seepage analyses. As a comparison, the analytical and numerical hydrostatic pressures on the wall corresponding to high (EL+24.75) and lower (EL+1.5) water levels are shown in Figure 4.

As expected from the assumption that the subsurface flow takes places in all the foundation soil layers on both the flood and protected sides of the floodwall, the steady state pore pressures are half way between the hydrostatic pore pressures for high and low water levels. However, as reflected in Figure 3, the transient pore pressures shown in Figure 4 indicate that the subsurface flow only penetrates through the upper rip rap layer during a one-day surging period due to the high hydraulic conductivity of this scour protection layer. In the clay layers, however, the transient pore pressures are almost the same as the hydrostatic pressures for the lower water level that was used as the initial condition in the seepage analysis, since only a little seepage takes place in these clay layers due to their low permeability. Nevertheless, during a storm surge, excess pore pressures develop in the clay layers due to a soil volume change induced by the water surcharge and the SSI of the floodwall (Dong and Schwanz, 2011). However, such excess pore pressures do not occur in the sand layer between EL-62 to EL-77 due to the drained effect in this layer. In addition, the transient flow barely reaches the sand layer because of the clay barrier layers above. Therefore, the active pore pressures on the floodwall in the clay layers is attributable to the transient and excess pore water pressures, and they are equal to the initial

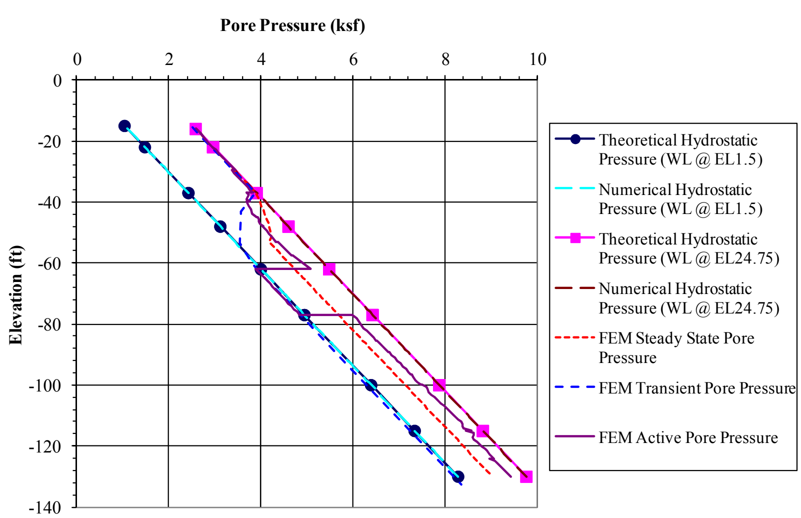


Figure 4. Pore pressure distribution in front of a vertical concrete cylinder pile.

hydrostatic pressures in the sand intrusion layer. The active pore pressures in the clay layers lie between the steady-state pore pressures and hydrostatic pressures for high water levels.

HYDRAULIC STABILITY

Likelihood of gap formation

Based on the active pore pressures and total horizontal earth pressures obtained from the finite element analysis, the formation of a gap due to tension cracks between the vertical pile and the clay layers during storm surging are investigated using the procedure described in the IPET report (2007). In this procedure, the total horizontal earth pressures on the vertical pile wall are compared with the hydrostatic pore pressures that would exist if a gap were present. If the later exceeds the former, then a gap is assumed to form. In this paper, the likelihood of gap formation between the vertical pile and the clay layers is evaluated by comparing the total horizontal earth pressures with the active pore pressures. Figure 5 shows the distributions of the steady state, transient and active pore water pressures as well as the total horizontal and vertical earth pressures on the wall, obtained from the finite element analysis. It can be seen from Figure 5 that the total horizontal earth pressures are greater than the active pore pressures due to the low shear strength of the clay layers, indicating that it is unlikely that a gap will form under storm surging conditions at the floodwall cross-section being considered. It should be noted that the horizontal earth pressures in the clay layers, especially below the sand intrusion layer, are greater than the vertical earth pressures due to the SSI of the floodwall as discussed previously.

Seepage cutoff

The design criteria for the seepage cut-off of the floodwall during storm surges are adopted from the HSDRRS design guide (USACE, 1986). The required factors of safety for three seepage analysis approaches as described before are listed in Table 2. Using the active pore pressures and soil pressures obtained from the finite

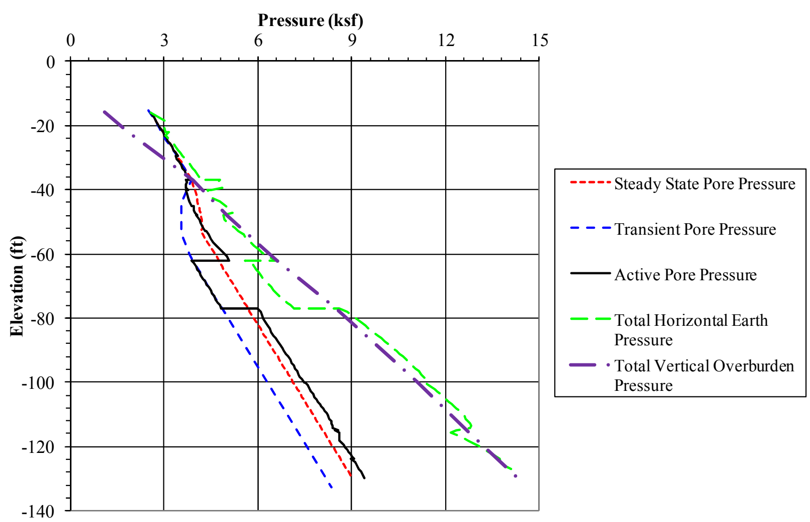
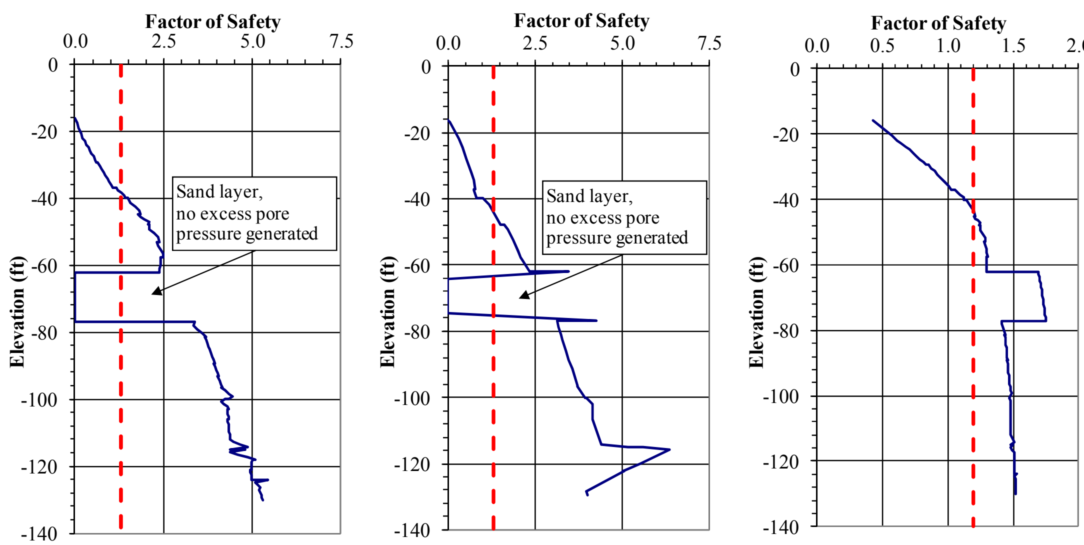


Figure 5. Comparisons of pore pressure with earth pressures.

element seepage analysis, the factors of safety for different tip elevations of seepage cut-off along the floodwall are calculated as shown in Figure 6. The required tip elevations of seepage cut-off at the considered floodwall cross-section, based on each design criteria, are also listed in Table 2. The deepest elevation is chosen as the final design tip elevation of seepage cut-off for the floodwall cross-section being considered.

Table 2. Seepage Analysis Criteria.

Criteria	F_S	*Tip elevation of cut-off (ft)*
Exit gradient	1.3	-38
Terzaghi piping	1.3	-45
Total weight heave	1.2	-45



(a) (b) (c)

Figure 6. Distributions of factors of safety based on the criteria for (a) exit gradient, (b) Terzaghi piping and (c) total weight heave.

CONCLUSION

The determination of pore water pressures under storm surge conditions is important for assessing the hydraulic stability and seepage cut-off of the floodwall. Attention needs to be focused on the conventional assumptions of steady-state and/or transient pore pressure distributions, since neither of them is applicable for the floodwall during storm surge loading. In addition to the transient pressures, the active pore pressures on the floodwall under surge conditions also contribute to the excess pore pressures that develop in the clay layers due to soil volume changes induced by the water surcharge and SSI with the floodwall. Determining such active pore pressures is beyond the capability of conventional seepage analyses, but it can be achieved using finite element analysis to include SSI effects. Based on the design seepage criteria and active pore pressures obtained from such a finite element seepage analysis, the penetration depth of jet grouted soil columns between the cylindrical and closure piles, which function as a seepage cut-off for the floodwall, can be determined properly.

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