Slope Stability Analysis of Levee

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Abstract: The stability of levees can be affected during fluctuations in the water table. It is also possible for the flood caused by the typhoon to have an influence on the position of the water table in an earth levee. This paper compares the traditional methods methodology with a combination of transient seepage and slope stability analysis for analyzing rapid drawdown scenarios. Firstly the stability of a levee was calculated by conventional methods, then considering the effect of water level changes in the seepage area, the simulated transient pore-water pressure response from a finite element SEEP / W analysis was used for levee stability simulation. The Silt Solidified Piles have a positive effect on the stability of the levee. The results provide design basis for the projects.

1. Introduction
Slopes may be above ground level as embankments or below ground level as cuttings. Earth slopes are formed for levees, earth dams, canal banks, railway embankments and at many other locations. Instability may result from rainfall, increase in groundwater table and change in stress conditions.

The rapid draw-down scenario is one of the most severe loading conditions which can afflict a levee. Rapid draw-down consists of a relatively high water table which has remained against an earth levee for a period of time so that pseudo steady-state conditions are created in the levee. The high water table would be consistent with high water levels during a flooding season. The devastation of the flood caused by the typhoon in China’s South-East coastal areas is having a significant impact on the stability of earth Levees. The flood-waters, in levees made of gravel, clay and so on, may disappear within a relatively short period of time, and thus the pore-water pressures present in the levee during the flooding do not have enough time to dissipate. As a consequence, the pore-water pressures heightened on the up-stream side of the levee, thus the instability-related hazers increased.

This paper compares the traditional methodology for analyzing stability of levee based on the rapid drawdown boundary condition during the flood scenarios with a combination of transient seepage and slope stability analysis. Besides, the positive effect of the silt solidified piles was considered.

2. Theoretical analysis methods
2.1. Traditional methods
Code for design of sea dike project (GB/T 51015-2014) recommends the Swedish slice method which is the oldest and simplest method of slice method law[1]. Its basic assumption is that the sliding surface is a cylindrical surface and the sliding soil is a rigid body that does not deform, while the forces on the side of the soil strip are not considered. In the stability analysis of cohesive soil slope, the procedures based on Swedish slice method are usually defected by low automation and poor
visualization.

2.2. Morgenstern-Price method

Slope-stability problems are usually analyzed using limit equilibrium methods of slices. When evaluating the stability conditions of soil slopes of simple configuration, circular potential slip surfaces are usually assumed[2]. In many situations, however, the actual surfaces of rupture are found to deviate significantly from the circular shape. Reservoir bank slopes are more prone to instability and damage due to the effects of reservoir water soaking and floating.

2.3. The effect of the pore-water pressure

Rapid drawdown is a condition in which water level suddenly down after a long period in the water level during flood scene[3]. During this condition, the pore water pressure and the hydrostatic pressure are changed sharply if the velocity of upping-lowering water level is too fast, and then the collapse of the slop appears, which is common phenomenon in levees. The transient pore-water pressures can be simulated by SEEP/W. The flood event was defined by a standard dimensionless unit hydrograph[4]:

\[
\frac{h - h_0}{(h_p - h_0)} = \left(\frac{t - t_0}{t_p}\right)^m e^{-\frac{t - t_0}{t_p}}
\]

(1)

where \( h \) is the river level, \( h_0 \) is the initial river level, \( h_p \) is the peak river level, \( m \) is a shape factor, \( t \) is the time, \( t_0 \) is the time at the onset of the flooding event (0 days), and \( t_p \) is the time to the peak river level. Equation 1 can be rearranged to obtain the river level at any point in time in terms of total head.

Besides, unsteady flow model can be adjusted for real time forecasting of floods. The 1D unsteady flow model is the core computing program of MIKE11:

\[
\frac{\partial Z}{\partial t} + \frac{1}{B} \frac{\partial Q}{\partial X} = q
\]

(2)

where \( Z \) is the average water level, \( Q \) is the rate of flow.

3. The engineering example

In this section, the slope stability analysis of an engineering example using the two methods mentioned above can be mentioned as below. Different from the traditional method(Case 1) using alternative bulk density material(clay or gravel), the effect of the pore-water pressure was considered in the manner of steady-state(Case 2) and transient condition(Case 3) respectively. In the steady-state analysis (Case 2), stabilized piezometric line was used; and flood hydrograp in the transient analysis (Case 3) correspondingly. The left and right boundaries of the levee do influence the pore-water pressure response under the levee, so the cross-section of the levee is large enough to prevent this effect, the model is shown by Figure 1.

Figure 1. The model domain of the levee

According to the detailed field measurements and the 1D unsteady flow model, the boundary on the floodplain slope of the levee is used on this engineering example, as shown by Figure 2.
Figure 2. Flood hydrograph applied on the left levee slope

The saturated-unsaturated material model was used to characterize three materials above the water within the domain for the SEEP/W analyses shown by Figure 3.

(a) Vol. water content function of silt

(b) Vol. water content function of silty
The volumetric water content, the physical properties and hydraulic conductivity functions of soil were listed in Table 1.

| Material           | Water content (%) | Cohesion (kPa) | Phi (°) | Hydraulic Conductivity ($\times 10^{-7}$ cm/s) | Compressibility ($\times 10^3$ cm²/s) |
|--------------------|-------------------|----------------|---------|-----------------------------------------------|--------------------------------------|
| silt               | 68.6              | 6.3            | 2.8     | 22.3                                          | 1.849                                |
| mucky silty clay   | 46.1              | 9              | 7.4     | 28.7                                          | 1.029                                |
| clay               | 36.9              | 18.5           | 9.3     | 1.84                                          | 0.4                                  |
| silty clay         | 35.1              | 14.3           | 11.7    | 2.66                                          | 2.51                                 |
| silty sand         | 25.3              | 4.5            | 27.3    | 1260                                          | 0.286                                |

Due to the Silt Solidified Piles is a main part of the levee, the effect on the piezometric lines is considered by a standard dimensionless unit hydrograph. The location of the piezometric lines are shown by figure 4.

4. The critical factor of safety

During the six days of the flood, the pressure head contours generated by the transient seepage analysis have an obvious changes accompanied with the fluctuations in water levels. It can be seen from the figure 5 that the pore water pressures within the levee have not changed substantially due to the relatively quick rise in the water level even though the river level is near the levee crown in the day 2 (about 48 hours) refer to figure 2.
Figure 5. Pore water pressures computed for day 2

On the other hand, solidification pile is an important way for reuse of dredging, in this engineering example the Silt Solidified Pile prevent water through this levee over the pile. The location of the silt solidified pile is shown in the figure 6, and the pore-water pressure response where the levee contacts the silt solidified pile is shown in figure 7.

Figure 6. The location of the silt solidified pile

Figure 7. Pore-water pressure

The minimum critical factor of safety was reached 1.446 at a duration of 2 days, which corresponds to the peak in pore-water pressure (Figure 8). The critical factor of safety was 1.360 when the traditional method (case 3) was used for analyses when the flood water level is arrived. The diagram of stability calculation is shown by figure 9.

Figure 8. The stability of the levee of 6 days in Case1
Figure 9. The stability of the levee of 6 days in Case 2

The difference between the critical factor of safety result from the uncertainty of the wetting front within the levee and elevated pore-water pressures within the underlying confined aquifer[5]. In the Case 1, the simulated transient pore-water pressure response is used by a standard dimensionless unit hydrograph as mentioned in the section 2.3, however, the piezometric lines was defined artificially as shown by figure 2. This is also evident when comparing the pore-water pressure at the base of each slice over the same slip surface for each stability case as shown by figure 10.

Figure 10. Pore-water pressure at the base of each slice surface

The factor of safety can be affected during the vary of the pore-water pressure. Due to the Silt Solidified Pile have an effect on the pore-water pressure, a reasonable estimate for the piezometric line corresponding to the confined aquifer was only possible in Case 3. It can be seen in figure 11 that the factor of safety rise to 1.643 with the boundary condition of the piezometric line mentioned above. Thus the Silt Solidified Piles can be positive and functional to the stability of the levee.

Figure 11. The stability of the levee in Case 3

5. Conclusions

The analyses presented in this paper show that the stability of the levee can be improved by the Silt Solidified Piles, and the rapid drawdown scenarios have a reasonable effect on the factor of safety of
the levee during the flood season. With the advent of more intensive field measurement, there is opportunity to more closely simulate the stability of the levee.

References
[1] Ministry of Water Resources of the People's Republic of China. (2014) Design Code for Seawall Engineering (GB / T 51015-2014). China Planning Press, Beijing. pp: 026-030.
[2] Lu T. H. (2005) Soil mechanics. Hohai University Press, Nanjing. pp:199–203.(in Chinese)
[3] Upomo T C, Effendi M K, Kusumawardani R. (2018) Behaviour of levee on soft soil caused by rapid drawdown. In: AIP Conference Proceedings. AIP Publishing. pp: 020-045.
[4] Calgary, Alberta. (2012) Manual G U. Geo-slope international Ltd. Canada.
[5] Fredlund M, Lu H H, Feng T. (2011) Combined seepage and slope stability analysis of rapid drawdown scenarios for levee design In: Geo-Frontiers: Advances in Geotechnical Engineering. pp: 1595-1604.