Numerical simulation of bank protection structure deformation effected by the river level fluctuations

Rui Hu*[1], Yixuan Xing[1]
[1] School of Earth Science and Engineering, Hohai University, Nanjing, China
*Corresponding author: No.8 Fochengxi Road, Nanjing, China, rhu@hhu.edu.cn

Abstract: In this Study, a bank protection structure at Yangtze River bank in Nanjing section is taken as an example and a 2D water-soil coupling model is established, in which the influence of water level fluctuation on groundwater seepage and soil shear strength is considered. In the simulation, Drucker-Prager yield criterion has been adopted to describe the elasto-plasticity of soil. According to the water level data of the Yangtze River during the monitoring period, the displacement of bank protection structure is calculated and the structural deformation under extreme water level condition is predicted. The simulation results show a good agreement between horizontal displacement of monitoring points and the fluctuation of the water level. In the simulation scenario with extreme low water level, the maximum displacement of the pile is about 65mm which has exceeded warning value of this project and it may cause excessive deformation, which should be seriously considered

Keywords: Bank protection structure, deformation analysis, the extreme river-water level, deformation predication.

1. Introduction

Bank protection structure has been widely used in wharf construction, cofferdam excavation and waterway engineering. This structure is an important barrier to maintain the safety of the embankment. The deformation of bank protection structure is not only affected by soil pressure caused by the excavation of the river way, but also by the water pressure with the seasonal river water level fluctuations. Furthermore, the depth of the groundwater table will affect the mechanical parameters of the soil. Therefore, the deformation analysis of bank protection structure, in addition to calculating the classical soil mechanics, should also consider the impact of groundwater seepage in the embankment.

1.1. Soil-water Interaction in Embankment

The deformation of bank protection structure is not only affected by the inner earth pressure, but also by the hydrostatic pressure caused by the fluctuation of river water level. This fluctuation leads to the changes of soil seepage field and groundwater level and therefore affects the soil mechanical properties. Since the deformation of structure mainly occurs along the horizontal direction (vertical to the river flow direction) and the displacement is small, the influence of soil consolidation on the permeability coefficient could be neglected.

The seepage field is described by Darcy's law. According to the calculated groundwater level, the bulk density and shear strength of soil are progressively adjusted. The shear strength parameters (cohesion c and friction angle φ) below the groundwater level are calculated according to:

$$c_s = c \cdot \alpha_c \, , \; \varphi_s = \varphi \cdot \alpha_\varphi \tag{1}$$

Where α_c and α_φ are the reduction coefficients of shear strength parameters.

2 Use of COMSOL Multiphysics® Software

2.1 Geometry

In bank protection structure engineering, steel sheet pile is normally used to support the embankment. A section vertical to the pile wall is selected to establish the geometric model which is shown in **Figure 1**, with a horizontal length of 120 meters, and a height of 40 meters. An ideal elastic-plastic model and Drucker-Prager failure criterion are adopted in the simulation. According to the soil physical mechanical property, the soil is divided into 3 layers along the depth. The mechanical parameters of each layer are list in **Table 1** in the appendix. The parameters include the bulk density (γ), elastic modulus (E), Poisson ratio (μ), cohesion (c), the inner angle (φ), porosity (n) and permeability (K). The length of steel sheet pile is 18 meters; The elastic modulus and Poisson's ratio of pile are E_s=200GPa and μ=0.2 respectively. The struts at the top of pile is simulated by spring element in the numerical model, allowing free elongation of 40mm and the rigidity coefficient is $k_s=8*10^4$kN/m. The interaction between piles and soil is described by ideal elastic plastic spring element which can transfer the stress-strain relationship between them. The elastic coefficient is set to $k=1*10^5$ kN/m.

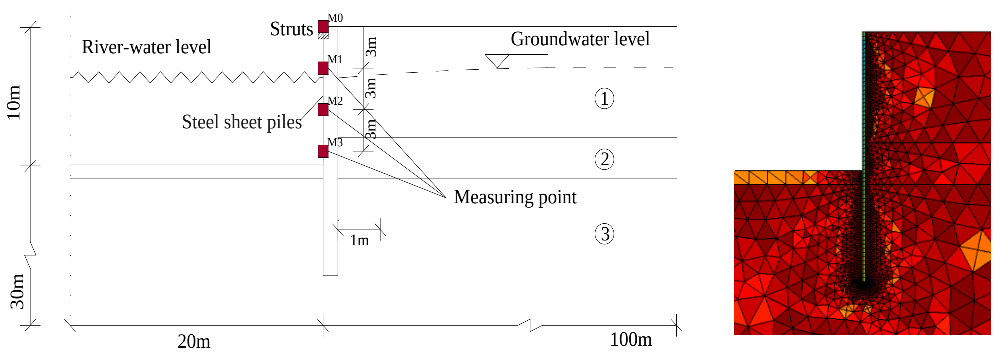

Figure 1. The geometry (left) and grid (right) of the bank protection structure model.

2.2 Application Modes

Based on the *deep_excavation* model in the COMSOL Application Libraries we developed it by coupling the Darcy's Law. The geometry of this model is shown in **Figure 1**. As the river water level fluctuates, the hydrostatic pressure on the steel sheet pile will change. We defined a depth-dependent hydraulic pressure on the left side and added the steady-state seepage field data to the Solid Mechanics module as an initial condition.

Besides that, the soil mechanical parameter is modified through the groundwater level (pore-water pressure = 0) calculated by Darcy's Law which is the key coupling factor between this two physical fields. We redefine the parameters of soil by using the Boolean expression.

In this study, the deformation of steel sheet pile is not only affected by active earth pressure with excavation, but also by hydrostatic pressure that is related to the depth. Meanwhile, due to the effects of soil seepage shear strength and changing pore water pressure, the stress-strain state of the revetment structure is affected. The main type of groundwater in embankment is phreatic water. The groundwater level is mainly controlled by the seepage field. Evaporation and water supply are set to be zero. The initial and boundary water head is -3m and the river water level fluctuates according to the measured data.

According to the change of the river level, we firstly calculated the seepage field in the embankment. Subsequently, based on strength reduction method, the shear strength parameters of soil were adjusted by the groundwater table. Finally, the deformation was calculated by the *deep excavation model*.

3 Simulation Results

The deformation tends to be stable via the early excavation. After that the deformation of bank protection structure is mainly affected by water level fluctuation. As an example, the result of one scenario (**Figure 2**, river water level at -6m) shows the distribution of total pressure field and seepage field and the white line represents the groundwater level (pore-water pressure = 0). Based on the Drucker-Prager yield criterion, we achieved the displacement of the steel sheet pile (**Figure 3**) and plastic deformation of the structure (**Figure 4**). The maximum displacement in this case is about 60mm.

The results indicate that the water head difference in the side of the pile caused the discharge of groundwater to the river and the change of groundwater level. In particular, the variation of total pressure under water level is obvious. Under the hydrostatic pressure and soil pressure, the displacement of structure in the middle part of excavation section is relatively large. The plastic strain zone of soil is shown in **Figure 4**. It shows that the plastic deformation is mainly produced in the first layer of soil and distributes in the area below the depth of water level.

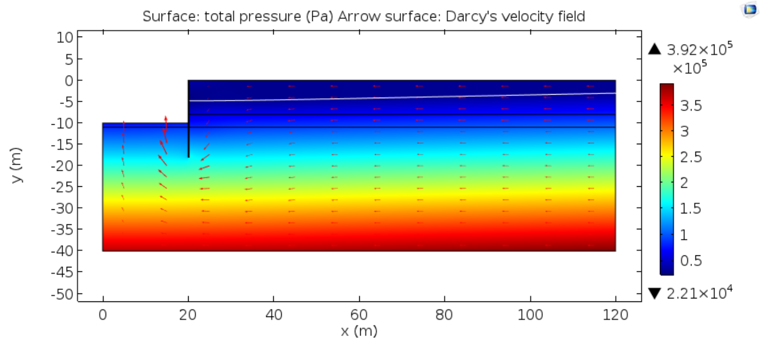

Figure 2. The distribution of total pressure field and seepage field at the river level of -6m. (The white line is the groundwater level).

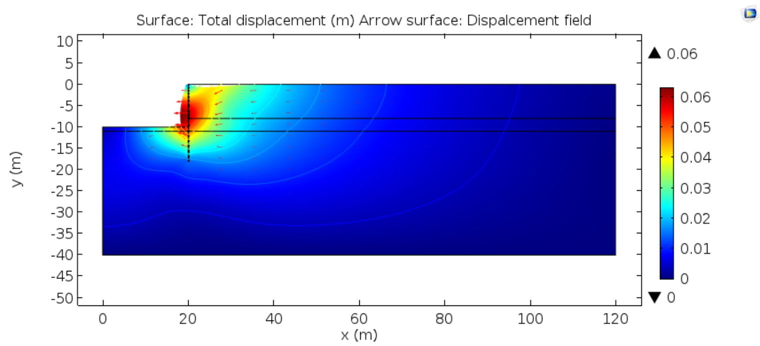

Figure 3. The displacement of the structure at the river level of -6m (scale factor: 30).

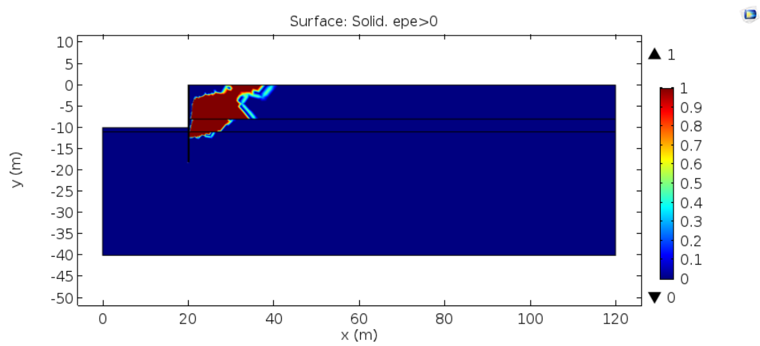

Figure 4. The plastic deformation of the structure at the river level of -6m.

3.1 Influence of water level fluctuation on horizontal displacement

Based on the monitoring data of the Yangtze River water level for 120 days (**Figure 5a)**), the deformation of this model is calculated. In the bank protection structure, the horizontal displacement is the main deformation. In order to analyze the response of the structural deformation to the water level fluctuation, we selected 4 displacement monitoring points (**Figure 1**). The horizontal displacement curve of these monitoring points is shown in **Figure 5b).**

The simulation results indicate that the variation of horizontal displacement and water level fluctuation have good consistency. Due to the resistance of the struts, the displacement is relatively small (18~24mm).

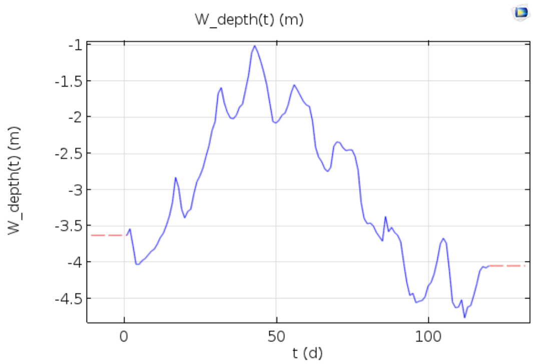

Figure 5a). The monitoring data of the Yangtze River water level for 120 days

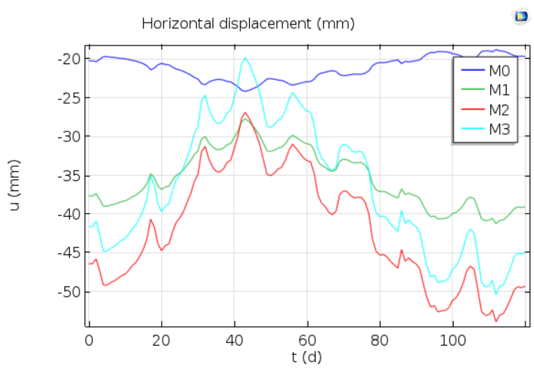

Figure 5b). The horizontal displacement curve of monitoring points

3.2 Prediction of structural deformation under extreme water level case

According to the water level monitoring statistics, in the past ten years the highest and lowest water level of Yangtze River are respectively -0.3m and -8.4m. Based on the introduced numerical model, we have calculated and obtained the distribution of plastic zone (**Figure 6**), the horizontal displacement and the generalized shear stress of steel sheet pile (**Figure 7**).

In the case of extreme high water level, the plastic deformation is produced in the first layer of soil and the plastic area is small. The maximum horizontal displacement of 25.1mm occurs at the top of the pile and the maximum shear stress of the pile is reactively small (4.9MPa). In the case of extreme low water level, the plastic zone is mainly distributed in the upper soil and plastic area expands to the third layer. The maximum horizontal displacement of 65mm occurs at the depth of 8m which has exceeded warning value of 56mm. The maximum shear stress of 18.5MPa of the pile occurs at the depth of 7m, which is less than the yield limit of the steel sheet pile (335 MPa). Therefore, there is a potential risk of excessive structure deformation, which should be seriously considered and taken care of

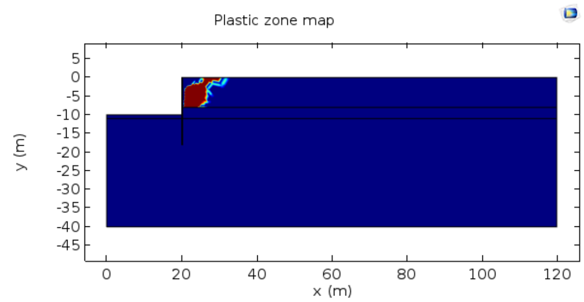

Figure 6a). The distribution of plastic zone in extreme high water level.

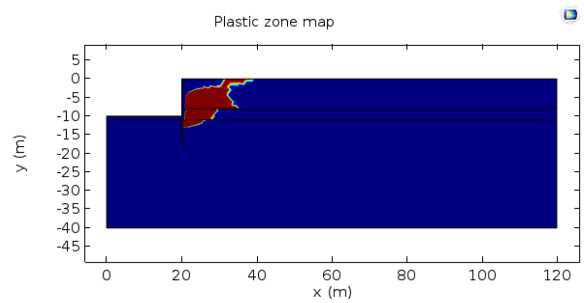

Figure 6b). The distribution of plastic zone in extreme low water level.

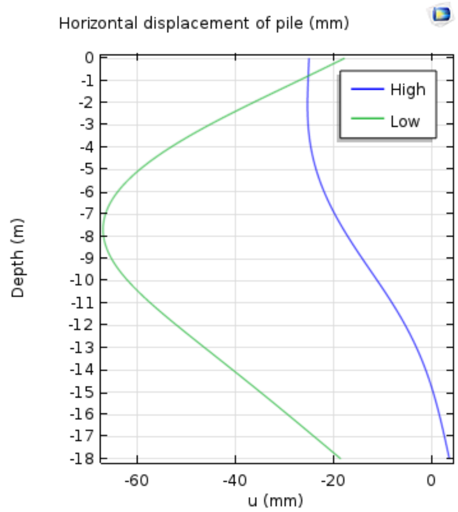

Figure 7a). The horizontal displacement of pile in extreme water level case.

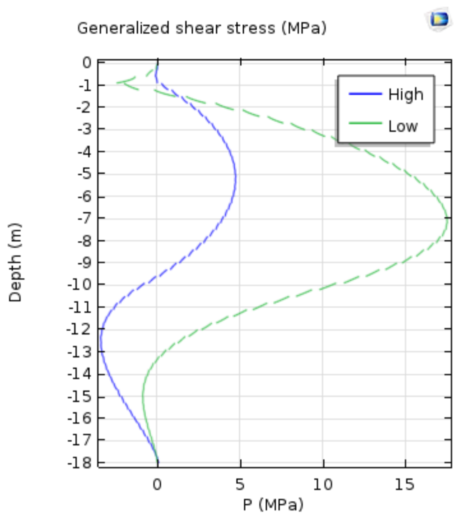

Figure 7b). Generalized shear stress of pile in extreme water level case.

4. Conclusions

In this study, the coupled numerical model has simulated the interaction between seepage and soil pressure. The simulation results show that the river water level fluctuation has clear influence on the lateral displacement of the pile. Meanwhile, the distribution of plastic zone is related to the depth of groundwater level. Based on this model, we predicted the deformation of bank protection structure under extreme water level case. For the next step, we will validate and develop this model by comparing the results with long-term in-situ displacement measurements in order to provide usefull suggestions for engineering design.

5. References

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6. Appendix

Table1: Parameters employed in the numerical simulation

	Soil layer		
	1	2	3
Density of gravity γ/kN·m^{-3}	17.2	17.8	17.7
Elastic modulus E/MPa	3.46	3.72	5.40
Poisson's ratio μ	0.3	0.3	0.3
Cohesion c/kPa	8.1	10	6.5
Internal friction angle φ/°	5.5	25.4	24.7
Porosity n	0.54	0.52	0.49
Permeability K/m^2	0.5	0.53	0.45