Study on the influence of bank slope soil deformation on wharf structure

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Abstract: After a large-scale construction period, there are a large number of old high piled wharfs in China's ports. The pile cap piles and beam members of some wharfs close to the earth retaining structure appear obvious dislocation, and some of them are increasing year by year. In this paper, the typical section of Tianjin Port 16 ~ 18 wharf is taken as the research object, and a three-dimensional mathematical model is established to simulate the deformation trend of wharf structure with bank slope soil under unbalanced load condition. The results show that the pile cap plays a positive role in the stability of the wharf slope. Partial load can cause the deformation of soil along the bank. The horizontal earth pressure acting on several rows of piles behind the pile cap is large, which leads to large deformation and internal force of the pile body. When the force between the pile top and the beam exceeds the lap strength between them, the pile top and beam will be staggered. The fundamental method to avoid or improve the seaward movement of high piled wharf and bank slope is to block or reduce the horizontal earth pressure from the rear storage area to the front. The scheme of sheet pile wall or bored pile can be selected according to the actual situation.

1. Introduction
In recent years, the Chinese government attaches great importance to safety production and earthquake prevention and disaster reduction[1][2], and has made a lot of efforts in many aspects, but the investment in port wharf structural safety is relatively small, and the research on bank slope deformation of high pile wharf is even less. At present, most of the domestic research in this area is still at the level of simplified two-dimensional mathematical model research and qualitative analysis, and there is no systematic and comprehensive research work from the perspective and depth of the combination of prototype observation and three-dimensional mathematical model. The simplified two-dimensional mathematical model still has a lot of shortcomings in considering the complex engineering properties of soil, and the practicability of its research results is still very poor. 85% of China's deep-water berths above 10000 DWT adopt high piled wharf, which shows the important position and role of high-rise wharf in China's water transportation industry. Among this high-rise wharf, the full hall high-rise pile wharf built on soft foundation accounts for a considerable proportion. Therefore, it is of great significance to conduct in-depth study on the bank slope stability of full hall high-rise wharf[3-7].

In this paper, Tianjin port 16 ~ 18 section of the typical section of the terminal as the research object. Obvious deformation of bank slope has appeared in this section, and dislocation has appeared between pile cap and beam, beam and panel near retaining wall of rear bearing platform. The overlapping length of some beam plate components is very small, which seriously affects the safety of
wharf structure. In view of the existing situation of the wharf, this paper establishes a mathematical model by collecting relevant soil and load data to simulate the deformation trend of wharf structure along with bank slope soil under specific working conditions, so as to explore the influence of bank slope soil deformation on wharf structure and predict the deformation trend of bank slope, so as to grasp the change dynamics of wharf structure at all times and take effective measures in advance, ensure the safe production of the wharf.

2. Overview of the study area
The 16 ~ 18 section wharf of Tianjin Port No.4 company was completed in 1961. It is located on the west side of the second jetty. The wharf length is 549.5m. The front bearing platform is a flexible pile platform structure without beam slab, most of which are prefabricated components. The front crane beam is an inverted T-shaped section, and the rear crane beam is a reinforced concrete panel with local thickening to 50cm. The wharf is divided into 11 structural sections, from north to south, they are Ji, Ding 3, Ding 4, Ding 5, Ding 6, Ding 7, Geng, Xin 1, Xin 2, Ren and GUI. Among them, Ji district is the transition section connected with berth 15, and Kui area is located at the transverse head of the second jetty. The length of the standard section of the wharf is 62m, including 18 bent frames with a spacing of 3.5m. The rear bearing platform is a simply supported beam slab structure, the panel is prestressed slab, and the beam is non prestressed slab. The bent spacing is 3.5m and the pile spacing is 3.2m. The bank slope type is -2.6 ~ 1.8m sand cushion (the elevation datum adopts the theoretical lowest tide level of Xingang), the upper part is riprap prism, and the top of prism is rubble concrete block. The width of the front bearing platform is 13.75m, that of the rear of berths 16 and 17 is 28.10m, and that of the rear of berth 18 is 31.3m. The design elevation of wharf surface is +5.6m, and the designed bottom elevation of apron is -10.0 ~ -9.0m. The structural section of wharf is shown in Figure 1.

![Figure 1. Schematic diagram of wharf structure section](image_url)

The design process load of the wharf is 3t/m² for the front cap, 5t/m² for the rear pile cap and storage yard, and a bulk cargo warehouse is used for the rear yard. Cat 980g loader (dead weight 30t, maximum shovel weight 10t) and Steyr dump truck (deadweight 12t, load 36t) are used as the control load of mobile machinery. The load of gantry crane is Mh-6-25, and the maximum lifting weight is 25t.
3. Finite element analysis of bank slope stability

3.1 Finite element software
The finite element analysis of this paper adopts the large commercial finite element software ANSYS which is widely used in the world. In general, M-C criterion is more reliable and widely used in soil calculation, but its disadvantage is that there are discontinuous points such as sharp top and edge angle on the yield surface in three-dimensional stress space, which leads to the numerical calculation is not convergent. While D-P criterion is a circle on the partial plane, which is more suitable for numerical calculation. Therefore, Drucker Prager criterion, which matches Mohr Coulomb criterion, is selected as yield criterion of soil in order to facilitate numerical calculation.

3.2 Matching of D-P criterion and M-C criterion
The volume strain caused by the rearrangement of soil particles can significantly affect the shear capacity of soil itself. In the simple shear test, for over consolidated clay or dense sand, the volume of soil shrinks slightly at the initial stage of loading, and the shear stress reaches the peak value quickly. At this time, it usually corresponds to a small shear strain. After that, the volume of the sample gradually expands, and the curve enters the softening section. Until the failure, the volume does not expand. However, for normally consolidated clay or loose sand, the stress-strain curve does not show dilatancy, and the appearance of stress peak is often accompanied by large shear strain and corresponding to large volume shrinkage.

It can be seen from the above that the volume change of shear swelling over consolidated clay or dense sand is the main reason for the peak stress. In finite element analysis, shear angle is usually used $\phi$. To express the volumetric strain $\psi > 0$. When the volume is constant $\psi < 0$. However, the existing finite element analysis of geotechnical problems often only considers the internal friction angle $\phi$. The effect of shear is not fully considered. For example, the assumption of associated flow rule $\psi = \phi$ is still widely used in engineering. This not only overestimates the volume strain of the soil, but also improves the strength of the soil by considering the shear rise angle, that is, the failure load obtained by using the non associated flow rule is smaller than that by using the associated flow rule for the same type of material. If $\psi = 0$ means the shear rise angle is completely ignored, it is obvious that a more conservative result will be obtained. Therefore, in order to better describe the deformation characteristics of soil, the general non associated flow rule should be adopted $0 \leq \psi \leq \phi$.

3.3 Calculation scope and grid
In this paper, a three-dimensional numerical model of high piled wharf is established. The calculation domain is 93.6m × 35.1m × 62m (length × height × depth). In order to reduce the calculation, a symmetrical boundary is set at the depth of 31 meters. The three-dimensional finite element model is as Figure 2.
### 3.4 Calculation parameters and calculation scheme

The basic mechanical parameters of soil used in 3D finite element calculation are shown in Table 1.

| Material Science  | E (kPa)  | (g cm⁻³) | λ   | c (kPa) | Φ (°) | ψ (°) |
|-------------------|----------|----------|-----|---------|-------|-------|
| Soil layer        | 2.00×10⁴ | 1.835    | 0.4 | 24      | 25    | 6     |
| Soil layer        | 2.00×10⁴ | 1.800    | 0.4 | 20      | 25    | 6     |
| Soil layer        | 2.00×10⁴ | 1.730    | 0.4 | 14      | 25    | 10    |
| Soil layer        | 2.00×10⁴ | 1.734    | 0.4 | 11      | 15    | 4     |
| Soil layer        | 4.00×10⁴ | 1.500    | 0.45| 10      | 15    | 4     |
| Soil layer        | 1.00×10⁵ | 2.039    | 0.3 | 0       | 35    | 9     |
| Soil layer        | 8.00×10⁴ | 2.039    | 0.3 | 0       | 30    | 7.5   |
| Soil layer        | 4.00×10⁴ | 1.734    | 0.45| 10      | 15    | 4     |
| Piles, beams and slabs | concrete | 3.00×10⁸ | 2.400 | 0.2   |
| Cushion material  | reinforced concrete | 3.00×10⁸ | 2.450 | 0.2   |

### 3.5 Simulation conditions

In the three-dimensional finite element calculation, the working condition of this paper is that the half area (along the depth direction) of the back pile cap is subject to 3t and 5t uniform load respectively, and the half area of the storage yard (along the depth direction) is applied with 5t uniform load.

### 4. 3D finite element analysis and calculation results

#### 4.1 Overall deformation analysis of bank slope and structure

Figure 3 shows the displacement vector diagram of the bank slope under the current load. It can be seen from the figure that the maximum displacement is in the storage area behind the bank slope, which is the place with thick soil layer, but the displacement is mainly settlement. The partial displacement of the bank slope is mainly sliding under the syncline, and the maximum displacement is 0.8726m, which means that the load on the rear dump has a great impact on the overall displacement of the bank slope.

![Figure 3. Vector diagram of bank slope displacement](image)

Due to the unsymmetrical load applied, the bank slope will produce asymmetric deformation in the z-axis direction. Figure 4 shows the deformation diagram of z-axis direction. It can be seen from the figure that under the action of asymmetric load, the wharf structure and bank slope have deformation along the depth direction, with the order of centimeter. In the middle of the bank slope, the deformation tends to be negative to Z axis, and the red part at the outermost side of the high piled wharf will deform in the positive direction of Z axis. This deformation trend is due to the asymmetric load on the wharf structure and bank slope. However, due to the interaction of soil in depth direction, this deformation has little influence.
4.2 Pile and beam structure analysis
Figure 5 is the displacement vector diagram of pile and beam structure. It can be seen from the figure that the maximum displacement occurs at the lower middle part of the last row of piles, that is, the position with the largest bank slope deformation. This shows that the main cause of pile deformation is the earth pressure on the bank slope.

4.3 Bored pile scheme
According to the above working conditions, the corresponding rectification measures are formulated. Bored piles are drilled in the rear site. The reinforced concrete slab is used on the ground of the site. The site load is transferred to the pile through the slab, and then transferred to the deep foundation through the pile. This will reduce the forward earth pressure behind the retaining wall, so as to reduce the soil displacement. Assuming that the distance between bored piles is 5m and the elevation of pile bottom is the same as that of wharf pile foundation, the calculation results are shown in Figure 6 ~ Figure 9.
It can be seen from Figure 6 to Figure 9 that the scheme has obvious effect on reducing the horizontal force of bank slope soil on wharf structure, and the horizontal displacement of soil behind retaining wall is obviously reduced. On the one hand, the bored piles transmit the site load to the deep foundation and reduce the lateral earth pressure of the middle and upper soil layers. On the other hand, the existence of bored piles has a certain shielding effect on the horizontal displacement of the soil, which is conducive to maintaining the stability of the bank slope.

5. Conclusion

In this paper, the mathematical model simulation technology is used to analyze two kinds of means, respectively, the deformation law of wharf bank slope and the influence of bank slope deformation on wharf structure are studied respectively. The main causes of bank slope deformation are summarized, and the corresponding solutions are proposed.

(1) In this paper, the elasto-plastic finite element method is used to simulate the whole pile wharf and bank slope. In order to describe the deformation characteristics of soil more accurately, the D-P yield criterion and M-C yield criterion are matched, and a three-dimensional model is established. The calculation results show that the deformation of bank slope and wharf structure is large when the stacking area behind the retaining wall is applied, and the horizontal displacement and settlement of bank slope soil are obviously increased, but the surcharge effect of wharf cap area plays a positive role in bank slope stability. In addition, partial load can cause the deformation of soil along the bank.

(2) The calculation results show that the main causes of the seaward displacement of the bank slope of the high piled wharf are the self weight of the soil and the rear surcharge. The horizontal earth pressure acting on several rows of piles behind the pile cap is large, resulting in large deformation and internal force of the pile body. When the force between the pile top and the beam exceeds the lap strength between them, the pile top and the beam will be staggered.

(3) When the retaining wall is gradually displaced to the sea due to large horizontal earth pressure, the expansion joint between the retaining wall and the wharf structure will be gradually squeezed, and the horizontal force on the retaining wall will be partially transferred to the wharf structure, which will increase the dislocation between the pile top and the beam. Therefore, the fundamental method to avoid or improve the seaward movement of high piled wharf and bank slope is to block or reduce the
horizontal earth pressure from the rear storage area to the front. According to the actual situation, the scheme of sheet pile wall or bored pile can be selected for specific implementation.

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Reference
[1] Liu, Z. (2018) Research and application of structure assessment technology under dynamic and static loads of high piled wharf. Tianjin University.
[2] Wang, Y.Z., Zhu, Z.Y., Zhang B.B., et al. (2006) Finite elements analysis on slope stability of piled wharf. The Ocean Engineering, 24: 27-31.
[3] Wang, F. (2012) Research on factors influencing bank stabilization of wharf engineering on the soft ground. Tianjin University.
[4] Tian, S.Z., Zhang, Y., LI, Y.S. (2006) Study on deformation of a high-pile wharf slope from field observation [J]. Journal of Waterway and Harbour, 27: 180-184.
[5] Wei, R.L., Wang, N.X., Yang, S.H. (1992) Interaction between pile-supported pier and bank slope[J]. Chinese Journal of Geotechnical Engineering, 14: 38-49.
[6] Ding, Q. (2010) Study on deformation of Piled Wharf under rear surcharge. Tianjin University.
[7] Liu, S.Z. (2016) The research of slope deformation on high-pile wharf and CDM reinforcement technology with ABAQUS. Tianjin University.