Stability analysis of gravity quay with an application of furrowed crushed-stone subgrades

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Abstract: A new type of furrowed crushed-stone cushion is introduced for a caisson-structured quay. Numerical analysis was conducted to examine the stability, stress and sliding differences between quay models with furrowed and fully-paved crushed-stone cushion. The numerical analysis results show the difference between the safety factors is minimal. The stress states of two cushion structures are basically the same. The same sliding is found for both cushion structures. It is concluded that the subgrade with furrowed crushed-stone cushion will not adversely affect the stability of caisson-structured quay.

1. Introduction
More and more China offshore projects have to be constructed in open sea and far sea, some of which involve riprap bedding to improve the bearing capacity of soft soil ground. Quay stability is a focus of design and construction. The Chinese standard JTS 167-2-2009 Code for Design and Construction of Gravity Quay requires that the top and bottom surfaces of the riprap bed should be checked for horizontal anti-sliding stability [1]. In this code, the stress of the riprap bed of gravity quay is calculated by assuming that the bed is rigid, only considering the weight of the bed and the downward propagation of the top stress of the bed, and ignoring either the stress other the bed itself or the internal sliding failure of the riprap bed. Qin et al. theoretically deduced an improved calculation method using three control points by analysing the influence of the earth pressure applied on the front and back part of the thick riprap bed. Through the calculation of an engineering example, it is proved that the improved calculation method can more accurately reflect the actual distribution of the bed stress [2]. He et al. analysed the distribution of bed stress by establishing a finite element numerical model and discussed the possible slip surface, indicating that the location of the failure surface can be related to the height and width of the quay structure, rear load and soil parameters [3]. Zhi et al. established the finite element model and analysed the distribution of the earth pressure in front and back of the riprap bed with finite element software PLAXIS, and summarized the calculation formula of the earth pressure in the riprap bed [4]. In these cases, gravity quay stability analysis is performed by numerical analysis methods.

Graded crushed stone is a kind of granular material used in engineering. A typical application of crushed stone in the construction of harbour engineering is as subgrade with furrows under the concrete tunnel sections of the Hongkong-Zhuhai-Macao Bridge. In order to understand the bearing capacity of this kind of furrowed subgrade, a series of large mode tests were conducted and its characteristics had
been secured [5]. A gravity quay was selected as an example to present the performance of furrowed crushed-stone subgrade.

2. Analysis method

Strength reduction method is a method for finite element to assess the slope stability. Its principle can be simply summarized as follows: reduce the soil mechanical parameters by a trial safety factor, substitute these reduced parameters into calculation until a limit equilibrium state of failure occurs. At this time, the trial safety factor before failure is the target safety factor of slope. This method is commonly used for Mohr-Coulomb failure criterion. The safety factor is defined by the following formula:

\[
\frac{c_{\text{trial}}}{F_{\text{trial}}} = \frac{c}{F}
\]

\[
\phi_{\text{trial}} = \arctan\left(\frac{1}{F_{\text{trial}}} \tan(\phi)\right)
\]

In most cases, the strength reduction method and the limit equilibrium method can give approximately safety factor equal to the one obtained by common slope stability analysis such as the slice method.

3. Prototype and numerical model

3.1. Prototype

Take a quay as the calculation prototype, as shown in Figure 1, this is a typical concrete caisson structure constructed with concrete C40. The caisson is 6.8 m long and 8 m high backfilled with medium coarse sea sand. The caisson lays under riprap bed with 10 kg - 100 kg mass of stones. The caisson itself is backfilled with 5 kg to 30 kg of crushed stone and riprap. A protective cushion of 500 kg to 700 kg ripraps is designed on the seaward side while itself is protected by accopodes revetment. A concrete wave retaining wall is designed behind the caisson. The top elevation of quay is 6.3 m, bottom elevation is -4.0 m. The top elevation of original mud is -8.0 m to -9.0 m. The caisson front twist-shaped elevation is -0.58 m. The design low water level is 0.01 m and the design low water level is 1.30 m.

![Figure 1 The design drawing of a quay section (elevation in m; dimension in mm)](image-url)
3.2. Numerical analysis model
In the numerical model, crushed stones are used as the cushion layer under the caisson. It is 1.5 m thick with furrow width of 1.06 m, depth of 0.35 m. The furrow ridge has a spacing of 1.8 m. It can be simplified into a plane strain problem while it is not necessary to deal with 3-dimensional complexities. Figure 2 is a sectional view of the calculation model. For a purpose of comparison, calculation is also made for the case of fully paved crushed stone cushion.

Figure 2 Model geometry for numerical analysis

3.3. Calculation parameter of material properties
Shang et al. have studied the friction coefficient between concrete tunnel model and crushed stone subgrade under with and without furrows through large model tests [6]. Through analysis of crushed stone subgrade with different gradations, it is found that the friction coefficient is not sensitive to whether there are furrows, nor to the moving direction of concrete tunnel model, nor to the roughness of the subgrade, nor to the particle size distribution of crushed stones. But it is really related to the vertical load applied on the subgrade. They believe that the friction coefficient in the test tends to be stable after reaching an extreme value and has a slow growth trend. The reason for this phenomenon is that the gravel movement at the bottom of the plate is complicated and there is rolling friction. After the friction coefficient reaches the extreme value, the crushed stones are compacted tightly and cease to roll, and hence the friction coefficient slowly increases. In the test, the friction coefficient varies from 0.38 to 0.43 for gravel with a particle size of 2 cm to 6 cm under full paving. The friction coefficient varies from 0.41 to 0.44 with furrows. Therefore, in order to simplify this calculation, take a medium value as the friction coefficient of crushed stone, such as 0.40.

The friction force between concrete and crushed stone can be simulated by “interface” function. Shear stress in the interface function is defined by the following equation:

\[ F_{\text{max}} = cA + \tan\phi (F_n - pA) \]  

(3)

where \( c \) is the cohesion along the interface; \( \phi \) is the interface friction angle, \( p \) is pore water pressure, and \( F_n \) is the interface normal stress.

There is no cohesive force between subgrade and caisson, and the cohesive force is zero in the interface function of Equation (1) shall be taken as zero. Therefore \( \tan\phi = 0.4 \), resulting in \( \phi = 22^\circ \). It should be noted that \( \phi \) is not the internal friction angle of gravel material, but is an angle parameter representing the interface function between cession bottom and crushed stone subgrade.

According to the recommendations of FLAC 3D (Fast Lagrangian Analysis of Continua) manual, the \( k_n \) and \( k_s \) in the interface function should be taken as 10 times of the stiffness modulus of adjacent grids:

\[ \max[\frac{(K + \frac{4}{3}G)\Delta z_{\text{min}}}{3\Delta z_{\text{min}}} \]  

(4)

where \( K \) and \( G \) are the volume change and shear modulus of the mesh, and \( \Delta z_{\text{min}} \) is the minimum width of the adjacent mesh in the orthogonal direction.
For the cushion of crushed stone, take the value of the modulus of elasticity as the determined from the large model test [5]. For riprap subgrade below cushion, take their material parameters as recommended by He et al. [3], i.e. 20 MPa for the compression modulus and 0.285 for Poisson's ratio. Takes the same value for the modulus of backfilling riprap. Assume the dry densities of crushed stone and riprap subgrade are 1600 kg/m³, and 2000 kg/m³ for the rock backfills.

3.4. Boundary condition
The bottom boundary of the numerical model is constrained by vertical and horizontal displacements, and the boundary conditions around the model are constrained by lateral displacements, which are basically consistent with the actual engineering boundary conditions. For the water table, consider that the water level is 5 m lower than the upper surface of the caisson as Figure 1 specifies, and take the design low water level as the calculated water level, i.e. at elevation of 0.01 m.

4. Calculation results

4.1. Safety factor and sliding trend
Figure 2 and 3 show the sliding trend and the safety factors for the subgrade with fully paved crushed-stone cushion and furrowed crushed-stone cushion, respectively. It is shown that the safety factor of caisson with furrowed cushion is 1.55 and 1.55 for caisson with fully paved crushed-stone cushion. This minimal difference will be ignored, denoting both cushion structures have virtually coincided in sliding mode as the have almost identical distribution pattern of the shear strain rate. It is also shown that when the riprap subgrade is deeper in dimension, the sliding surface of the quay passes through the rear toe of the quay and slides out from the front toe under the quay structure, causing overall sliding.

4.2. Stress condition
Figures 4 and 5 are stress contour when the two calculation models reach the minimum safety factor. It can be seen that there is no obvious difference between the stress contour for both conditions. In the horizontal direction, the caisson is pushed horizontally by the front (seaward side) and the rear rockfill,
resulting in a sliding trend towards the front of the caisson through the rear toe of the quay. At this time, shear stress concentrations are found at the front toe, at the contact between the caisson and the front surface twisted-Wang slope protection, and the 45-degree angle direction on the right rear side of the caisson. These three parts can interconnect to each other and finally form the possible slip surface.

![Figure 5 The xz-stress contour for fully-paved crushed-stone cushion](image)

Figure 5 The xz-stress contour for fully-paved crushed-stone cushion

![Figure 6 The xz-stress contour for furrow-paved crushed-stone cushion](image)

Figure 6 The xz-stress contour for furrow-paved crushed-stone cushion

5. Conclusions
Through numerical analysis on an example quay project, the stability of caisson-structured quay with furrowed cushion are calculated and analysed. The following conclusions are drawn:

1. The difference between the safety factors of the two type cushion structures is minimal to be ignored. The safety factor of the former is 1.54 and the safety factor of the latter is 1.55. The stress states of two type cushion structures are basically the same.

2. The sliding trend of two type cushion structures is the same. The sliding surface of the quay passes through the rear toe of the quay and slides out from the front toe under the quay structure, causing overall sliding.

3. The above analysis shows that the subgrade with furrowed crushed-stone cushion will not adversely affect the stability of caisson-structured quay.

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