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Laboratory Test and Numerical Simulation for Geotextile Bag with Sand Cofferdam of Immersed Tunnel

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Abstract. The mechanical indexes of the geotextile and filling sand were obtained by laboratory test based on geotextile bag with sand cofferdam of Zhoutouzui immersed tunnel in Guangzhou, and a fine calculation model was established. The deformation development law of geotextile bag with sand cofferdam was explored by refined numerical calculation. Combining with the existing research results, the deformation mechanism was determined. Numerical results were verified by theoretical analysis and the control index of design and construction was proposed. The results show that cofferdam moves to the side of dry dock under the action of unbalanced pressure, and the displacement decreases from the top to the bottom. Cofferdam appears settlement under gravity and pumping action as well as the displacement increases with the pumping water level decline. The main reason of cofferdam's large deformation is density increase caused by dewatering, which increases overlying pressure from upper geotextile bag to lower one and makes geotextile flattening deformation. Foundation soil experiences vertical pressure consolidation, lateral extrusion and local sliding, which causes the maximum and minimum deformation present to the top and toe of geotextile bag. The cofferdam has no sliding failure and is in overall stability as well as the numerical results are consistent with results deduced by theoretical analysis, so the cofferdam should take the height as the control index.

1. Introduction

The immersed tunnel has been more widely used in sea-crossing engineering with its advantages [1-3]. Meanwhile, the temporary cofferdam used to assist the tunnel construction obviously increases. The geotextile bag with sand is frequently being used in temporary cofferdam engineering due to its superior mechanical and deformation characteristics, which are gradually paid more attention by many scholars and researches were conducted[4-10]. While the existing researches mostly focus on laboratory test consisted of limited geotextile bag with sand and simplified numerical calculation, so the comprehension of mechanical characteristics of immersed tunnel during pumping process is not enough.

The laboratory test of limited geotextile bag is apparently difficult to present real mechanical characteristics of geotextile bag with sand cofferdam, and it exist some defects that using simplified numerical method to calculate the complicated cofferdam problem. In contrast, the refined numerical analysis is a more accurate and effective way to explore the mechanical properties of geotextile bag with sand cofferdam. Ensuring stability of temporary geotextile bag with sand cofferdam during the construction and application process is critical to immersed tunnel successfully applied. The deformation of the cofferdam determines the overall stability to a certain extent, so it is necessary to



mainly explore deformation characteristics of geotextile bag with sand cofferdam.

The deformation development law of geotextile bag with sand cofferdam during pumping phase was revealed by refined numerical calculation based on Zhoutouzui immersed tunnel in Guangzhou. Combining with the existing research results, the deformation mechanism was determined. The control index of design and construction was proposed and the rationality was verified by theoretical analysis. The research results have a significant meaning to guide design and practice of geotextile bag with sand cofferdam of the immersed tunnel.

2. Engineering Situation

The construction of Zhoutouzui immersed tunnel adopted the temporary combination cofferdam of geotextile bag with sand and steel sheet pile. The length, width and height of cofferdam are respectively 47.4m, 40m and 14.8m. And the compactness of geotextile bag with sand is 80%. The slope ratio of cofferdam is 1:1 on the river side, while on the dock side is 1:1 in upper 7m place and 1:1.25 in bottom 7.8m place. Water stop core-wall of cofferdam adopted steel sheet pile, filling sand and bagged clay. The steel sheet pile through the soft soil and penetrating depth into the rock is not less than 0.5m. Cofferdam section is shown in Fig.1. Unit area quality, thickness, vertical tensile strength, transverse tensile strength and bursting strength of geotextile bag are 188g/m², 1.22mm, 26kN/5cm, 25kN/5cm and 4kN. The density, friction angle, non-uniform coefficient and curvature coefficient of filling sand is 1.88g/cm³, 32.4°, 2, and 0.98. Friction angle between the geotextile bag with sand obtained through the test is 33°, and friction angle between the sand and geotextile bag is 27.6° as well as the cohesion is 12.35kPa. The vertical deformation modulus of cofferdam is 25MPa, and the horizontal deformation modulus at the bottom is 3MPa, which linearly increases with the cofferdam's height increases. The physical and mechanical parameters of soil and cofferdam are listed in table 1.

Table 1. Physico-mechanical parameters of soil and structure

Geotechnical name	Density ρ / (g·cm ⁻³)	Consolidated-quickly shear		Compressi on modulus /MPa	Poisson ratio	Thickness /m
		Cohesion c /kPa	Internal friction angle φ /(°)			
Silt fine sand	1.76	0.0	16.0	2.49	0.28	2.6
Plastic clay	1.95	33.2	16.2	4.95	0.33	4.8
Hard plastic clay	1.96	38.0	17.1	6.62	0.31	6.0
Completely decomposed sedimentary rocks	2.07	42.1	22.3	14.05	0.25	6.6
Strongly decomposed sedimentary rocks	2.10	55.2	26.1	23.0	0.24	9.8
Bagged clay	1.95	32.0	15.0	5.05	0.33	—
Steel sheet pile	7.85	—	—	206000	—	0.0155

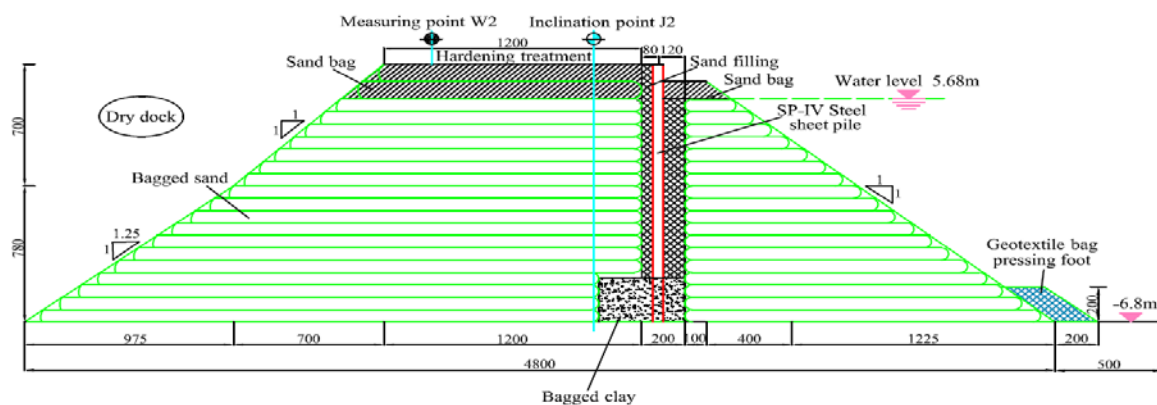


Figure 1. The profile of Zhoutouzui tunnel in Guangzhou (unit: cm)

Fig.1 indicates that the highest tide level of cofferdam is 5.68m. The pumping was conducted from January 21st to February 19th, which lasted for 30 days and total pumpage is 180000 cubic. The water should be pumped with an average depth of 0.5m a day within 15days, and this job can be off and on during the subsequent 15 days. Most noticeably of all, the water nearly be pumped to 1m from the dock bottom on February 16th, which virtually constituted by mud. The water leakage did not appear in the process of pumping due to water stop core-wall in the cofferdam.

3. Material Parameters of Geotextile Bag with Sand Cofferdam

3.1. Tensile Test of Geotextiles

The strengths is different in zonal and meridional directions because of different yarn quantity. It is necessary to carry out tensile tests in both directions of geotextile and obtain corresponding load-displacement curves. The test materials are shown in table 2, and tensile instrument adopted universal material testing machine, as shown in Fig.2.

Table 2. Test parameters of geotextile

Material	Direction	Length (mm)	Width(mm)
Geotextile	Zonal	200	100
	Meridional	200	100



Figure 2. Tensile test of geotextiles

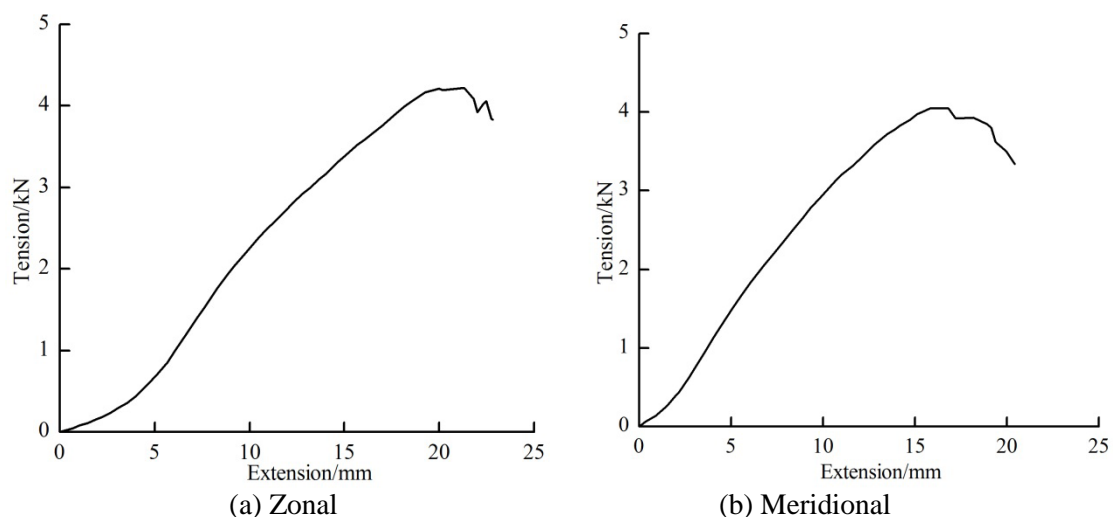


Figure 3. The load-displacement of geotextile

Fig.3 indicates that the geotextile strength is respectively 21.17 kN/m and 18.47 kN/m in zonal and meridional direction.

3.2. Direct Shear Test of Filling Sand

The inhomogeneity coefficient C_u of filling sand is 2.0 and the curvature coefficient C_c is 0.98. The relationship curves between shear stress and shear displacement as well as shear strength and normal stress were obtained by direct shear test (Fig. 4).

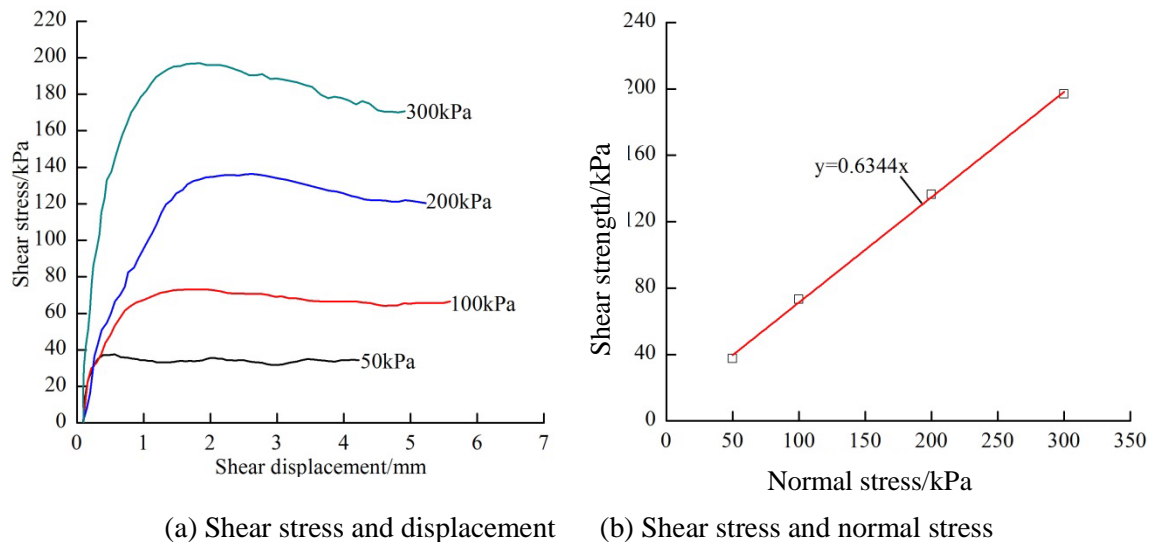


Figure 4. The test results of direct shear

The results of direct shear test is shown in Fig.4. The shear strength formula is $\tau = 0.6344\sigma$ by linear fitting. The internal friction angle of filling sand is calculated for $\phi = \arctan 0.6344 = 32.4^\circ$.

4. Numerical Calculation

4.1. 3D Calculation Model

The model considering interface and anisotropic characteristics was established (Fig. 5). The calculation width(Y) of the model is 15m, and the length(X) and height (Z) were obtained by boundary sensitivity analysis, which are respectively 85m and 30m. Three-dimensional solid elements were applied to simulate soil, bagged sand and bagged clay and Mohr-coulomb constitutive model was selected for calculation. Model used shell elements to simulate steel sheet pile and used geotechnical grille elements to simulate geotextile bag. Both pile and bag adopted elastic constitutive model. Horizontal displacement was restrained in the model lateral direction and vertical displacement was restrained at the bottom. It is the free surface at the top of the model and pumping boundary simulation through boundary node head during pumping phase. The interface contact element of the geotextile bag with sand used the Goodman element [11] that existing in nonlinear continuum mechanics to simulate. Numerical calculation has four conditions including the calculation of initial pore pressure (steady flow)→initial stress calculation (displacement clear)→cofferdam construction→pumping in the dry dock side (unsteady flow lasted for 30 days) .

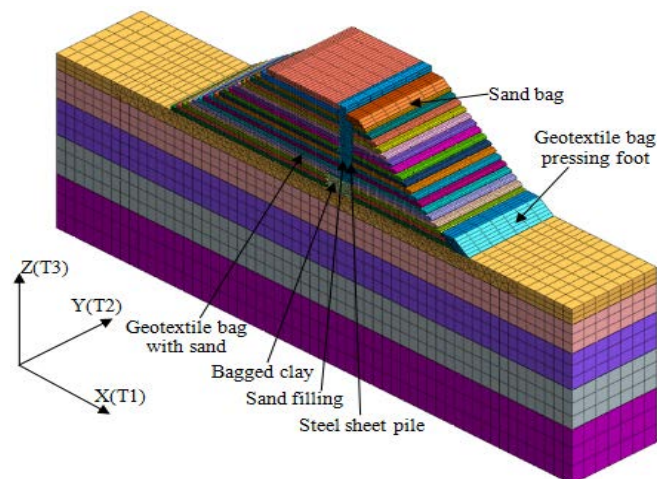
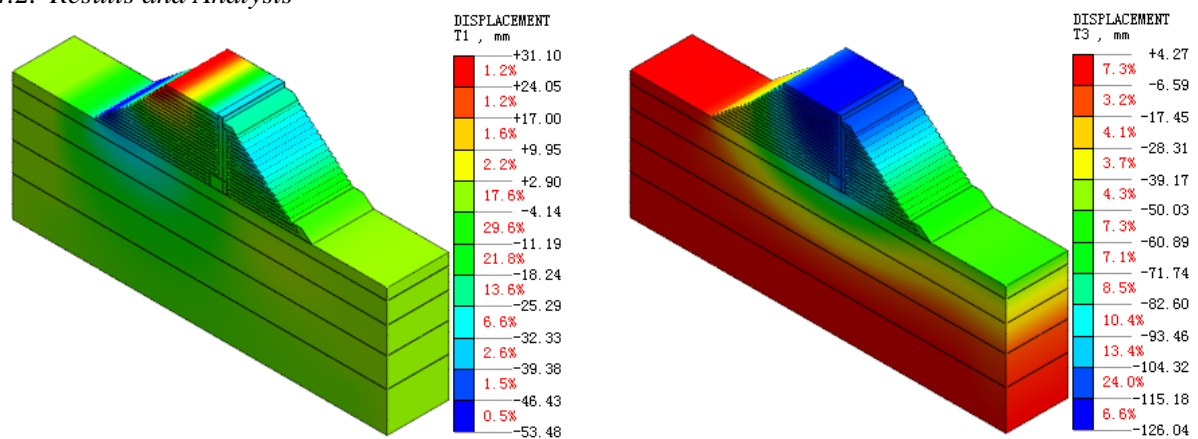


Figure 5. The calculation model of cofferdam

4.2. Results and Analysis



(a) Horizontal displacement nephogram on the 9th day (b) Vertical displacement nephogram on the 25th day

Figure 6. The displacement nephogram of cofferdam

The horizontal and vertical displacements of the cofferdam are shown in Fig.6. The horizontal displacement is positive when moving to the dry dock side. Meanwhile, downward vertical displacement is negative. Foundation soil firstly experiences vertical pressure consolidation, then lateral extrusion and finally appears local sliding (Fig.4), which causes the maximum and minimum deformation present to the top and toe of the cofferdam due to the effect of upper geotextile bag with sand cofferdam.

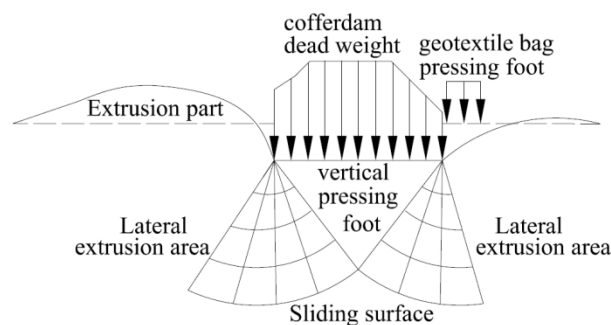


Figure 7. Foundation sliding under weight of cofferdam

The 9th day horizontal displacements of point J2 (Fig.5) and 25th vertical displacements of point W2 were extracted, which compared with corresponding measurements results as shown in Fig.8.

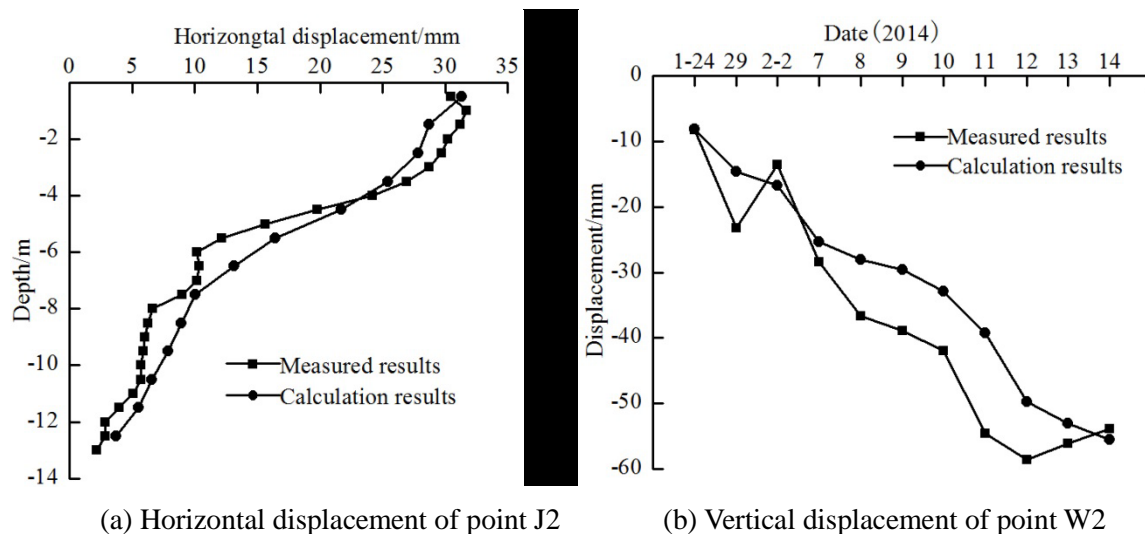


Figure 8. The calculation results and measured results

Comparison results show that the numerical results reflect the displacement tendency of geotextile bag with sand cofferdam and the calculation results are coincident with the measured values. So the modeling method is effective in this work. Cofferdam moves to the side of dry dock under the unbalanced pressure and the displacement decreases from the top to the bottom, which is similar to deformation characteristic of a cantilever beam. Cofferdam appears settlement under gravity and pumping action, and the displacement increases with the pumping water level decline.

Fig.9 indicates that the overall level of shear stress is low. While partial foundation on the dock side appears lateral extrusion and sliding, which causes dislocation of geotextile bag with sand of cofferdam toe (frame selection), where the shear stress significantly increases to 227.2kPa. The maximum and minimum shear stress caused by lateral loads are 65kPa and 3.7kPa, both of them are less than the corresponding shear strength that $13.8 \text{ (dump height)} \times 18.8 \text{ (unit weight)} \times \tan 33^\circ$ (friction coefficient) = 168.6kPa and $1 \text{ (dump height)} \times 18.8 \times \tan 33^\circ = 12.2\text{kPa}$, so there is no sliding failure in the geotextile bag with sand cofferdam.

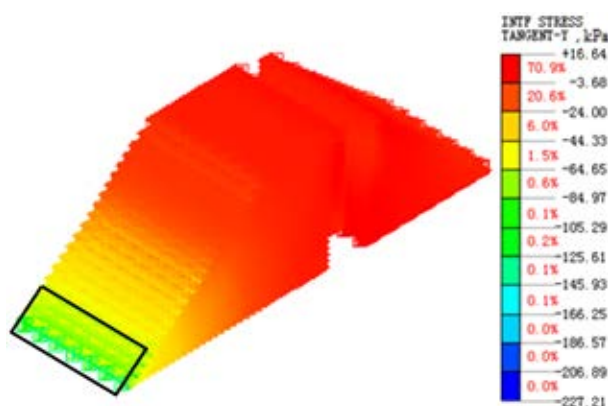


Figure 9. The shear stress of interface element

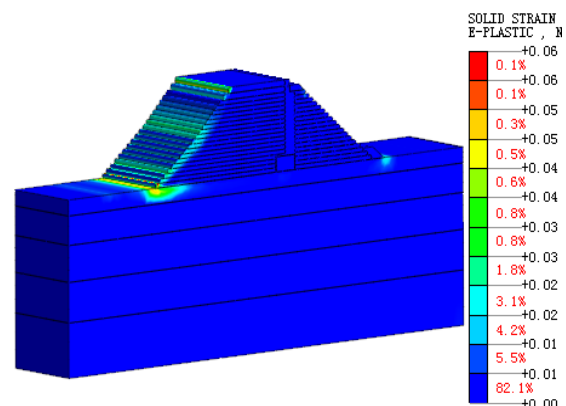


Figure 10. The deformation plastic zone of cofferdam

The equivalent plastic zone of cofferdam deformation is shown in Fig.10. Obviously, the cofferdam is failure to form a transfixion plastic zone. According to the slope instability criterion [12], the cofferdam is in a stable condition. In addition to above results, numerical calculation contains several

other conclusions as follows. (1) There still exist some disadvantages that ignoring the own characteristics of geotextile bag with sand cofferdam and using displacement limits of pit to evaluate the mechanical state of cofferdam. Such as the example calculated in this work, the displacement will overrun when the pit standard [13] reference for cofferdam, which doesn't agree with the reality. (2) The slope rate of geotextile bag with sand cofferdam is significantly greater than earth-rock cofferdam of hydraulic engineering. The calculation results show that cofferdam is of stability due to the obvious reinforcement effect of geotextile bag with sand, which effectively improve the whole stability and it should be given full consideration in the engineering practice.

5. Control Index of Cofferdam Design

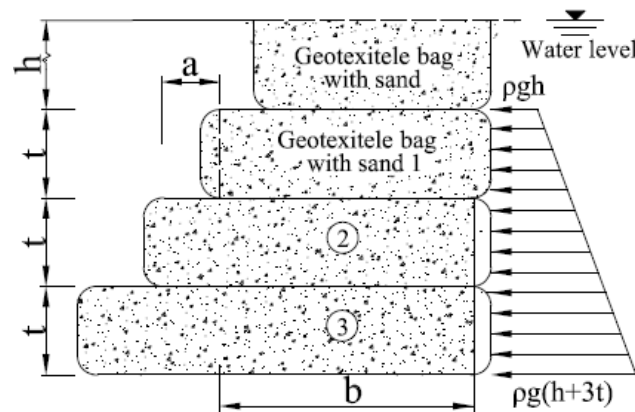


Figure 11. Transverse force of geotextile bag with sand cofferdam

Fig.11 is the transverse force of geotextile bag with sand cofferdam. According to theoretical analysis, cofferdam mainly affected by water pressure and interface friction in transverse direction except the big wind waves action. The deformation of cofferdam consists of the bag compressive and relative displacement between geotextile bags with sand. The 2nd cofferdam in the Fig.14 was used to force analysis as follows.

Friction:
$$F = \mu\gamma[(h+t)b + (h+2t)(b+a)] \quad (1)$$

Water pressure:
$$W = \rho g t \left[\left(h + \frac{3}{2}t \right) \right] \quad (2)$$

Where ρ is the water density (g/cm^3), μ is the coefficient of friction between geotextile bags with sand, b and a are the contact width (m) of cofferdam, t is the thickness (m), γ is the unit weight of sand (kN/m^3). The dry and buoyant unit weights are adopted when cofferdam is above and below the water level. h is the depth of water level (m). On the basis of function 1, it can be obtained as follow.

$$F = \mu\gamma[(h+t)b + (h+2t)(b+a)] > 2\mu\gamma b \left(h + \frac{3t}{2} \right) \quad (3)$$

The results of interface friction test of geotextile bag with sand [14] show that the interface friction angle is 33° ($\mu=0.65$) when the compactness is 80%. Because the optimal mechanical properties will appear when compactness is 80%~85%, so the function 3 can be expressed as follow.

$$F > 1.3\gamma b \left(h + \frac{3t}{2} \right) \quad (4)$$

The actual engineering of geotextile bag with sand cofferdam satisfies $1.3\gamma b > \rho g t$, so it results in

$F > W$, which indicates that the relative sliding failure between geotextile bags under water pressure. Cofferdam is in stability and the analysis results are in accord with numerical results.

According to the test results of literature [12], the compressive strength of geotextile bag with sand is about 3MPa when the length, width, height and compactness are 25cm, 25cm, 10cm and 80%. The interface shear strength of bottom geotextile bag is 1.95MPa under the 3MPa pressure, which is equivalent to 195m water pressure. What's more, 195m exceeds the limit height of geotextile bag (150m) and brings about vertical compression failure of cofferdam. In fact, the cofferdam should take dump height as main control index to prevent vertical compression failure under the action of medium and below wind wave.

The reason why the large deformation appears is that the unit weight of geotextile bag with sand changes gradually from buoyant unit weight to dry unit weight with the water level decreases during pumping process. The change of unit weight obviously increases the pressure of upper geotextile bag with sand to the lower one. Owing to the special properties of the geotextile bag with sand, the bags gradually are flattened under the effect of overlying pressure and make significant displacement.

6. Conclusions

The research on the deformation of geotextile bag with sand cofferdam provides great significance to cofferdam's design and construction. The refined stimulation for pumping of geotextile bag with sand cofferdam was conducted and mainly obtains the conclusion as follows.

(1) Cofferdam moves to the side of dry dock under the action of unbalanced pressure, and the displacement decreases from the top to the bottom. Cofferdam appears settlement under gravity and pumping action as well as the displacement increases with the pumping water level decline.

(2) The main reason of cofferdam's large deformation is density increase caused by dewatering, which increases overlying pressure from upper geotextile bag to lower one and makes geotextile flattening deformation.

(3) Foundation soil experiences vertical pressure consolidation, lateral extrusion and local sliding, which causes the maximum and minimum deformation present to the top and toe of geotextile bag with sand

(4) Refined numerical results indicate that the cofferdam example does not appear sliding failure and not form a transfixion plastic zone. Cofferdam is in a stable condition, which is consistent with the theoretical conclusion. So cofferdam should take dump height as main control index.

(5) It is insufficient that using displacement limits of foundation pit to assess mechanical state of geotextile bag with sand cofferdam, meanwhile, the slope rate of the cofferdam design should fully consider reinforcement effect of geotextile bag.

7. Acknowledgments

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