Field testing and numerical analysis on behaviour of sand filled geotextile container coastal dike on soft soil foundation

Huiming Tan, Fumao Chen & Jia Chen
College of Harbour Coastal and Offshore Engineering, Hohai University, China

ABSTRACT: With the development of geosynthetics, more and more soil filled geotextile containers have been used in coastal engineering, such as dikes, groynes and revetments. This paper reports the field testing as well as finite element numerical analysis on the practical case of sand filled geotextile container dike on soft soil foundation in coastal areas, and the performances of dike were captured and discussed, including vertical and lateral deformations. In order to improve the dissipation of excess pore water pressure of foundation soil (i.e. mud clay) due to dike construction, the prefabricated vertical drains (PVDs) were installed in foundation. The measured data and computed results show the PVDs are effective to improve the consolidation of foundation soils, the settlement and lateral displacement of dike can be reduced as well, and the maximum lateral displacement was about 0.63m located at the first ground layer of mud clay. As a result of the reinforcement of geotextile container, the settlement and lateral displacement of dike have been obviously reduced. According to the computational analysis on the stability of sand filled geotextile container coastal dike using the shear strength reduction method, the geotextile container are helpful to improve the stability of dike and the potential sliding surface generally existed in the dike body without the reinforcement of geotextile.

Keywords: sand filled geotextile container; dike; deformation and stability; field testing; numerical analysis

1 INSTRUTION

Sand filled geotextile container coastal dike is a new type of water conservancy construction. It is layered constructed with the sand near the site, which is filled into the bags that wove by the nylon or polypropylene film and other geotextile materials. As a construction material, the sand filled geotextile container is cheap and has an adequate material source, which is especially appropriate for areas where there is a lack of stone and transportation. It will be a good and much less expensive alternative to replace traditional materials, but it is more economic and effective when applied to large-scale construction works(Jong Gun Park, Hak Won Kim and Jeong Hee Ko 2016).As for the stability of the sand filled geotextile container coastal dike, someone believe that it is no problem(Luca Martinelli and Barbara Zanuttigh 2011, Zhu Ping,Yan Shu-wang and Liu Run 2004),and someone points that the sand filled geotextile container banking easily develops the slip band under the condition of external scouring(Yi Meng; Xiaoyu An and Yue Zhao 2015).The settlement and horizontal displacement are the key issues of the dike especially on the soft foundation(E.C. Shin,J.K. Kang and Y.I. Oh 2009, Yoo 2015). The prefabricated vertical drains (PVDs) are effective for the soft foundation(Yue-Bao Deng; Gan-Bin Liu; Indraratna, Buddhima; Rujikiatkamjorn, Cholachat and Kang-he Xie 2017, Koji Suzuki and Hiroki Takeuchi 2008) but E.M. Da Silva et al.(E.M. Da Silva; J.L. Justo; P. Durand; E. Justo; M. and Vázquez-Boza) reported that the influence of the geotextile in the settlements is negligible.

The consolidation settlement and the overall stability of sand filled geotextile container dike are closely related to the characteristics of foundation soil, the characteristics of dike itself and the foundation treatment method. The traditional calculation and analysis method cannot reflect the settlement and stability of dike during construction, nor consider the reinforcement role of the sand filled geotextile container on the soil. In addition, it cannot reflect the influence of settlement and stability due to the schedule change of the foundation treatment. Therefore, this paper carries on the site monitoring and numerical simulation to the sand filled geotextile container dike, which is in Tianjin City, China, to study the consolidation settlement and the overall stability of the dike, to discuss the deformation characteristics during construction, to analyze the influence of different foundation treatment on its settlement and stability, and provide reference for engineering practice.

2 SITE CONDITION

The site is located in Tianjin City, China. From top to bottom, the profiles of the soil are muddy soil, silty clay, silty clay with shell, organic clay and silt. The main parameters of soil are listed in Table 1.

Table 1 Soil parameters

Soil	muddy soil	silty clay	silty clay with shell	organic clay	silt
Gravity (*kN/m*^{3})	16.2	17.6	18.6	18.4	19.6
Porosity ratio	1.835	1.275	0.913	1.06	0.732
Compression modulus(*kPa*)	2000	2700	5940	3200	11340
Cohesion(*kPa*)	1	6	12	12	10
Internal friction angle (*deg*)	0.7	9	15	10.5	22.2
Poisson's ratio	0.35	0.3	0.35	0.3	0.3
Vertical permeability coefficient(*cm/s*)	4.88E-06	4.77E-07	1.70E-06	4.25E-07	1.69E-05
Horizontal Permeability Coefficient(*cm/s*)	8.08E-06	8.08E-06	3.40E-06	8.50E-07	2.80E-05
Thickness(*m*)	5.2	3.8	1.9	2.0	38.0

The cross-section of dike is illustrated in Figure 1. The top elevation of wave wall on dike is 10.0m, considering the settlement after construction. Due to the low shear strength of soft soils in foundation, the main dike body consists of the large hydraulic sand filled geotextile container, and the thickness of each geotextile container layer is 0.5 m. The riprap mounds are filled for protection at the dike toe. Moreover, an existing semi-circle breakwater is located at the sea side of dike, and the semi-circle breakwater has been constructed for four years.

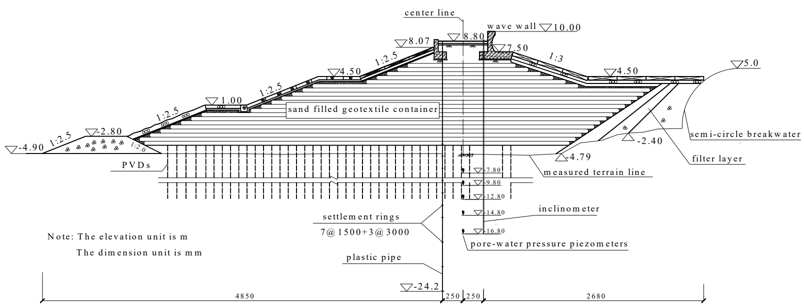


Figure 1 Dike section and instrument layout

3 INSTRUMENTATION

To verify the design assumptions and monitor the performance of the coastal dike, several instruments were installed on site to monitor settlement deformation, horizontal displacement and pore water pressure. The specific installation location of the instruments is shown in Figure 1. The installed instruments are as follows.

1. Settlement ring and plastic pipe.10 settlement rings, from -3.8m to -24.2m, were tied to the plastic pipe unevenly, which was vertically installed in the dike foundation to a depth of 32m on the left side of the center line.

2. Inclinometer. The inclinometer was vertically installed in the dike foundation on the right side of the center line. The lengths of the inclinometer above and below the ground are 0.5 and 25 m,

respectively.

3. Pore-water pressure piezometers. 5 piezometers were installed in the center line of the dike foundation from -4.96m to -16.8m.

However, due to the limit of the site construction condition, the field observation of settlement deformation monitoring began after the completion of the sand filled geotextile container construction. Thus, the monitoring data were incomplete, and the following settlement analysis is mainly based on numerical modeling.

4 NUMERICAL MODELING

4.1 *Numerical model*

In order to analyze the influence of foundation settlement and slope stability caused by the dike construction, the fluid-structure coupling finite element numerical model was established. The finite element analyses were performed with the Plaxis using two-dimensional plane strain analysis. The model width was selected as five times the dike height on each side in this study. The soil layers were modeled using 15-node triangular elements. The 15-node elements provided a fourth-order interpolation for displacements, and the numerical integration involved 12 stress points. The stress-strain relationship of soil in practical engineering is very complex. The Mohr-Coulomb model (M-C) is used as the constitutive model in this analysis. The Mohr–Coulomb model mainly requires four parameters: Young's modulus, Poisson's ratio, cohesion, internal friction angle. The parameters are summarized in Table 1.

4.2 *Simplification of PVD calculation*

Due to the three dimensional characteristics of sand well, the sand well foundation should be simulated by three-dimensional finite element method. However, the number of sand well in foundation is large, and the calculation of the three-dimensional model is time-consuming. Thus, the three-dimensional sand wells are usually converted into two-dimensional wall in computation (Chen Xiao-dan and Zhao Wei-bing 2005, Chen Lihong;Chen Zuyu and Li Guangxin 2004). Furthermore, based on Barron theory, adjusting the permeability coefficient of soils is also able to consider the effect of well resistance and smearing effect. The specific adjustment method used in this analysis is as follows (Chen Xiao-dan and Zhao Wei-bing 2005):

$$\frac{k_{px}}{k_{ax}} = \frac{4(1+\nu)}{9}\frac{(n-1)^2}{n^2\mu} \tag{1}$$

$$\mu = \frac{n^2}{n^2-s^2}\ln\frac{n}{s} - \frac{3n^2-s^2}{4n^2} + \frac{k_{ax}}{k_s}\frac{n^2-s^2}{n^2}\ln s \tag{2}$$

$$B_w = \frac{\pi r_w^2}{\sqrt{3}d} \tag{3}$$

$$B_w = n^2 B \tag{4}$$

Where k_{ax} = horizontal permeability coefficient of sand drain foundation, k_{px} = horizontal permeability coefficient of finite element calculation, ν = the Poisson 's ratio of the soil, μ = conversion factor, k_s = permeability coefficient in smear area, s =the ratio of the smear radius and the sand well radius, n =drain diameter ratio, B_w =the thickness of the sand wall, B =equivalent half width, r_w =radius of vertical drainage body.

5 MEADURED AND COMPUTED RESULTS

5.1 *Lateral displacement*

Figure 2 is the comparison of the measured and calculated results of dike horizontal displacement. It can be seen that the horizontal displacement increases initially and then decreases with depth. The calculated and measured maximum horizontal displacements are 128.2 mm and 120.5 mm, located at the muddy clay layer in foundation. This is mainly because gravel layer and sand filled geotextile container layer will be embedded in the mud layer in the site construction of the dike filling; meanwhile the mud will be squeezed out partly resulting in the thickness of the mud layer thinner, which is difficult to reflect in numerical simulation. In addition, the measured values are basically close to zero at the bottom, and the calculated values are basically stable at about 11.2mm. This is mainly because the actual measured results by inclinometer on site are relative horizontal displacement which is relative to the bottom, and the numerical results are absolute horizontal displacement. In summary, the numerical simulation results are in good agreement with the measured results, which is able to reflect the deformation characteristics of the dike body filling. The computational model can be used for the further research.

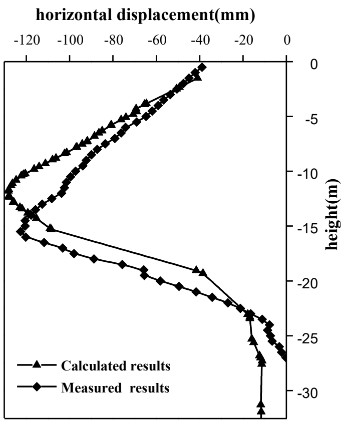


Figure 2 Comparison of horizontal displacement measurement and calculation results of the dike

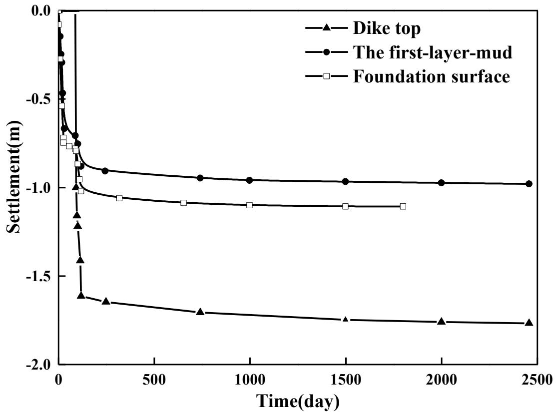


Figure 3 Dike settlement consolidation process during and after construction

5.2 *Settlement*

Figure 3 shows the settlement process in different positions of dike sections at different construction stages, and three different feature positions, dike top, foundation surface and the first mud layer in foundation are selected. The settlement at each position of the dike is gradually increased with the construction process. During the construction loading stage (sand filled geotextile container filling, superstructure construction, etc.), the settlement increases obviously, and the settlement difference between the feature points will increase slightly; during the load maintenance stage (sand filled geotextile container filling has completed and superstructure construction has not begun),the dike still settles due to the soil consolidation drainage, but the settlement rate is gradually reduced, and the settlement difference between the feature points is basically stable. Compared to the settlement of the three feature positions, the settlement is increased as the elevation increases. From the settlement difference between dike top and surface, surface and the first layer of muddy clay, the first layer of muddy clay has a great influence on the total settlement of dike.

5.3 *Dike Stability*

Dike stability is a key issue for the safety of dike. There are many influence factors on the dike stability, and the dike stability is different at different stages during the dike construction process. The finite element numerical simulation is used to solve the safety factor using the strength reduction method (Sun Cong and Li Chun 2014). The finite element strength reduction method does not need to assume the shape and position of the sliding surface, nor does it need slice. In this analysis, the coefficient Σ*Msf* is defined as the reduction factor of the intensity, and its expression is as follows:

$$\sum Msf = \frac{\tan\phi_{input}}{\tan\phi_{reduced}} = \frac{c_{input}}{c_{reduced}} \tag{5}$$

Where $\tan\phi_{input}$, c_{input} are the strength value of the program when the material properties is defined; $\tan\phi_{reduced}$, $c_{reduced}$ are the intensity value of the reduced strength parameter used in the analysis process. At the beginning of the calculation, *ΣMsf* = 1.0, and then *ΣMsf* is incremented until the calculation model is destroyed. The *ΣMsf* value at this time is the value of the safety factor of the model.

With a stable water condition, at four different construction stages: sand filled geotextile container filling, maintenance after sand filled geotextile container filling, superstructure construction, maintaining

1 year after construction, the stress state of the dike and the foundation is also different. In addition, horizontal displacement appears with the vertical settlement at the same time. All of these will have an impact on the dike stability. Figure 4 shows the total displacement increment shadow of the possible damage mechanism during the superstructure construction of the dike. The sea side slope is relatively safe due to the presence of the semi-circular breakwater, and the possible sliding instability of the dike exists on the land side slope. According to the position of the potential sliding surface, the upper two layers (muddy soil and silty clay) in the soil layer have lower shear strength, so the potential sliding surface passes through them. In addition, due to the dike body is filled with sand filled geotextile container, which has a good tensile strength, the potential sliding surface usually appears at the edge of the geotextile container where the shear strength of soil is lower.

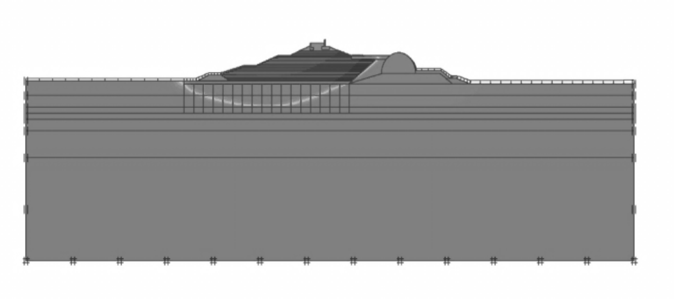


Figure 4 Total displacement increment shadow of the possible damage mechanism

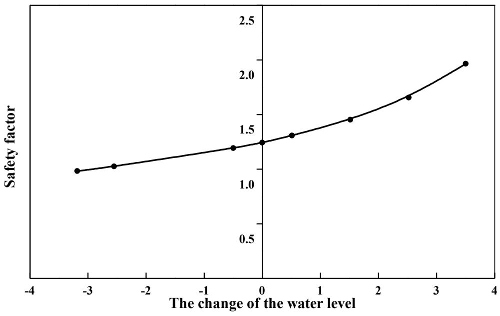


Figure 5 Influence of water level change on the overall stability of the sea side dike slope

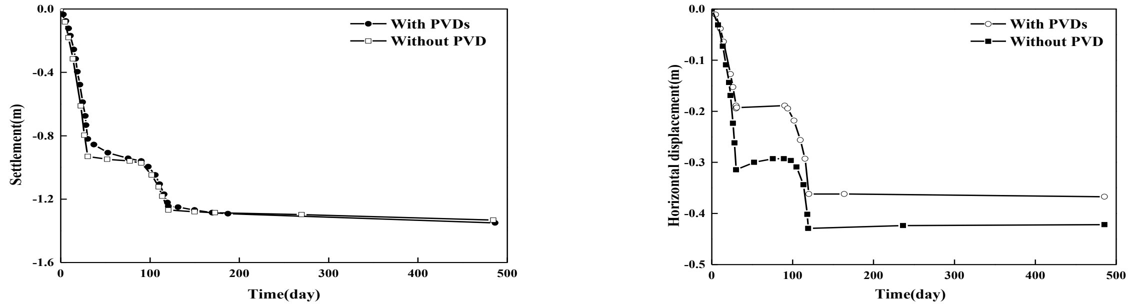
When the water level falls on the slope of the soil, the position of the saturation line in the slope is still high, and it will not fall as the slope water level. There will be unsteady seepage in the soil which is unstable for the slope stability, and the faster the water level descends, the higher the position of the saturation line in the soil will be, the worse the stability of the slope. In order to analyze the dike stability of sudden drawdown of water level, the exploration of water level change was carried on to the dike slope of the sea side. Figure 5 shows the results of the effect of water level change on the stability of the sea side dike. Maintaining the high water level (5.41m), then adjusting the water level sudden drawdown to calculate the safety factor of slope stability. With the continuous decline of the water level, the water level difference is getting bigger and the slope stability of the sea side dike is decreased and the safety factor is decreased. When the water level is reduced to about 3.5m, the slope stability coefficient is 1.96, and when the water level drops to -2.55m, the safety factor of the slope is reduced to 1.03, which is close to the critical steady state. As the water level continues to decline, the slope of the stability of the safety factor is less than 1, meaning to the slope has been unstable.

6 DISCUSSION

6.1 *Effect of PVDs*

The settlement consolidation process of dike without the PVDs is showed in Figure 6.Figure 6(a) reflects the effect on the surface settlement after foundation treatment of the PVDs. The settlement with PVDs is more than the settlement without the PVD at the same time during the construction stage. This is because the PVDs add drainage channel in the soil, resulting in the excess pore water pressure caused by upper loading can dissipate quickly and soil consolidation settlement rate is also faster. However, the total settlement of the dike foundation with PVDs is slightly less than the total settlement without the PVD. This is because the soil shear strength is low when the foundation without the PVD, resulting in it is easy to produce the horizontal displacement. Due to the viscous-plastic properties of the soil, the horizontal displacement cannot fully recovered with the effective stress improving, resulting in the total settlement of the dike foundation with PVDs is slightly less than the total settlement without the PVD.

Figure 6(b) reflects the effect on the dike horizontal displacement after foundation treatment of the PVDs. The PVDs has a great effect on the dike horizontal displacement. In the loading stage, pore water can be quickly discharged due to the presence of PVDs, and the effective stress and shear strength are improving, resulting in the horizontal displacement of the soil is significantly smaller than the foundation without the PVD. At the load maintenance stage, whether or not the PVDs are installed, the horizontal displacement is smaller, and the reduction without the PVDs is larger. This is mainly due to the excess pore pressure has been basically dissipated in the loading stage with the installation of PVDs, and the total stress has been converted into effective stress, therefore the improvement of the shear strength is not obvious. When the total stress is not increased without the PVD at the load maintenance stage, the total stress converts to the effective stress partly, improving the shear strength of the soil, therefore the horizontal displacement is reduced to a certain extent. It can be seen from the comparative numerical computation results that the PVDs treatment for foundation can decrease the horizontal displacement and settlement of the dike effectively and improve the stability of the dike.



(a) Dike surface settlement (b) horizontal displacement

Figure 6 Effect of PVDs on variation process of settlement and horizontal displacement

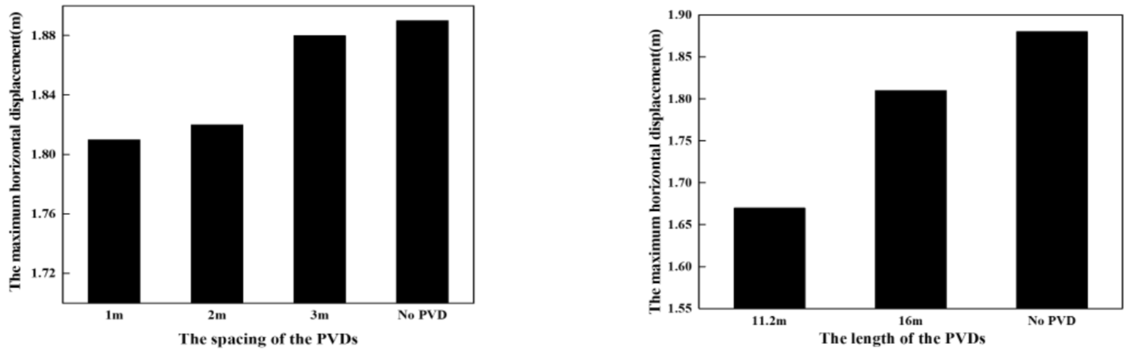


Figure 7 Effect of PVDS on the maximum horizontal displacement of dike

Figure 7 shows the effect of different PVDs spacing and length on the maximum horizontal displacement of the dike in steady state. As the PVDs spacing increases and the PVDs length decreases until the without the PVD, the final settlement of the dike top and horizontal displacement of the dike both are increasing. During the application of the upper load, due to the installation of the PVDs, the excess pore water pressure dissipates rapidly, and the effective stress and the shear strength of the soil increases, meanwhile, the horizontal displacement of the soil is relatively small.

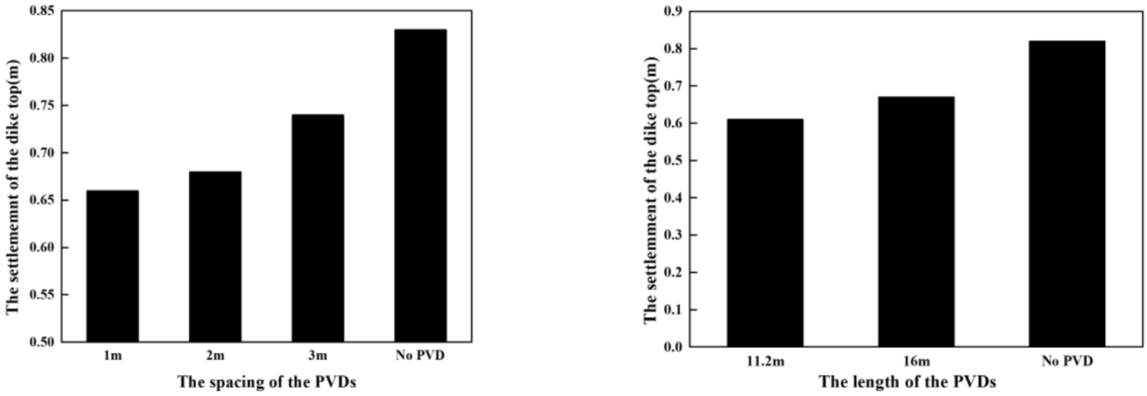


Figure 8 Effect of PVDs on the dike settlement

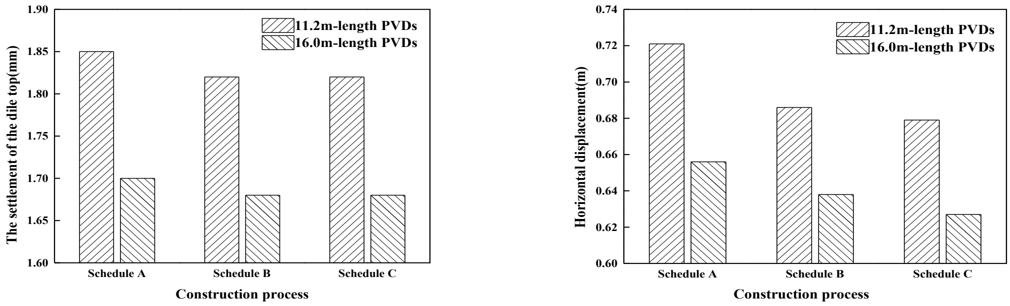
Figure 8 shows the effect of different PVDs spacing and length on the final settlement of the dike top in steady state. The installation of PVDs adds the drainage channels in the soil, which can improve the drainage efficiency of per unit time. Load and other external conditions will not affect the final settlement of the soil. However, the installation of PVDs can not only affect the settlement process, but also the total settlement, which is mainly due to the installation of the PVDs has a significant impact on the horizontal displacement of the dike, resulting in that the final settlement with the same upper load is different. Therefore, decreasing the spacing and increasing the length of the PVDs is beneficial to the dissipation of the pore water pressure, which can also improve the dike stability, decrease the horizontal displacement and the final settlement to a certain extent.

6.2 *Effect of construction process*

In order to analyze the influence of the construction schedule on the settlement and deformation of the dike, the following three schemes are considered in the numerical simulation. As shown in Table 2, maintaining the total time (90 days) of construction stage, the difference of settlement deformation of the three stages: sand filled geotextile container filling, maintenance after sand filled geotextile container filling and superstructure construction are investigated respectively by comparison calculation.

Table 2 Construction schedules

Scheme	sand filled geotextile container filling（day）	maintenance after sand filled geotextile container filling（day）	superstructure construction （day）
A	20	70	30
B	40	50	30
C	60	30	30



(a) final settlement of dike (b) maximum horizontal displacement

Figure 9 Effect of construction schedule on dike deformation

Figure 9 respectively reflects the effect of different construction schedule on the final settlement of the dike top and the maximum horizontal displacement of the dike when the length of the PVDs is 11.2 m, 16m and the spacing is 2 m. It can be seen from the figure that changing the construction schedule at different stages will have a certain influence on the final settlement and horizontal displacement of the dike when the total instruction time is constant. With the increase of the initial construction speed, the final settlement and the horizontal displacement of the dike increase in different degree, and the effect on the horizontal displacement is obvious. This is mainly due to that when the total load is same and the initial construction speed becomes faster, the higher the pore water pressure will be, and the effective stress increases slower, and the horizontal displacement of the soil is more obvious. Although the later stage of maintenance is longer, soil strength restoring a little, the plastic deformation of the soil will not restore, eventually leading to a larger settlement and horizontal displacement. The settlement difference is small, which is basically 1.82m and 1.7m or so when the length of the PVDs are 11.2m and 16m, and the variation range of the horizontal displacement are 0.68-0.72m and 0.63-0.66m. Compared to the 11.2m-PVDs, the 16m-PVDs is less affected by the construction schedule. With the increase of the length of PVDs, the pore water of the soil is easier to discharge, especially for the deep soils, so the effect of the construction progress on settlement and horizontal displacement is smaller.

7 CONCLUSIONS

This paper presents the behavior of sand filled geotextile container coastal dike on soft soil foundation by field testing and finite element computation on the practical application in China. The dike characteristics and detailed instrumentation are reported as well. The plane strain numerical model is constructed and calibrated based on the measured data, and the numerical model has captured the performance of the dike and foundation soils successfully. The influences of PVDs in soft soil foundation on dike stability and consolidation process have also been analyzed by numerical computation. Based on the results of the field testing and finite element computation, the following conclusions can be obtained.

(1) The numerical simulation and monitoring results show that the horizontal displacement increases initially and then decreases with depth. The maximum horizontal displacement is 128.2mm, located at the muddy clay layer in foundation.

(2)The settlement at each position of the dike is gradually increased with the construction process.

During the construction loading stage, the settlement increases obviously and the settlement difference between the feature points will increase slightly. Compared to the settlement at different locations, the first layer of muddy clay has a great influence on the total settlement of dike.

(3)The results of dike stability analysis show that the safety factor of dike slope is different at different construction stages. The minimum safety factor of dike slope stability during construction process is 1.545 after superstructure construction. The sea side slope is safer than land side due to the presence of the semi-circular breakwater, and the potential sliding surface usually appears at the edge of the geotextile container where the shear strength of soil is lower.

(4) The change of water level has significant effect on the stability of dike slope. When the water level at sea side sudden drawdown occurs from 5.41m to -2.55m, the stability safety factor of the dike slope is decreased to 1.03, which is close to the critical stability state.

(5) The comparative numerical computation results show that the installation of PVDs in foundation and the reduction of the spacing between PVDs decrease both the settlement of dike post-construction and the horizontal displacement. With the increase of the length of PVDs, the horizontal displacement and settlement of dike can be reduced, and the influence of the length of PVDs on the horizontal displacement is more significant.

(6)The results of the comparison of the construction schedule show that when the total construction period is constant, with the increase of initial construction speed, the final settlement and the horizontal displacement of the dike increase in different degree, and the effect on the horizontal displacement is obvious. Moreover, the construction schedule has more significant effect on settlement and horizontal displacement of dike, when the shorter PVDs are installed in foundation soil.

ACKNOWLEDGEMENT

This research is supported by the National Natural Science Foundation of China (No. 51309087, 51639002). The authors would also like to thank the reviewers for their valuable suggestions.

REFERENCES

Jong Gun Park, Hak Won Kim, Jeong Hee Ko, Tae Sup Park.Field Tests and Behaviour Analysis of Saemangeum Inner Dike Construction with Geotextile Tube Method Applied[J].Irrigation and Drainage,2016,Vol.65: 48-57

Luca Martinelli;Barbara Zanuttigh;Nunzio De Nigris and Mentino Preti.Sand bag barriers for coastal protection along the Emilia Romagna littoral, Northern Adriatic Sea, Italy[J].Geotextiles and Geomembranes,2011,Vol.29: 370-380

Zhu Ping;Yan Shu-wang;Liu Run.Application of Geotextile Bag Dehydrated Soil to Dike Construction[J].Transactions of Tianjin University,2004,Vol.10(4): 297-303

Yi Meng，Xiaoyu An，Yue Zhao.Study on overall stability of sand-filling bag embankment by centrifuge model test[A]. International Conference on Electric, Electronic and Control Engineering (ICEECE 2015)[C],2015.

E.C. Shin;J.K. Kang;Y.I. Oh.Stability analysis of stacked geotextile tubes used in temporary dike construction[J].Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering,2009,: 1546-1549

Yoo, Settlement behavior of embankment on geosynthetic-encased stone column installed soft ground – A numerical investigation[J].Geotextiles and Geomembranes,2015,Vol.43(6): 484-492

Yue-Bao Deng;Gan-Bin Liu;Indraratna, Buddhima;Rujikiatkamjorn, Cholachat;Kang-he Xie.Model Test and Theoretical Analysis for Soft Soil Foundations Improved by Prefabricated Vertical Drains.[J].International Journal of Geomechanics,2017,Vol.17(1): 1-12

Koji Suzuki;Hiroki Takeuchi.Performence of Band Shaped Vertical Drain for Soft Hai Phong Clay[J].Soils and Foundations,2008,Vol.48(4): 577-585

E.M. Da Silva;J.L. Justo;P. Durand;E. Justo;M. Vázquez-Boza.The effect of geotextile reinforcement and prefabricated vertical drains on the stability and settlement of embankments[J].Geotextiles and Geomembranes,

Barron, Ra.Consolidation of Fine-Grained Soils by Drain Wells[J].Transactions of the American Society of Civil Engineers,1948,Vol.113: 718-742

Chen Xiao-dan，Zhao Wei-bing. Equivalent analyzing method of plane strain of drain pile ground considering well resistance and smearing [J] Rock and Soil Mechanics, 2005,(4): 567-571

Chen Lihong,Chen Zuyu,Li Guangxin, Algorithm of Equivalent Plane Strain for Analyzing Sand drain Foundation by Finite Element Method [J], China Civil Engineering Journal, 2004,Vol.37 (6): 82-86

Sun Cong;LI Chun,Finite Element Method of Strength Reduction with Softening Constitutive Model [J]. Chinese Journal of Rock Mechanics and Engineering,2014,Vol.33(10): 2147-2153