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A pilot test on a membraneless vacuum preloading method

Liqiang SUN[1], Wei GUO[2], Jian CHU[3], Wen Nie[*3], Yuxiao REN[1,2], Shuwang YAN[1,2], Jinfang Hou[4]

[1]State key laboratory of hydraulic engineering simulation and safety, Tianjin University, 92, Weijin Road, Tianjin, China, 300072

[2]School of Civil Engineering, Tianjin University, 135 Yaguan Road, Jinnan District, Tianjin, China

[3]School of Civil & Environmental Engineering, Nanyang Technological University, 50 Nanyang Ave, Singapore, 639798

[4]CCCC Tianjin Port Engineering Institute Co. Ltd., Tianjin, China, 300222

[*]Corresponding author (e-mail: wnie001@e.ntu.edu.sg)

Abstract:

A membraneless vacuum preloading method is proposed in this paper for soft soil improvement. The method offers several advantages over the conventional vacuum preloading in which membrane is used to create the airtight condition and sand blanket layer to distribute vacuum. To assess the effectiveness of the proposed method, a pilot test was conducted at a land reclamation site in Tianjin, China. The ground settlement and the pore water pressure (PWP) at different elevations in soil were measured. After vacuum preloading, the average water content of the soft soils reduced by approximately 12% and the undrained shear strength increased twofold. The average degree of consolidation at the end of the vacuum preloading achieved 85.1% based on the settlement data and 84.5% based on the pore water pressure data. The pilot test data have shown that the proposed method exhibits similar efficiencies to the conventional vacuum preloading method.

Keywords: Geosynthetics; vacuum preloading; soil improvement; land reclamation

1. Introduction

Vacuum preloading is one of the common methods used for the improvement of engineering properties of soft soil (Holtan et al., 1965; Chu et al., 2000, 2009; Wang et al., 2016; Bergado et al., 2002; Seah, 2006; Doyle and Qiu, 2016; Indraratna et al., 2011, 2015, 2016a, 2016b). The conventional vacuum preloading system consists prefabricated vertical drains (PVDs), horizontal pipes embedded in a layer of sand blanket, membranes, and vacuum pumps (Qian et al., 1992; Chu et al., 2000). The sand blanket acts as a drainage layer and distributes the vacuum pressure from the horizontal pipes to PVDs. The sand blanket also contributes to the formation of a working platform in soft clay soils (Chu et al., 2013). The membranes are used to seal the whole area to create an airtight condition. As only a limited size of membranes can be placed at one time, subsection of the site is required for a large land reclamation project. In this case, internal dikes may have to be used for partition and anchoring of membranes. Construction of the internal dikes on soft clay is expensive and time consuming. Furthermore, clean sand is required for the sand blanket and it may not be available. In this case, it will be desirable to have an alternative vacuum preloading method that does not required the use of sand blanket and membranes. When membranes are not used, internal dikes are not required either.

In the past, a similar approach to use clay slurry as the sealing layer for vacuum preloading was proposed, see Chu et al. (2008) for detail. However, this method can be affected by the formation of tension cracks in the clay layer due to desiccation effect. Once the cracks connect with the horizontal pipes or PVDs, the vacuum pressure will leak. It should be mentioned that there is another membraneless method to use airtight tubing system to connect PVDs directly with vacuum lines as presented by Bergado et al. (2002), Seah (2006), Chai et al. (2008) and Chu et al. (2008). However, the membraneless method proposed in this paper is different. The proposed method uses special couplings to connect vacuum pipes directly with PVDs so to remove the need for a sand blanket. It uses a layer of clay instead of membranes to cover the horizontal pipes. A similar method of using horizontal band drains (HBDs) to connect with PVDs loosely was also adopted in China in the past (Long et al., 2015). However, the vacuum pressure transmission was not effective in this case (Long et al., 2015).

In this paper, a membraneless vacuum preloading method is proposed in which the airtight condition is provided by a layer of clay slurry pumped on the top of the horizontal vacuum pipes. PVDs are connected directly to the horizontal vacuum pipes using special designed connectors to act in lieu of the sand blanket. To evaluate the performance of the proposed method, a pilot test was conducted at a land reclamation site in Tianjin, China. The ground settlement, the vacuum pressure in PVDs and the pore water pressure (PWP) in the soil were monitored during vacuum preloading. The average degree of consolidation (DOC) was calculated based on both settlement and PWP data.

2. Membraneless vacuum preloading system

The proposed membraneless vacuum preloading method is schematically shown in Fig. 1a. The horizontal vacuum pipes are placed in the middle of two-adjacent rows of PVDs. Each PVD is then connected to the horizontal vacuum pipes through a special couplings system in a way as shown in Figs. 1b. After connecting all the PVDs with the horizontal vacuum pipes, an approximately 1.0-m-thick clay slurry is placed by pumping to cover all the horizontal vacuum pipes. If the ground is too soft, one or two layers of lightweight nonwoven geotextile can be laid to form a working platform (Chu et al. 2013) for PVDs installation.

3. Pilot Test

To access the efficiency of the proposed method, a pilot test was conducted at a land reclamation site in Tianjin, China. The pilot test area covers the northeast corner of a land reclamation project as shown in Fig. 2. Four sides of the diamond-shaped test area were of equal length of 40 *m*. The site investigations for the land reclamation site included borehole sampling and vane shear tests that were conducted before and after vacuum preloading. The field instruments included PWP transducers, surface settlement plates, and multi-level settlement gauges. The layout of the instruments and locations of the site investigation tests are shown in Fig. 2. Data were recorded at frequent intervals during the entire consolidation process.

3.1. Subsoil conditions

The soil profile consisted of a 6.0-m-thick very soft marine clay (top layer), and an 11.0-m-thick soft marine clay layer (second layer) overlying a stiff silty clay layer (bottom layer) as shown in Fig. 3a. The top layer (from EL 5 to -1 m) was dredged marine clay that was placed as fill material for land reclamation. As a result, consolidation took place in the second clay (from EL -1 to -12 m) and was still ongoing. This will be explained more using measured pore water pressure data in section 4.4 of this paper. The basic engineering properties of the soils are also shown in Fig. 3. It can be seen that, except for the bottom layer, the water contents of the soils were generally at or above the liquid limits, and the undrained shear strengths of the soils were very low. The proposed method was adopted to improve the engineering properties of the two layers of soft clay.

3.2. Test procedure and instrumentations

The vacuum preloading test was conducted by following the procedure detailed in Section 2. The PVDs (100 × 6 mm) spaced at 0.8 m in a square grid were installed 20-m-deep into the clay. Each PVD is then connected to the horizontal vacuum pipes using the PVD-pipe connector (Fig. 4c) and the pipe-pipe connector (Fig. 4d). A picture of PVDs connected to horizontal vacuum pipes is shown in Fig. 4a. At the boundaries of the vacuum preloading site, a temporary enclosed dike was constructed using clay filled geotextile bags as shown in Fig. 4e. The ground below the dike was reinforced using two-layer of bamboo mats and one-layer of lightweight nonwoven geotextile (Fig. 4e). The temporary dike was 1.0-m-high, 0.5-m-wide on top and 1.5-m-wide on the bottom. The surfaces of the temporary dikes were covered by membranes to prevent the pumped slurry from seeping into the dikes.

The PWP transducers were installed at two locations, see PWP-1 and PWP-2 in Fig. 2. For each location, five pieces of PWP transducers were installed into one borehole at elevations of +3.0, 0.0, -4.0, -8.0 and -14.0 m, respectively. The vacuum pressures in the PVD was measured from an additional PWP transducer inserted it into the filter of the PVD at ground surface (EL +5 m). To prevent the soil from flowing into the PVDs, the surface of the connecting area was sealed using geotextile. Nine settlement plates (Fig. 2) were installed on the ground surface to measure the settlement during the consolidation procedure. The multi-level settlement gauges were also installed at two locations. For each location, seven pieces of multi-level settlement gauges were installed at elevations of +4.3, +2.59, -0.45, -2.4, -6.35, -10.2 and -14.0 m, respectively. All the monitoring data were recorded at frequent intervals during the vacuum preloading.

After installation of the instruments, clay slurry was pumped into the reclamation site (Fig. 4b). The slurry was mixed on the site using local marine clay. The water content and unit weight of the mixed clay slurry were 120% and 14 kN/m^3, respectively. The thickness of the pumped slurry was approximately 0.8 m. After consolidation or desiccation, the thickness of the clay slurry reduced. To avoid subsequent drying of the surface of the clay slurry layer during vacuum preloading, the water was kept on the top of the sediments as shown in Fig. 4b. The vacuum pressure was applied using two jet pumps.

4. Results and data analysis

4.1. Vacuum and pore water pressures

The applied vacuum pressure versus duration curve is plotted in Fig. 5a. The slightly increase in positive pore water pressure before 8^{th} day was caused by water level changes due to the newly pumped clay slurry. The vacuum pressure was applied on the 8^{th} day which caused the vacuum pressure in PVDs to increase. On the 37^{th} day, vacuum was stopped to conduct vane shear tests and soil sampling. This explained the sudden reduction in the vacuum pressure on 37 days as shown in Fig. 5a. Conducting vane shear tests during vacuum preloading would not have been possible if membranes were used. The decrease in the vacuum pressures on the 76^{th} day (see Fig. 5a) was due to cracks occurring on the surface as a result of desiccation of the top clay slurry layer at one area. This problem was fixed by pumping another layer of clay slurry and subsequently the vacuum pressures were recovered.

The PWPs measured at locations PWP-1 and PWP-2 (see Fig. 2) are plotted versus duration in Figs. 5b and 6c, respectively. It can be seen that the vacuum pressures in the soil could be maintained during the vacuum preloading. The cracks in the clay slurry only influenced the PWPs in the soil up to 3.0 m deep. When another layer of clay slurry was placed on top (on the 76^{th} day in Fig. 5a), the cracks were sealed and the PWPs in soil recovered, see the PWP on the 90th day in Figs. 5b and 5c.

4.2. Ground settlement

During PVDs installation, an average settlement of 0.552 m was recorded due to the dissipation of pore water pressure during installation procedure of the PVDs. Further settlements were induced by vacuum preloading. The average settlements versus time curves measured at different elevations are plotted in Fig. 6. For clarity, only four out of the seven measured settlement curves are plotted. It can be seen that settlement developed at every elevation down to -13.17 m (or 18.17 m below the ground surface). This indicates that the vacuum preloading was effective for the entire soft clay. The average ground settlements measured from the nine settlement plates is also plotted in Fig. 6. Towards the end of the vacuum preloading, the settlement curves show tendencies to converge. The average ground settlement due to vacuum preloading was 1.2 m.

4.3. Degree of consolidation

The effectiveness of the vacuum preloading can be estimated using the average degree of consolidation (DOC). One method to calculate the average DOC is using settlement data in which DOC is defined as the ratio of present ground settlement (S_t)

to the ultimate primary consolidation settlement (S_∞). In this paper, the Asaoka's method (Asaoka, 1978) was adopted to estimate S_∞ using the ground surface settlement data (Fig. 6). Based on a plot of settlement data S_n (n = 1, 2, …) versus S_{n-1}, at a time interval of 4 days (t_n - t_{n-1}= Δt = 4 days), the ultimate ground settlements for the reclamation site is estimated to be 2.082 m. The final DOC is calculated as 85.1% as summarized in Table 1.

The DOCs can also be estimated using the PWP distribution profiles (Chu and Yan, 2005). In this method, the average DOC is estimated as the ratio between the area covered by the PWP distribution curve at elevation z at a given time $u_t(z)$ and the suction line $u_s(z)$, and the area covered by the initial PWP line $u_i(z)$, and the suction line $u_s(z)$,

$$U_{avg} = 1 - \frac{\int [u_t(z) - u_s(z)]\,dz}{\int [u_i(z) - u_s(z)]\,dz} \tag{1}$$

$$u_s(z) = \gamma_w\,(h - z) - 80 \tag{2}$$

where U_{avg} is average degree of consolidation, $u_i(z)$ is the initial PWP at elevation z, $u_t(z)$ is the PWP at elevation z and at time t, $u_s(z)$ is the suction value at elevation z, h is elevation on the ground surface and h = +5 for the site, and γ_w is the unit weight of water.

The PWP distribution profiles at both locations are plotted in Fig. 7 based on the measured PWP data as shown in Fig. 5b. The hydrostatic water pressure was calculated based on the water level of +5 m in the reclamation site. It can be seen from Figs. 7a and 7b that the excess water pressures in the second layer (soft marine clay) is a sign that the soil was still undergoing consolidation. The measured PWPs at elevation of -14 m at the initial state, such as 171kPa by PWP-1 and 174kPa by PWP-2, are lower than the hydrostatic water pressure (190 kPa). This is because the bottom layer, stiff silty clay (see Fig. 3a), had lower water content and higher undrained shear strength and was likely to be overconsolidated. For this reason, some negative PWPs might have been induced during the installation of the pore pressure transducers. Another possible reason could be the small seepage force acting at this point. The water level at the reclamation site was at +5 m and the average sea level was at +1.56 m. This created a seepage from the reclamation side to the seaside although the flow was small due to the low permeability of the soil. It should be pointed out that the average DOC is estimated based on the hydrostatic water pressure with the water level at +5 m.

Using Eq. (1), the average DOC on the 60th days are estimated as 62.68% and 59.94% for PWP-1 and PWP-2, respectively. The DOC on the 108 days are 83.65% and 83.30% for PWP-1 and PWP-2, respectively. As an average DOC of 84.48% was achieved within 108 days, the proposed method is just as effective as the conventional vacuum preloading. A comparison of the DOCs measured using settlements and PWPs is also given in Table 1. The DOCs calculated based on PWP distribution profiles and settlement data only has difference of 2% in 108 days.

4.4. Water content and vane shear strength variations

After vacuum preloading, soil samples at different depths were taken to measure its water contents. Fig. 8a shows the average water contents profiles at different elevations at initial, 40th days and 120th days of the vacuum preloading. It can be seen that the average water content of the soil in the top two layers reduced approximately 12% after vacuum preloading. However, the water contents of the soil at the bottom layer was low and the change induced by consolidation was low too. The water content reduced from 24.7% to 23.55% at 40 days and to 22.7% at 120 days of consolidation.

Field vane shear tests were conducted in the site at initial, and on 40th days and 120th days of the vacuum preloading, and the results are plotted in Fig. 8b. It can be seen that the undrained shear strengths of the soils in the top two layers after vacuum preloading have increased 2 to 3 folds. The average undrained shear strength of the soil in the top layer increased from 5.6 kPa to 20 kPa after vacuum preloading, and that in the second layer increased from 14 kPa to 30 kPa. Although the change in the water content of the bottom layer was small, the change in the undrained shear strength was still of 65%. This phenomenon has also been observed by another vacuum consolidation projects at similar locations in Tianjin (Yan and Chu, 2003).

5. Conclusions

A pilot test was conducted to investigate the performance of a membraneless vacuum preloading method. In this method, the airtight condition is provided by a layer of clay slurry covering on the top of the horizontal vacuum pipes. The prefabricated vertical drains (PVDs) are connected directly to the horizontal vacuum pipes using the special designed connectors. The results of the pilot test show that the proposed method exhibits similar efficiencies to the conventional vacuum preloading method. After vacuum preloading, the total settlement on ground surface was 1.77 m. The undrained shear strength of the soils measured by the vane shear tests increased twofold. The average degree of consolidation of soil at the end of vacuum preloading was 85.1% based on the settlement data and 83.48% based on the pore-water pressure data.

6. Acknowledgements

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7. References

Asaoka, A., 1978. Observational procedure of settlement prediction. Soils Found. 18(4), 87-101.

Bergado, D.T., Balasubramaniam, A.S., Fannin, R.J., Holtz, R.D., 2002. Prefabricated vertical drains (pvds) in soft Bangkok clay: A case study of the new Bangkok International Airport project. Can. Geotech. J. 39(2), 304-315.

Chai, J., Carter, J., Hayashi, S., 2005. Ground deformation induced by vacuum consolidation. J. Geotech. Geoenviron. Eng. 131(12), 1552-1561.

Chai, J., Miura, N., Bergado, D.T., 2008. Preloading clayey deposit by vacuum pressure with cap-drain: Analyses versus performance. Geotex. Geomembr. 26(3), 220-230.

Chu, J., Guo, W., Lam, K.P., Yan S. W., 2013. Use of clay slurry and waste for land reclamation. 18th Southeast Asian geotechnical & Inaugural AGSSEA conference. 29-31 May, Singapore, pp 755-760.

Chu, J., Bo, M.W., Choa, V., 2004. Practical considerations for using vertical drains in soil improvement projects. Geotex. Geomembr. 22(1-2), 101-117.

Chu, J., Bo, M.W., Choa, V., 2006. Improvement of ultra-soft soil using prefabricated vertical drains. Geotex. Geomembr. 24(6), 339-348.

Chu, J., Varaksin, S., Klotz, U., Menge, P., 2009. Construction processes. Proc. 17th Int. Conf. on Soil Mech. and Geot. Eng., March 19, Alexandria, Egypt, 4, pp 3006–3135.

Chu, J., Yan, S.W., 2005. Estimation of degree of consolidation for vacuum preloading projects. Int. J. Geomech. 5, 158-165.

Chu, J., Yan, S.W., Indraranata, B., 2008. Vacuum preloading techniques - recent developments and applications, GeoCongress 2008: Geosustainability and Geohazard Mitigation, pp 586-595.

Chu, J., Yan, S.W., Yang, H., 2000. Soil improvement by the vacuum preloading method for an oil storage station. Geotechnique 50(6), 625-632.

Chung, S.G., Kweon, H.J., Jang, W.Y., 2014. Observational method for field performance of prefabricated vertical drains. Geotex. Geomembr. 42(4), 405-416.

Doyle, K., Qiu, T., 2016. Piecewise-Linear modeling of vombined vacuum and surcharge preloading at the second Bangkok International Airport. Geo-Chicago 2016, pp. 836-844.

Holtan, G.W., 1965. Vacuum stabilization of subsoil beneath runway extension at Philadelphai International Airport, Proc. of 6^{th} Int. Conf. of Soil Mech. & Found. (ICSMFE) 2, pp 61-65.

Indraratna, B., Rujikiatkamjorn, C., Ameratunga, J., Boyle, P., 2011. Performance and Prediction of Vacuum Combined Surcharge Consolidation at Port of Brisbane. J. Geotech. Geoenviron. Eng. 137(11), 1009-1018.

Indraratna, B., Perera, D., Rujikiatkamjorn, C., Kelly, R., 2015. Soil disturbance analysis due to vertical drain installation. Proc. ICE Geotech. Eng., 168(3), 236–246

Indraratna, B., Zhong, R., Fox, P., Rujikiatkamjorn, C., 2016a. Large-strain vacuum-assisted consolidation with Non-Darcian radial flow incorporating varying permeability and compressibility. J. Geotech. Geoenviron. Eng. DOI: 10.1061/(ASCE)GT.1943-5606.0001599, 04016088.

Indraratna, B., Rujikiatkamjorn, C., Zhong, R., 2016b. Recent developments of vacuum-assisted consolidation of soft estuarine clays. Geotechnical and Structural Engineering Congress 2016, pp. 950-959.

Long, P.V., Nguyen, L.V., Bergado, D.T., Balasubramaniam, A.S., 2015. Performance of PVD improved soft ground using vacuum consolidation methods with and without airtight membrane. Geotex. Geomembr. 43(6), 473-483

Qian, J.H., Zhao, W.B., Cheung, Y.K., Lee, P.K.K., 1992. The theory and practice of vacuum preloading. Comput. Geotech. 13(2), 103-118.

Seah, T.H., 2006. Design and construction of ground improvement works at Suvarnabhumi Airport. Geotech. Eng. J. SEAGS AGSSEA 37, 171-188.

Sun, L., Lu, J., Guo, W., Yan, S., Jia, T., 2015. Models to predict compressibility and permeability of reconstituted clays, ASTM - Geotech. Test J. 39(2), 324-330.

Tan, T.S., Inoue, T., Lee, S.L., 1991. Hyperbolic method for consolidation analysis. J. Geotech. Geoenviron. 117(1), 1723-1737.

Tan, S.A., 1995. Validation of hyperbolic method for settlement in clays with vertical drains. Soils Found. 35(1), 101-113.

Tan, S.A., Chew, S.H., 1996. Comparison of the hyperbolic and Asaoka observational method of monitoring consolidation with vertical drains. Soils Found. 36(3), 31-42.

Yan, S., Chu, J., 2003. Soil improvement for a road using the vacuum preloading method. ICE - Ground Improv. 7(4), 165-172.

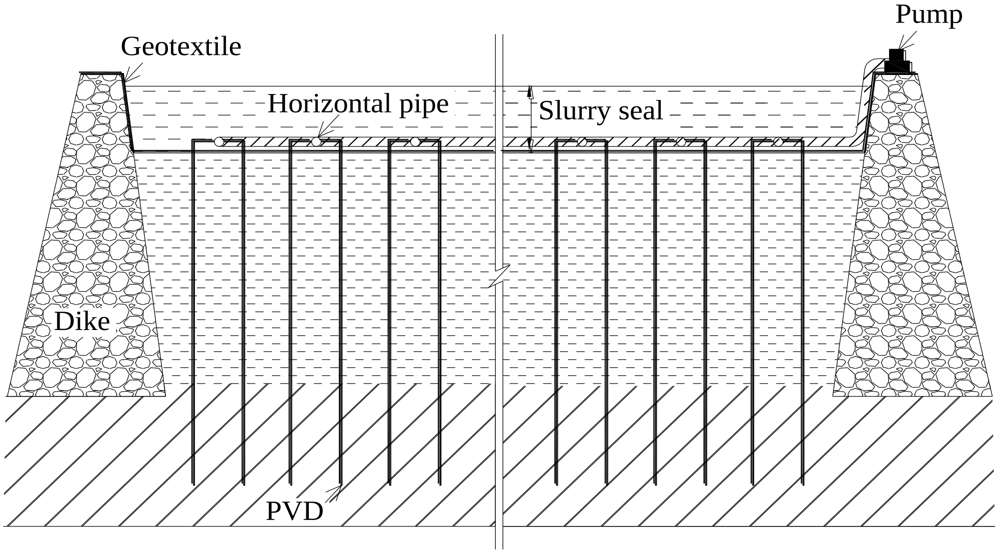
Yan, S., Chu, J., 2005. Soil improvement for a storage yard using the combined vacuum and fill preloading method. Can. Geotech. J. 42(4), 1094-1104.

Wang, J., Cai, Y., Ma, J., Chu, J., Fu, H., Wang, P., Jin, Y., 2016. Improved vacuum preloading method for consolidation of dredged clay-slurry fill. J. Geotech. Geoenviron. Eng. DOI: 10.1061/(ASCE)GT.1943-5606.0001516, 06016012.

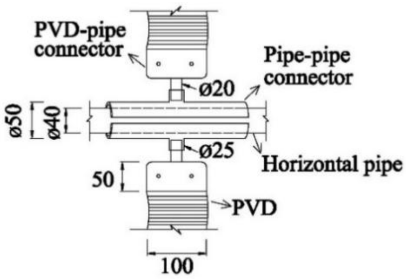
Zhu, S.L., Miao, Z.H., 2002. Recent development and improvement of vacuum preloading method for improving soft soil. Proc. ICE - Ground Improv. 6(2), 79-83.

Table 1. Calculation of the degree of consolidation (DOC) using the measured settlement and pore water pressure data

Based on settlement data (Asaoka, 1978)				Based on PWP data (Chu and Yan, 2005)			
S_{PVD} (mm)	$S_{t=120}$ (mm)	$S_{t=\infty}$ (mm)	$U_{t=\infty}$ (%)		$U_{t=30}$ (%)	$U_{t=60}$ (%)	$U_{t=120}$ (%)
572	1200	2082	85.11	PWP-1	39.47	62.68	83.65
				PWP-2	41.85	59.94	83.30
				Avg.	40.66	61.31	83.48



(a)



(b)

Fig. 1 Schematic arrangements of the proposed membraneless vacuum preloading method using slurry as sealing cap (a) the whole system and (b) the tubing connectors.

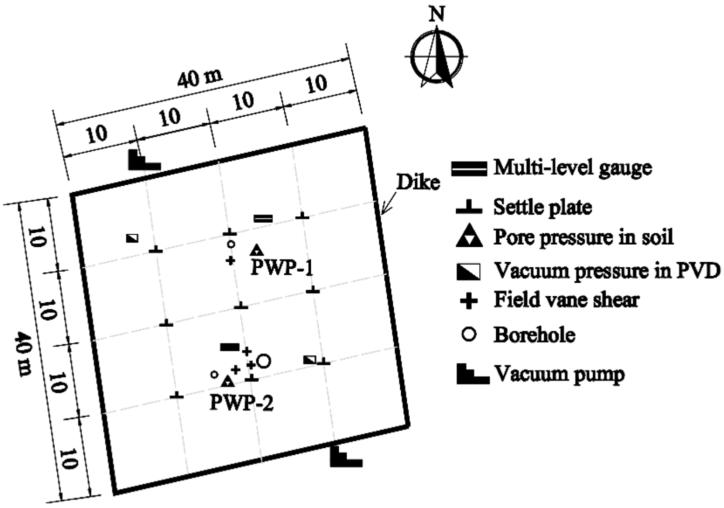


Fig. 2 Layout of field test and plan view of test instrumentations

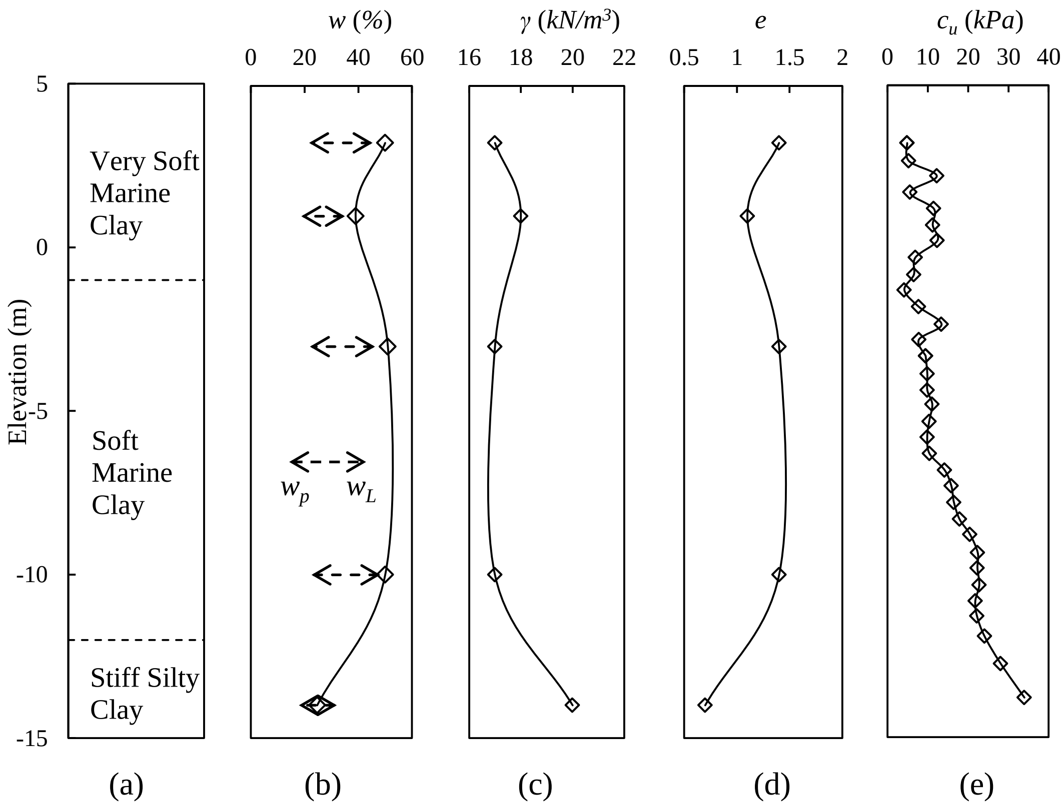


Fig. 3 Basic soil properties at the site: (a) simplified soil profile, (b) water content *w*, liquid limit w_L, and plastic limit w_p; (c) unit weight γ, (d) void ratio *e*, and (e) vane shear strength c_u.

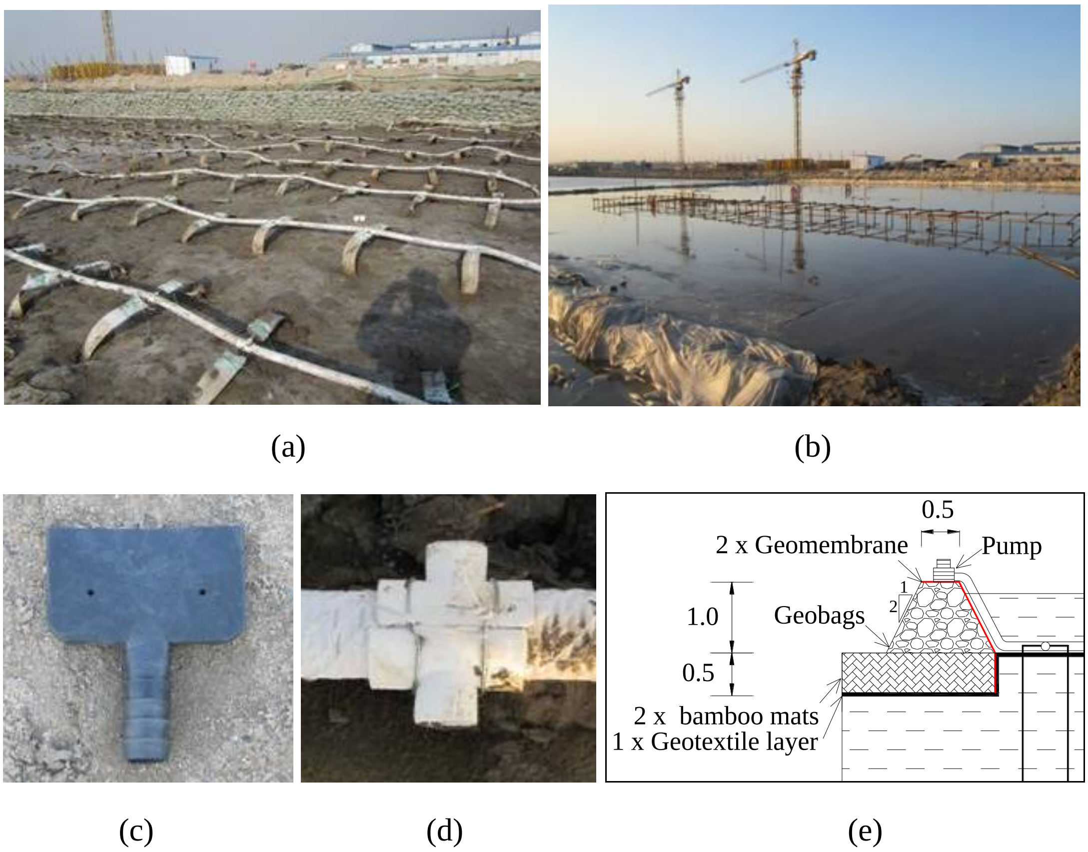
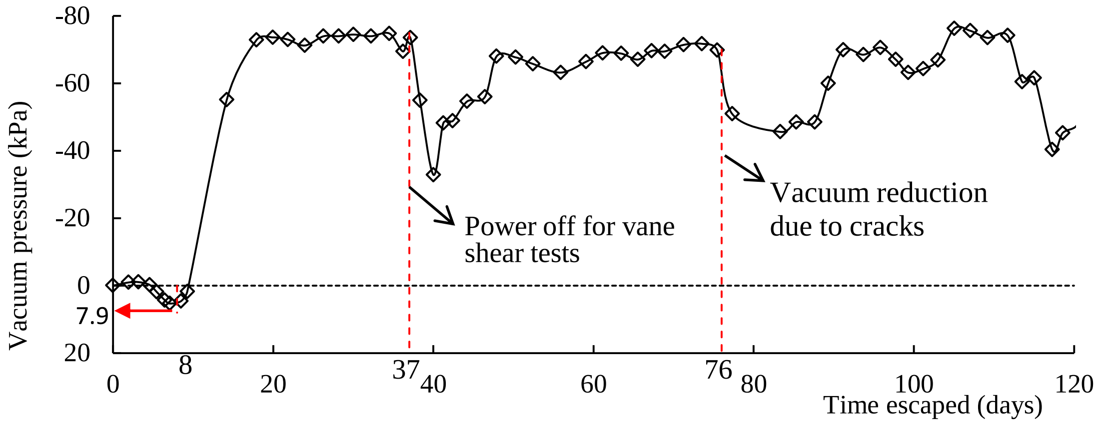
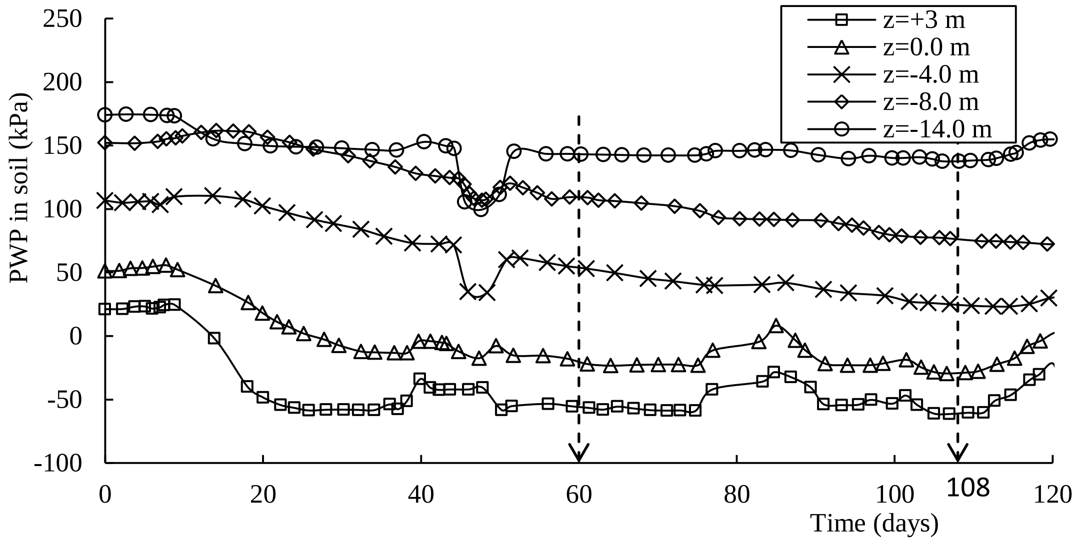


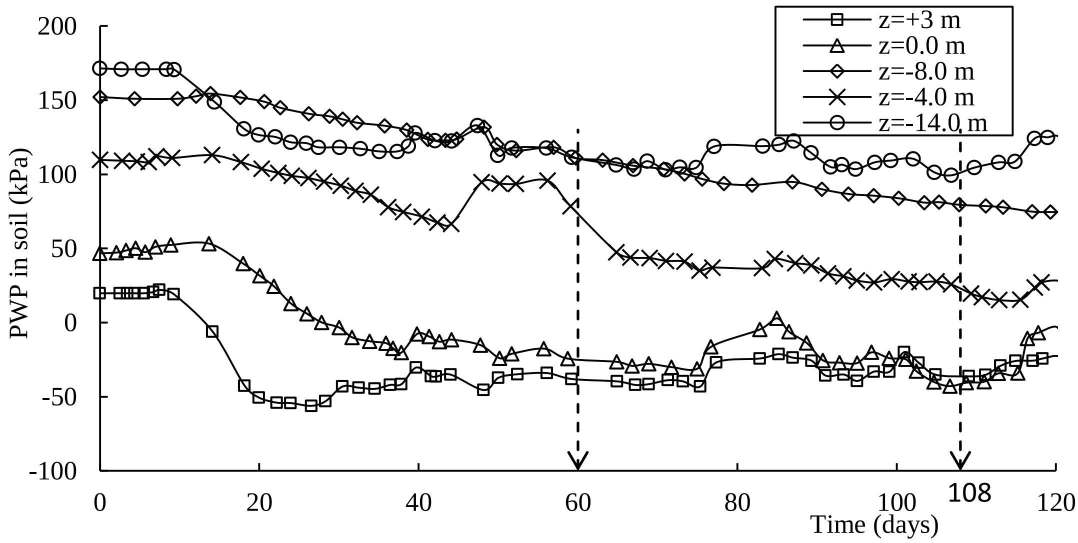
Fig. 4 Method of using the proposed method in the site (a) photo of the site after connecting the PVDs with horizontal vacuum pipes, (b) photo of the site after pumping the slurry into the site, (c) photo of the PVD-pipe connector, (d) photo of the pipe-pipe connector, and (e) sketch of the temporary dike



(a)



(b)



(c)

Fig. 5 Measured vacuum and pore water pressure versus time curves (a) vacuum pressure, and total PWPs measured at (b) PWP-1 and (c) PWP-2

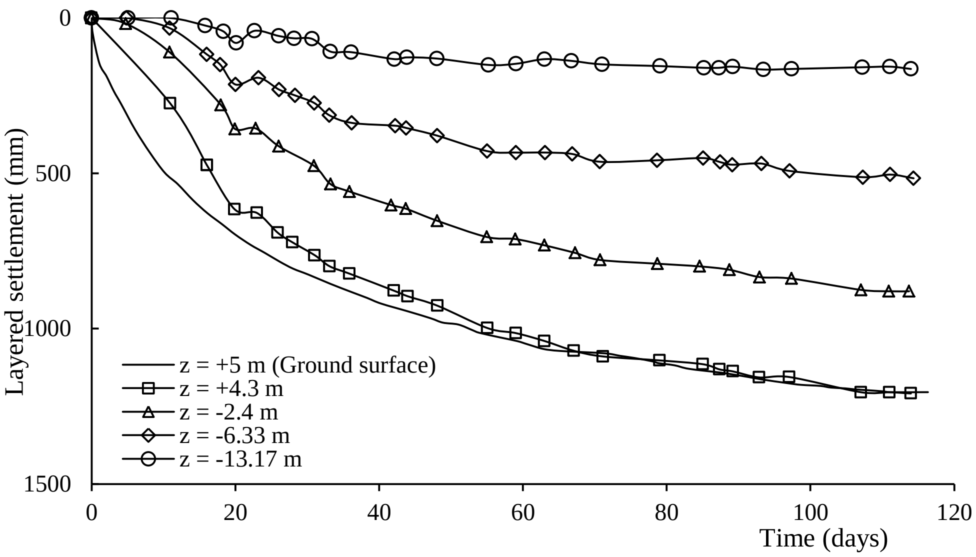
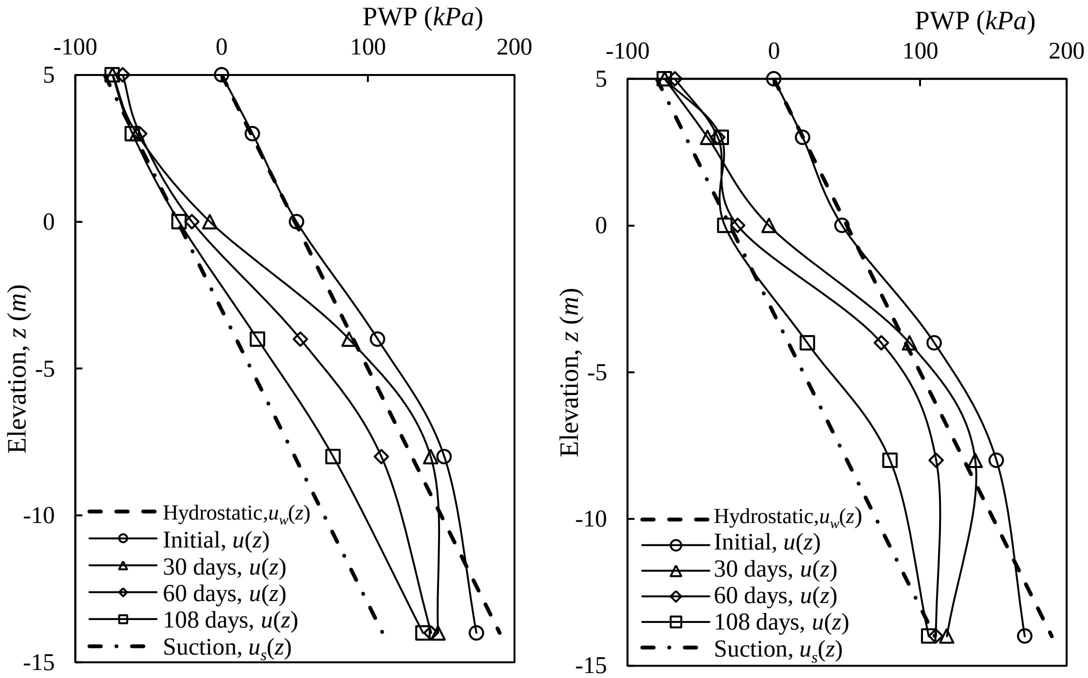


Fig. 6 Measured ground settlement versus consolidation time curves



(a) (b)

Fig. 7 PWP profiles used for DOC calculation based on pore water pressure data measured by (a) PWP-1 and (b) PWP-2

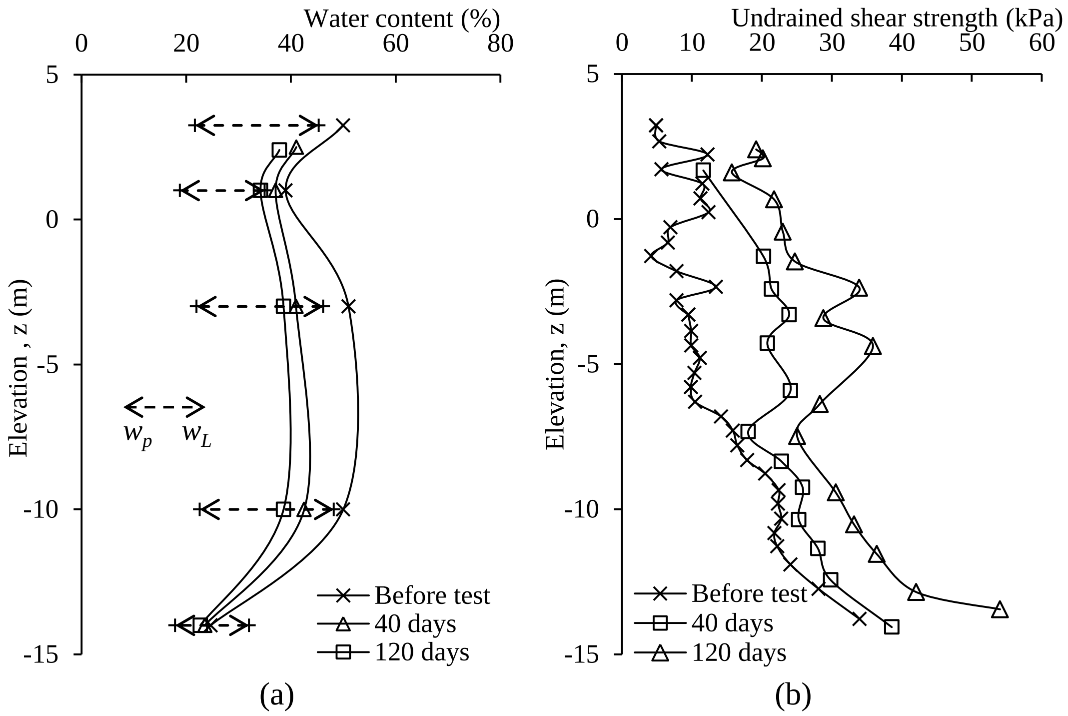


Fig. 8 Properties of soil after membraneless vacuum preloading (a) water content, and (b) undrained shear strength