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A FIELD TEST STUDY ON UNDER WATER VACUUM PRELOADING METHOD

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ABSTRACT

Vacuum preloading technique incorporating prefabricated vertical drains is one of the most widely used ground improvement methods in the world for improving the engineering properties of soft clays. Although many successful on-shore cases on application of the technique have been reported, the effectiveness of applying the technique under water has not yet been investigated. Moreover, many technical and operation factors, that are playing important roles in vacuum consolidation, are also not yet fully understood. To study the feasibility of under water vacuum preloading, a large-scale field test was conducted. A 50 m by 50 m geo-membrane was laid under water in an 80 m wide by 100 m long pond. The geo-membrane was custom made with drainage outlet pipes to release the trapped air bubbles during the placement under water. Prefabricated vertical drains were installed on an equilateral triangular grid at a spacing of 1.2 m to a depth of 7 m. Internal drainage pipes were provided in the sand cushion layers to provide a passage for the prefabricated vertical drains with the external vacuum pumps. Instruments such as piezometers, vacuum sensors, inclinometers, settlement plates and extensometers were installed to monitor the performance of the system. An automatic and remote wireless monitoring system was installed for data collection because of difficult access. Vane shear tests and cone penetration tests were conducted before and after vacuum preloading to determine the effectiveness of the operation. This paper documents the constructions of the field test and reports the major observations from the monitored readings. The operation has demonstrated that under water vacuum preloading is feasible and that with proper design and construction procedure, a very tight seal can be provided by the geo-membrane separating the water and the underlying prefabricated vertical drains through out the test. The monitored results demonstrate that the stiffness and strength of the soft clay can be improved effectively.

INTRODUCTION

Hong Kong is a small territory of about 1103 km^2. There is an ever-increasing demand for land to copy with her increasing development. Reclaiming the sea is one of the major methods in forming new lands for development, in which the treatment of marine deposit is the key problem (Lumb, 1977). Conventional practice in Hong Kong is to dredge the marine deposit, build the seawalls and fill the enclosed space by sand or to apply surcharge load. These approaches have many shortcomings, such as adverse environmental impact to the marine ecology and the nearby residents during the dredge process and long time needed for the construction plus removal and large volume of surcharge loading required in the surcharge method (Sharma and Lewis, 1994; Daniel and Koerner, 1995). Compared to the conventional methods, the under water vacuum preloading method is environmentally safe and effective to improve the shear strength of marine deposits and decrease the post-construction settlement (Qian et al., 1992). Thus, it provides an alternative for the treatment of marine deposits during reclamation.

Although the vacuum preloading method has been widely used and many successful on-shore case histories on application of the technique to improve the engineering properties of soft clay have been reported (Shang et al., 1998; Chu et al., 2000; Tang and Shang, 2000; Yan and Chu, 2005), the effectiveness of applying the technique under water is yet to be investigated. To study the feasibility of applying the technique under water, a large-scale field test was conducted. In this paper, the soil improvement procedure, field instrumentation, vane shear tests and cone penetration tests are described. Based on the field monitoring data, the pore water pressure distributions versus depth are plotted at different loading duration. The development of vertical settlement with time is presented. After under water vacuum preloading, the undrained shear strength of the soil increased obviously, and the water content of the soil decreased substantially.

CONSTRUCTION OF FULL-SCALE FIELD LOAD TEST

Site conditions

The field test was conducted at about 2 km south of the Shenzhen airport where the geological condition is very similar to that in Hong Kong (see Figure 1 for location). The test site was rectangular in shape and the depth of the water was 1.5 m. The area improved by the vacuum preloading was square in shape with a total of 2500 m^2. Site investigation before the field test showed that soft clay layer present within 7 m below the ground surface, below which was the firm stratum.

Figure 1. General site location plan near the Shenzhen airport

Construction Procedure

Construction started on 28 August 2006. The soil improvement work in the field test can be described briefly as follows:

1. Water in the pond was first pumped out.
2. A 0.6 m sand cushion was then placed on the ground surface.
3. Prefabricated vertical drains (PVDs) were then installed on an equilateral triangular grid at a spacing of 1.2 m to a depth of 7 m.
4. Instruments were then installed. At the same time, vane shear test and cone penetration test were conducted to investigate the subsoil.
5. Drainage pipes were then laid horizontally in the sand cushion to provide a linkage between the PVDs and the main pipes, which were connected to three numbers of vacuum pumps.
6. Water was then pumped back into the pond.
7. When the data collected by the instruments showed that the sub-soils were under hydrostatic conditions, a custom-made geo-membrane (see Figure 2 for geo-membrane details) was laid under water to separate the water from the PVDs and all the pipes. Five numbers of outlet drains were custom made on top of the membrane so that any air bubbles trapped during the placement could be dissipated to the atmosphere. The edges of the geo-membrane were tied with ropes, which helped to steer the direction of the placement and helped to un-fold the geo-membrane. Steel rods were placed inside the plastic pipes to help sinking the membrane down into water and to prevent water from entering the connecting pipes. Sand bags were also placed along the edges to increase the weight of the geo-membrane and to provide a good contact between the geo-membrane and the soft clay layer.

The construction preparation work took about two months, where most of the time was spent on installing instruments. All of the preparation work was ended on 30 October 2006. Vacuum load was then applied from 2 November 2006 to 7 February 2007 (about 3 months). After the test was finished and the pond de-watered, vane shear test and cone penetration test were conducted again.

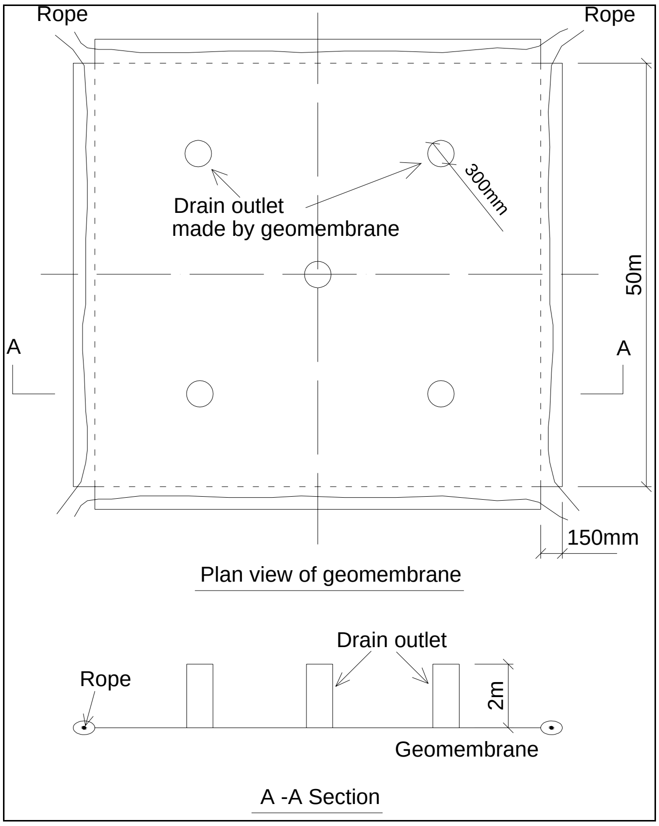

Figure 2. Schematic diagram of custom made geomembrane

Instrumentation

Since the field test was conducted under water where physical access is a problem, an automatic data collection and wireless data transmission system was used in this study.

All instruments were calibrated before the installation. The layout and profile of instrumentations are shown in Figure 3. Instruments such as piezometers, vacuum sensors, in-place inclinometers, extensometers, surface settlement plates, and moisture probes were installed. Except settlement plates, all instruments were connected with a data logger. During the test, raw data generated from the sensors (e.g. piezometers, inclinometers, extensometers, etc.) were transmitted to a data logger, which was connected to the office computer via a GSM Modem. This wireless data transmission from Shenzhen to Hong Kong greatly facilitated remote and real-time monitoring of the suction variation and settlement with time as the test was progressing. The whole system is shown schematically in Figure 4. Solar-power panels were used to generate electricity to the whole system and no external power supply is needed. In additional to downloading data remotely from the test site, it also helped to alter the sampling frequency freely in the office if needed.

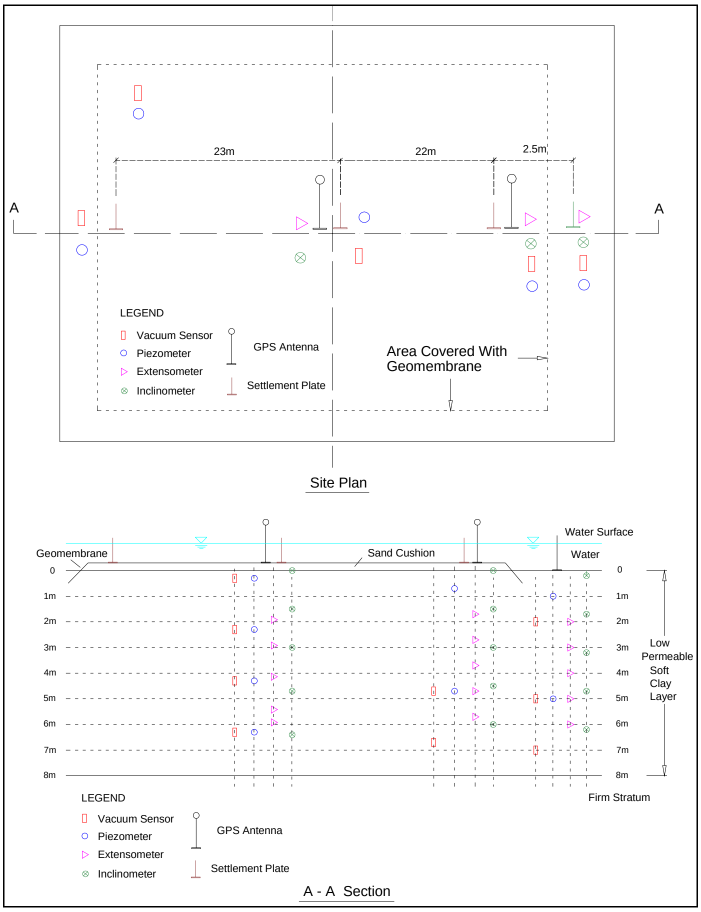

Figure 3. Layout and cross-section view of instrumentation

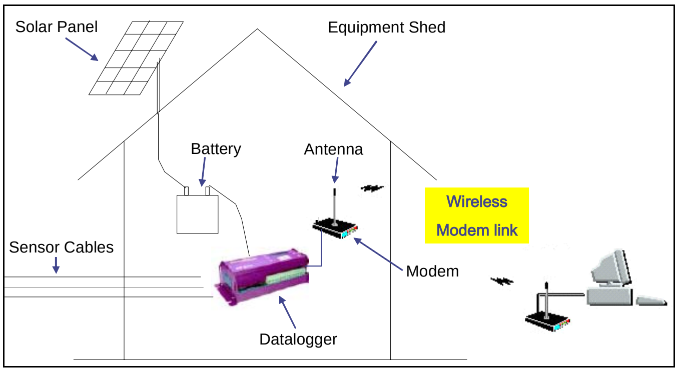

Figure 4. Schematic of the automatic data collection and wireless transmission system

MONITORING RESULT AND ANALYSIS

Pore water pressure monitoring data

During the test, it was shown that both the vacuum pressures in the sand cushion and the water pressures on the sealing membrane affected the change of excess pore pressures (see Figure 5. for measured pore water pressure curves). Vacuum pressure was applied from 3 November 2006 to 7 February 2007 or about 96 days. During the vacuum preloading process, the vacuum pressure was successfully maintained at 80 ± 3 kPa in a total of 62 days. In some occasions, the water in the pond was lowered for maintenance purposes and for installing two GPSs cells for cross checking against conventional survey. Only 2 days were required to raise the vacuum pressures from zero back up to 70 kPa, indicating that the sealing of the geo-membrane was good. During the test, only one pump was in use during the first 43 days, whereas the rest were used as a backup. After 16 December 2006, the number of pumps was increased to two and three (from 28 December 2006 to 18 January 2007). However, there was very little effect to the vacuum pressures in the sand cushion as the number of pumps increased. The water depth on the geo-membrane was not a constant value because the tides and the pond level adjacent to this site affected it. During the test, the highest water pressure was 15 kPa and the lowest was 8 kPa.

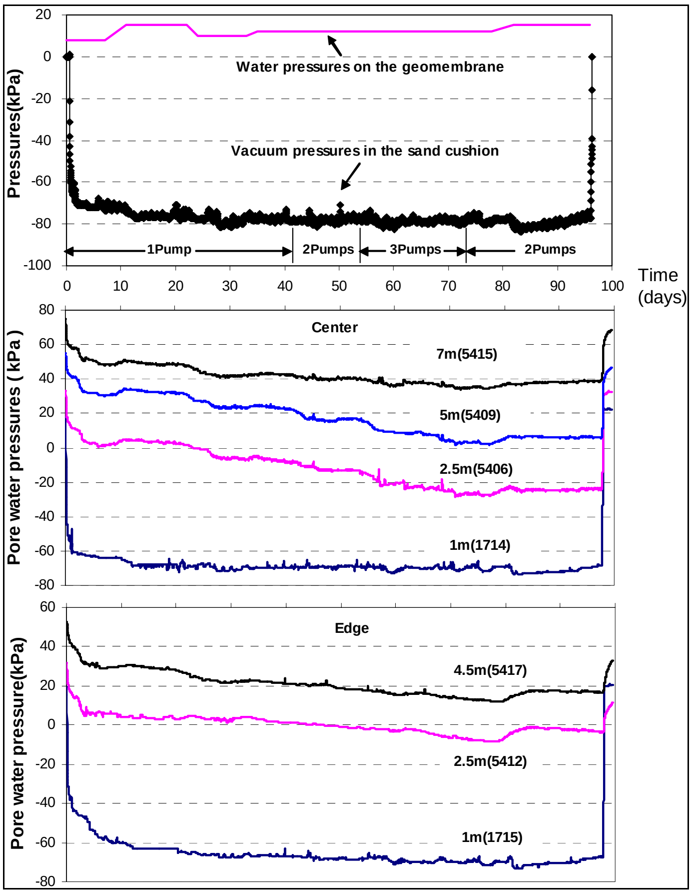

Figure 5. Variation of vacuum pressures in sand cushion and water pressures on the sealing membrane

After all the instruments were installed, geo-membrane laid down and water pumped back into the pond, the pore pressure showed linearly increased with depth and its values were equal to the hydrostatic pressures of the same depths (see Figure 6.). The pore water pressures at 1 m depth, both at the center and at the edge, quickly reached and kept at –70 kPa, indicating that consolidation of the layers from 1 m upward was completed very quickly. After vacuum was applied, the change in the pore water pressures followed closely to that before it was applied, which suggested that the subsoil condition was very homogeneous and pore water pressure change was directly proportional to the applied suction.

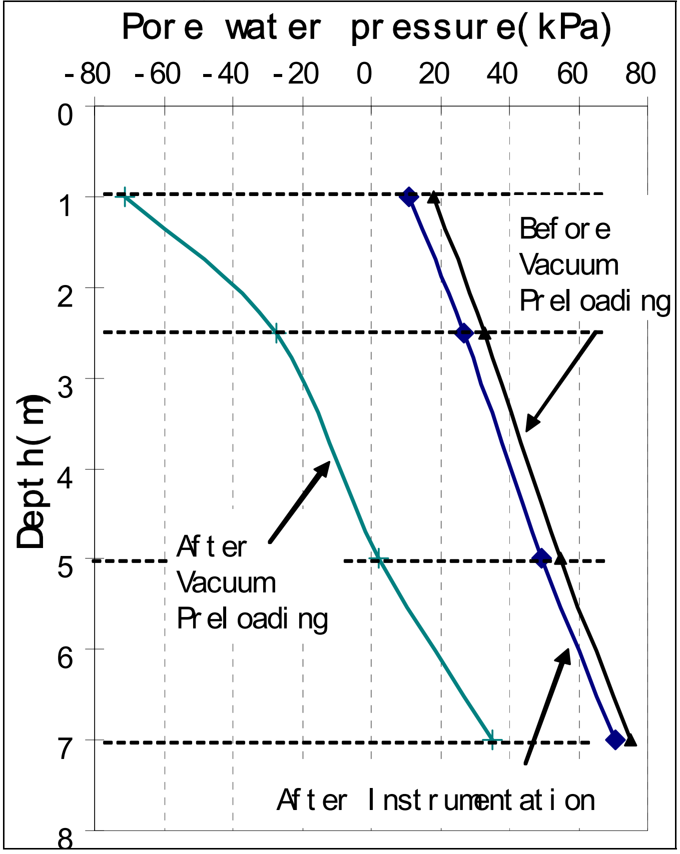

Figure 6. Variation of pore water pressures with depth

Figure 5 also shows that the use of more pumps had helped to increase the excess pore pressures in subsoil at deeper layers.

The curves in Figure 5 also shows that during under water vacuum preloading, any increase of water depth on the geo-membrane would induce positive excess pore water pressure in soil, which was similar to applying surcharge loads in conventional preloading method.

Distribution of pore water pressures in the subsoil

Based on the monitoring data shown in Figure 5, Figure 7 shows the distributions of pore water pressures against depth and lateral extent, and Figure 8 shows the change in position of zero value pore pressure 80 days after vacuum was applied. Due to the scattered data points, a simple linear interpolation was suggested for the value of the excess pore pressures between the center and edge. For the shallow depth of less than of 1 m, the variation of excess pore water pressure was quite uniform from the center to edge (between –80 kPa to –70 kPa). Below 3 m depth, the change in pore pressures was greater at the center than at the edge as shown by the 10-kPa contours. It was because vacuum was first created at the center and propagated from the center towards deeper layer and towards the outside boundary. The lateral boundary had allowed water to enter the system and reduced the excess pore pressure.

The depth of zero value pore pressure at the center was lower than that at the edge and the difference between the center and the edge increased with time (see Figure 8). This suggested that if there were more vacuum pressures applied to the system, it would have been possible for the excess pore pressure to migrate to bottom of the soft layers within 90 to 120 days as indicated by the trend in Figure 8.

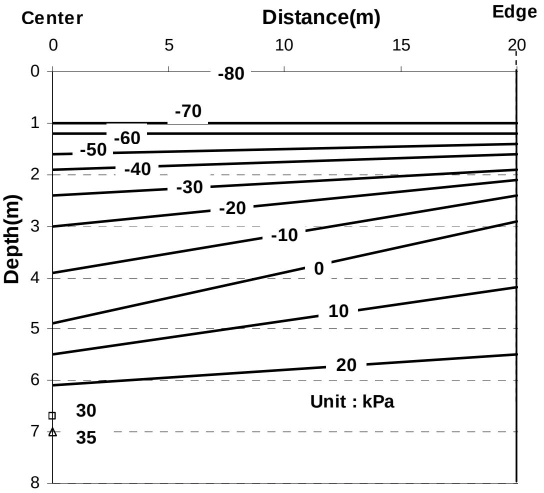

Figure 7. Contour of excess pore pressure after 80 days

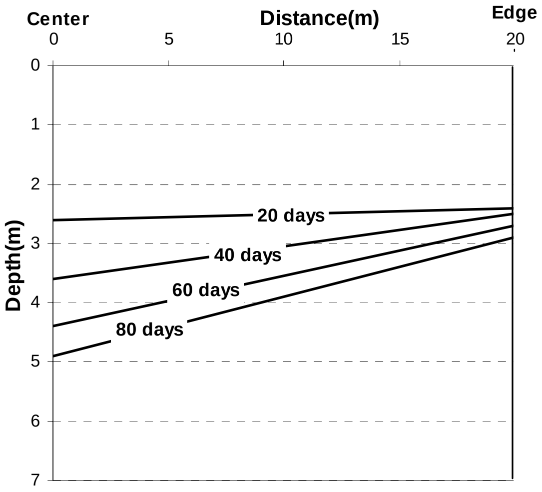

Figure 8. Change in position of zero value pore pressure line

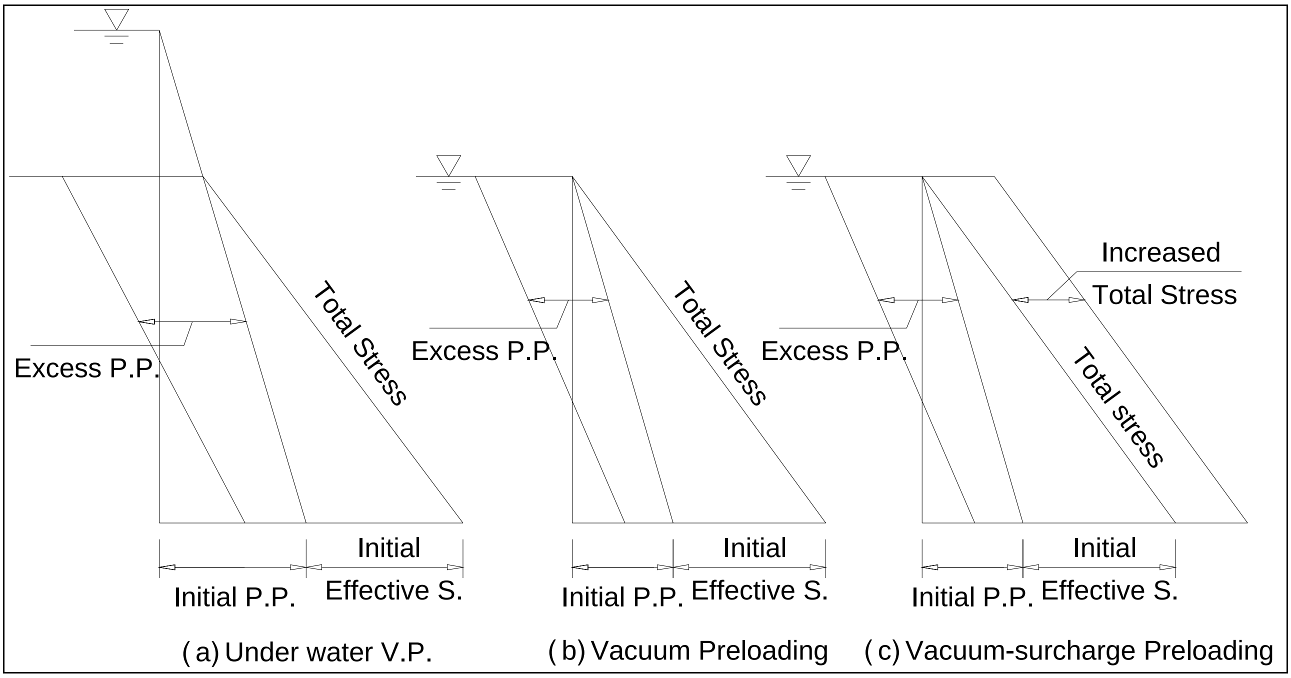

Figure 9. Comparison of mechanism of different vacuum methods

Mechanism of under water vacuum preloading

The mechanism of under water vacuum preloading method can be illustrated with the assistance of Figure 9, which shows the variation pore water pressures against depth for different loading conditions.

Before under water vacuum preloading was applied, pore water pressures in soil varied with a change of water depth on the ground surface, while maintaining a constant effective stress. After applying vacuum loadings, the water pressures first varied from positive to negative if the air pressure was considered as zero, and then turned into negative gradually from surface to deeper layer. Because the total stress was maintaining as a constant value, the effective stress in the soil during under water preloading would equal to the difference between initial pore pressures and monitored values, which means that the water pressures on membrane can be considered as a preloading load.

Compared to vacuum preloading method used on land, the preloading load in under water vacuum preloading method included two parts: vacuum loading and water loading. The difference between under water preloading method and vacuum-surcharge method is that during under water vacuum preloading, only negative excess pore water pressures were induced while maintaining a constant total pressure if the water depth was kept at a constant value; whereas in vacuum-surcharge preloading method, the water pressure at the boundary decreased in addition to an increase in the total stress. During under water vacuum preloading, any positive pore water pressures above the geo-membrane could be considered a benefit because it acted similarly to surcharge loads in conventional vacuum-surcharge preloading method.

Measured settlement

The variation of surface settlement at different positions monitored by the settlement plates and settlement at different layers measured by the extensometers during under water preloading are shown in Figure 10.

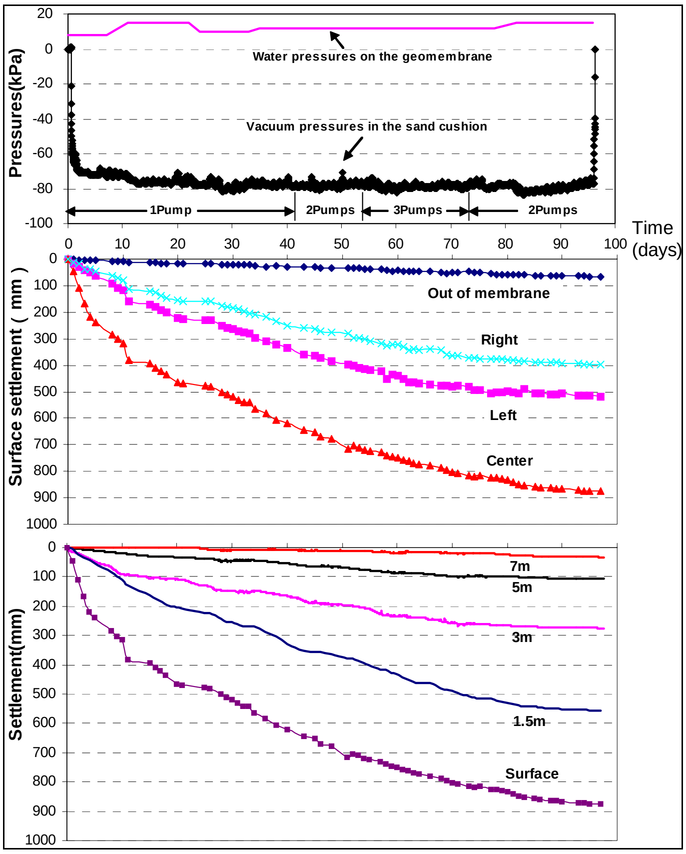

Figure 10. Variation of settlement under vacuum and water loading

The surface settlement increased quickly immediately after applying vacuum loading, then the settlement rate decreased gradually with time. The maximum surface settlement at the center had reached 890 mm, about 13 percent of the total thickness of soft clay, after under water vacuum preloading. Because of the non-uniform distribution of the excess pore pressure in horizontal direction, the surface settlement was obviously non-uniform. After unloading, the surface of the site showed an obvious concave shape. Settlement at various depths obviously occurred after applying the vacuum loads, which indicated that the vacuum preloading was effective for the entire soft layer.

Reduction in water content

The variation of water content monitored by the moisture probes during under water vacuum preloading is shown in Figure 11. Water content at different layers decreased obviously after applying vacuum load within the improved area while it had kept at a constant value outside the geo-membrane. The reduction of water content in the soil became smaller with depth increased.

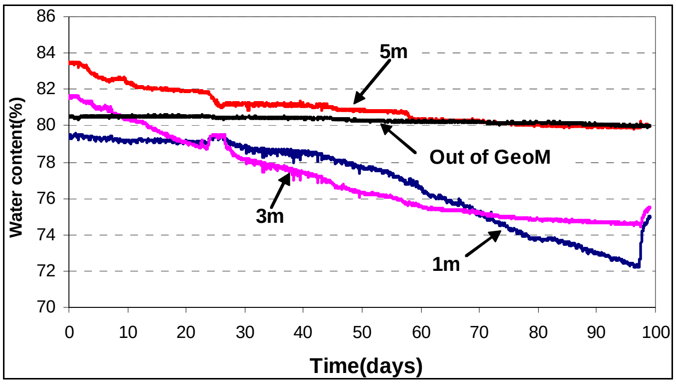

Figure 11. Variation of water content with time

Increase in strength

Vane shear test and cone penetration test were conducted before and after the under water vacuum preloading and the typical results are presented in Figures 12 and 13, which show that substantial improvement in shear strength, lateral friction and cone tip friction were achieved throughout the whole soft layer.

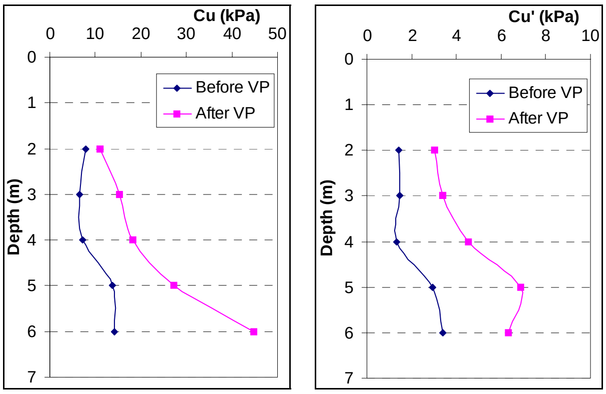

Figure 12. Comparison of vane shear test results before and after the field test

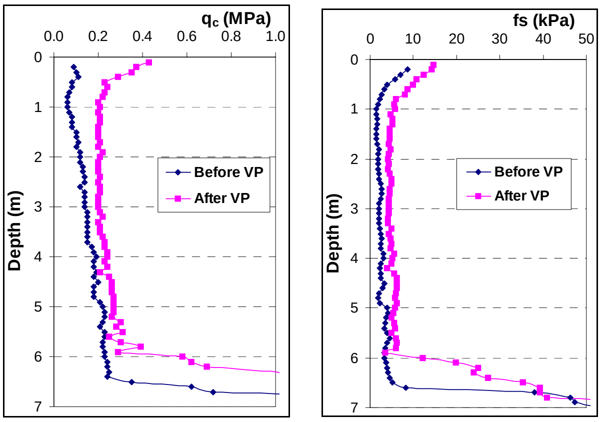

Figure 13. Comparison of CPT results before and after the field test

CONCLUSIONS

A field test study on under water vacuum preloading was reported. This paper focused on the construction method and the observations of the monitored results. Based on the measured readings in the field, computer simulations are being investigated to calibrate the numerical models so that the constitutive behavior of the soft clay can be verified for a better prediction of the consolidation characteristics and settlement for similar works in the future.

Based on the study, the following conclusions can be made:

(1) A custom made geo-membrane was tested in the field. The design and placing of the geo-membrane under water was successful for which it had allowed any trapped air bubbles displaced easily to the atmosphere. The ropes along the edges had allowed easy handling and positioning of the geo-membrane. The steel rods along the edges provided dead weight to the geo-membrane and maintained a good seal between the water and the underlying soft clay layer.

(2) Automatic data collection and wireless data transmission system was used in the field test. The whole system worked well during the test and saved significant among of time in data retrieval.

(3) After applying vacuum load, pore water pressures decreased significantly and linearly with depth. This indicated that the construction of vacuum preloading could be accomplished under water. Pore water pressures within the underlying layer could be decreased further depending on the capacity of the pumps.

(4) During under water vacuum preloading, only negative excess pore water pressures were induced if the water depth was kept at a constant value whereas the water pressures on the geo-membrane could be considered as a surcharge, which is benefit to the consolidation process.

(5) After the field test, the maximum surface settlement represented about 13 percent of soft layer thickness. Non-uniform settlement profile was expected because the horizontal extent of the geo-membrane was not infinite in the test site.

(6) After under water vacuum preloading was carried out, the undrained shear strength of the soil increased significantly, and the water content decreased substantially. It indicated that this method was feasible for the treatment of under water soft soil.

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