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PERFORMANCE OF VACUUM CONSOLIDATION IN A THICK CLAYEY DEPOSIT IN SHANGHAI

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ABSTRACT: A vacuum consolidation test was successfully carried out in a (more than 25 m) thick soft clayey deposit in Shanghai. At the site, there is a clayey silt layer located about 5.3 to 6.8 m depth with a relative higher hydraulic conductivity, and a cement deep mixing formed cut-off wall was able to prevent the vacuum leakage through this layer. Prefabricated vertical drains (PVDs) were installed with a spacing of 1.4 m and triangular pattern to a depth of 14 m. The measured results indicate that the degree of vacuum consolidation reached more than 90% in PVD improved zone for a period of about 38 days. Analysis results indicate that the vacuum pressure induced ground deformations can be calculated reasonably well by a previously proposed method. Further field monitoring results show that one month after stopping the vacuum loading, 10 to 65% of the vacuum pressure induced lateral displacement was rebounded, and the percentage rebounding increased with the depth.

Keywords: Vacuum preloading, soft soil, settlement, lateral deformation, swelling.

INTRODUCTION

The principle of vacuum consolidation was proposed in 1950s (Kjellman, 1952). While the large scale engineering application of the technique had been started only after 1980s, which is mainly due to the development on sealing materials. The method has been widely used in China, Japan, Vietnam, Australia etc. (e.g. Tang et al. 2000; Lou 2002; Indraratna et al. 2009; Saowapakpiboon et al. 2010; Mesri et al. 2012; Chai and Carter, 2011; Chai et al. 2013). The advantages of vacuum preloading are: (1) lower cost; (2) faster application of preloading pressure, and (3) environmenttally friendly.

In China, the technique has been successfully applied in Tianjin (Chu et al. 2000), Guangdong and Zhejiang areas. But it has not been widely adopted in Shanghai area because of lack of experience as well as field verified design methods. Shanghai is located on the delta area of Yangtze River and there is a thick clayey deposit. The clayey soils in Shanghai contain more silt than the soft soils in Tianjin and Guangdong areas, and have water contents of about or less than 50%. However, directly constructing roads or other earth structures on the deposit, large deformation will occur. In the past, preloading was carried out mainly by using surcharge load. To speed up the preloading process and reduce preloading cost, in recent years, several vacuum preloading projects were conducted in newly developed area.

This paper reports the field results of a vacuum preloading test section in a large storage yard in Pudong District, Shanghai. The soil strata and consolidation and deformation properties of the deposit are described first. Then the measured vacuum pressure distribution in the deposit, settlements and lateral displacements during vacuum preloading as well as after release of the vacuum pressure are reported in detail. Finally the effectiveness of vacuum preloading for the thick soft clayey deposit in Shanghai is discussed. It is believed that the case history reported can enrich the literatures of soft ground improvement.

PROJECT DESCRIPTION

Test location and soil profile

The project is located in the west of Tanghuang Road and south of Yingbin Avenue A1, Pudong District, Shanghai. The total project area is about 10 km^2 and planned vacuum preloading area is about 1.7 km^2 for the first stage of the project. The test section described in this article is about 24,000 m^2 (Fig.1). The requirement is to result in more than 0.4 m settlement by vacuum pressure.

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Note: Discussion on this paper is open until June 2014

At the site, there is a silty clay layer about 3.0 m thick at the ground surface followed by a mucky silty clay layer of about 2.3 m thick. Below it is a clayey silt layer of about 1.5 m thick (an inter-layer) and a mucky silty clay layer again with a thickness of about 2.2 m. After that there is a mucky clay layer of about 8.0 m thick and a clay layer of about 7.0 m thick. At this site the soil layers below the clay layer has not been investigated. Information from other site in Shanghai indicates that there is a sand layer around 25 m depth from the ground surface (Ma et al. 2011). Ground water level is about 1.0 m below the ground surface. Some of the physical and mechanical parameters of soil strata are listed in Table 1. The values of ϕ' and c' are assumed based on local experience and OCR values are back calculated.

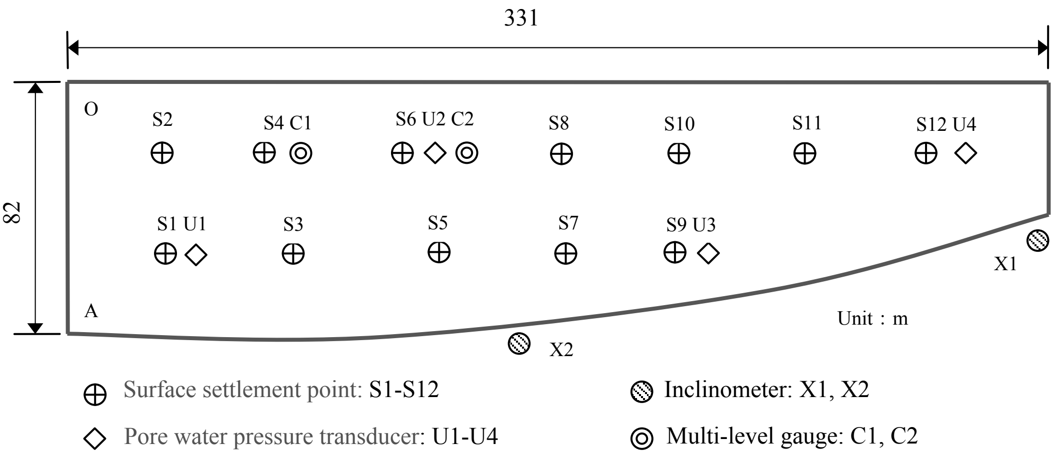


Fig.1 Test area and the arrangement of monitoring points

Table 1 Soil strata and parameters at the test site

No.	Soil	Think-ness(m)	w (%)	γ_t (kN/m^3)	ϕ'	c'	e	c_v (m^2/s)	k_v (m/s)	λ	OCR
1	Silty clay	1.0 2.0	31.4	18.6	31	5	0.888	4.5×10^{-7}	5.1×10^{-8}	0.119	2.2 1.6
2	Mucky silty clay	2.3	40.5	17.4	30	5	1.178	3.7×10^{-7}	3.2×10^{-8}	0.134	1.5
3	Clayey silt	1.5	35.4	18.1	31	5	0.984	6.9×10^{-7}	3.0×10^{-6}	0.134	1.5
4	Mucky silty clay	2.2	40.5	17.4	30	5	1.178	3.7×10^{-7}	3.2×10^{-8}	0.134	1.4
5	Mucky clay	8.0	50.9	16.7	30	5	1.437	1.5×10^{-7}	3.2×10^{-9}	0.186	1.07
6	Clay	7.0	40.9	17.5	30	5	1.168	2.4×10^{-7}	3.2×10^{-8}	0.171	1.0

Note: e is void ratio, γ_t is total unit weight, ϕ' is effective stress friction angle, c' is effective cohesion, c_v is consolidation coefficient in vertical direction, k_v is hydraulic conductivity in the vertical direction, λ is the slope of virgin compression in e-ln(p') plot (p' is consolidation stress), and OCR is overconsolidation ratio.

Field test and monitoring

It is required that the preloading has to be completed in a period of about 3 months, and vacuum preloading was selected. Since the clayey silt layer, 5.3 to 6.8 m from the ground surface has a relative higher hydraulic conductivity (k_v = 3.0×10^{-6} m/s), to prevent vacuum leakage from this soil layer, a cut-off wall around the vacuum preloading area was constructed using cement depth mixing method. Two rows of 0.7 m in diameter columns were overlapped to form a wall of 1.2 m in width, and the wall was installed to 10 m deep from the ground surface (Fig. 2). The other procedures of the field preloading are as follows.

1) Sand mat construction. Medium-coarse sand was placed on the ground surface as a surface drainage layer with a thickness of about 0.5 m. The sand has a silt content less than 5% and hydraulic conductivity higher than 10^{-6} m/s.

2) Installation of PVDs. The PVDs used had a cross-

section of 100 mm by 4.5 mm. The installation depth was 14 m and spacing of 1.4 m in triangular pattern.

3) Installation of monitoring points. Pore water pressure gauges (U1-U4), multi-level settlement gauges (C1 and C2), and inclinometer casings (X1 and X2) were installed as shown in Figs 1 and 2.

4) Installation of drainage and sealing system and surface settlement marks. To enhance the surface drainage system, perforated geosynthetic pipe were laid on the ground surface along the lines of PVDs and again a geotextile layer was placed on the top of them. The diameter of the geosynthetic pipe is 50 mm, and the hole on the pipe has a diameter of 6 mm with a density of 4 holes around a periphery circle and a spacing of 100 mm along the longitudinal direction of the pipe. Then two layers of geomembrane (thickness of 0.14 mm each) were laid out and their edges were embedded into a ditch of about 1.5 m in depth. Surface settlement marks (S1-S12 in Fig. 1) were installed above the geomembrane.

5) Vacuum consolidation and monitoring. Vacuum pressure was applied for 38 days. The termination of vacuum preloading was judged on surface settlement requirement of more than 0.4 m. The ground responses were monitored during and after the vacuum consolidation.

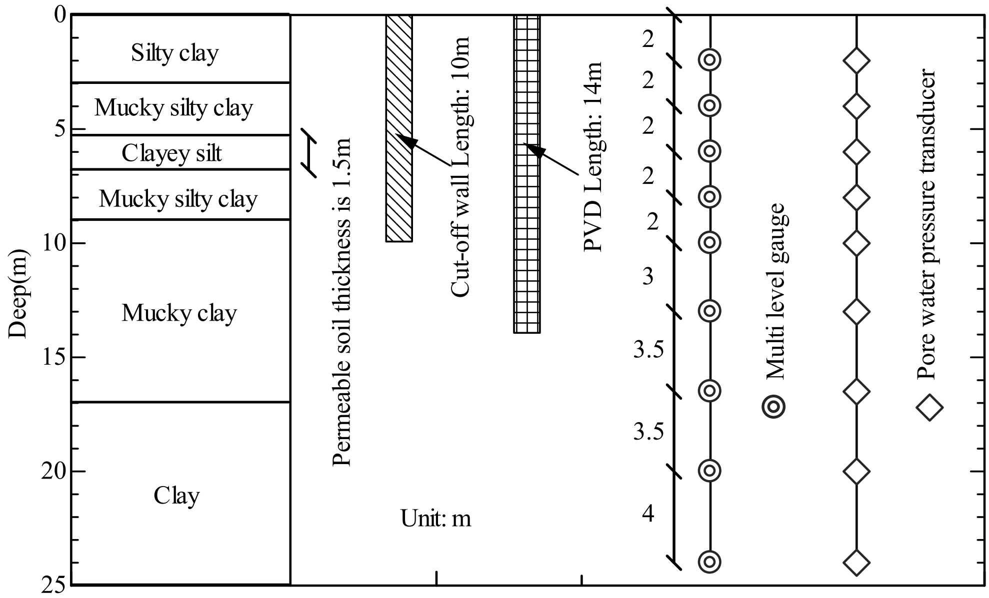


Fig. 2 Soil profile, cross-sectional view of monitoring points, PVD and cut-off wall

MEASUREMENTS AND ANALYSES

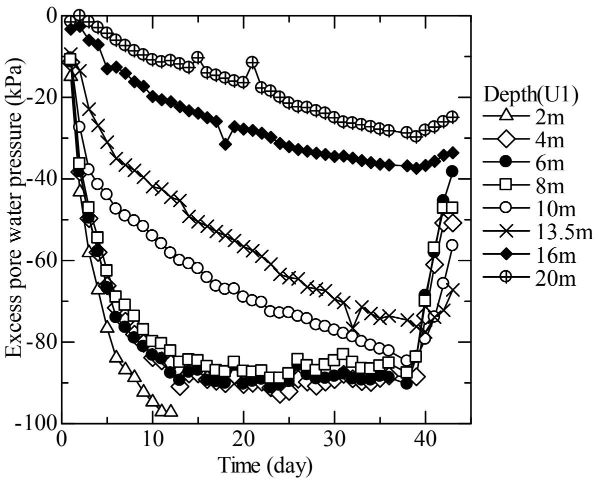
Pore water pressure, settlements and lateral displacements were monitored during the application of vacuum pressure and continued for another week after the release of the vacuum pressure, i.e. to 44th day. For the lateral displacement, one more measurement was carried out one month (69th day) after the release of the vacuum pressure.

Pore water pressures

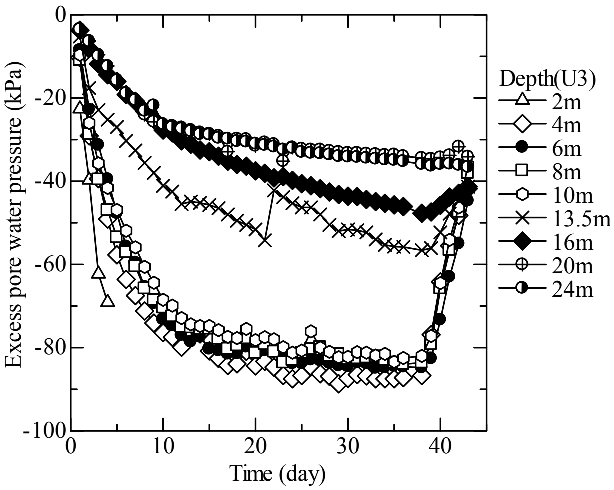
At four (4) pore water pressure monitoring locations (U1 to U4 in Fig. 1), the measured results are similar and only the measured excess pore water pressure (u) at U1 and U3 are presented in Figs 3(a) and (b) respectively. At U1 location, up to 8 m depth, the u values reached the steady value of about 90 kPa about two weeks after commencing the vacuum loading. At 10 m and 13.5 m (close to the end of PVDs) depths, u increased during the whole vacuum preloading period, and at 13.5 m depth, u value is about -75 kPa when the vacuum pump was stopped. At U3, up to 10 m depth, variations of u value show the same tendency with an apparent steady value of about -85 kPa, but at 13.5 m depth, excess pore water pressure is about -55 kPa when the vacuum pump was ceased. At 24 m depth (10 m below the end of PVDs), the measured u value is about -35 kPa (Fig. 3(b)). Another interesting point is that when the vacuum pump was stopped, the vacuum pressures within the PVDs improved zone reduced much faster than that in the zone without PVDs.

Figures 4(a) and (b) show the distributions of excess pore water pressure with depth at U1 and average values of excess pore water pressure from 4 locations (U1 to U4) at the end (38th day) of vacuum loading and one week after (44th day), respectively. From Fig. 4(b), it can be seen that a layer of about 5 m thick from the ground surface (above the clayey silt layer which has a higher hydraulic conductivity), the measured average *u* value is about -85 kPa. Below it *u* is gradually reduced to about -65 kPa at the end of the PVDs. If there is a sand layer below the clay layer at the site, the deposit can be considered as a two-way drainage one (Ma et al. 2011). Then the reduction of measured excess pore water pressure close to the end of the PVDs as well as below the PVDs can be considered due to the effect of the bottom drainage boundary.

From the results in Figs. 3 and 4, it can be observed that the consolidation of the soil layers with PVD improvement and about 10 m depth from the ground surface was almost finished at the time of stopping the vacuum pump. But for soil layers below 10 m depth, the consolidation was still not finished.

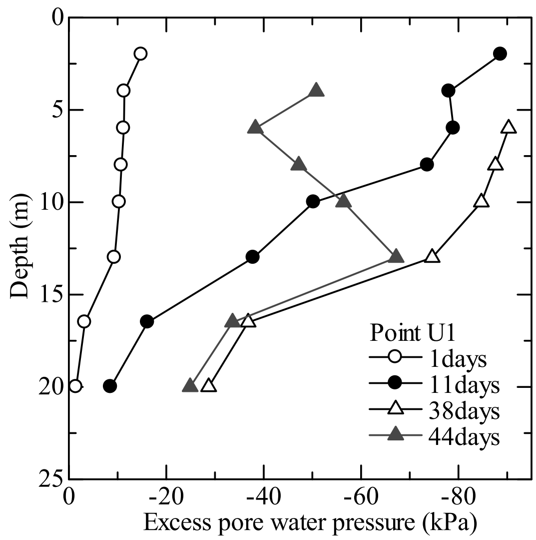


(a) U1

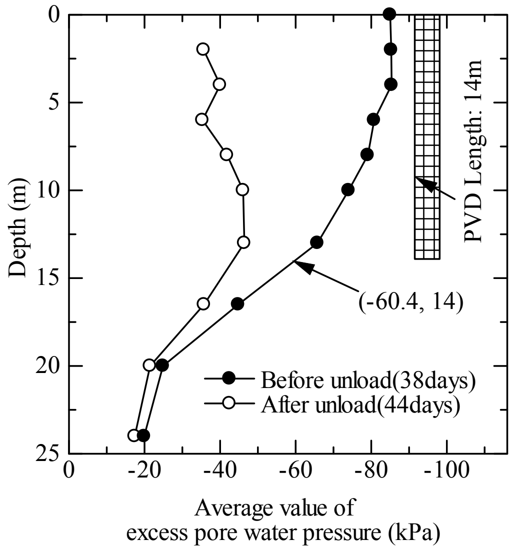


(b) U3

Fig. 3 Excess pore water pressure varied with time at different depth



(a) Pore water pressure transducer U1



(b) Average value of excess pore water pressure at before and after unload

Fig. 4 Distributions of excess pore water pressure with depth

Settlements

Settlements of the ground surface were measured at twelve (12) points (S1-S12 in Fig. 1), and the values corresponding to the end of vacuum consolidation are depicted in Fig. 5. Except S5, all points had settlement larger than the required 0.4 m with an average value of about 0.5 m. The variation of the surface settlements may due to the spatial variation of the soil strata.

The multi-level settlement gauges, C1 and C2, were installed adjacent to the surface settlement point S4 and S6 respectively. The measured curves of settlement versus elapsed time at C1 location are plotted in Fig. 6. From the figure, following two points can be made.

(1) The settlement of soil layers below the PVDs improved zone is about 0.1 m, and it means that the compression of the PVD improved zone is about 0.4 m.

(2) The most compression of the soil layers from the ground surface to about 8.0 m depth was finished at an elapsed time of about 25 days. After that the settlement difference between 2.2 m and 8.1 m depth is almost not changed (Fig. 6). And further settlement was mainly caused by the compression of the soil layers below about 8.0 m depth.

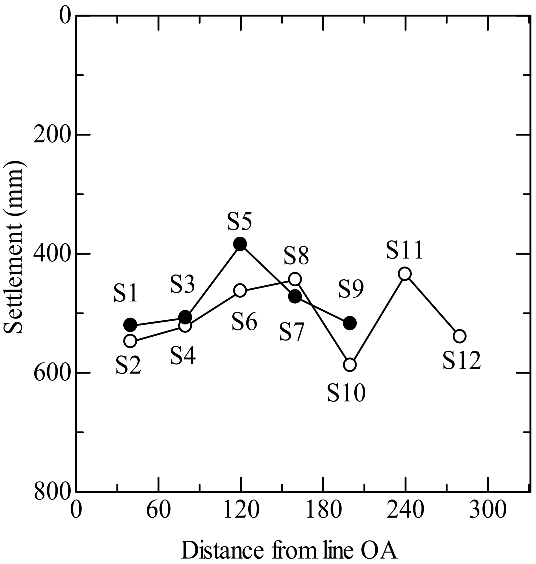


Fig. 5 Settlement at ground surface

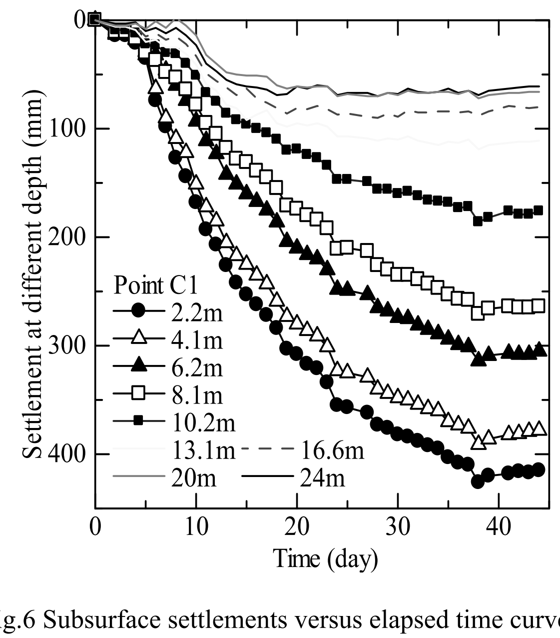


Fig.6 Subsurface settlements versus elapsed time curves at location C1

If assuming a discharge capacity of the PVDs used of 500 m^3/year, hydraulic conductivity ratio of $k_h/k_s = 2$ (k_h and k_s are hydraulic conductivity in the horizontal direction of natural soil deposit and of the smear zone respectively), the diameter of the smear zone, $d_s = 0.3$ m, ratio of the coefficient of consolidation in the horizontal (c_h) and vertical direction (c_v), $c_h/c_v = 2$, then using the condition of the degree of consolidation larger than 90% at 38 days of elapsed time, a ratio of field to laboratory coefficient of consolidation C_f (Chai and Miura, 1999) of about 2.5 can be back evaluated. The mobilized coefficient of consolidation in the horizontal direction will be 1.85×10^{-6}m^2/s (58 m^2/year).

Chai et al. (2005) proposed a method for calculating vacuum consolidation induced ground deformation. With this method, the settlement is calculated as the one-dimensional (1D) settlement multiplied by an equal to or less than unit factor (α). α is a function of initial effective stress in the ground, magnitude of vacuum pressure and active and at-rest earth pressure coefficients. Considering the geometry of the improved area, a plane strain deformation pattern is assumed in the calculation. In Chai et al. (2005)'s method, there is a parameter, β, which is used to calculate earth pressure coefficient under the edge of a vacuum consolidation area. The value of β is less than or equal to 1.0, and in this study, β=0.67 is used. The slope of e-ln(p') (e is void ratio and p' is consolidation pressure) relationship in overconsolidated range, κ, is needed in deformation calculation and it is assumed as $\kappa = 0.1\lambda$. The calculated compressions of each subsoil layer are compared with the measured values at C1 location in Table 2. Although there are discrepancies, generally the calculated values are close to the measured data.

Table 2 Comparison of calculated and measured compressions of subsoil layers

No.	Thickness (m)	Measured (mm)	Calculated (mm)	
1	3	157	149.1	
2	2.3			69
3	1.5	193	157	40
4	2.2			48
5	8	153.4	196	
6	7	85.6	83.7	

Lateral displacement

As shown in Fig. 1, inclinometer casings were installed at X1 and X2 locations. X2 is approximately at the middle of the longer side of the treated area, and the measured results are shown in Fig. 7. It can be seen that inward lateral displacement occurred mostly within the PVD improved zone with a maximum value of about 280 mm at the ground surface.

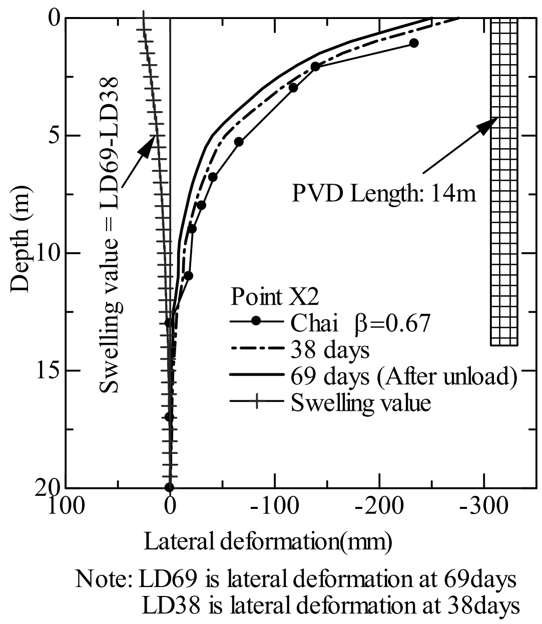


Fig. 7 Lateral displacement profiles at X2 location

In Fig. 7, the calculated lateral displacement profle corresponding to the end of vacuum preloading is included also. It can be seen that the calculated lateral displacement almost matched the measured data.

The results in Table 2 and Fig. 7 indicate that the method proposed by Chai et al. (2005) is useful for calculating vacuum pressure induced ground deformation corresponding to the end of a vacuum consolidation.

Rebounding after release of vacuum pressure

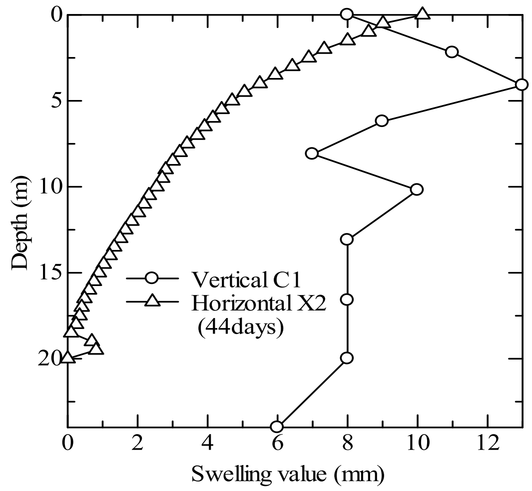
The swelling deformations of the ground 6 days after release the vacuum pressure are shown in Fig. 8.

The vertical rebound at the ground surface is about 10 mm. The measured amount of vertical rebound at 5 m depth is slightly larger than that at the ground surface. The reasons considered are: (1) the amount of horizntal rebound (outwoard lateral displacement) at the ground surface is more than tiwce of that at 5 m depth (Fig. 8(a)), which may reduce certain vertical upheaving, and (2) scartter of the measured data.The surface settlement points were installed above the sealing geomembrane and they could be easily disturbed by human activities.

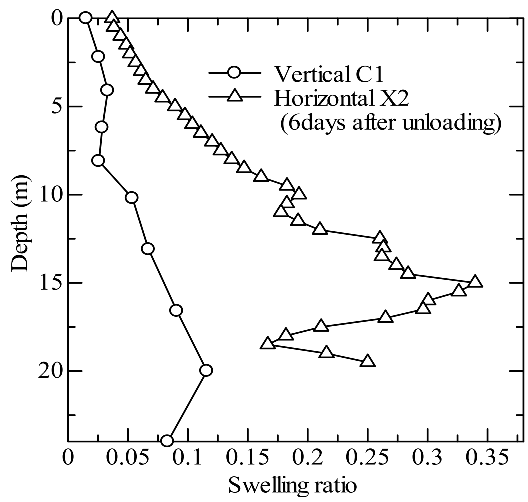
Defining swelling ratio (*SR*) as:

$$SR = \frac{SV}{EV} \tag{1}$$

where *SV* is amount of horizontal or vertical swelling, and *EV* is the corresponding value of deformation at the end of the vacuum loading. Both vertical (C1 location) and horizontal (X2 location) swelling ratios are plotted in Fig. 8(b). It shows that vertical swelling ratios are 2 to 10%, and larger at deeper locations. It may indicate that the deformation of the soil layers below the PVD improvement contains more elastic component (reversible). The lateral displacement has a larger *SR* value with a maximum value of about 35%, and also, *SR* value increased with the depth.



(a) Horizontal and vertical swelling values



(b) Horizontal and vertical swelling ratio

Fig. 8 Horizontal and vertical swelling values 6 days after unload

About one month after the vacuum pump was stopped, the lateral displacement profile was measured. Unfortunitely other monitoring items were not measured. The lateral *SR* values at 44th days and 69th days are compared in Fig. 9. It can be seen that *SR* values of about one month after release the vacuum pressure is about twice of that after 6 days. In the zone below the PVD improvement, the *SR* value is about 60%, i.e. about 60% of the vacuum pressure induced lateral displacment was reversable or elatic deformation.

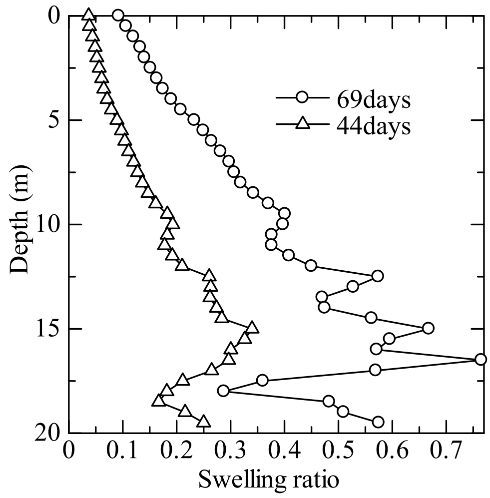


Fig. 9 Swelling ratio of lateral deformation after unload

CONCLUDING REMARKS

A vacuum consolidation test section was sucessfully constructed on a thick soft clayey deposit in Shanghai. There is a clayey silt layer about 5.3 to 6.8 m depth with a relative higher hydraulic conductivity, and a soil-cement cut-off wall was able to prevent the vacuum leakage through this layer. Since the soft clayey soils in Shanghai has a relative higher coefficient of consolidation, for a prefabricated vertical drain (PVD) improved subsoil with a PVD spacing of 1.4 m in triangular pattern and PVDs installed to 14 m depth, the degree of vacuum consolidation can reach more than 90% for a time period of about 38 days.

Analysis results indicate that a vacuum pressure induced ground deformations (settlement and lateral displacement) can be calculated by a previously proposed method reasonably well.

Rebounds of the ground were measured 6 days after the release of the vacuum pressure, and the lateral displacement profile was monitored again about one month after stopping the vacuum loading. Define the amount of rebound divided by the corresponding value of the deformation at the end of the vacuum loading as swelling ratio (*SR*), 6 days after stopping vacuum pump, the vertical *SR* is about 2 to 10% and lateral *SR* is about 4 to 35%. One month after release the vacuum pressure, the lateral *SR* increased to 10 to 65%. *SR* increased with the depth indicates that amoung the vacuum pressure induced ground deformation, the relative elastic component increased with depth.

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