Some Engineering Observations in the Application of Vertical Drains

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ABSTRACT: Vertical paper drains were installed at very soft soil layers to accelerate settlement rate. Several types of monitoring devices were instrumented to measure the changes in settlement and ground pore water pressure. The measured results are consistent with consolidation theory. Also, the standard penetration test N values become higher after soil improvement. For these measurements, the effects of construction sequences on the performance of vertical drains and monitoring devices were described. Six cast-in-place piles were constructed subsequently in the improved soil. The effects of vertical drains on the efficiency of construction and the accuracy of pile diameter were observed.

1 INTRODUCTION

The site of Shihlin incinerator plant, a total area of 10 ha (100,000m^2), is located at the side of Keelung river of northern Taipei. Five meters height fill on the original site were required to meet the design elevation. The geological condition in this area belongs to soft alluvium of lake and river. For the alluvium, the soft clay layer between EL. -14m and -32m is the main compressible layer. It was estimated that at least twelve years is needed for the compressible layer to reach 95% primary consolidation settlement if no ground improvement is made. To reduce the required consolidation time and accelerate settlement rate, vertical paper drain was installed through the compressible layer.

It is known that the vertical drain has been widely used for soft clay layer to accelerate consolidation and this method has been well verified. However, to better understand the application of the vertical drain and accumulate the related design and construction experience, this project instrumented 6 kinds of different monitoring devices to observe the performance of vertical drain.

In this paper, the measured results are compared with theoretical analysis. The design plan, in-situ treatment, and construction sequences are also presented as an example for future design and construction.

2 GEOLOGICAL DESCRIPTION

The subsurface of this site belongs to the river and lake alluvial deposits of the Holocene Epoch. According to the geological exploration and the result of boring tests, the soil profile can be divided into five distinguished strata, as shown in Fig. 1. It can be seen that the soft

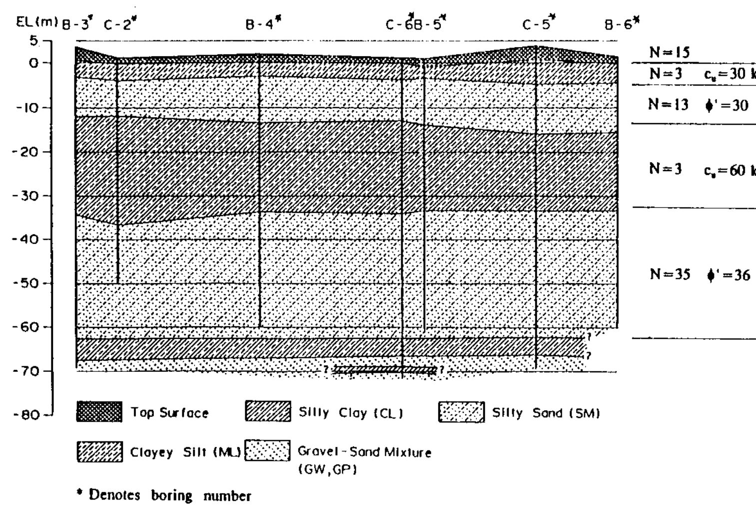

Figure 1 Soil profile of plant site.

clay stratum with 18 m in thickness from EL. -14m to EL. -32m is the main compressible layer of the plant site. The average material properties for this layer are shown in Table 1.

Table 1. Soil parameters for compressible clay layer.

Compression Index, C_c	0.3
Recompression Index, C_r	0.04
Initial Void Ratio, e_o	0.95
Coefficient of Consolidation, c_v (cm^2/s)	0.005
Coefficient of Volumetric Compressibility, m_v (cm^2/kg)	0.025

3 VERTICAL DRAIN AND MONITORING SYSTEM

The vertical drains with a depth of 36m were installed in triangular shape with 1.8m equal spacing. A total length of the vertical drain is about 1,320,000m. The design criteria for the vertical drain are listed in Table 2.

Table 2. The material properties of vertical drain.

Width (mm):	100 ± 10
Thickness (mm):	2 ~ 6 (ASTM D1777)
Tensile Strength (kg):	> 60 (ASTM D1682)
Elongation Rate:	< 70% (ASTM D1682)
Vertical Drainage at 3 kg/cm^2 Soil Pressure (liter/s):	> 0.01
Permeability Coefficient (cm/s)	10^{-4} to 10^{-1}

To examine the settlement behavior, six kinds of monitoring devices are embedded or installed inside and outside the site. The details are as follows: (1) 12 sets of piezometers were installed at different depths to measure the changes in pore water pressure; (2) 5 sets of settlement platforms were buried at ground surface to measure the total settlement; (3) 4 sets of settlement systems with probe extensometer were installed at every specified depth to observe the settlement of every soil layer; (4) 24 settlement observation points were installed around the plant site; (5) 1 perpetual bench mark was chosen; (6) 4 wells were drilled to observe the changes of water table.

These monitoring devices were measured every three days except that settlement observation points was every one week and bench mark was every three months. A total of 18 months was taken to measure these data. Both the plane and profile arrangements for these monitoring devices are shown in Figs. 2 and 3, respectively.

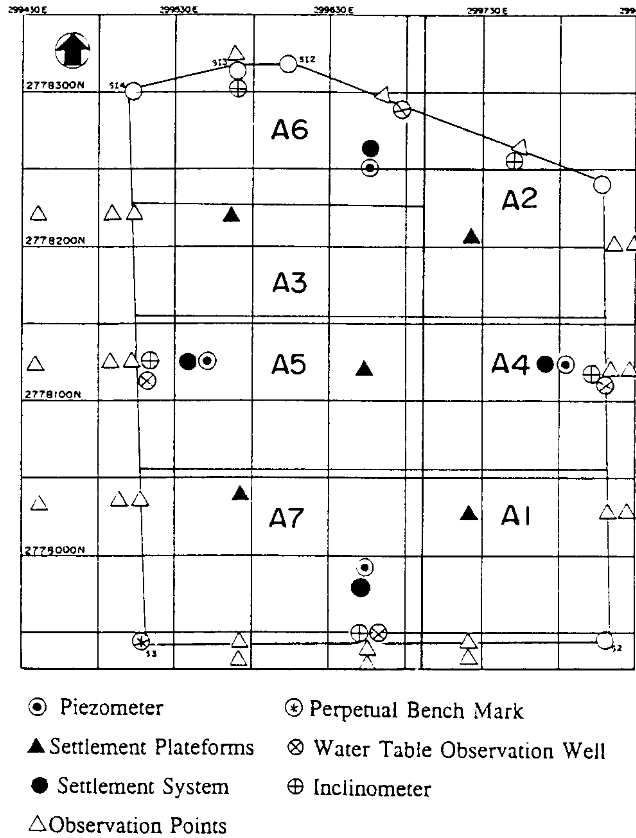

Figure 2 Plane arrangement of monitoring devices.

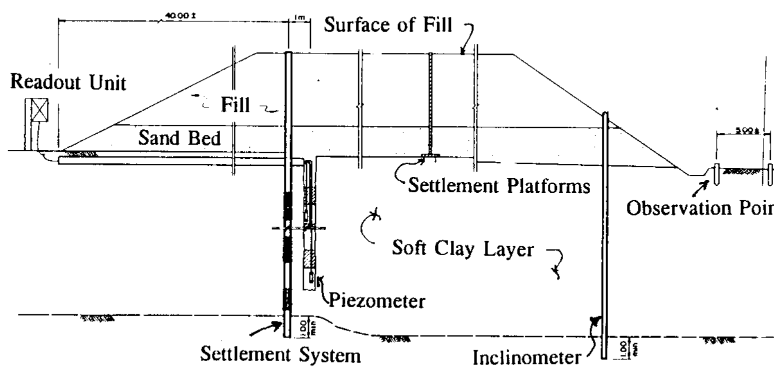

Figure 3 Profile arrangement of monitoring devices.

4 CONSTRUCTION STAGE

For the convenience of construction management, the plant site were divided into seven small areas, as shown in Fig. 2. Areas A1, A2 and A4 belong to pre-stage construction, as Areas A6, A7 and Areas A3, A5 belong to mid-stage and post-stage, respectively. In every area, vertical drain was installed first, then 50cm sand bed and 5m earth fill was followed. Although the separate site construction method is beneficial to the earth fill, the monitoring devices were easily interfered when embankment fill was deposited in other areas.

The vertical drain with ferric anchor and outer casing were drilled into subsurface using hydraulic pressure. After the expected depth was reached, the casing was removed. During the installation of vertical drain, the operation need to be cautious to minimize soil disturbance.

Most of construction works in the first 5 months were to install the vertical drain and place the sand bed, while the earth fill was done in the next 10 months. The earth was filled layer by layer and the thickness of every layer is 30cm. Every layer need to be rolled and compacted. The height of monitoring devices for settlement platform and settlement system need to be extended when the fill height increases, and the soil closed to monitoring device need to be compacted.

After the site was improved, cast-in-place piles were then constructed in the second phase. A suitable cast-in-place pile construction method need to be selected to ensure the accuracy of pile diameter and the efficiency of construction. Instead of reverse circulation drill (RCD) method, rotary drill bucket method was adopted because the vertical drain will affect the revolution of auger for RCD method and resulting in the collapse of soil. Six test piles were drilled using rotary drilling bucket method and the effect of paper drain was rather insignificant for the reason that paper drain was easy to be torn off.

5 ANALYSIS AND EVALUATION OF GROUND BEHAVIOR

As described previously, the loading condition during construction is time dependent because the earth fill was made layer by layer. Olson (1977) proposed a method to include the sand drain with vertical and radial flow which was extended from the one-dimensional vertical flow method by Terzaghi and Frohlich (1936). According to the method proposed by Olson (1977), six months period, as shown in Fig. 4. is required to reach 95% consolidation settlement if the vertical drain is installed with 1.8m in distance and 36m of depth. On the other hand, it was estimated that a twelve-year period is needed to reach 95% consolidation without vertical drain. Clearly, a lot of consolidation time can be saved using vertical drain.

Fig. 5 presents the monitoring results for five 95% settlement platforms. For these curves, Curves SE-1, SE-2 and SE-4 are quite smooth, but SE-3 and SE-5 show some irregular jumps in both curves. By reviewing construction record, the order of construction in SE-1, SE-2 and SE-4 precisely follows the design plan: vertical drains were installed first, then sand bed was placed and embankment fill was deposited.

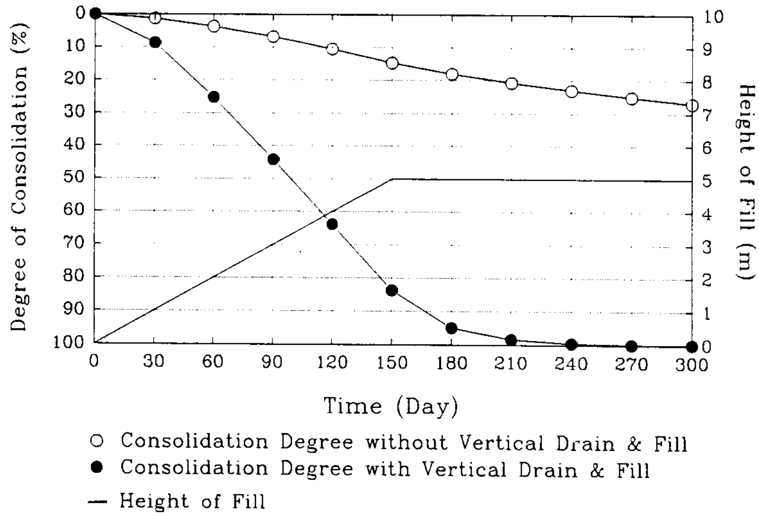

Figure 4 Predicted relation of consolidation degree and time during different fill layers.

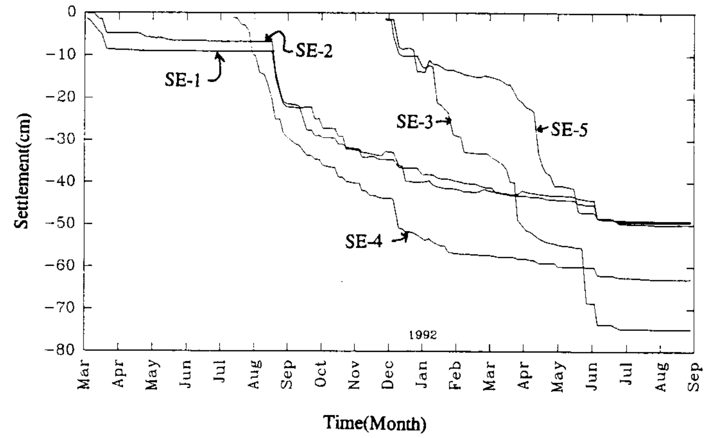

Figure 5 Monitoring results from settlement platform.

However, areas of SE-3 and SE-5 had been temporarily deposited 7～8m height earth materials resulting in instant jump and slow settlement when these earth materials were removed.

For the data of settlement systems, the results can be observed not only the absolute settlement of ground surface but also the relative settlement along the monitoring depth. Therefore, the variation of settlement for various soil layers can be evaluated. Fig. 6 presents the variation of settlement along different depths and soil layers. It can be seen that about 90% of settlement occurred at the depth between -14m and -32m. The results are consistent with original design plan which predicts most settlement would happen at soft clay layer. Curves TE1 through TE4 at shallow depth show unexpected trend. The major reason is attributed to the interference of temporary deposit and the separate site construction method, as noted previously.

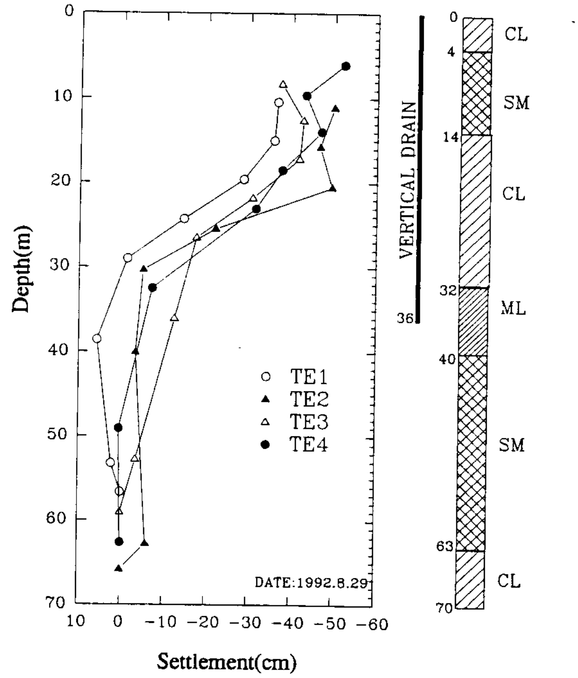

Figure 6 Monitoring results from settlement system.

Table 3 summarizes the unit settlement plotted in Fig. 6. It can be found that clay layer produces the largest unit settlement than those of silt and sand. The difference is significant between clay layer and silt layer, as the difference is small between silt and sand. These results are consistent with analytical result.

Table 3 Comparison of unit settlement for different soil layers.

Stratum	Thickness (m)	Settlement(cm)/Thickness(m)				
		TE1	TE2	TE3	TE4	Avg.
SM(-4m～-14m)	10	0.1	0.4	0.2	0.4	0.28
CL(-14m～-32m)	18	2.1	2.5	1.6	2.3	2.13
ML(-32m～-40m)	8	0.6	0.2	0.6	0.5	0.48
SM(-40m～-63m)	23	0.2	0.1	0.4	0.2	0.23

For the basic consolidation theory (Lambe and Whitman, 1979), the predicted settlement is 44cm for the clay layer with thickness of 18m. Fig. 6 shows the actual settlements are between 28cm and 45cm (mean = 39cm). Although the actual mean settlement is about 10% less than that of prediction one, both are reasonably consistent.

For water pressure, the results from 12 sets of piezometers show that the variation between water pressure and time is quite small. It indicates that the vertical drain can fully and immediately dissipate the excess pore water pressure after embankment.

The main purpose of this project was to improve the soil condition. After soil improvement, the standard penetration test (SPT) N values are between 4 and 8 with an average of 6. The result is superior to the original N value of 3, as noted in Fig. 1. This comparison indicates that an appropriate improvement of soft clay layer was achieved.

6 CONCLUSIONS AND RECOMMENDATION

Vertical drain can be effectively used at compressible layer to reduce the drainage path and accelerate settlement rate, especially for soft clay layer. The measured results are consistent with theoretical prediction. After soil improvement, the SPT N values become higher.

To understand the overall behavior of soil settlement, the settlement platform and settlement system should be used together. Also, the monitoring devices are easily affected by environment and construction sequences. Therefore, these factors need to be considered for the installation of monitoring devices.

The drilling equipment should be deliberately considered when the vertical drain was already installed underground. According to the experience of this project, rotary drill bucket is a suitable construction method because the pile diameter and the efficiency of drilling operation are not significantly affected by the vertical drain.

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