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Instrumentation at Changi land reclamation project, Singapore

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Ground improvement is often required in land reclamation projects on soft soil deposits to reduce future settlement under the projected future dead and live loads. In the case of thick deposits of marine clay, it is often necessary to accelerate the consolidation process of the clay using prefabricated vertical drains. In such projects, the degree of improvement has to be ascertained to confirm whether the soil has achieved the required degree of consolidation before the removal of surcharge. This analysis can be carried out by means of observational methods for which the ground behaviour is continuously monitored from the date of instrument installation. This paper provides a case study of the applications of geotechnical instrumentation for construction control in the Changi East reclamation project in the Republic of Singapore. Field instruments adopted in this project included settlement plates, deep settlement gauges, earth pressure cells, pneumatic piezometers, electric piezometers and water standpipes. Some of the field instruments were installed offshore. Special techniques were adopted to protect these offshore instruments before placement of sand fill by hydraulic pumping. Geotechnical instruments were also used in the construction control process to monitor the deformation of ground and the stability of the earth and retaining structure. Field instrumentation readings obtained from a pilot test area comprising a vertical drain area (horizontal vertical drain spacing 1·5 m × 1·5 m) and an adjacent control area (no vertical drains) are also presented in this paper.

1. INTRODUCTION

In land reclamation projects on soft soil deposits, it is necessary to carry out ground improvement in order to negate future settlement under the projected dead and live loads. The simplest method is to preload the foundation soil with a load equal to or higher than the future load so that the soil can be consolidated and gain the required effective stress. In the case of a thick deposit of marine clay, prefabricated vertical drains are normally used to accelerate the consolidation process. A surcharge equivalent to the working load, after taking into account the submergence effect after the fill has sunk into water, is placed to consolidate the soil until the required degree of consolidation is obtained. Assessment of the degree of consolidation of the marine clay therefore becomes one of the most important tasks for construction control. One of the most suitable methods for assessing the degree of consolidation of soil is by means of field instrumentation. For the Changi East reclamation project, a geotechnical instrumentation programme was implemented that included the installation of settlement plates, deep settlement gauges, piezometers and water standpipes. During the process of consolidation, the instrument monitoring data were analysed by means of Asaoka and hyperbolic methods for settlement gauges to determine the ultimate settlement and degree of consolidation of the underlying soft marine clay due to the embankment load. Piezometer monitoring data were used to determine the excess pore water pressures and degree of consolidation of the marine clay.

2. LAND RECLAMATION AT CHANGI EAST, SINGAPORE

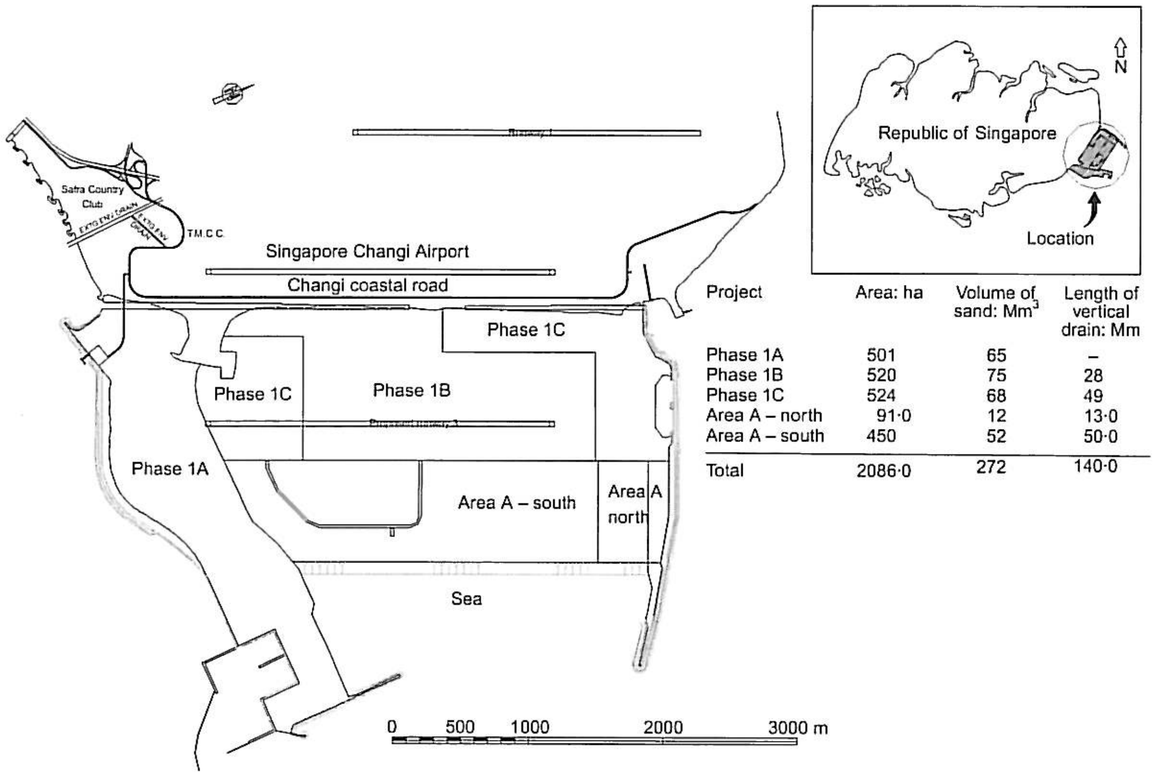
From 1992 to 2004, the Changi East reclamation project in the Republic of Singapore involved the filling of approximately 200 million m^3 of sand for the reclamation of a total land area of about 3000 ha. Land reclamation was carried out using granular fill materials dredged from the seabed at various offshore borrow sources. Figure 1 shows the location and various phases of the Changi East reclamation project in Singapore.

The land reclamation project includes a new airport runway with terminal, taxiways and other airport infrastructure. Prefabricated vertical drains with surcharge were the ground improvement method used along the airport runway, terminal and taxiways. Gradual settlement was accepted at locations where no essential infrastructures were located, and therefore ground improvement was not required at such locations.

This land reclamation project required areas that were currently submerged to be raised to levels permanently above sea level. The fill material chosen was well-graded, free-draining granular soil with a fines contents of less than 10%. When the fill was placed by pumping, some fines in the fill were further removed.

3. OVERVIEW OF GEOTECHNICAL FIELD INSTRUMENTATION USED IN PROJECT

The geotechnical instrumentation adopted in this project provided continuous records of the ground behaviour from the



Project	Area: ha	Volume of sand: Mm^3	Length of vertical drain: Mm
Phase 1A	501	65	–
Phase 1B	520	75	28
Phase 1C	524	68	49
Area A – north	91·0	12	13·0
Area A – south	450	52	50·0
Total	2086·0	272	140·0

Figure 1. Location of Changi East reclamation project in Republic of Singapore

point of instrument installation. By analysing the instrument monitoring results, the degree of consolidation of the foundation soil at any stage can be assessed.

The field instruments adopted in this project to study the consolidation behaviour of underlying soils were surface settlement plates, deep settlement gauges, multi-level settlement gauges, liquid settlement gauges, pneumatic piezometers, electric piezometers, open-type piezometers, water standpipes, inclinometers, deep reference points and total earth pressure cells. A total of 7246 geotechnical instruments were installed at the Changi East reclamation projects. A detailed breakdown of the instrument numbers and types installed at the project is provided in Table 1. Various geotechnical field instruments were installed in instrumentation clusters to enable the instrument functions to complement each other. All instruments found in the instrument clusters were also extended and protected throughout the surcharge placement operations. In coastal land reclamation projects, instruments were installed either offshore prior to reclamation or onshore after reclamation to the vertical drain installation platform level. In the project,

Soil instruments	Phase 1A	Phase 1B	Phase 1C	Area A north	Area A south	Asean Aerospace	Total
Pneumatic piezometer	26	781	458	122	227	12	1626
Open-type piezometer	9	70	84	29	54		246
Electric piezometer		122	150				272
Settlement plate	125	778	1092	173	707	16	2891
Settlement gauge		72					72
Deep settlement gauge	23	790	450	131	266	12	1672
Multi-level settlement gauge	3	17	11		25		56
Deep reference point		8	10	3	12	1	34
Water standpipe		29	59	14	49	3	154
Inclinometer	25	52	47	23	24	3	174
Inclinometer with measurement of vertical displacement		9	2				11
Earth pressure cell	3	12	7	5	11		38
Total	214	2740	2370	500	1375	47	7246

Table 1. Total number of instruments installed in Changi East reclamation project

instruments installed offshore were used in several untreated control areas, and those installed onshore were used for treated areas where vertical drains were installed.

Instrument monitoring was carried out at regular intervals so that the degree of improvement could be monitored and assessed throughout the period of the soil improvement works for the project. Instruments were monitored at close intervals of up to three times a week during sandfilling and surcharge placement operations.

3.1. Offshore field instrumentation

Offshore instrumentation was carried out prior to commencement of the reclamation works. Offshore platforms measuring 6 m by 6 m were installed at selected strategic locations at 30 m offset from the proposed soil improvement areas. As the vertical drain areas were to be only 30 m away, this instrument platforms would act as a control area to enable this untreated area to be compared with the adjacent vertical drain treated areas.

The instrument platforms were installed by driving steel H-piles into the seabed. Following the driving of the H-piles, the platform and scaffoldings were installed. Instruments installed from the platform level were seabed settlement plates, deep settlement gauges, pneumatic piezometers, vibrating-wire electric piezometers, water standpipes and inclinometers. The instruments were installed at various elevations so as to study the deformation of the soil at the various sublayers. The instruments installed at the protection platform could therefore provide complete information on the soil behaviour throughout the entire reclamation fill and surcharge loading history of the marine clay.

Total settlement of the seabed was measured with the seabed settlement plate, and the settlements of the sublayers were obtained from the deep settlement gauges. Excess pore water pressure build-ups and dissipation as a result of sand filling and surcharge placement operations and consolidation of the marine clay could also be registered at the various piezometer elevations. Figure 2 presents a schematic diagram of an offshore field instrumentation platform.

3.2. Onshore field instrumentation

After the hydraulic sandfilling to an elevation of +4 mCD (where mean sea level is at +1·6 mCD), and just prior to installation of the prefabricated vertical drains, instruments were installed in clusters. The instrument clusters were installed throughout the soil improvement areas along the proposed runway, taxiway and linkways. They were installed at locations having typical soil profiles and at locations of variation of the soil profile and characteristics. Types of instrument installed in the onshore instrument clusters are surface settlement plates, deep settlement gauges, multi-level settlement gauges, pneumatic piezometers, vibrating-wire electric piezometers, water standpipes, earth pressure cells and inclinometers. Data from these instruments can be obtained only just prior to or soon after installation of the prefabricated vertical drains. The information obtained is sufficient to assess the performance of the vertical drains, since a high magnitude of settlement and fast rate of dissipation of pore pressure occurs only after vertical drain installation. Monitoring was carried out regularly up to three times a week till the handing over of these parcels of land.

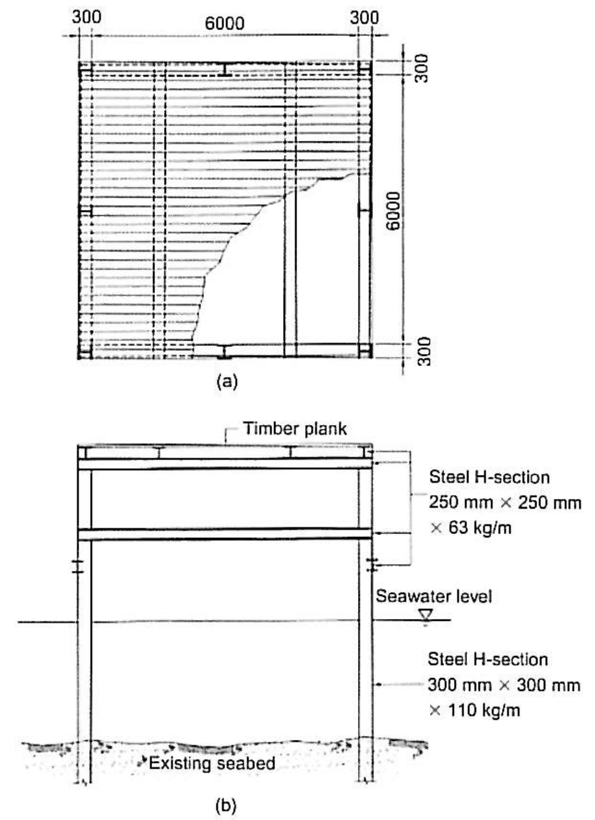


Figure 2. Schematic diagram of an offshore instrumentation platform: (a) plan; (b) section (dimensions in mm)

3.3. Automatic monitoring field instrumentation

After the completion of soil improvement works comprising vertical drains and preloading, systems for automatic monitoring were installed in selected locations. The purpose of installing such systems here was to monitor the deformation behaviour of the treated marine clay automatically in real time from the office. The automatic monitoring instruments are connected to an automatic data acquisition system powered by battery and solar panels. This operating system allowed for continuous logging, control and storage of all measurements taken from the site under all weather conditions.[1,2]

4. ASSESSMENT OF GEOTECHNICAL INSTRUMENTATION DATA

Various types of geotechnical instrument suitable for land reclamation projects and their functions are discussed briefly in this section.

4.1. Settlement gauges

Settlement gauges are utilised to measure the settlement of reclaimed fills and settlement due to ground improvement works. Settlement gauges used in land reclamation projects include seabed settlement plates, surface settlement plates, deep settlement gauges, liquid settlement gauges and multi-level settlement gauges.[3,4] Deep reference points were used as datum for the settlement gauges.

4.2. Piezometers

Piezometers are utilised to measure the pore pressure in the soil. If regular monitoring is carried out to measure the piezometric head together with the static water level, changes of excess pore pressure due to additional load and thus the degree of consolidation can be computed. Piezometers used in land reclamation projects include pneumatic, vibrating-wire and open-type piezometers.[1,3-5]

4.3. Water standpipes

Water standpipes were installed at the sand formation within piezometer clusters to measure the hydrostatic water level at these locations. This enabled evaluation of the excess pore water pressures for the piezometers.

4.4. Inclinometers

Inclinometers consist of a grooved plastic or aluminium casing installed vertically in a borehole socketed to the firm/dense stratum. For installation in marine and offshore conditions, the use of a plastic casing is advisable, as it is not subject to corrosion. Inclinometers were installed in the offshore protection platforms and at the edges of several surcharge fill areas. Inclinometers were monitored daily during the sandfilling and surcharge placement operations to determine and control the rate and magnitude of lateral displacement. At other times, inclinometers were monitored up to three times a week.[1,4,5]

4.5. Deep reference point

The deep reference point is essentially the survey datum reference point to which all elevation measurements of instruments are tied in. It is essential that it is installed in a very dense or hard formation to ensure that it is not subject to any settlement. It is positioned at locations at the site that are far from other permanent survey benchmarks.[1,4,5] The settlement gauges in the instrument clusters were periodically surveyed in from the deep reference points.

4.6. Total pressure cell

Total pressure cells measure the combined effect of effective stress and pore water pressure. With the installation of water standpipes close by, the vertical effective stress of the surcharge load can be computed. Total pressure cells were installed on the vertical drain platform level before surcharge fill was placed, and this enabled the surcharge load to be ascertained.

5. ASSESSMENT OF DEGREE OF CONSOLIDATION

Two simple instruments that can assess the degree of consolidation are settlement plates and piezometers.[1,4,5]

5.1. Settlement gauges

The average degree of consolidation for the soft clay layer can be computed based on settlement as defined by

$$U_s\ (\%) = \frac{S_t}{S_u} \quad (1)$$

where U_s (%) is the average degree of consolidation, S_t is the field settlement at any time t, and S_u is the predicted ultimate settlement.

Using measured field settlements and predicted ultimate settlements, the degree of consolidation can be estimated for each sublayer and also for the entire compressible soil layer or clays treated with vertical drains and preloading by the Asaoka[6] or hyperbolic[7-9] methods.

5.2. Piezometers

The average residual excess pore pressure is defined as the ratio of excess pore pressure at time t to the initial excess pore pressure. Therefore the degree of consolidation for a soil element, U_u, can be defined as

$$U_u\ (\%) = 1 - \frac{U_t}{U_i} \quad (2)$$

where U_t is the excess pore pressure at time t, and U_i is the initial excess pore pressure, which is equal to the additional load. Note that Equation 2 defines the degree of consolidation for a soil element only; this is different from Equation 1, which defines an average degree of consolidation for the complete soft clay layer.

6. PILOT TEST AREA

The Singapore marine clay at Changi is a quaternary deposit that lies within valleys cut in the Old Alluvium. The pilot test area comprises two distinct layers of marine clay: the upper marine clay layer and the lower marine clay layer. An intermediate stiff clay layer separates these two distinct marine clay layers.

The location of the pilot test area was selected after general land reclamation was completed at a location where deep deposits of marine clay were present. The pilot test area was carried out as a test site both to verify the spacing requirements for the vertical drains and to verify the machinery used for installation of the vertical drains. The authors have previously reported on a different trial site with various spacings of vertical drains within the same reclamation project.[4] The spacing of vertical drains reported in the previous work is different from that in the pilot test area considered here, which has a smaller spacing.

The upper marine clay is soft, with undrained shear strength values ranging from 10 to 30 kPa. The intermediate layer is a silty clay layer. The lower marine clay is lightly overconsolidated, with an undrained shear strength[1,4,5] varying from 30 to 50 kPa. It is not homogeneous but occasionally interbedded with sandy clay, peaty clay and sand layers. Below the lower marine clay is a stiff sandy clay layer locally known as Old Alluvium. The coefficient of permeability of the upper marine clay in the vertical direction[1,4,5] is 10^{-9} to 10^{-10} m/s and in the horizontal direction is 10^{-8} to 10^{-9} m/s.

The pilot test area consists of a vertical drain area in which vertical drains were installed at 1·5 m spacing to depths of 35 m, and an adjacent control area where no vertical drains were installed. Both areas were treated with the same height of surcharge preload. Instruments were installed and monitored at both areas. The instruments in the control area were installed prior to reclamation in offshore instrument platforms. These instruments were protected as the reclamation filling works commenced in the area. Figure 3 shows the geological profile

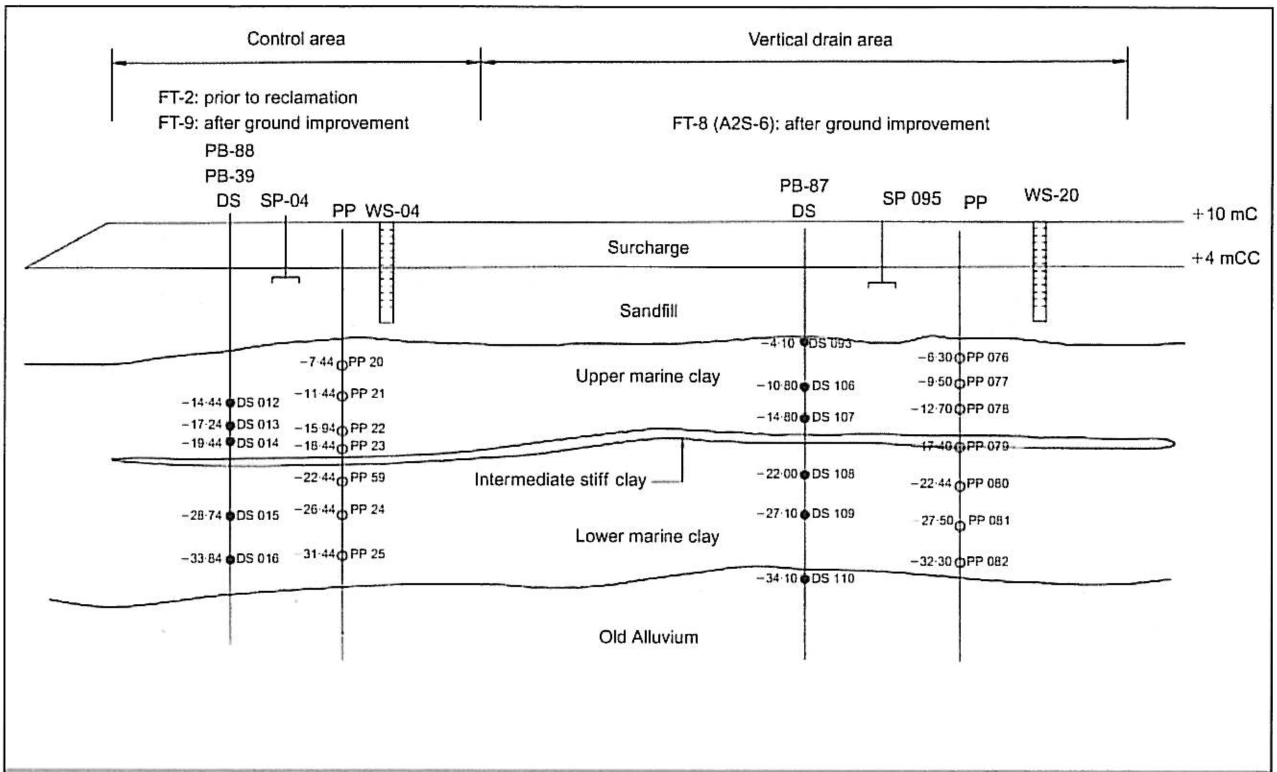


Figure 3. Typical details of onshore and adjacent offshore field instrumentation clusters: SP, settlement plate; DS, deep settlement gauge; PP, pneumatic piezometer; WS, water standpipe

of the case study area[3-5] and typical details of the onshore and adjacent offshore field instrumentation clusters. There were slight differences in the installation depths of the instruments owing to slight variations in soil profile and differences in installation depth due to boring operations.

Instruments in the vertical drain area were installed onshore at the vertical drain platform level of +4 mCD just before or soon after vertical drain installation at 1·5 m square spacing. Surcharge was subsequently placed to +10 mCD. The instrumentation results were analysed out for both the vertical drain area and the control area after a monitoring period of about 26 months, which equates to a surcharging period of 20 months. Figure 4 shows the construction sequence of works at the case study area.

Figures 5 and 6 indicate the magnitudes of settlement in the vertical drain area and the control area. The deep settlement gauges that were installed in the different sublayers indicate decreasing settlement with depth, as would be expected. Also as expected, the vertical drain area indicated much higher settlement readings than the control area. This indicates that the vertical drains are functioning in accordance with their requirements. The settlement plates (SP-95) and deep settlement gauge (DS-93) that were installed at the original seabed level gave similar readings for the magnitude and rate of settlement.

Figures 7–9 show typical Asaoka and hyperbolic plots and interpretations for the settlement plate in the vertical drain area. The Asaoka and hyperbolic methods enable the ultimate

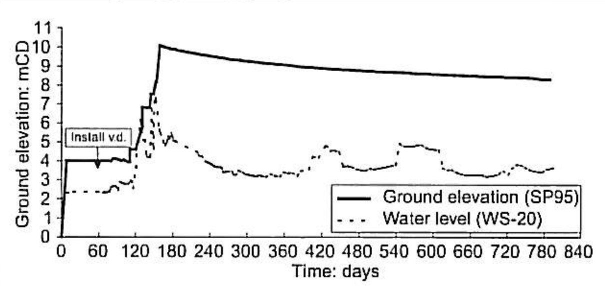


Figure 4. Construction sequence of works at case study area

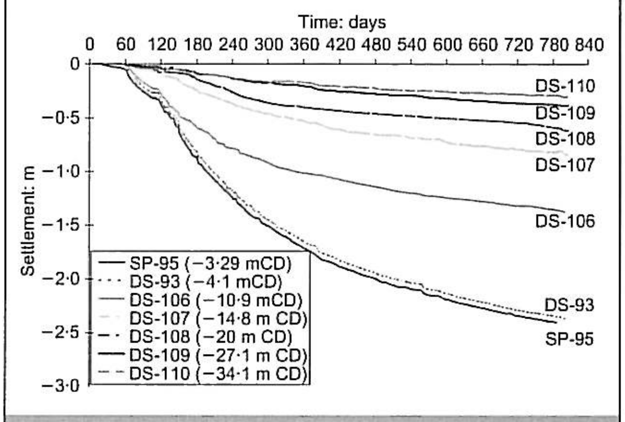


Figure 5. Field settlement results at vertical drain area

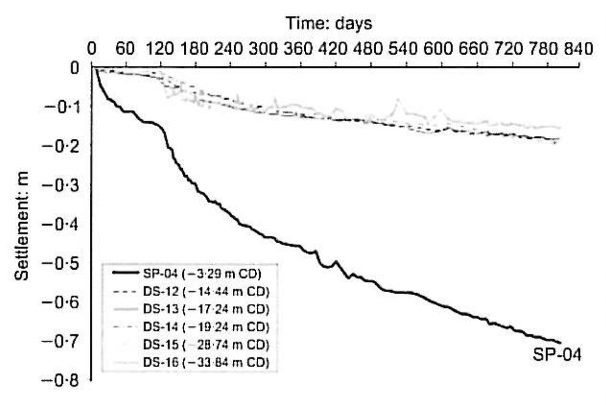


Figure 6. Field settlement results at control area (no drains)

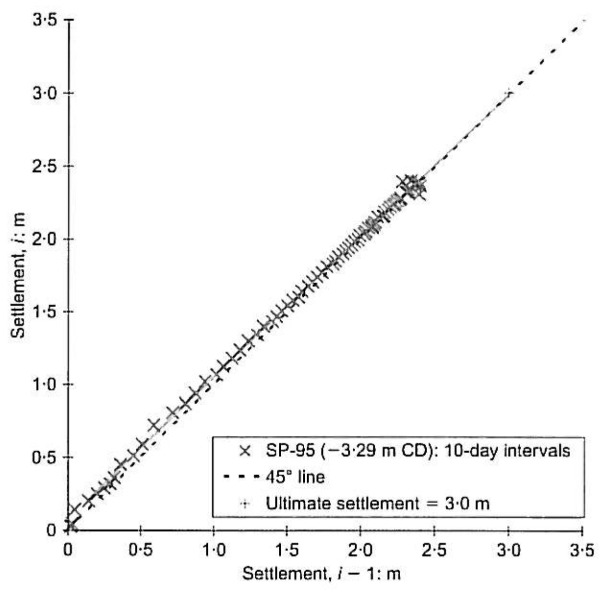


Figure 7. Asaoka plot of settlement plate at vertical drain area

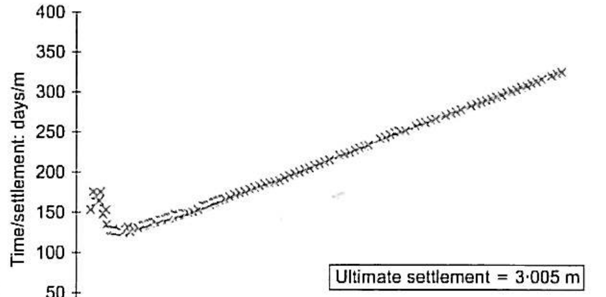


Figure 8. Hyperbolic plot of settlement plate at vertical drain area

settlements of soft soil foundations to be predicted. The Asaoka procedure[6] generates a straight line only if the soil behaviour fulfils the assumptions of Terzaghi's theory of one-dimensional consolidation. The hyperbolic method[7–9] is also useful in tracing the loading history of ground improvement work; changes in the loading sequence will appear as deviations from the hyperbolic line, which can be detected.

Figure 10 compares the settlement plate results from the vertical drain area and the control area. The more rapid improvement of the vertical drain area is clearly evident. Figure 11 compares the field settlement isochrones for various surcharge durations. As expected, the magnitude and rate of settlement of the vertical drain area are much higher than those of the control area.

The piezometer monitoring data in the vertical drain area, including correction of the piezometer tip, are shown in Figure 12. Figure 13 indicates the comparison of excess pore pressure isochrones between the vertical drain area and the control area at various periods after surcharge placement. The rapid dissipation of excess pore water pressure with time is clearly evident in the vertical drain area. The slow rate of dissipation of excess pore water pressure with time at the control area can also be seen. It is evident that the degree of consolidation of the vertical drain area is far greater than that of the control area.

Table 2 compares the degree of consolidation as obtained by the observational methods at the vertical drain area. It is seen that the methods give consistent results. The degree of consolidation of the piezometers is found to tie in well with that of the settlement gauges at the vertical drain area, which is about 80%. The degree of consolidation of the piezometers in the control area as obtained from the isochrones of the piezometers is less than 20%. The analysis of the instrumentation results was carried out after a monitoring period of 26 months, which equates to a surcharging period of 20 months.

Ultimate settlement predictions by the Asaoka and hyperbolic methods are only valid provided a minimum of 60% degree of consolidation has been attained,[1] and therefore the piezometer method more accurately captures the degree of consolidation of the control area.

7. CONCLUSION

The ultimate settlement predicted from the settlement gauges by the hyperbolic and Asaoka prediction methods was found to be about 3 m. The assessment of degree of consolidation is found to be in good agreement for the Asaoka, hyperbolic and piezometer methods. The settlement gauges and piezometers indicate that the vertical drain area had attained a degree of consolidation of about 80%. The piezometers indicate that the control area had attained a degree of consolidation of only about 20%. The instrumentation results in the vertical drain Area indicate a much higher degree of improvements than in the control area, which indicates that the vertical drains are performing to improve the soil drainage system. In addition to the field instrumentation case study, this paper also discusses the methods of land reclamation and field instrumentation.

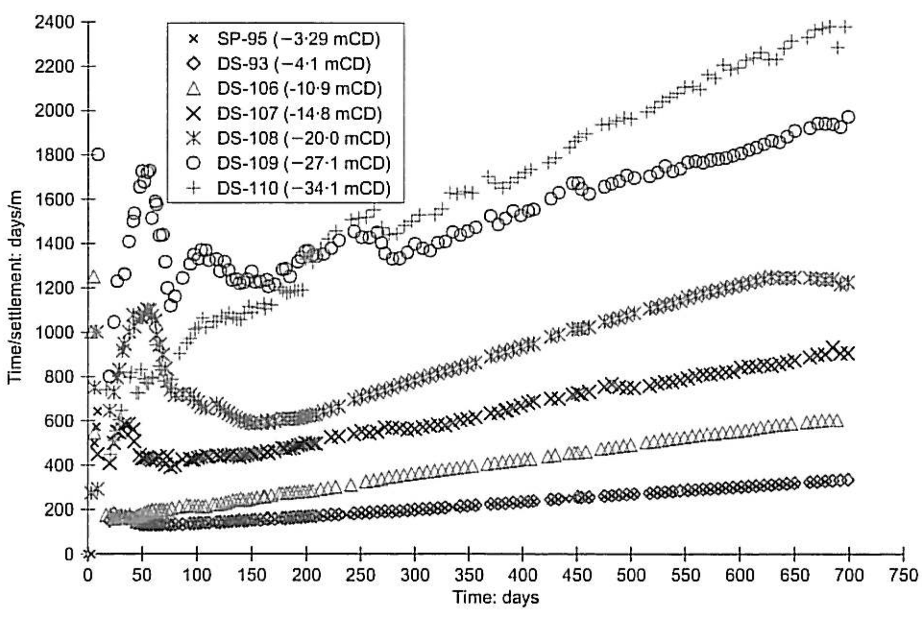


Figure 9. Combined hyperbolic plot at vertical drain area

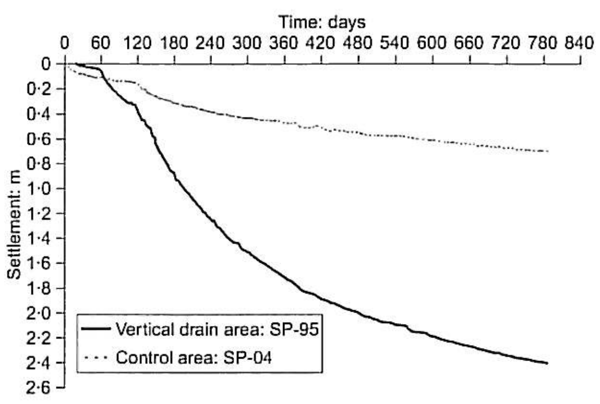


Figure 10. Comparison of field settlement at case study area

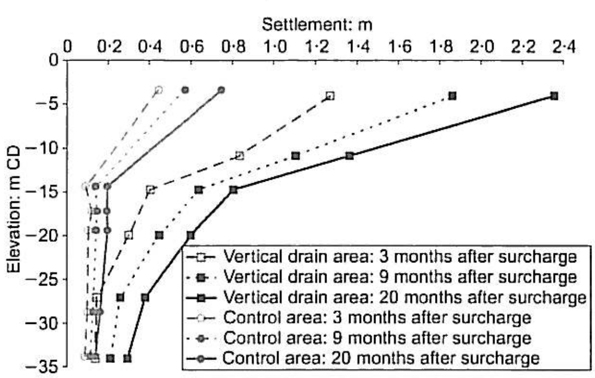


Figure 11. Comparison of field settlement isochrones at case study area

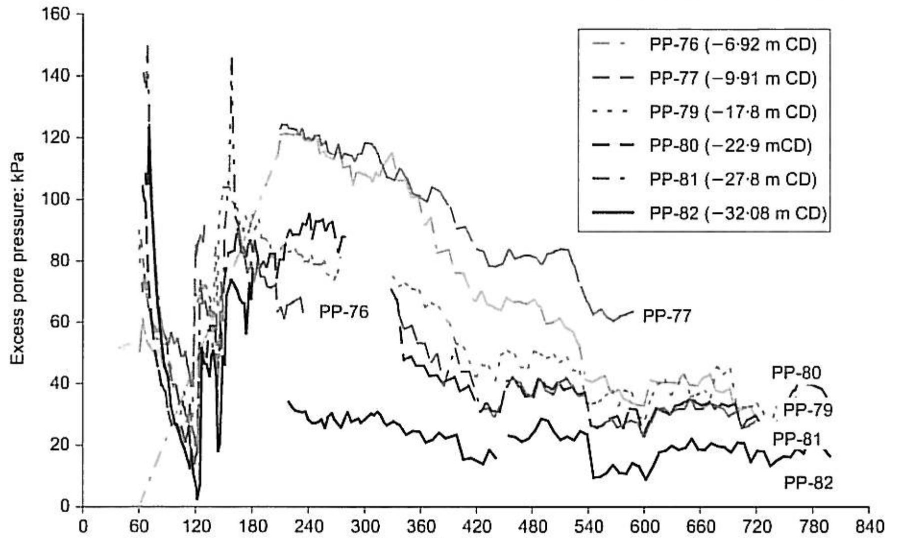


Figure 12. Excess pore water pressures at vertical drain area

Sub-area	Comparison	Asaoka	Hyperbolic	Piezometer
Vertical drains 1·5 m × 1·5 m	Ultimate settlement: m	3·000	3·005	–
	Settlement to date: m	2·404	2·404	–
	Degree of consolidation: %	80·1	80·0	80·0
Control area No drains	Ultimate settlement: m	–	–	–
	Settlement to date: m	0·706	0·706	–
	Degree of consolidation: %	–	–	20·0

Table 2. Degree of consolidation comparisons at pilot test area (20 months after surcharge)

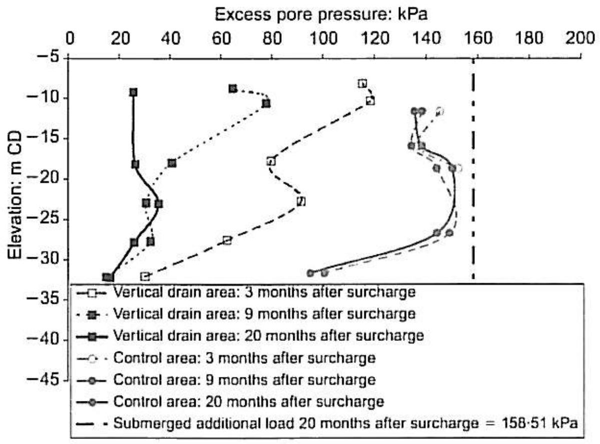


Figure 13. Comparison of piezometer excess pore pressure isochrones

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