FIELD INSTRUMENTATION MONITORING OF LAND RECLAMATION PROJECTS ON MARINE CLAY FORMATIONS

A. Arulrajah[1], M.W. Bo[2] and H. Nikraz[1]
[1]*Department of Civil Engineering, Curtin University of Technology, Perth, W. Australia*
[2]*Bullen Consultants Ltd.,United Kingdom*

ABSTRACT

In land reclamation on marine clay formations, ground improvement works is often necessary to be carried out in order to negate future settlement under the projected dead and live loads. In the case of thick deposits of marine clay, it is necessary to accelerate the consolidation process. The use of prefabricated vertical drains with preloading option is the most widely-used ground improvement method for such cases. In such ground improvement projects in soft soil, the degree of improvement attained by the marine clay has to be ascertained to confirm whether the soil has achieved the required degree of consolidation to enable surcharge removal. This analysis can be carried out by means of observational methods for which continuous records of ground behavior can be monitored from the date of instrument installation. Field instruments are used to verify the performance of the soil improvement works and to ensure that the specified degree of consolidation due to the sandfill and surcharge loading had been achieved prior to the removal of the surcharge. Field instruments installed, monitored and analyzed in such projects include settlement plates, deep settlement gauges, earth pressure cells, pneumatic piezometers, electric piezometers and water-standpipes. The type of field instrumentations installed and their method of analysis is discussed in this paper. Field instrumentation readings obtained at a Case Study Area comprising a Vertical Drain Area (1.5m x 1.5m) and an adjacent Control Area (No Drain) in the land reclamation project is also discussed in this paper.

1 INTRODUCTION

Land reclamation on soft compressible clays for vital facilities requires some form of soil improvement work. The prefabricated vertical drain with preloading method is a popular and well documented method of soil improvement of compressible soils. This method of ground improvement was used in the ongoing Changi East Reclamation Project in the Republic of Singapore. Prior to the removal of the surcharge load, the degree of improvement attained by the foundation soil must be ascertained to confirm whether the design criteria has been achieved. Field instrumentation monitoring is the only means available of providing continuous records of the ground behaviour from the point of instruments installation. Without a proper soil instrumentation method or program, it would be impossible to monitor the current degree of improvement of the soil at any point of time. By analyzing the field instrument monitoring results, it is possible to verify the degree of consolidation of the foundation soil before allowing the removal of the surcharge load.

Prior to the installation of vertical drains in the Changi East Reclamation Project, an instrumentation programme was implemented which included the installation of settlement plates, deep settlement gauges, earth pressure cells, piezometers and water stand-pipes. During the process of consolidation, the settlement gauges monitoring data was analyzed by means of the Asaoka and Hyperbolic methods to determine the ultimate settlement and degree of consolidation of the underlying soft marine clay due to the fill and surcharge load. Piezometer monitoring data was used to determine the dissipation of excess pore water pressures and degree of consolidation of the marine clay.

2 OVERVIEW OF FIELD INSTRUMENTATION

The use of field instrumentation is essential for assessing the degree of consolidation of the marine clay under the reclaimed fill as this assessment is paramount to ascertain when the surcharge can be removed. Field instrumentation monitoring will provide a continuous record of the marine clay behaviour under the fill and surcharge load right from the point of the initial instrument installation. In the Changi East Reclamation project, field instruments were installed either off-shore prior to reclamation or on-land after reclamation to the vertical drain installation platform level. Field instruments were installed in instrumentation clusters to enable the various instruments functions to complement each other. All instruments found in the instrument clusters were extended and protected throughout the surcharge placement operations.

2.1 FIELD INSTRUMENTATION MONITORING

Prior to the removal of the surcharge load, the degree of improvement attained by the foundation soil must be ascertained to confirm whether the design criteria has been achieved. Field instrumentation is the only means available of providing continuous records of the ground behaviour from the point of instruments installation. Without a proper soil instrumentation method or program, it would be impossible to monitor at any point of time the current degree of improvement of the soil. The field instrumentation monitoring data can be analysed to predict the ultimate settlement of the reclaimed land and degree of consolidation of the marine clay under the surcharge fill. Back-analysis of the field settlement and piezometer data will also enable the coefficient of consolidation due to horizontal flow to be closely estimated. Field 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 3 times a week during sandfilling and surcharge placement operations. At other times the instrument was monitored usually at a frequency of once a week.

2.2 OFF-SHORE FIELD INSTRUMENTATION

Off-shore field instrumentation was carried out prior to the commencement of the reclamation works. Off-shore platforms measuring 6 meters by 6 meters were installed at selected strategic locations at 30 meter offset from the proposed soil improvement areas. The purpose for offsetting the platforms from the proposed soil improvement areas is to ensure that the instruments and vertical drain rigs would not be damaged during the vertical drain installation works. The instrument platforms would act as a “Control Area” to enable comparisons to be made of this untreated area with the adjacent vertical drain treated areas.

The instrument platforms were installed by the driving of 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 include seabed settlement plates, deep settlement gauges, pneumatic piezometers, vibrating-wire electric piezometers, water stand-pipes and inclometers. The instruments were installed at various elevations so as to study the behaviour of the soil at the various elevations of each-sublayer. The instruments installed at the protection platform could provide complete information of 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 while the settlement of the various layers were obtained from the deep settlement gauges. The continuous settlement data during the project including the initial sandfilling, surcharge placement and preloading periods of the location was therefore obtained. 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 studied from the piezometers installed at various elevations. Figure 1 presents a schematic diagram and picture of an off-shore field instrumentation platform after intial reclamation works.

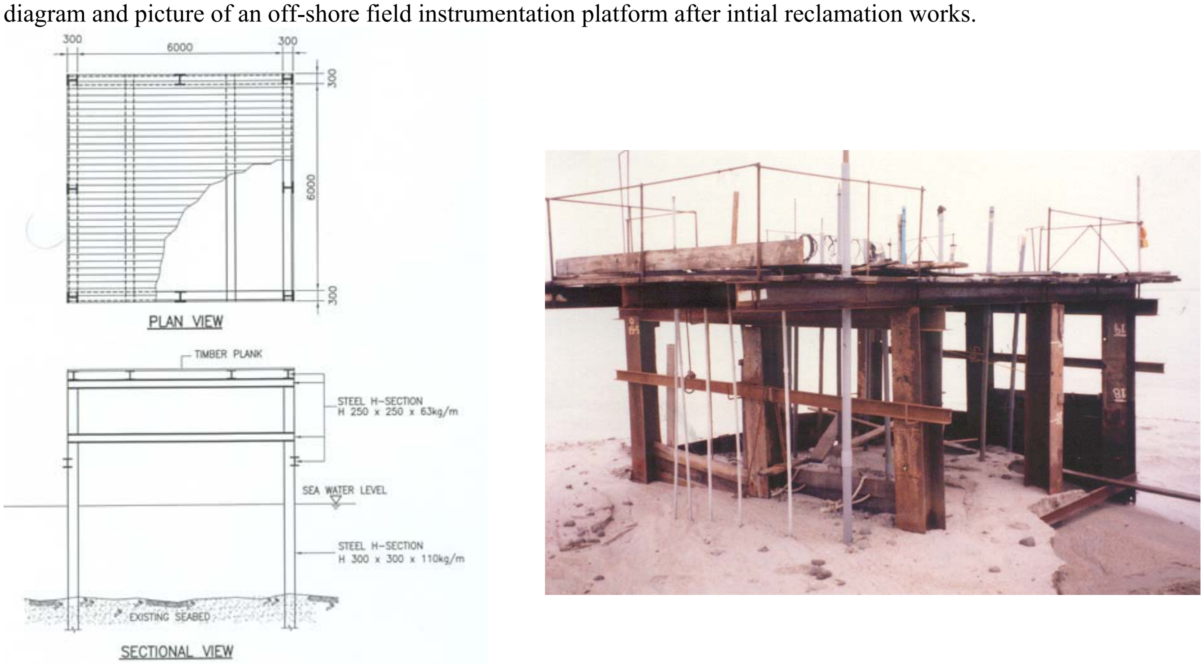
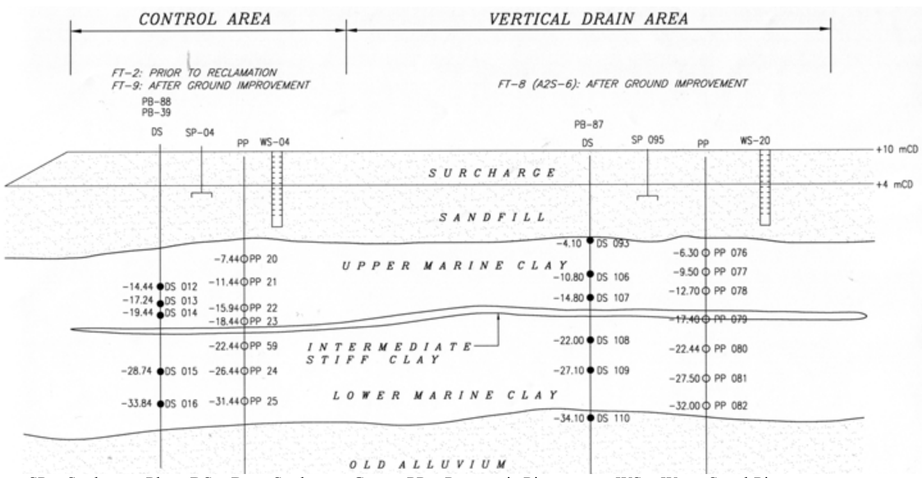


Figure 1: Schematic diagram and picture of an off-shore field instrumentation platform after initial reclamation.

2.3 ON-LAND FIELD INSTRUMENTATION

After the hydraulic sandfilling to an elevation of +4mCD (where Mean Sea Level is at +1.6mCD) and just prior to the installation of the prefabricated vertical drains, field instruments were installed in instrument clusters. Instrument clusters were installed at locations having typical soil profiles and at locations of variation of the soil profile and characteristics. Types of instruments installed at the on-land instrument clusters are surface settlement plates, deep settlement gauges, multi-level settlement gauges, pneumatic piezometers, vibrating-wire electric piezometers, water stand-pipes, earth pressure cells and inclinometers. Information from these instruments could only be obtained just prior to or soon after the installation of the prefabricated vertical drains. The information obtained however, is sufficient to assess the performance of the vertical drain since high magnitude of settlement and fast rate of dissipation of pore pressure occurs only after vertical drain installation. Figure 2 shows the typical details of on-land field instrumentation (Vertical Drain Area:1.5m x 1.5m) and adjacent off-shore field instrumentation (Control Area: No Drain) after land reclamation.



SP = Settlement Plate, DS = Deep Settlement Gauge, PP = Pneumatic Piezometer , WS = Water Stand-Pipe

Figure 2: Typical details of on-land and adjacent off-shore field instrumentation clusters.

2.4 LONG-TERM FIELD INSTRUMENTATION

After the completion of soil improvement works comprising vertical drains and preloading, long-term monitoring instruments were installed in selected locations. The purpose of the instruments here was to monitor the long-term deformation behaviour of the treated marine clay. As the long-term instruments are relatively expensive to monitor using these capabilities, long-term monitoring instruments are recommended to be installed only after the completion of all ground improvement and sand densification works. Instruments used for the long-term field instrumentation works comprises of liquid settlement gauges and electric piezometers which can be installed at various elevations of the marine clay. The long-term instruments are often extended to monitoring huts which are located at a safe location away from the movement of traffic and from the hands of potential vandals. The long-term monitoring instruments are connected to an automatic data acquisition system powered by battery and solar panels. This multi-tasking operating system allows for continuous auto-logging, control and storage of all measurements taken from the site under all weather conditions. Figure 3 shows the typical arrangement of a long-term field instrumentation cluster.

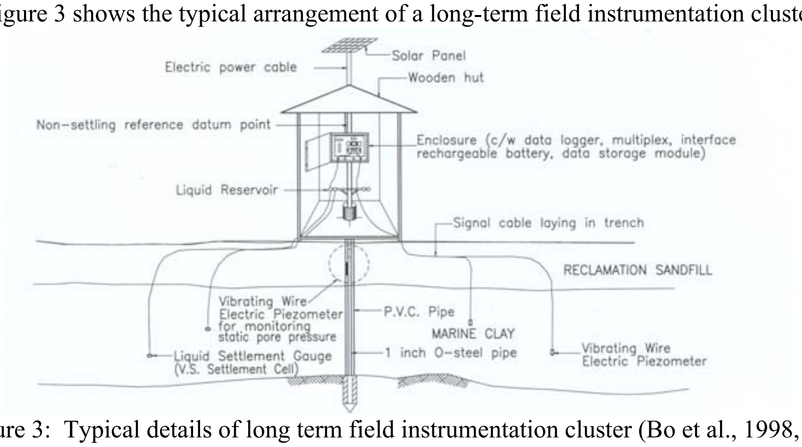


Figure 3: Typical details of long term field instrumentation cluster (Bo et al., 1998, 2003).

3 SETTLEMENT GAUGES

In the Project Site, several types of settlement monitoring instruments were installed to monitor the settlement of the marine clay under the reclaimed fill load. These are settlement plates, deep settlement gauges, multi-level settlement gauges and liquid settlement gauges. The detailing of the settlement gauges has been described by Bo et al. (2003).

3.1 SETTLEMENT PLATES

Settlement plates consist of seabed settlement plates and surface settlement plates. Seabed settlement plates consist of a steel or concrete base plate while surface settlement plates consist of a steel base plate. Settlement plates due to their relative low cost of production and monitoring are the most common instrument used in land reclamation and other ground improvement projects. Seabed settlement plates were placed on the seabed at the off-shore field instrumentation platforms prior to the commencement of land reclamation works. Surface settlement plates were installed after reclamation to the vertical drain platform level of +4 mCD. The surface settlement plates are installed just before or immediately after the installation of vertical drains in order to capture the ground deformations due to the rapid dissipation of excess pore water pressures as soon as vertical drains are installed. The seabed and surface settlement plates are monitored from the time of installation till the point of surcharge removal works. A PVC pipe extension is provided for the settlement plate to eliminate the effect of the settling sand fill gripping onto the rod of the settlement gauges. Measurements of field settlement is carried out by surveying the elevation of the top of the steel pipe. Figure 4 shows the comparison of field settlement between the Vertical Drain Area and adjacent Control Area.

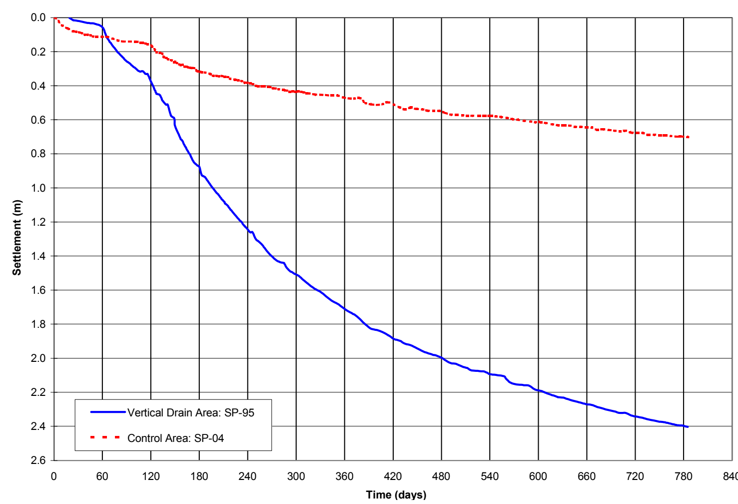


Figure 4: Comparison of field settlement between Vertical Drain Area (1.5 m x 1.5 m) and Control Area (No Drain).

3.2 DEEP SETTLEMENT GAUGES

The deep settlement gauges were installed prior to reclamation from the off-shore protection platforms. Deep settlement gauges were also installed in clusters on-land after reclamation to the vertical drain platform level either before or immediately after the installation of vertical drains. Deep settlement gauges consist of a screw plate at the end of the steel pipe. Each deep settlement gauges is installed in a separate borehole at different elevations of the marine clay sub-layers. Installation at various elevations enables measurement of the magnitude of deformation of these sub-layers. The deep settlement gauge installed at the seabed level of the marine clay will provide the same magnitude and rate of settlement as that of the seabed or surface settlement plate installed at the same location. The deep settlement gauges that were installed in different sublayers indicate decreasing settlement with depth as would be expected. A PVC pipe extension is provided for the deep settlement gauges to eliminate the effect of the downdrag onto the rod of the settlement gauges. Measurements of field settlement is carried out by surveying the elevation of the top of the steel pipe.

Figure 5 indicates the construction sequence of filling and preloading at Vertical Drain Area. Figure 6 and 7 indicate the magnitudes of settlements in the Vertical Drain Area and the adjacent Control Area respectively.

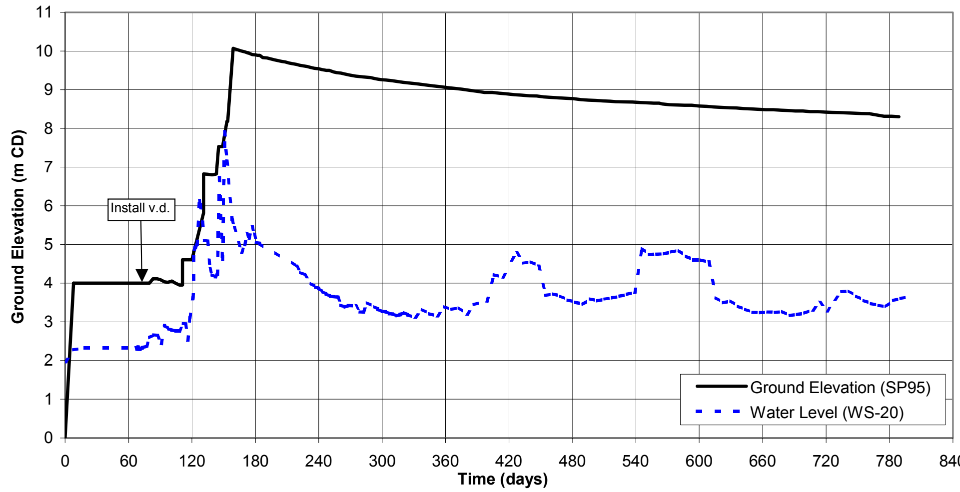


Figure 5: Construction sequence of filling and preloading at Vertical Drain Area

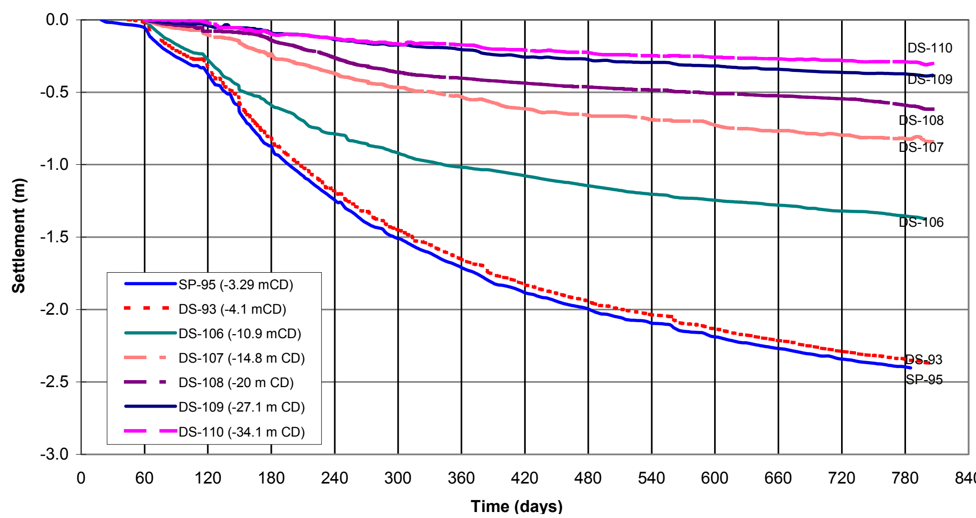


Figure 6: Field settlement results at Vertical Drain Area (1.5m x 1.5m).

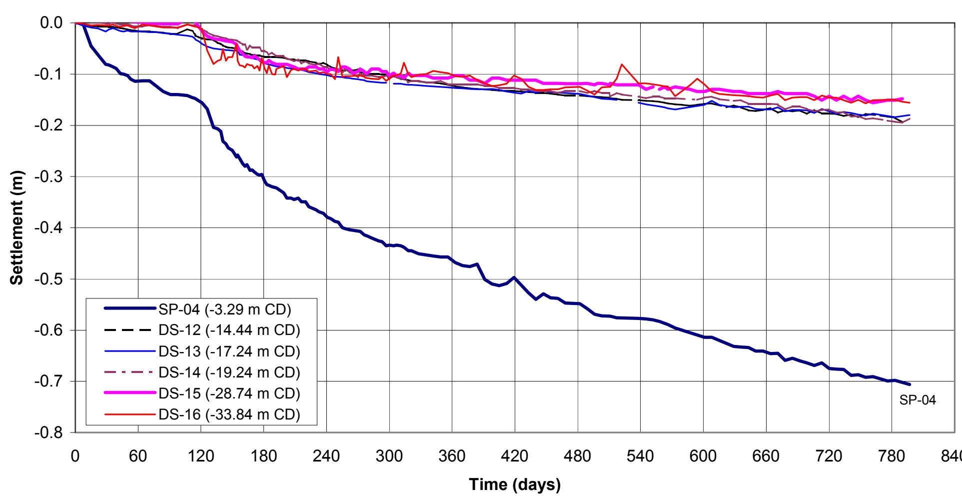


Figure 7: Field settlement results at Control Area (No Drain).

3.3 MULTI-LEVEL SETTLEMENT GAUGES

The multi-level settlement gauges were installed either from the off-shore protection platforms or on-land after reclamation to the vertical drain platform level. The multi-level settlement gauge consists of a series of "spider" metal rings placed at various locations along an access tube with a magnetic datum at the base. At the base of the access tube is a magnetic datum point. The multi-level settlement gauge access tube is installed into a borehole which is drilled to the hard formation. A magnetic beeping probe is used to monitor the settlement of the spiders at the various elevations. In essence, the "spider" rings are supposed to settle together with the soil mass during consolidation settlement. The multi-level settlement gauges indicates far lower magnitudes of settlement as compared to the deep settlement gauges for the same sub-layers (Bo et al., 1998, 2003).

3.4 LIQUID SETTLEMENT GAUGES

The liquid settlement gauge can be monitored automatically and as such was used for long-term instrumentation monitoring. The liquid settlement gauge consists of two liquid-filled tubes attached to a pressure transducer. The liquid-filled tubes serve as a column of water. The pressure transducer measures the pressure exerted by the column of water. The top of tubing serves as a reference datum and is terminated to a reference elevation reservoir typically mounted on a post on stable ground away from the measured area. The bottom of the tubing is connected to a pressure transducer and is placed on the ground for which the settlement is to be monitored. The tube and transducer settle together with the surrounding ground, effectively increasing the height of the column of water and the pressure of the transducer. Settlement is obtained by computing the change in differential elevation between the pressure transducer and the reference reservoir.

3.5 ASSESSMENT OF SETTLEMENT DATA

More realistic assessment of average degree of consolidation as well as degree of consolidation for sub-layers can be carried out by using ultimate primary consolidation settlement predicted from settlement monitoring data. This can be worked out by the Hyperbolic (Tan 1995) and Asaoka methods (Asaoka 1978). Ultimate settlement can be well predicted after getting sufficient field settlement monitoring data. The method of assessment of field settlement plates by the Asaoka and Hyperbolic methods described have also been discussed in detail by the authors (Arulrajah et al., 2003; Bo et al., 2003). Figure 8 shows the Asaoka plot for the settlement plate at the Vertical Drain Area. Figure 9 indicates the hyperbolic plot of the settlement plate at Vertical Drain Area. From measured settlement and predicted ultimate settlement, degree of consolidation can be computed:

$$U\% = S_t / S_{ult} \tag{1}$$

where S_t is settlement at time t, S_{ult} is ultimate primary settlement and U% is the degree of consolidation.

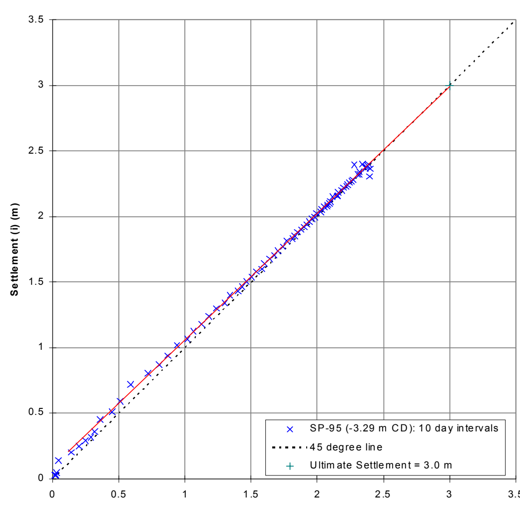


Figure 8: Asaoka Plot of settlement plate at Vertical Drain Area (1.5 m x 1.5 m)

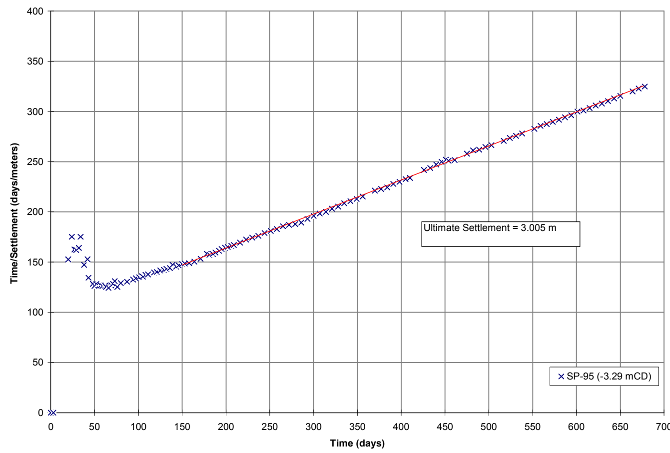


Figure 9: Hyperbolic plot of settlement plate at Vertical Drain Area (1.5 m x 1.5 m).

4 PIEZOMETERS

In the project, three types of piezometers were installed to monitor the dissipation of excess pore pressures of the marine clay under the reclaimed fill load. These are pneumatic piezometers, vibrating-wire electric piezometers and open-type piezometers. The piezometers were installed in individual boreholes at various predetermined elevations in the marine clay. The piezometers were installed in the same instrument clusters as the water stand-pipes and settlement gauges. Installation of piezometers at the same elevations as the deep settlement gauges enabled for the correction of the piezometer tip due to large strain settlements of the marine clay under the reclaimed fill. The detailing of the piezometers used in the project has been described by Bo et al. (2003).

4.1 PNEUMATIC PIEZOMETERS

Pneumatc piezometers were installed in the off-shore protection platforms as well as in the on-land field instrumentation clusters. The pneumatic piezometer consists of a pneumatic transducer which has been permanently installed in a borehole. Tubing runs from the transducer to a terminal on the surface. Readings for pneumatic piezometers are obtained with a pneumatic indicator.

4.2 ELECTRIC PIEZOMETERS

The vibrating wire electric piezometer was installed in the on-land field instrumentation clusters as well as the long-term field instrumentation clusters. The electric piezometer consists of a transducer which converts water pressure to tensional load on a steel strip that is fixed at both ends. When excited by a magnetic coil, the steel strip vibrates at its natural frequency, generating voltage pulses that are transmitted to the readout device. The readout device counts a set number of pulses and computes a natural period, the inverse of the natural frequency. The square of the natural frequency is proportional to the tension in the steel strip and hence, the pressure exerting the load on the strip.

4.3 OPEN-TYPE PIEZOMETERS

Open-type piezometers are installed in sub-layers with permeable sand formations. The purpose of the installation was to determine the drainage condition of the sub-layer at which the piezometer was installed.

4.4 WATER STAND-PIPES

Water stand-pipes were installed at the sand formation within piezometer clusters so as to measure the hydrostatic water level at these locations. This enabled the evaluation of the excess pore water pressures for the piezometers. The water stand-pipe consists of water intake opening slots that are small enough to prevent the ingress of the surrounding soil into the stand-pipe. A geofabric is often wrapped around the slotted portion of the water stand-pipe. A water-level indicator which emits a buzzing sound on contact with water is used to determine the water level.

4.5 ASSESSMENT OF PIEZOMETER MONITORING DATA

Piezometers were often installed in the same clusters as the settlement gauges, close to the same elevation as the settlement gauges to enable for correction of the piezometer tip due to large strain settlement. Water stand-pipes were installed in the clusters so as to measure the static water level at these locations and hence to ascertain the excess pore water pressures of the piezometers. The piezometers indicates measurements for piezometric head. Piezometers are utilized 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 degree of consolidation can be computed. Figure 10 indicates the comparison of excess pore pressure isochrones between the Vertical Drain Area and Control Area at various periods after surcharge placement. Average degree of dissipation is defined as ratio of excess pore pressure at time "t" upon initial excess pore pressure :-

$$U(\%) = 1 - (U_t / U_i) \quad (2)$$

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 ($\Delta\sigma'$).

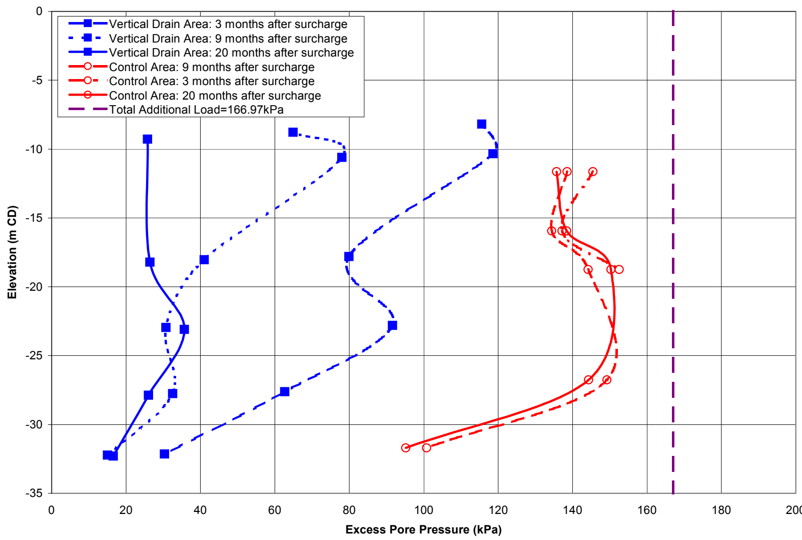


Figure 10: Comparison of piezometer excess pore pressure isochrones between Vertical Drain Area and Control Area.

5 COMPARISON OF PERFORMANCE ASSESSMENT AT CASE STUDY AREA

Table 1 compares the degree of consolidation of the Vertical Drain Area by the various assessment methods. 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 is about 20%. Figure 11 compares the degree of consolidation as obtained from the settlement gauge and piezometer results at the Case Study Area. The rapid dissipation of excess pore water pressure with time is clearly evident in the Vertical Drain Area.

Table 1: Comparison of performance assessment at Case Study Area (20 months after surcharge).

Sub-Area	Comparison	Asaoka	Hyperbolic	Piezometer
Vertical Drain	Ultimate Settlement (m)	3.000	3.005	-
1.5m x 1.5m	Settlement to date (m)	2.404	2.404	-
	Degree of Consolidation (%)	80.1	80.0	80.0
Control	Ultimate Settlement (m)	-	-	-
No Drain	Settlement to date (m)	0.706	0.706	-
	Degree of Consolidation (%)	-	-	20.0

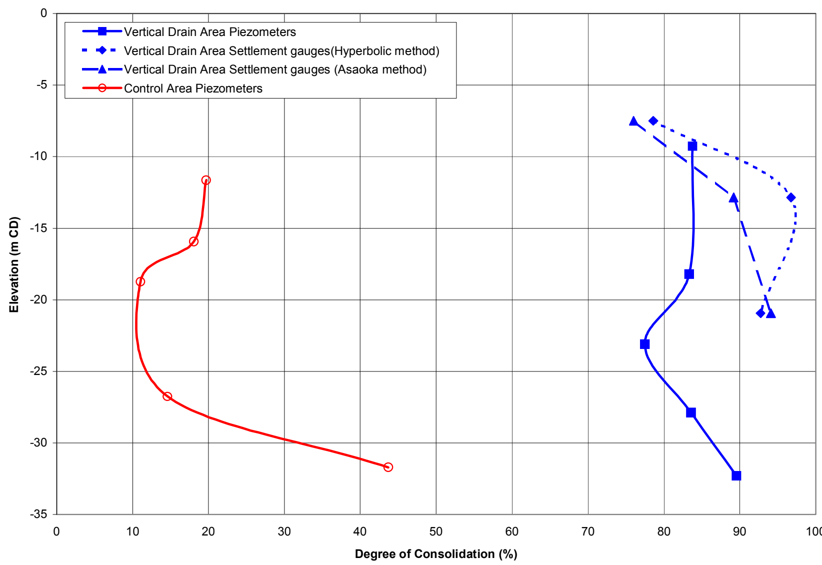


Figure 11: Comparison of degree of consolidation at Case Study Area (20 months after surcharge).

6 INCLINOMETER

Inclinometers installed in marine and nearshore conditions consist of a grooved plastic casing installed vertically in a borehole. Since the inclinometer is measuring relative movement rather than absolute movement, its toe has to be anchored in the dense/hard stratum to ensure that there is no settlement at this non-lateral displacement formation. Figure 12 compares the lateral deflection monitored in inclinometers anchored at SPT of 50 and 100 blows respectively.

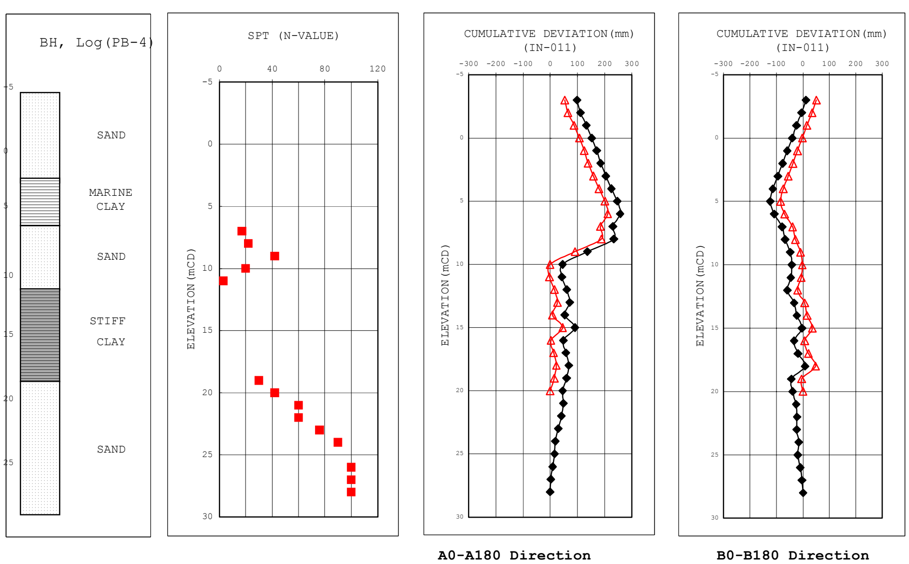


Figure 12: Lateral displacement between inclinometers anchored at SPT 50 and 100 blows (after Bo et al., 2003).

7 DEEP REFERENCE POINT

The deep reference point is essentially the survey datum reference point to which all elevation measurements of instruments are tied in too. It is essential as such that the deep reference point is installed in a very dense/hard formation of SPT N-values of 5 consecutive 100 blow counts to ensure that it is not subject to any settlements. The deep reference point is positioned at locations at the site which are far from other permanent survey benchmarks. Details of the deep reference point has ben discussed by Bo et al. (1998, 2003).

8 TOTAL PRESSURE CELL

Total pressure cells measures the combined pressure of effective stress and pore-water pressure. With the installation of water stand-pipes close by, the vertical effective stress of the surcharge load can be computed. Total pressure cells were installed in a trench 0.5 to 0.6 meters deep, at the vertical drain platform level (elevation of +4 mCD) just prior to the placement of the surcharge load. Total pressure cells should be installed with their sensitive side facing upward in order to measure correctly the surcharge load. Figure 13 highlights the comparative plot of earth pressure between total pressure cells installed with sensitive side facing up and down for a 6 meter height of surcharge.

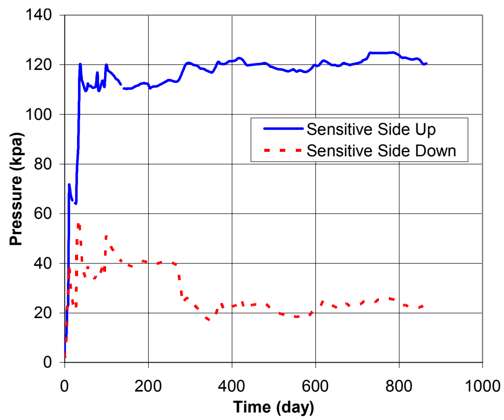


Figure 13: Comparison of earth pressure cells placed with sensitive side up and down (after Bo et al., 2003).

9 CONCLUSION AND RECOMMENDATIONS

In the implemetation of land reclamation projects with ground improvement works, a systematic field instrumentation monitoring programme is essential. The settlement gauges and piezometers are the two instruments deemed necessary for assessing the degree of consolidation of soft clay. Inclinometers are useful for control of the rate of filling. Total pressure cells are useful to verify the imposed load due to the fill and surcharge. Liquid settlement gauges and electric vibrating-wire piezometers are useful where remote monitoring and automatic recording is necessary.

In the Case Study area, the ultimate settlement predicted from the settlement gauges by the Hyperbolic and Asaoka prediction methods was found to be about 3 meters. The assessment of degree of consolidation is found to be very close for the Asaoka and Hyperbolic methods. The settlement gauges and piezometers indicate that the degree of consolidation of the Vertical Drain Area had attained a degree of consolidation of more than 80%. As expected, the instrumentation results in the Vertical Drain Area indicates much higher degree of improvements as compared to the Control Area which only had attained a degree of consolidation of less than 20%. Vertical drains installed in the project as such are performing to improve the soil drainage system.

10 REFERENCES

Arulrajah, A., Nikraz, H. and Bo, M.W. (2003). Factors Affecting Field Settlement Assessment and Back-Analysis by the Asaoka and Hyperbolic Method, *Australian Geomechanics Journal*, Vol. **38**, No. 2, June, pp. 29-37.

Asaoka. A. (1978). Observational Procedure of Settlement Prediction. *Soil and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering* Vol. 18, No. 4, Dec., 1978, (P 87-101)

Bo, M.W., Arulrajah, A. and Choa, V. (1998). Instrumentation and Monitoring of Soil Improvement Work in Land Reclamation Projects; *8th International Congress of the International Association for Engineering Geology and the Environment*, Vancouver, Canada.

Bo, M.W., Chu, J, Low, B. K. and Choa, V. (2003) S*oil Improvement–Prefabricated Vertical Drain Techniques*, Thomson Learning, Singapore 068808.

Dunnicliff, J. (1988). *Geotechnical Instrumentation for Monitoring Field Performance.* John Wiley & Sons.

Hanna, T.H. (1985). *Field Instrumentation in Geotechnical Engineering*, Trans Tech Publications, 1st Edition.

Tan, Siew-Ann (1995). Validation of Hyperbolic Method for Settlement in Clays with Vertical Drains. *Soil and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering* Vol. 35, No. 1, March, pp. 101-113.