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Geotechnical instrumentation monitoring of land reclamation projects on soft soil foundations

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ABSTRACT

In land reclamation on soft soil formations, ground improvement works are 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 a 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. This paper provides a comparison of the assessment of degree of consolidation by various methods at a case study area at the Changi East Reclamation project in the Republic of Singapore.

1 INTRODUCTION

Land reclamation on soft compressible clays for vital facilities requires some form of ground improvement work. The prefabricated vertical drain with preloading method is a popular and well accepted method of soil improvement for compressible soils. This method of ground improvement was used in the 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 soils 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 determine the current degree of improvement of the soil at any point of time. By analyzing and interpreting 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. During the process of consolidation, the settlement gauges monitoring data were analyzed by applying 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 were used to determine the dissipation of excess pore water pressures and degree of consolidation of the marine clay.

Field instruments suitable for the study of marine clay behavior and monitoring of land reclamation works comprise of 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 pressure cells.

2 OVERVIEW OF FIELD INSTRUMENTATION

Various field instruments were installed in instrumentation clusters to enable the instruments functions to complement each other. 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. Instrumentation monitoring will provide a continuous record of the soft soil behaviour under the fill and surcharge load from the point of the initial instrument installation. In coastal land reclamation projects, instruments are installed either off-shore prior to reclamation or on-land after reclamation to the vertical drain installation platform level.

3 CASE STUDY AREA

Singapore marine clay at Changi is a quaternary deposit that lies within valleys cut in the Old Alluvium. The Case Study Area comprises of two distinct layers of marine clay which are the "Upper Marine Clay layer" and the "Lower Marine Clay layer". The "Intermediate Stiff Clay Layer" separates these two distinct marine clay layers. The upper marine clay is soft with undrained shear strength values ranging from 10 to 30 kPa. Marine or organic matter is found in the upper marine clay. The intermediate layer is a silty clay layer. The lower marine clay is lightly overconsolidated with an undrained shear strength 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 characteristics of the marine clay found at Changi, Singapore has been discussed previously by Bo et al. (1997, 1998).

The Case Study Area consists of a Vertical Drain Area at which vertical drains were installed at 1.5 meters square spacing to depths of 35 meters, as well as an adjacent Control Area where no vertical drains were installed. This enabled comparisons to be made between an area treated with vertical drains with an untreated area. Both the areas were loaded with the same height of surcharge preload. Instruments were installed and monitored at both the Vertical Drain Area and the Control Area. The instruments in the Control Area were installed prior to reclamation in off-shore instrument platforms. These instruments were protected as the reclamation filling works commenced in the area. Instruments in the Vertical Drain Area were installed on-land at the vertical drain platform level of +4 mCD (Admiralty Chart Datum, where mean sea level is +1.6 mCD) just before or soon after vertical drain installation at 1.5 meter square spacing. Surcharge was subsequently placed to +10 mCD. The analysis of the instrumentation results was carried out for both the Vertical Drain Area and Control Area after a monitoring period of about 26 months which equates to a surcharging period of 20 months. Figure 1 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.

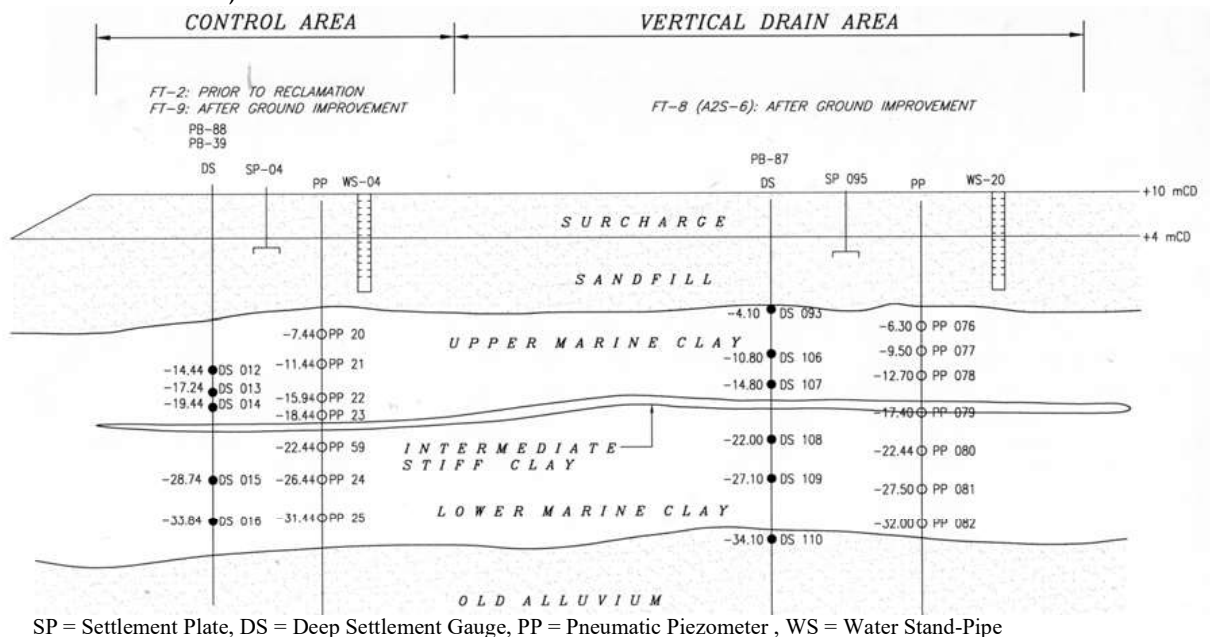


Figure 1: Typical details of on-land and adjacent off-shore field instrumentation clusters.

4 SETTLEMENT GAUGES

Figure 2 shows the construction sequence of works at the Case Study Area. Figures 3 and 4 indicate the magnitudes of settlements in the Vertical Drain Area and the Control Area.

The deep settlement gauges that were installed in the different sub-layers indicate decreasing settlement with depth as would be expected. As expected, the Vertical Drain Area indicated much higher settlement magnitudes as compared to the Control Area. This indicates that the vertical drains are functioning as expected. Ultimate settlement can be predicted for marine clays treated with vertical drains and preload by applying Asaoka (Asaoka, 1978) or Hyperbolic (Tan, 1995) methods. The settlement plates (SP-95) and the deep settlement gauge (DS-93) that were installed at the original seabed level gave similar reading for the magnitude and rate of settlement.

Figures 5 and 6 shows the typical Asaoka and Hyperbolic plots and interpretations for the settlement plate in the Vertical Drain Area. The method of application of these methods for land reclamation projects on marine clay have been discussed by Arulrajah et al. (2004) and Bo et al. (1997).

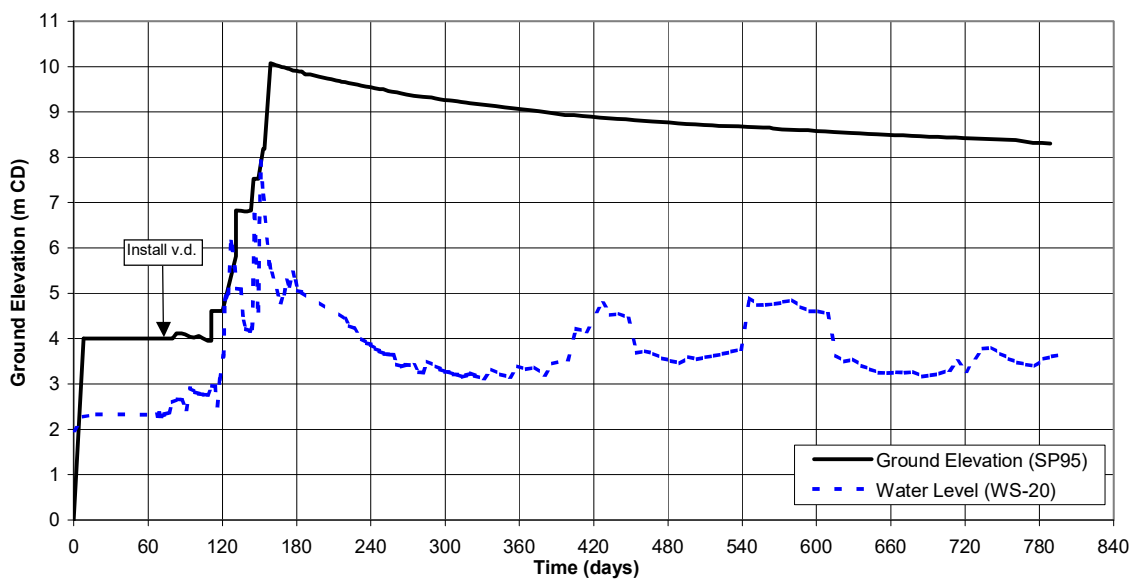


Figure 2: Construction sequence of filling and preloading at Vertical Drain Area (1.5 m x 1.5 m).

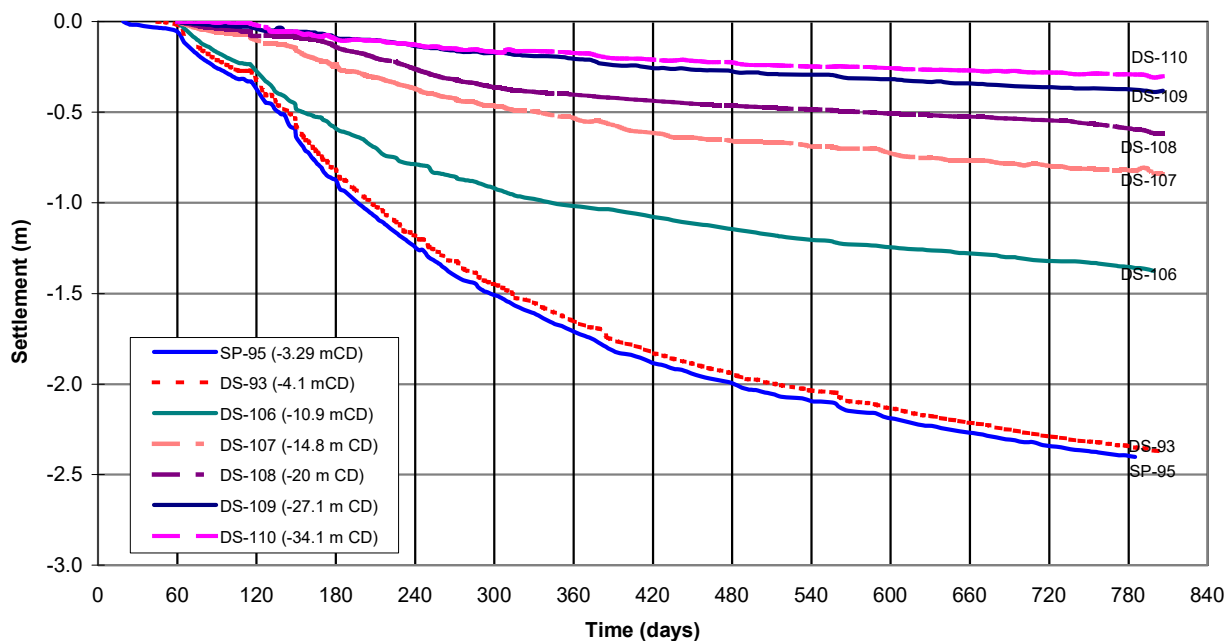


Figure 3: Field settlement results at Vertical Drain Area (1.5m x 1.5m).

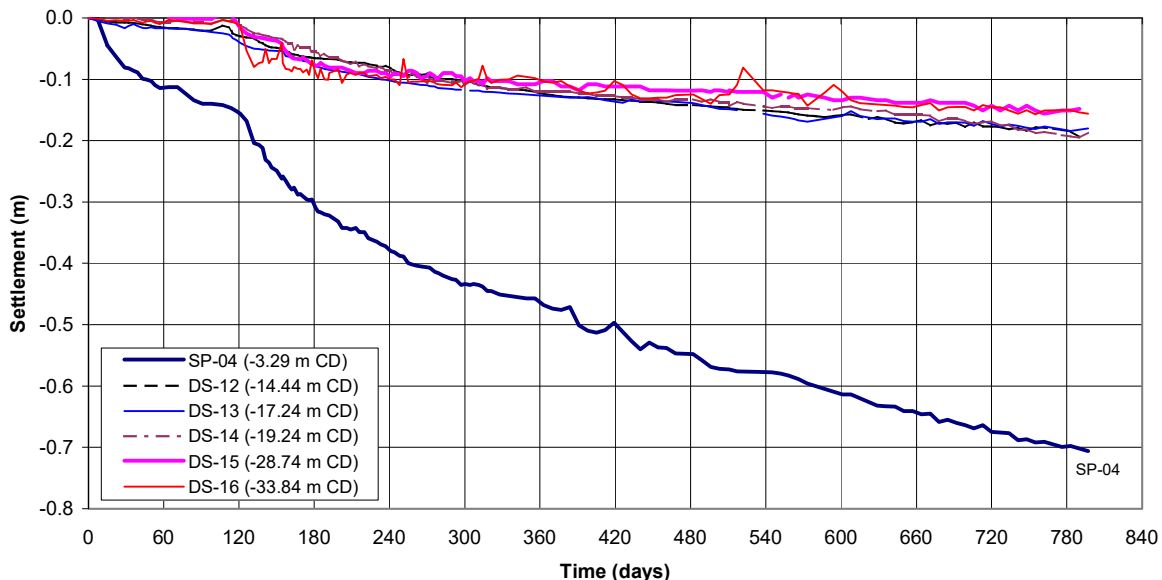


Figure 4: Field settlement results at Control Area (No Vertical Drains).

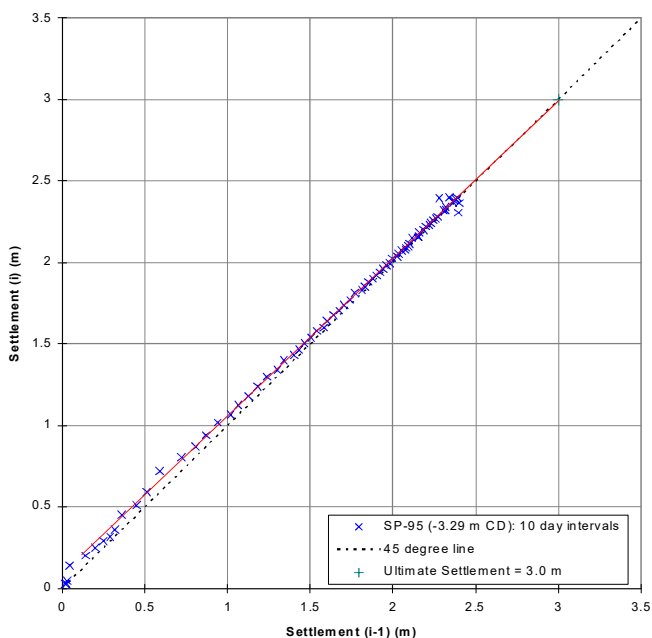


Figure 5: Asaoka Plot of settlement plate at Vertical Drain Area (1.5 m x 1.5 m)

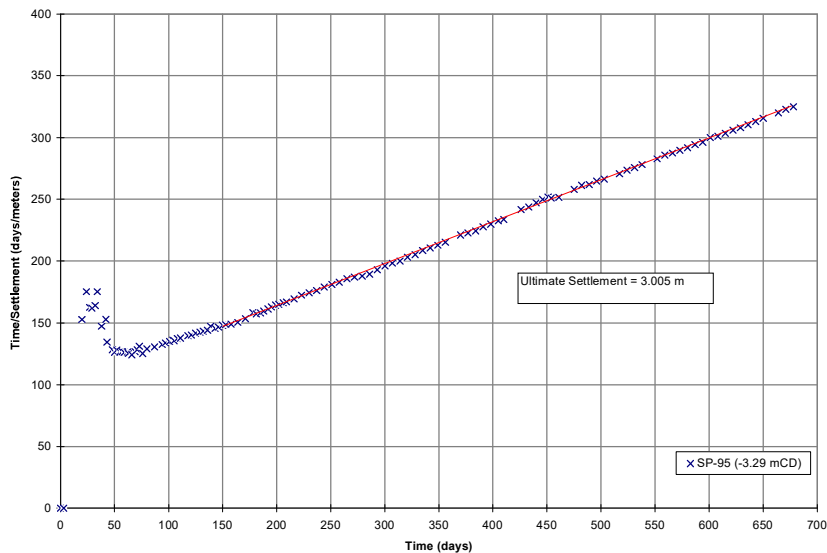


Figure 6: Hyperbolic plot of settlement plate at Vertical Drain Area (1.5 m x 1.5 m).

Degree of consolidation is defined as percentage of magnitude of settlement that occurred at time "t" upon ultimate primary consolidation settlement as indicated in Equation (1).

$$U_s (\%) = S_t / S_\alpha \quad (1)$$

where S_t = field settlement at any time t; S_α = ultimate settlement; and $U_s (\%)$ = average degree of consolidation.

5 PIEZOMETERS

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. Water standpipes were installed within piezometer clusters so as to measure the hydrostatic water level at these locations and thus enables the evaluation of the excess pore water pressures. Degree of consolidation for a soil element, U_u can be defined as Equation (2).

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

where $U_u (\%)$ = degree of consolidation for a soil element; U_t = the excess pore pressure at time t; and U_i = initial excess pore pressure which is equal to the additional load ($\Delta\sigma'$).

Figure 7 indicates the comparison of excess pore pressure isochrones between the Vertical Drain Area and 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 is also noted at the Control Area. It is evident that the degree of consolidation of the Vertical Drain Area is far greater than that of the Control Area.

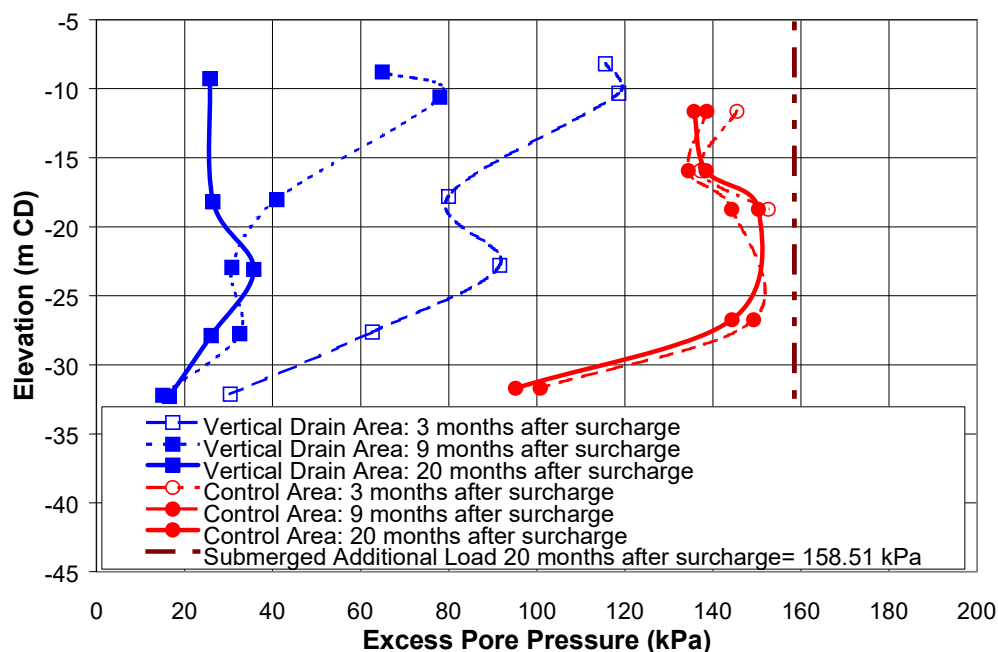


Figure 7: Excess pore water pressures at Vertical Drain Area.

Table 1 compares the degree of consolidation of the Vertical Drain Area by the various assessment methods. Ultimate settlement was obtained from the Asaoka and Hyperbolic methods and could not be obtained for the Control Area. The degree of consolidation in the Control Area is too low to estimate an ultimate settlement as at least 60 % of degree of consolidation is required for both methods to be valid. The degree of consolidation of the piezometers is found to agree 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%. 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 1.5m x 1.5m	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

6 CONCLUSIONS

This paper discusses the methods of field instrumentation in land reclamation projects and reports on a case study. The assessment of degree of consolidation is found to be in good agreement for the Asaoka, Hyperbolic and piezometer methods at a case study area. The settlement gauges and piezometers indicate that the degree of consolidation of the Vertical Drain Area had attained a degree of consolidation of about 80%. The piezometers indicate that the Control Area had only attained a degree of consolidation of about 20%. The instrumentation results in the Vertical Drain Area indicates much higher degree of consolidation as compared to the Control Area which indicates that the vertical drains are performing to improve the soil drainage system.

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