

FACTORS AFFECTING ASSESSMENT AND BACK-ANALYSIS BY PIEZOMETER MONITORING

A. Arulrajah¹, H. Nikraz¹ and M.W. Bo²

¹*Department of Civil Engineering, Curtin University of Technology, Perth, W. Australia*

²*Bullen Consultants Ltd., United Kingdom*

ABSTRACT

The use of prefabricated vertical drains with preloading option is the most widely-used ground improvement method for the improvement of marine clays in land reclamation projects. The assessment of the degree of consolidation of the marine clay is of paramount importance prior to the removal of preload in such ground improvement projects. This analysis can be carried out by means of piezometer monitoring. Piezometer monitoring data can be analysed to obtain the degree of consolidation of the improved marine clay. Back-analysis of the piezometer data will also enable the coefficient of consolidation due to horizontal flow to be estimated. Factors that affect the analysis of piezometers include period of assessment, hydrogeologic boundary condition, settlement of piezometer tip and reduction of initial imposed load due to submergence effect. The aim of this paper is to highlight the significance and impact of the various factors that affect assessment by the piezometer monitoring method.

1. INTRODUCTION

Ground improvement works in the ongoing Changi East Reclamation Project in the Republic of Singapore comprises the installation of prefabricated vertical drains and the subsequent placement of sand surcharge to accelerate the consolidation of the underlying soft marine clay. In such ground improvement projects on soft marine clay, 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 proceed with the surcharge removal. This analysis can be carried out by means of observational methods for which continuous records of ground behaviour can be monitored from the date of field instruments installation. Piezometer monitoring data can be used to ascertain the degree of consolidation of the marine clay from the time of initial installation. A Pilot Test Site was carried out at the reclamation project comprising of prefabricated vertical drains installed in sub-areas at various spacings. Surcharge placement was carried out for a duration of 32 months. Piezometers were analysed to investigate the various factors that affect their analysis. Factors that affect the analysis of piezometers include period of assessment, hydrogeologic boundary condition, settlement of piezometer tip and reduction of initial imposed load due to submergence effect.

Factors that affect field settlement assessment and back-analysis has been reported by Bo et al. (1999, 2003) and Arulrajah et al. (2003) based on analysis of the field settlement data at the Pilot Test Site. This paper complements the earlier findings reported by the authors (Arulrajah et al., 2003) and focuses on the piezometer monitoring data.

2. PILOT TEST SITE

The Pilot Test Site in the Changi East Reclamation project consisted of 4 sub-areas, three of which were installed with prefabricated vertical drains at various spacings. Long duration field settlement monitoring was carried out at regular intervals at these sub-areas. The seabed elevation at the site is about - 6 mCD (Admiralty Chart Datum, where mean sea level is +1.6 mCD) while the thickness of the soft marine clay in the location was up to 45 meters thick. Land reclamation was first carried out to the vertical drain platform elevation of +4 mCD. Field instruments comprising of pneumatic and electric vibrating-wire piezometers were installed from the vertical drain platform level soon after prefabricated vertical drain installation. Following the installation of prefabricated vertical drains, surcharge was next placed hydraulic filling to an elevation of +7 mCD simultaneously for all the sub-areas. As such, an assessment could be carried out and compared between the sub-areas treated with prefabricated vertical drains at various spacings when subjected to the same surcharge preload. The analysis of the piezometer monitoring results for the various sub-areas was carried out 32 months after surcharge placement which equates to a total monitoring duration of about 42 months.

Table 1 indicates the summary of the vertical drain spacings for the various sub-areas of the Pilot Test Site. Figure 1 shows the layout of the sub-areas in the Pilot Test Site. Figure 2 shows the cross-sectional soil profile of the field instrumentation elevations in the Pilot Test Site.

Table 1: Summary of Pilot Testing Site sub-area vertical drain spacings (Arulrajah et al., 2003).

Pilot Testing Site Sub-Areas	Vertical Drain Spacing
A2S-71	2.0 meter x 2.0 meter
A2S-72	2.5 meter x 2.5 meter
A2S-73	3.0 meter x 3.0 meter
A2S-74	No Drain

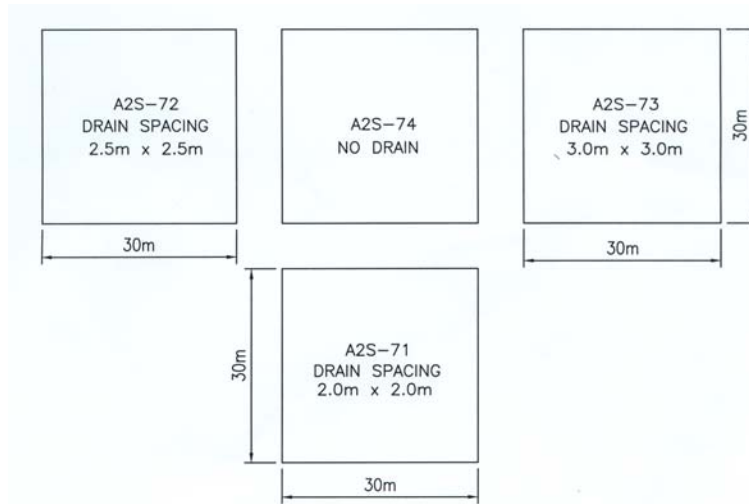


Figure 1: Layout plan and vertical drain spacing of sub-areas at the Pilot Test Site (Arulrajah et al., 2003)

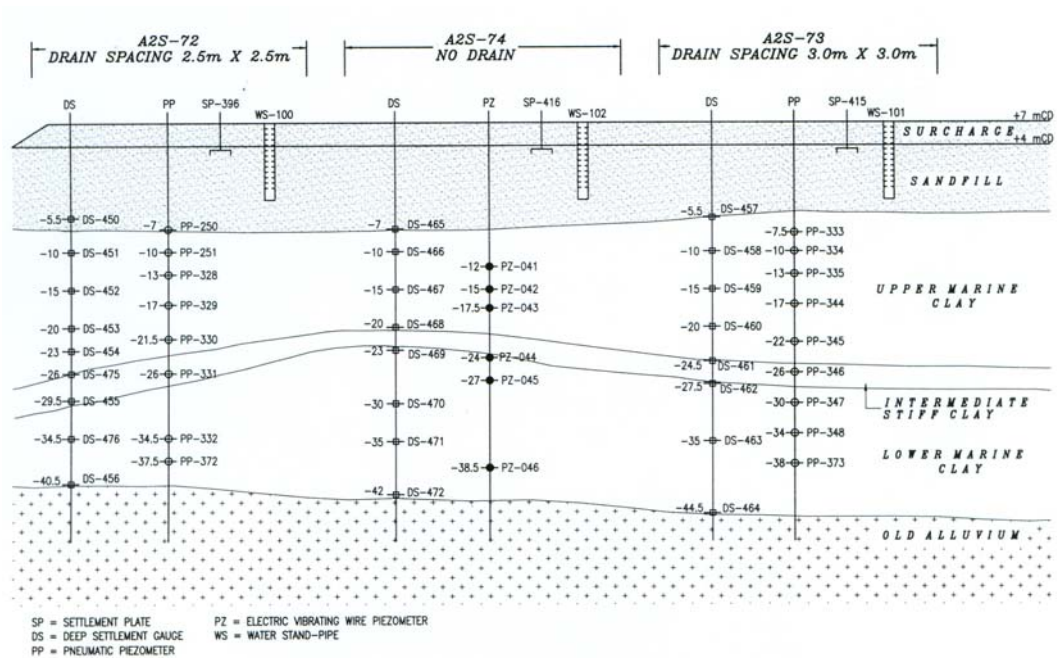


Figure 2: Cross-sectional soil profile showing instrument elevations at the Pilot Test Site.

3. ASSESSMENT OF PIEZOMETERS

Piezometers indicate measurements for piezometric head and were utilized to measure the pore pressure in the soil. Both electric vibrating-wire piezometers and pneumatic piezometers were used in the Pilot Test Site. Due to the large settlements of the marine clay under reclamation fills, the raw piezometer readings taken were corrected to account for the settlement of the piezometer tip.

3.1. PREDICTION OF DEGREE OF CONSOLIDATION

Piezometers were 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 the excess pore water pressures of the piezometers could be ascertained. Regular monitoring was carried out to measure the piezometric head together with static water level and changes of excess pore pressure due to additional load. Based on the ratio of the excess pore water pressure reading of the piezometer and the initial excess pore water pressure, the degree of consolidation of the piezometer can be ascertained:

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

where U_t is the excess pore pressure at time "t" and U_i is the initial excess pore pressure.

Piezometers were installed at different elevations and as such, the average degree of consolidation for the whole compressible unit as well as the average degree of consolidation of the sub-layers were determined. The settlement of the adjacent deep settlement gauges in the cluster at about the same respective elevation was used to correct the settlement of the piezometer tips. Correction is essential and if not made will lead to an underestimation of the degree of dissipation of the excess pore water pressure. Only primary consolidation settlement has been studied at the Pilot Test Site as the various sub-areas are still undergoing primary consolidation. Creep settlement does not occur at this juncture in the analysis and will only occur many years in the future.

3.2. PREDICTION OF COEFFICIENT OF CONSOLIDATION DUE TO HORIZONTAL FLOW

From field pore pressure measurements, the coefficient of consolidation due to horizontal flow, C_h can be back-analysed. The first step is the determination of the degree of consolidation at the particular time using equation (1). Subsequently, the non dimensional time factor, T_h has to be determined with the following equation:

$$U_r = 1 - \exp \frac{-8T_h}{F(n)} \quad (2)$$

$$F(n) = \frac{n^2}{(n^2 - 1)} \log_e(n) - \frac{3n^2 - 1}{4n^2} \quad (3)$$

where U_r is the average degree of consolidation with respect to radial flow, T_h is the non-dimensional time factor for consolidation by horizontal drainage, $F(n)$ is the vertical drain factor and n is the drain spacing ratio.

Coefficient of consolidation due to horizontal flow, C_h can be calculated using the total time method or the incremental time method (Bromwell and Lambe, 1968). In this study, piezometer predictions of C_h were carried out by the total time method. Vertical drainage is usually ignored for the piezometer prediction of C_h in this type of clay as the short-term contribution from vertical drainage is negligible:

Total time method:

$$C_h = \frac{T_h d_e^2}{t} \quad (4)$$

Incremental time method:

$$C_h = \frac{T_{h2} - T_{h1}}{t_2 - t_1} d_e^2 \quad (5)$$

where d_e is the diameter of equivalent soil cylinder.

4. FACTORS AFFECTING ASSESSMENT BY PIEZOMETERS

Piezometers were analysed to investigate the various factors that affect their analysis. Factors that affect the analysis of piezometers include period of assessment, hydrogeologic boundary condition, correction for settlement of piezometer tip and reduction of initial imposed load due to submergence effect. Factors that affect piezometer analyses are period of assessment after surcharge placement, hydrogeologic boundary phenomenon, correction for settlement of the piezometer tip and reduction of initial imposed load.

4.1. PERIOD OF ASSESSMENT AFTER SURCHARGE PLACEMENT

Pore water pressure is dissipating with increasing periods of assessment and as such there is a lower remaining excess pore water pressure with increasing periods of assessment. Correspondingly, the degree of consolidation will increase with increasing period of assessment. The isochrones of the excess pore water pressures is interpreted to obtain the average degree of consolidation of the various sub-areas.

Table 2 compares the degree of consolidation ($U\%$) and coefficient of consolidation (C_h) due to horizontal flow predicted by the piezometer method. The predictions were carried out using assessment periods of 12, 24 and 32 months after surcharge for the various vertical drain treated sub-areas of the Pilot Test Site.

Table 2: Comparison of average degree of consolidation from piezometers for 12, 24 and 32 months after surcharge placement (21.6, 33.7 and 41.9 months of monitoring).

Sub-Area	Piezometers	12 mths.	24 mths.	32 mths.
A2S-71 2.0 x 2.0 m	Degree of Consolidation, U (%)	79.7	83.0	86.2
	Back-Analysed C_h (m ² /year)	2.80	1.56	1.30
A2S-72 2.5 x 2.5 m	Degree of Consolidation, U (%)	73.9	81.9	82.5
	Back-Analysed C_h (m ² /year)	3.99	2.54	1.94
A2S-73 3.0 x 3.0 m	Degree of Consolidation, U (%)	63.0	72.2	73.1
	Back-Analysed C_h (m ² /year)	4.51	2.90	2.23
A2S-74 (No Drain)	Degree of Consolidation, U (%)	35.3	35.5	37.0

Table 2 indicates that the sub-area with the closest vertical drain spacing has attained the highest degree of consolidation for the various surcharging durations. At the end of the surcharging period of 32 months, the sub-area with the closest vertical drain spacing (A2S-71: 2.0 x 2.0) has achieved a degree of consolidation of 86.2 % while A2S-74 (No Drain) has achieved a degree of consolidation of 37.0%.

It is apparent that the coefficient of consolidation due to horizontal flow, C_h value of the clay converges to the final average value as longer time of assessment is used in the back-analysis by piezometer method.

The piezometer monitoring data indicates that the C_h value of the marine clay is lowest at the sub-area with the closest vertical drains spacing (A2S-71: 2.0 x 2.0) and highest at the sub-area with the furthest vertical drain spacing (A2S-73: 3.0 x 3.0). This is in similar agreement with the C_h values back-calculated by the Asaoka method as reported by Arulrajah et al. (2003) and confirms the higher degree of smear effect at locations with closer drain spacing. Figures 3 to 6 shows the excess pore water pressure isochrones of the various sub-areas for various periods of assessment after surcharge placement.

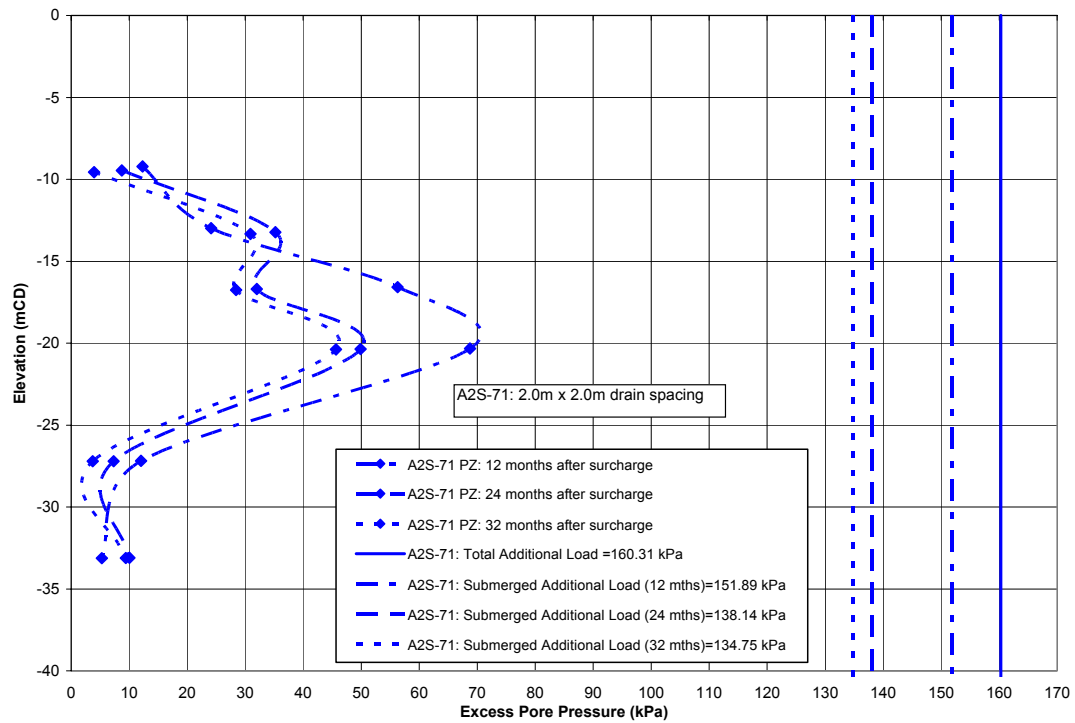


Figure 3: Comparison of A2S-71 (2.0 x 2.0 m) piezometer excess pore pressure isochrones 12, 24 and 32 months after surcharge.

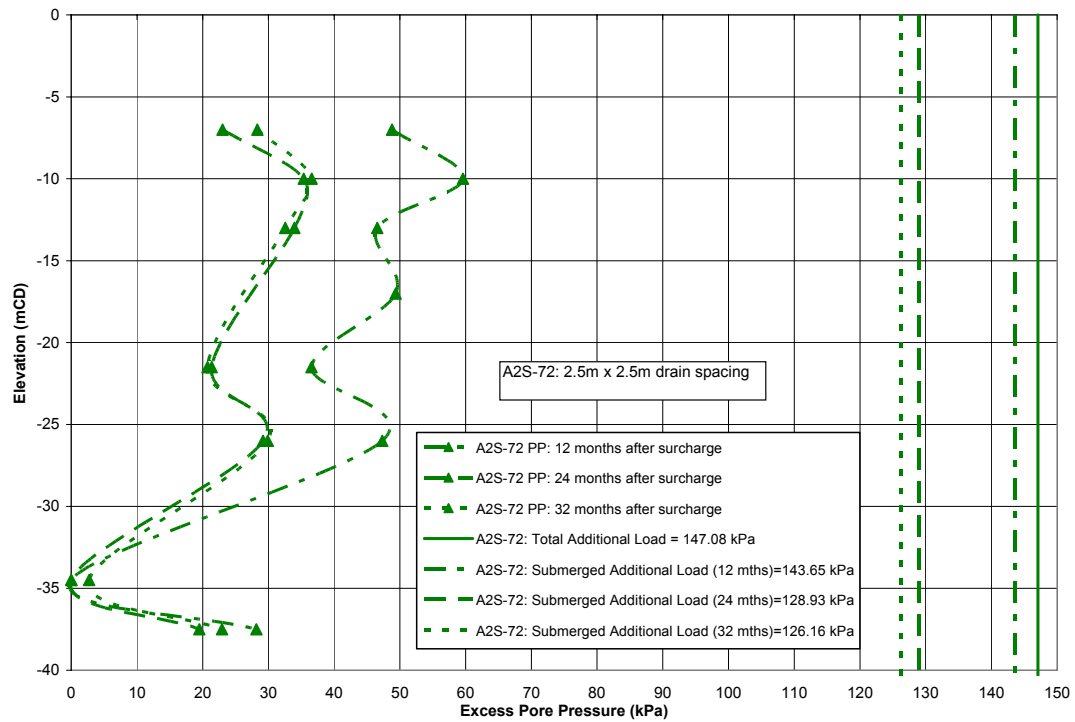


Figure 4: Comparison of A2S-72 (2.5 x 2.5 m) piezometer excess pore pressure isochrones 12, 24 and 32 months after surcharge.

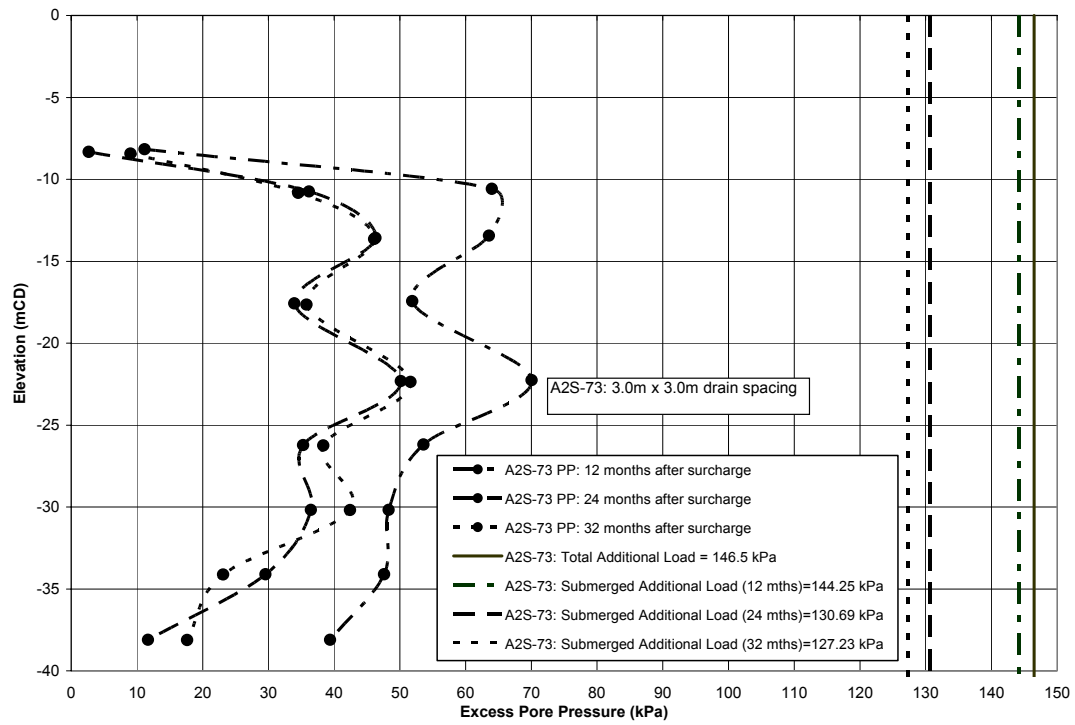


Figure 5: Comparison of A2S-73 (3.0 x 3.0 m) piezometer excess pore pressure isochrones 12, 24 and 32 months after surcharge.

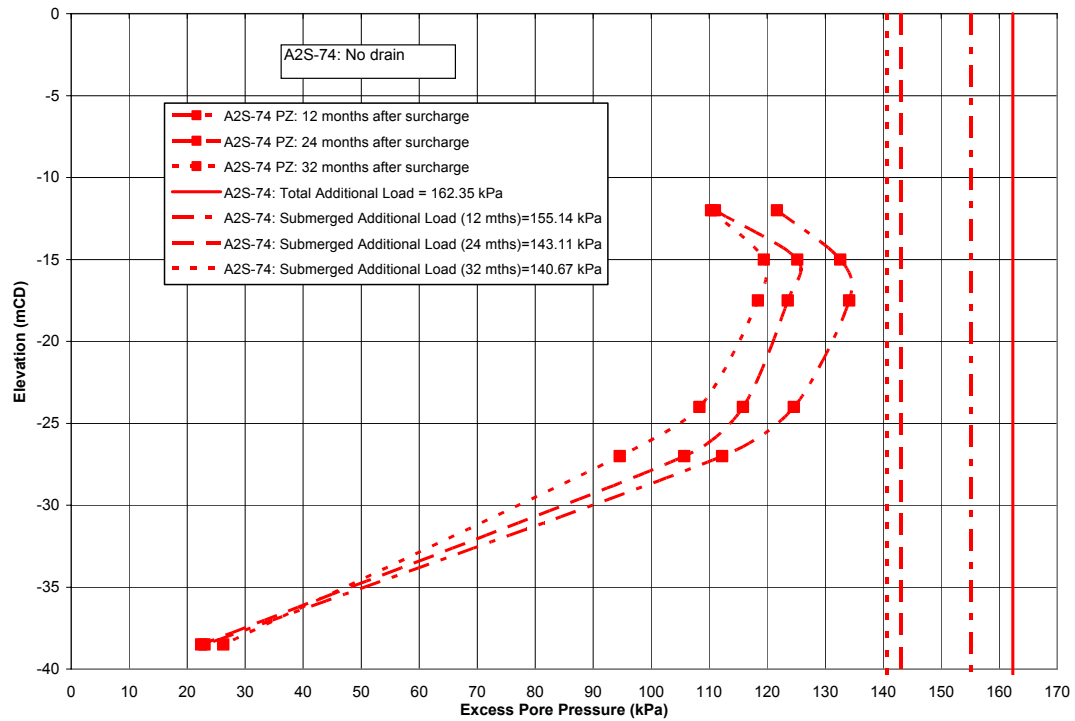


Figure 6: Comparison of A2S-74 (No Drain) piezometer excess pore pressure isochrones 12, 24 and 32 months after surcharge.

4.2. HYDROGEOLOGIC BOUNDARY PHENOMENON

If the piezometer is installed in offshore condition prior to reclamation, the initial excess pore water pressure can be obtained during the monitoring as the initial static pore pressure is known. Otherwise, the initial excess pore pressure has to be calculated from the assumed bulk density of the fill material (Bo et al., 1999). For the case of land reclamation projects, it is common to assume a bulk density of 17 to 19 kN/m³ for the sand fill material. Bo et al. (1999) has measured the density of sand in the past reclamation projects as varying from 15 kN/m³ to 19 kN/m³. As such, the calculated excess pore pressure based on assumed bulk density of the fill material could lead to an over-estimation of excess pore pressure for land fill cases and an underestimation for hydraulic filling.

Initial excess pore pressure is usually assumed to be equal to the applied additional load. However, it could vary from the in-situ measured pore pressure after loading for some cases where clay layer is underlain by the hydrogeologic boundary. This phenomenon has been explained by Schiffman et al. (1994). In such cases, the profile of pore pressure after additional load could be lower than that calculated. Overestimation of degree of consolidation could be encountered if the initial lower pore pressure is not taken into consideration. Situations like this will arise when the clay layer is underlain by a water aquifer which is being extracted for water supply. However, the hydrogeologic boundary phenomenon does not arise in the Pilot Test Site. Figure 7 illustrates the hydrogeologic boundary phenomenon.

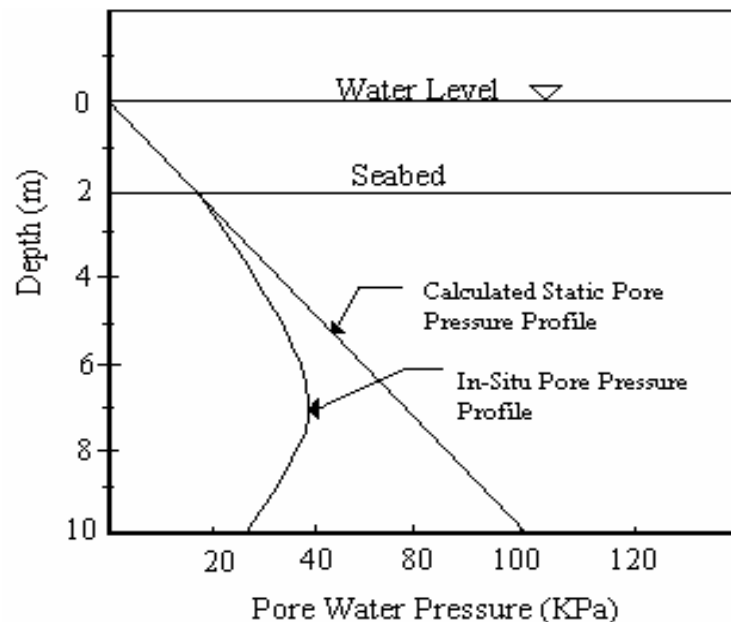


Figure 7: In-situ pore pressure which is lower than static pore pressure due to hydrogeologic boundary (after Schiffman et al. 1994).

4.3. CORRECTION FOR SETTLEMENT OF PIEZOMETER TIP

Due to the large strain settlements at site, all piezometer raw readings taken have to be corrected to account for the new elevation of the piezometer due to the settlement of the piezometer tip. Without correction, the calculated piezometric elevation would be higher than the actual and this will subsequently lead to the underestimation of the degree of consolidation. This behaviour has been reported by Bo et al. (1998). Figures 8 and 9 show the comparison of corrected and uncorrected piezometric elevation and excess pore pressures respectively for the Pilot Test Site. Figure 10 illustrates the comparison of corrected and uncorrected piezometer excess pore pressure isochrones of the various sub-areas, 24 months after surcharge.

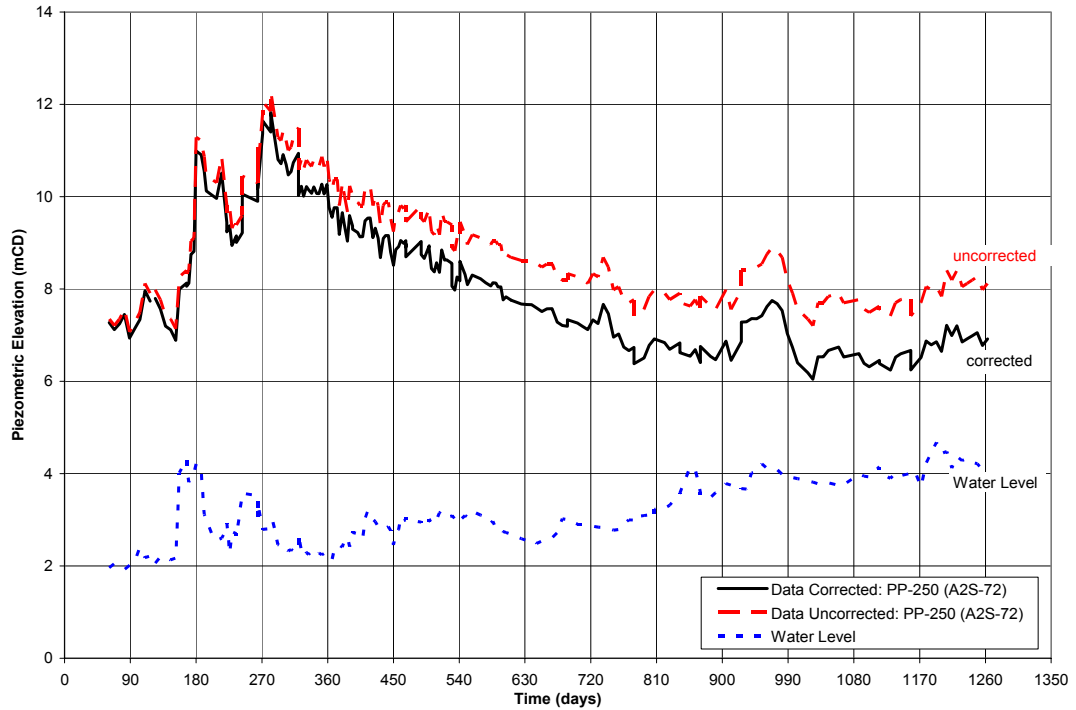


Figure 8: Comparison of corrected and uncorrected piezometric elevation (A2S-72: PP-250).

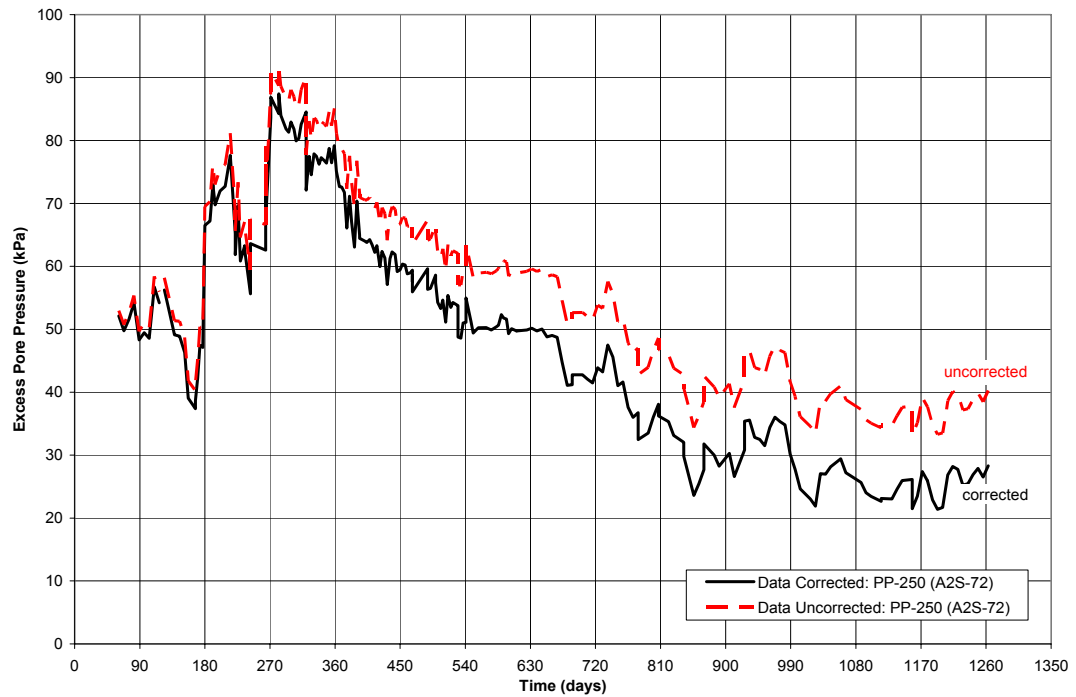


Figure 9: Comparison of corrected and uncorrected excess pore pressure (A2S-72: PP-250).

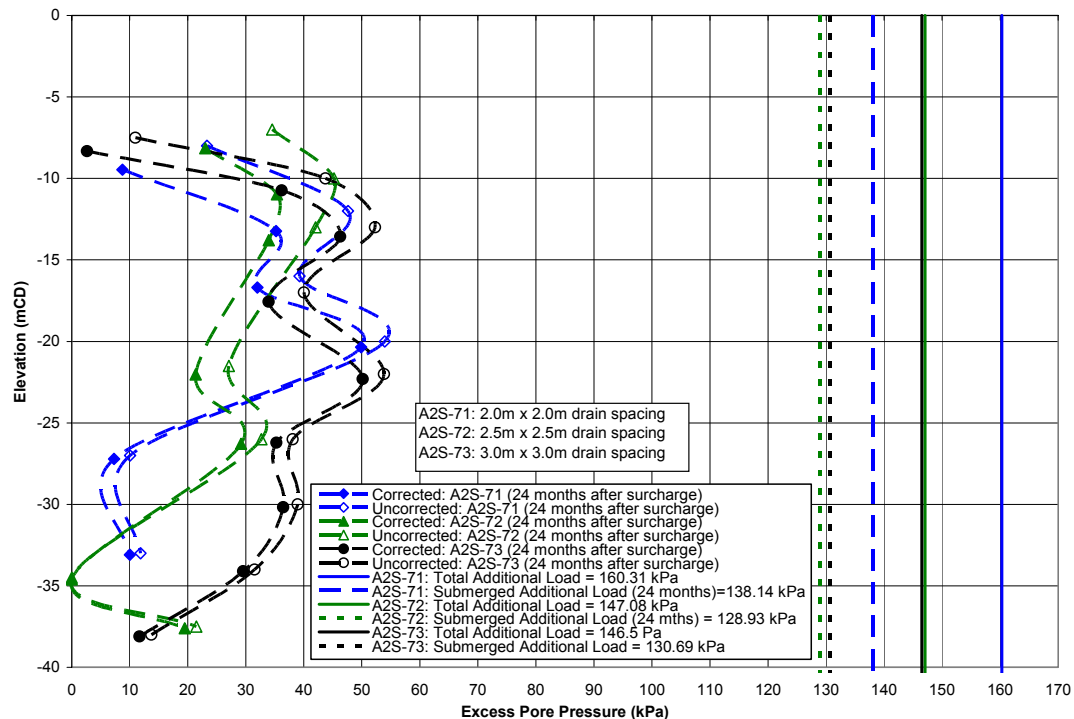


Figure 10: Comparison of corrected and uncorrected piezometer excess pore pressure isochrones 24 months after surcharge at Pilot Test Site.

4.4. REDUCTION OF INITIAL IMPOSED LOAD

For marine clay subjected to reclaimed fill load, the marine clay can seldom gain the effective stress equivalent to the initial imposed load due to the following reasons:

- Reduction of load due to sinking of fill below groundwater level
- Rise in groundwater level due to seasonal recharge

This behaviour was first reported by Mesri and Choi (1985). As such, degree of consolidation based on the initial imposed load is likely to be underestimated since the available effective additional load at assessed time is smaller than the initial load (Bo et al., 1999).

5. COMPARISON BETWEEN PIEZOMETER AND FIELD SETTLEMENT ASSESSMENT BY THE ASAOKA AND HYPERBOLIC METHODS

Piezometer readings obtained from the various sub-areas was analysed and compared with the field settlement assessments reported by Arulrajah et al. (2003) at periods of assessment of 12, 24 and 32 months after surcharge placement.

The comparison of degree of consolidation between the piezometers with the Asaoka and hyperbolic method reported by Arulrajah et al., (2003) is summarised in Tables 6, 7 and 8. The degree of consolidation predicted by the piezometers is found to be in good agreement with the Asaoka and Hyperbolic methods for the early period of assessment. However as the assessment period increases, the piezometer indicates lower degree of consolidation as compared to field settlement predictions. This is illustrated in Figure 11. Similar findings for lower piezometer readings compared to field settlement predictions have been reported by Bo et al. (1999). This can be attributed to the non-linearity of the stress-strain behaviour of soil (Mikasa, 1995). In the non-linearity theory, the effective stress gain is slower in initial stage whereas settlement rate is faster in such stage. Therefore degree of consolidation worked out from settlement ratio is much greater than that worked out from pore pressure.

The back-analysed C_h by the piezometer method indicates that there is a trend of the C_h value generally decreasing at longer periods of assessment after surcharge placement. This is illustrated in Figure 12. It is apparent that the coefficient

of consolidation due to horizontal flow, C_h value of the clay converges to the actual value as longer time of assessment is used in the back-analysis by piezometer method. The C_h values back-calculated by the Asaoka and piezometer method after 32 months of surcharge placement is found to be in good agreement. The piezometer monitoring data indicates that the back-analysed C_h value of the marine clay is lowest at the sub-area with the closest vertical drains spacing (A2S-71: 2.0 x 2.0) and highest at the sub-area with the furthest vertical drain spacing (A2S-73: 3.0 x 3.0). This is in similar agreement with the C_h values back-calculated by the Asaoka method and confirms the higher degree of smear effect at locations with closer drain spacing.

Table 6: Comparison between Asaoka, Hyperbolic and piezometer methods 12 months after surcharge (21.6 months of monitoring).

Sub-Area	Comparison	Asaoka	Hyperbolic	Piezometer
A2S-71 2.0 x 2.0 m	Degree of Consolidation, U (%)	71.3	76.3	79.7
	Back-Analysed C_h (m ² /year)	1.06	-	2.80
A2S-72 2.5 x 2.5 m	Degree of Consolidation, U (%)	68.0	73.9	73.9
	Back-Analysed C_h (m ² /year)	1.27	-	3.99
A2S-73 3.0 x 3.0 m	Degree of Consolidation, U (%)	55.4	63.2	63.0
	Back-Analysed C_h (m ² /year)	1.99	-	4.51

Table 7: Comparison between Asaoka, Hyperbolic and piezometer methods 24 months after surcharge (33.7 months of monitoring).

Sub-Area	Comparison	Asaoka	Hyperbolic	Piezometer
A2S-71 2.0 x 2.0 m	Degree of Consolidation, U (%)	85.3	89.7	83.0
	Back-Analysed C_h (m ² /year)	1.14	-	1.56
A2S-72 2.5 x 2.5 m	Degree of Consolidation, U (%)	86.3	87.2	81.9
	Back-Analysed C_h (m ² /year)	1.20	-	2.54
A2S-73 3.0 x 3.0 m	Degree of Consolidation, U (%)	69.0	76.0	72.2
	Back-Analysed C_h (m ² /year)	1.75	-	2.90

Table 8: Comparison between Asaoka, Hyperbolic and piezometer methods 32 months after surcharge (41.9 months of monitoring).

Sub-Area	Comparison	Asaoka	Hyperbolic	Piezometer
A2S-71 2.0 x 2.0 m	Degree of Consolidation, U (%)	91.8	93.7	86.2
	Back-Analysed C_h (m ² /year)	1.08	-	1.30
A2S-72 2.5 x 2.5 m	Degree of Consolidation, U (%)	89.5	89.8	82.5
	Back-Analysed C_h (m ² /year)	1.22	-	1.94
A2S-73 3.0 x 3.0 m	Degree of Consolidation, U (%)	79.0	81.1	73.1
	Back-Analysed C_h (m ² /year)	2.20	-	2.23

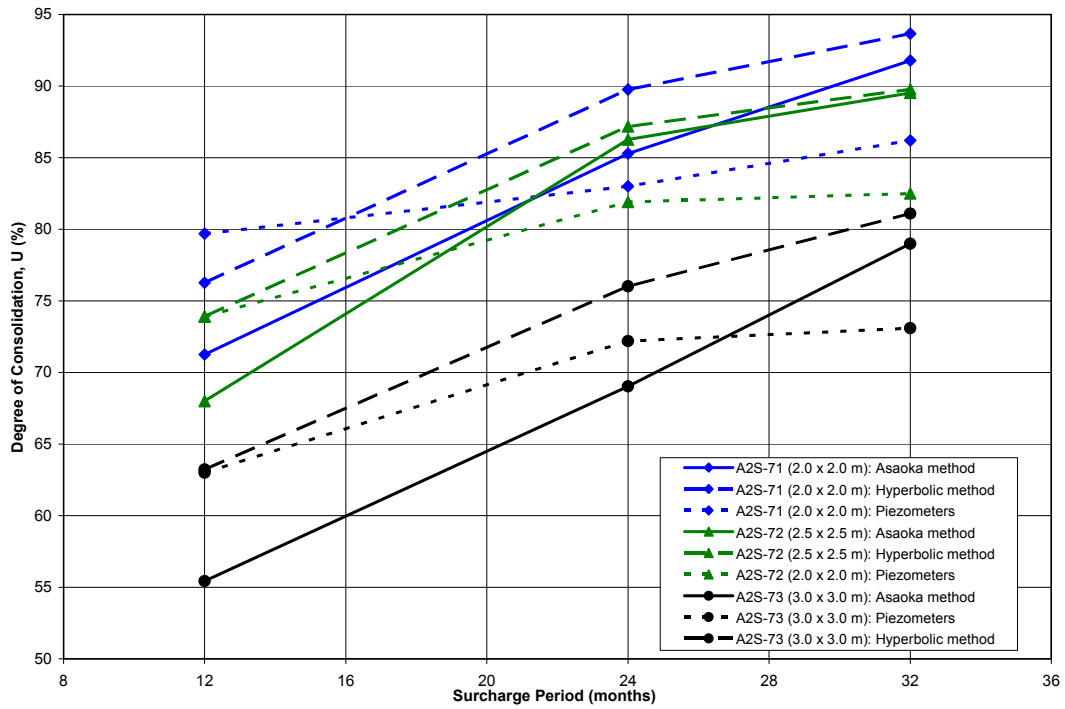


Figure 11: Comparison of variation in degree of consolidation at various surcharge periods by the Asaoka, Hyperbolic and piezometer methods.

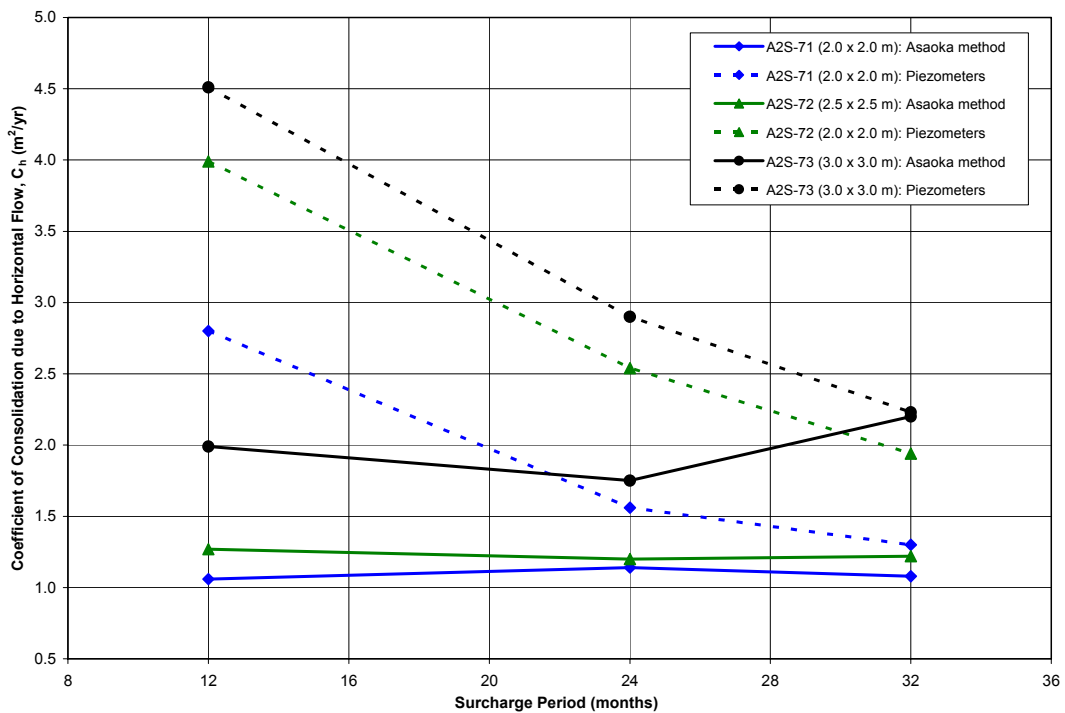


Figure 12: Comparison of variation in C_h at various surcharge periods by the Asaoka and piezometer methods.

6. CONCLUSIONS

The authors have reported on the various factors that affect the analysis of piezometers installed in marine clay and subjected to reclamation fills. The author's findings reveal that the degree of consolidation predicted by the piezometers is found to be in good agreement with the field settlement assessments by the Asaoka and Hyperbolic methods for the early period of assessment. However as the assessment period increases, the piezometer indicates lower degree of consolidation as compared to field settlement predictions. This can be attributed to the non-linearity of the stress-strain behaviour of soil (Mikasa, 1995).

The back-analysed C_h by the piezometer method indicates that there is a trend of the C_h value generally decreasing at longer periods of assessment after surcharge placement. It is apparent that the coefficient of consolidation due to horizontal flow, C_h value of the clay is reducing with time and as longer time of assessment is used in the back-analysis by piezometer method. The C_h values back-calculated by the Asaoka and piezometer method after 32 months of surcharge placement is found to be in good agreement. The study reveals that the C_h value of the marine clay is lowest at the sub-area with the closest vertical drains spacing and highest at the sub-area with the largest vertical drain spacing which is attributed to the larger smear effect at locations with closer drain spacing. This is in similar agreement with the C_h values back-calculated by the Asaoka method and confirms the higher degree of smear effect at locations with closer drain spacing.

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