Observational method of assessing improvement of marine clay

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The ongoing Changi East Reclamation Project in Singapore consists of land reclamation and ground improvement works of the foreshore for the future expansion of the Changi International airport and associated facilities. Reclamation works in the project involve the hydraulic placement of sand-fill over the seabed, which is underlain by thick, highly compressible Singapore marine clay. Ground improvement works in the project comprise the installation of vertical drains and the subsequent placement of surcharge to accelerate the consolidation of the underlying marine clay. A pilot test site was carried out in the project, comprising three sub-areas that were installed with vertical drains at various spacings, plus a fourth untreated sub-area. The four sub-areas were surcharged simultaneously and preloaded for a duration of 32 months. A comprehensive field instrumentation programme was implemented in the pilot test site, comprising settlement plates, deep settlement gauges, piezometers and water standpipes. The degree of improvement attained by the foundation soil at each sub-area was determined and assessed during the process of consolidation and 32 months after surcharge placement using the observational method. This paper describes the applications and comparisons between the Asaoka method, the hyperbolic method and piezometers in monitoring the improvement of marine clay under reclamation fills.

Keywords: degree of consolidation; field instrumentation; ground improvement; reclamation; vertical drains

Le projet de récupération de terre qui se poursuit à Changi East à Singapour consiste en une récupération des terres et une amélioration des sols du littoral dans le but d'agrandir l'aéroport international de Changi ainsi que ses installations associées. Les travaux portent sur la mise en place hydraulique d'un remblai de sable sur le fond de mer, qui est recouvert d'une argile marine épaisse, très compressible, de Singapour. Les travaux d'amélioration des sols consistent à installer des drains verticaux et à leur imposer ensuite une surcharge afin d'accélérer la consolidation de l'argile marine sous-jacente. Un site d'essai pilote a été réalisé dans le projet, comprenant trois sous zones qui ont été équipées de drains verticaux placés à diverses distances les uns des autres et une quatrième sous zone non traitée. Les quatre sous zones ont subi une surcharge simultanée et une pré-charges pendant 32 mois. Un programme d'instrumentation complet sur le terrain a été mis en uvre dans le site d'essai pilote, comprenant des plaques de tassement, des jauges profondes d'affaissement, des piézomètres et des remontées d'eau. Le degré d'amélioration atteint par le sol de fondation dans chacune des sous zones a été déterminé et évalué pendant le processus de consolidation et 32 mois après le placement de la surcharge en utilisant la méthode observationnelle. Cet exposé décrit les applications et comparaisons entre la méthode Asaoka, la méthode hyperbolique et les piézomètres pour suivre l'amélioration de l'argile marine sous remblais de récupération.

Notation

- C_h coefficient of consolidation due to horizontal flow
- C_v coefficient of consolidation due to vertical flow
- c y-axis intercept of constructed straight line of hyperbolic plot
- d_e diameter of equivalent soil cylinder
- d_w equivalent diameter of vertical drain
- $F(n)$ drain spacing factor
- m constant representing slope of constructed straight line of hyperbolic plot
- S_t settlement at time t
- S_{ult} ultimate primary settlement predicted by Asaoka or hyperbolic methods
- s settlement (hyperbolic plot)
- s_o constant representing y-axis intercept of constructed straight line of Asaoka plot
- T_h non-dimensional time factor for consolidation by horizontal drainage
- t time (hyperbolic plot)
- U degree of consolidation
- U_i initial excess pore pressure
- U_r average degree of consolidation with respect to radial flow
- U_t excess pore pressure at time t
- α theoretical slope of constructed straight line of hyperbolic plot
- β constant representing slope of constructed straight line of Asaoka plot
- $\Delta\sigma'$ additional load
- Δt selected time interval used for Asaoka plot

(GI 3178) Paper received 20 May 2003; last revised 25 November 2003; accepted 20 April 2004

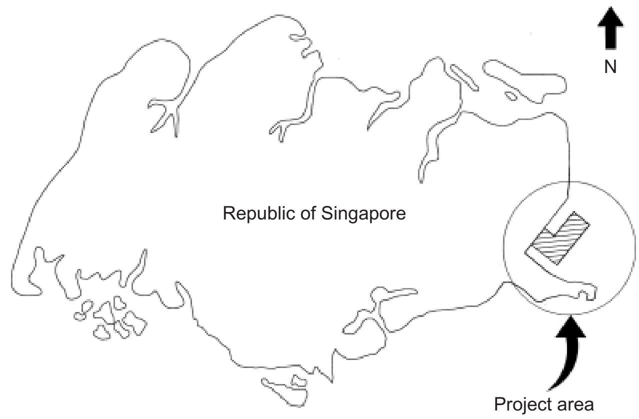

Fig. 1. Location of project site in the Republic of Singapore

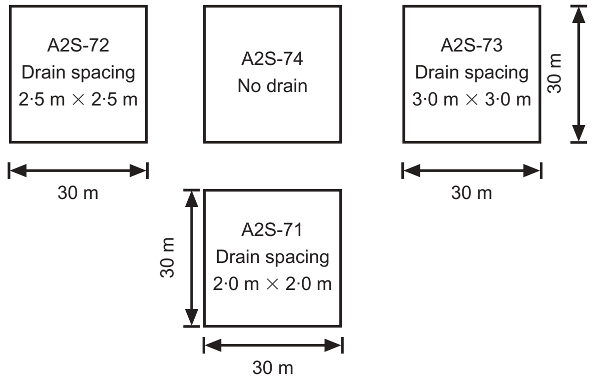

Fig. 2. Layout plan and vertical drain spacing of sub-areas at pilot test site

Introduction

Ground improvement works in the ongoing Changi East Reclamation Project in the Republic of Singapore comprise 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 in soft marine clay, the degree of improvement attained by the clay has to be ascertained prior to surcharge removal, to confirm whether the soil has achieved the required degree of consolidation. 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 instrumentation installation.

Field instrumentation monitoring data can be used to ascertain the settlement of the reclaimed fill from the time of initial installation. The data can be analysed to predict the ultimate settlement of the reclaimed land and the 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.

A pilot test site was carried out at the reclamation project in the Republic of Singapore, comprising vertical drains installed in sub-areas at various spacings. Fig. 1 shows the location of the reclamation site. Surcharge was maintained for a duration of 32 months. The field settlement and piezometer data of the various sub-areas were analysed to determine the ultimate settlement, degree of consolidation and coefficient of consolidation due to horizontal flow. In this study, the assessment of the improved marine clay was carried out by the observational method at an assessment period of 32 months after surcharge placement.

Table 1. Summary of pilot test site sub-area vertical drain spacings

Pilot test site sub-areas	Vertical drain square spacing
A2S-71	2·0 m × 2·0 m
A2S-72	2·5 m × 2·5 m
A2S-73	3·0 m × 3·0 m
A2S-74	No drains

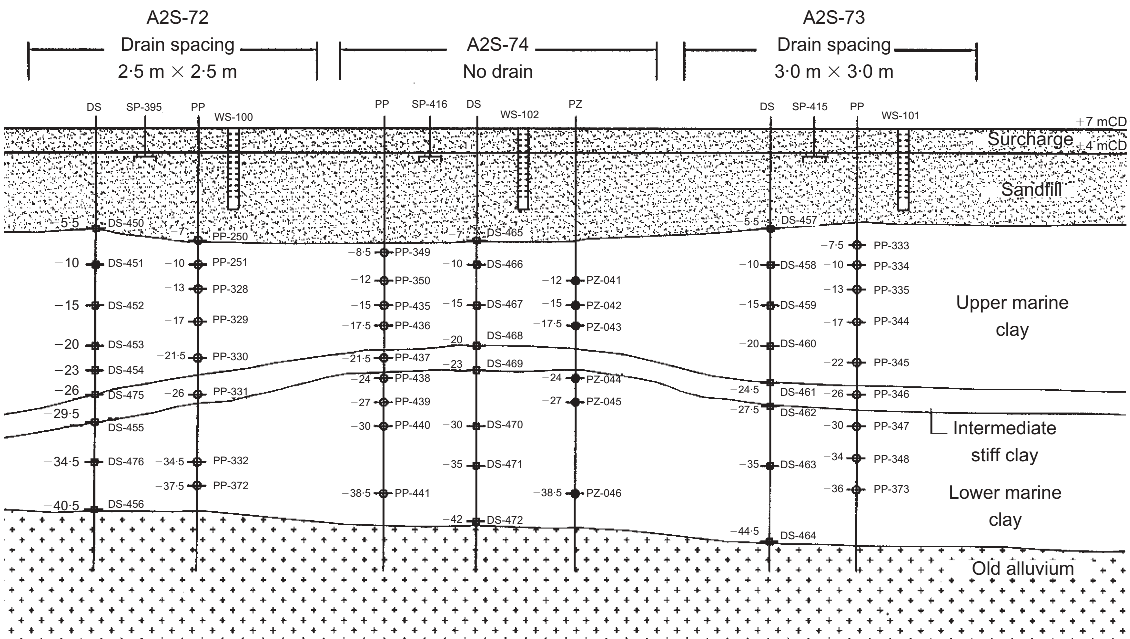

Fig. 3. Cross-sectional soil profile showing instrument elevations at pilot test site: SP, settlement plate; DS, deep settlement gauge; PP, pneumatic piezometer; PZ, electric vibrating-wire piezometer; WS, water standpipe

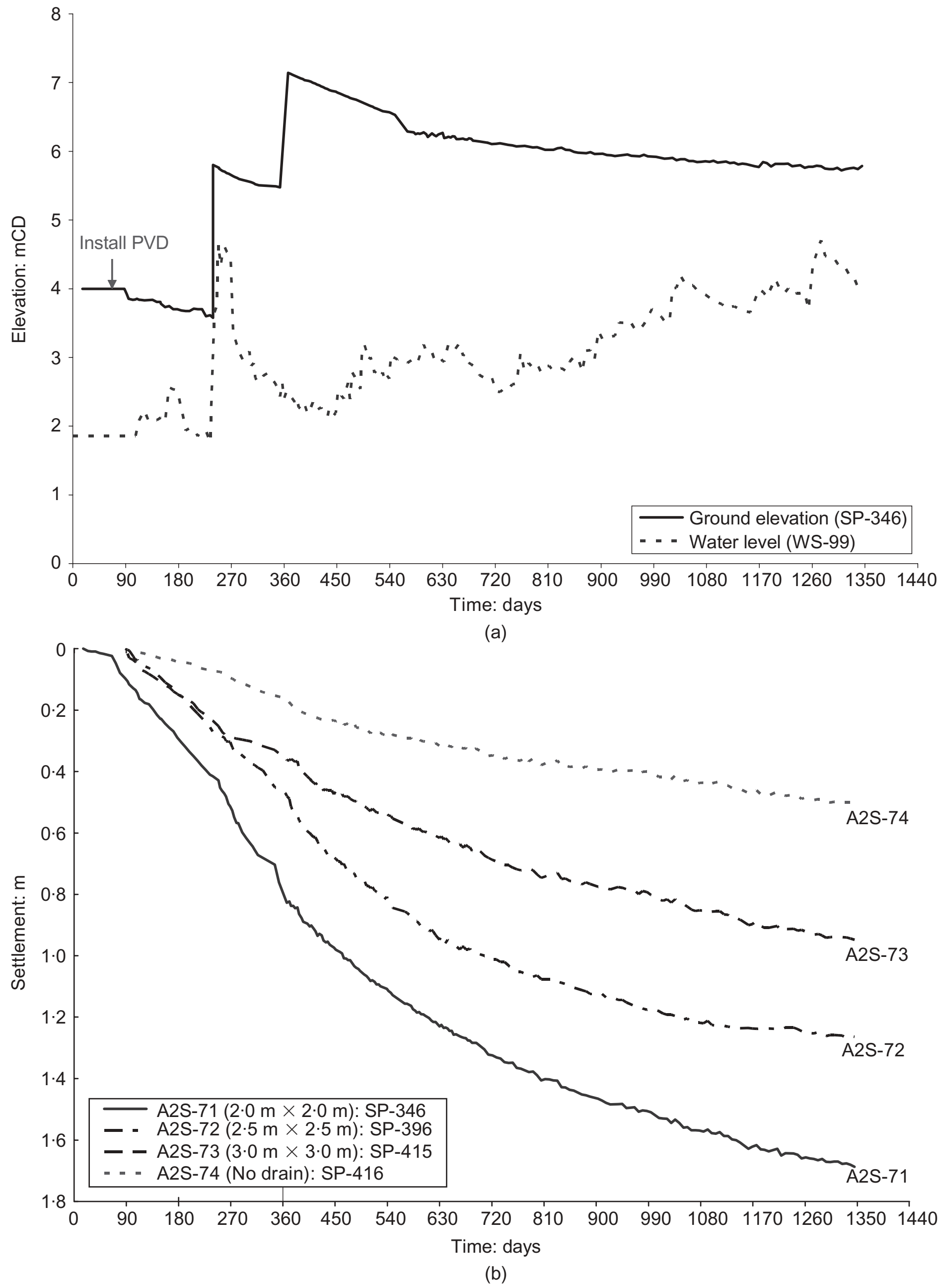

Fig. 4. Comparison of field settlement between sub-areas at the pilot test site: (a) elevation; (b) settlement

Description of pilot test site

The pilot test site consisted of four sub-areas, three of which were installed with vertical drains at various spacings. Long-duration field settlement monitoring was carried out at regular intervals at these sub-areas. The seabed elevation is about −6 mCD (Admiralty Chart Datum, where mean sea level is +1·6 mCD), and the soft marine clay in the location was up to 45 m thick.

The Singapore marine clay at Changi comprises two distinct layers: the *upper marine clay layer* and the *lower marine clay layer*. An *intermediate stiff clay layer* that is also present, and which separates these two distinct marine clay layers, is in reality a desiccated layer of the lower marine clay. The index and engineering properties of Singapore marine clay at the reclamation site have been discussed by Bo *et al.* (2003).

The upper marine clay has a liquid limit between 80% and 95%, plastic limit between 20% and 28%, and water content of 70–88%. It is generally overconsolidated, with an OCR of about 1·5–2·5. The coefficient of consolidation due to vertical flow (C_v) is between 0·47 and 0·6 m^2/year, and the coefficient of consolidation due to horizontal flow (C_h) is between 2 and 3 m^2/year.

The lower marine clay has a liquid limit of 65–90%, plastic limit of 20–30% and water content of 40–60%. It is lightly overconsolidated, with an OCR of 2. Its C_v is between 0·8 and 1·5 m^2/year, and its C_h is between 3 and 5 m^2/year.

The intermediate stiff clay is sandwiched between the upper marine clay and lower marine clay. This layer comprises predominantly stiff sandy silt or sandy clay. It has a liquid limit of about 50%, plastic limit of 18–20% and water content of 10–35%. It is moderately overconsolidated due to desiccation, with an OCR of 3–4. Its C_v is between 1 and 4·5 m^2/year, and its C_h is between 5 and 10 m^2/year.

Land reclamation was first carried out to the vertical drain platform elevation of +4 mCD. Field instruments comprising

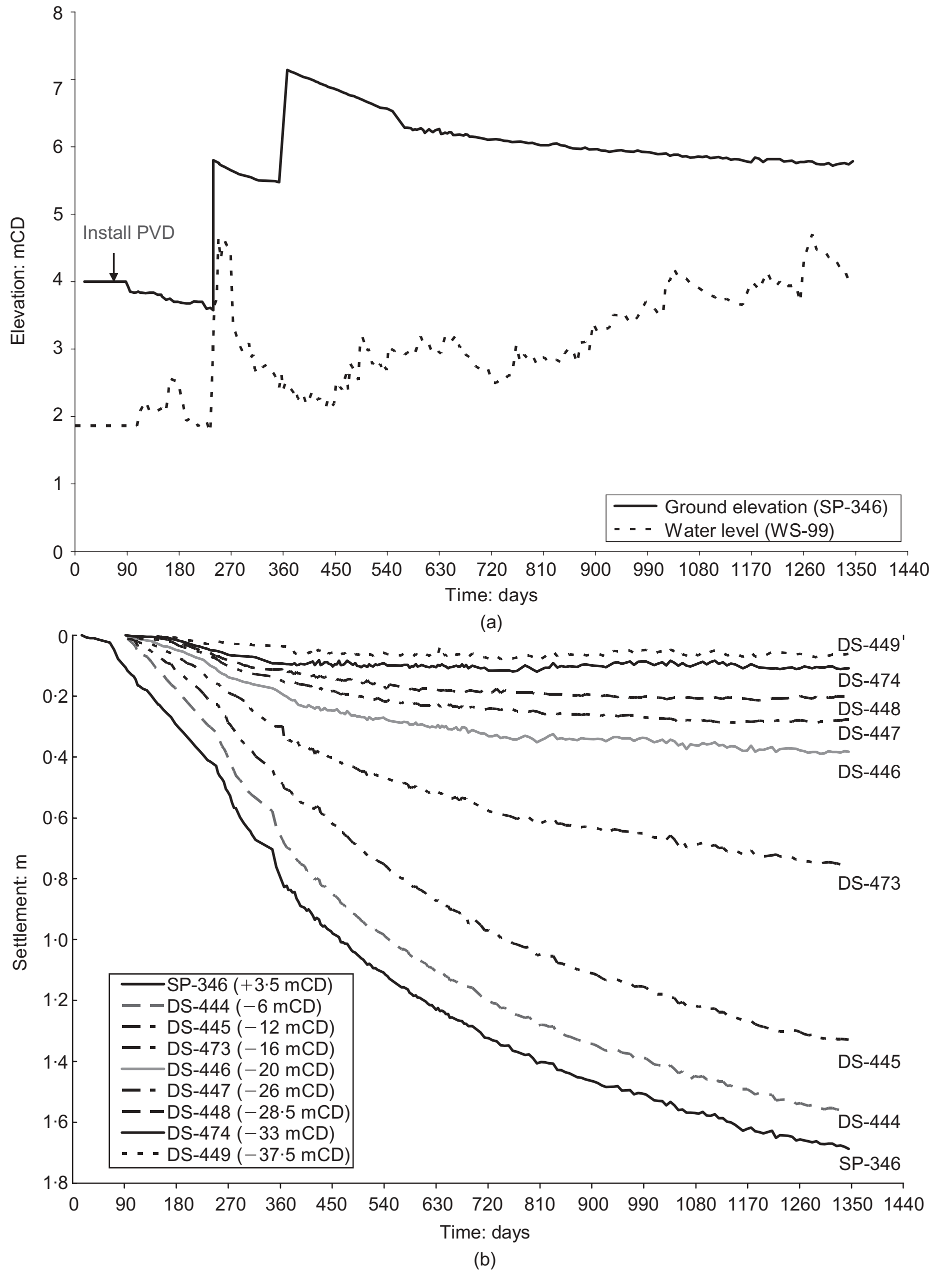

Fig. 5. Field settlement results of settlement gauges for A2S-71 (2·0 m × 2·0 m): (a) elevation; (b) settlement

surface settlement plates, deep settlement gauges, pneumatic piezometers, electric piezometers and water standpipes were installed from the platform level where vertical drains were installed. Instruments were installed prior to vertical drain installation.

Following the installation of vertical drains, surcharge was next placed with hydraulic filling to an elevation of +7 mCD simultaneously for all the sub-areas. In this way an assessment could be carried out and comparison made between the sub-areas treated with vertical drains at various spacings when subjected to the same surcharge preload. The analysis of the instrumentation 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.

The vertical drain spacings in the various sub-areas are summarised in Table 1. Fig. 2 shows the layout of the pilot test site, and Fig. 3 shows the profile of the field instrumentation at the site.

Field instrumentation at the pilot test site

The surface settlement plates were installed just before 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 the vertical drains were installed. The plates were installed approximately 0·5 m beneath the vertical drain platform level. Deep settlement gauges were also installed in clusters either before or immediately after the installation of vertical drains. The gauge used consists of a screw plate at the end of a steel pipe. Each gauge is

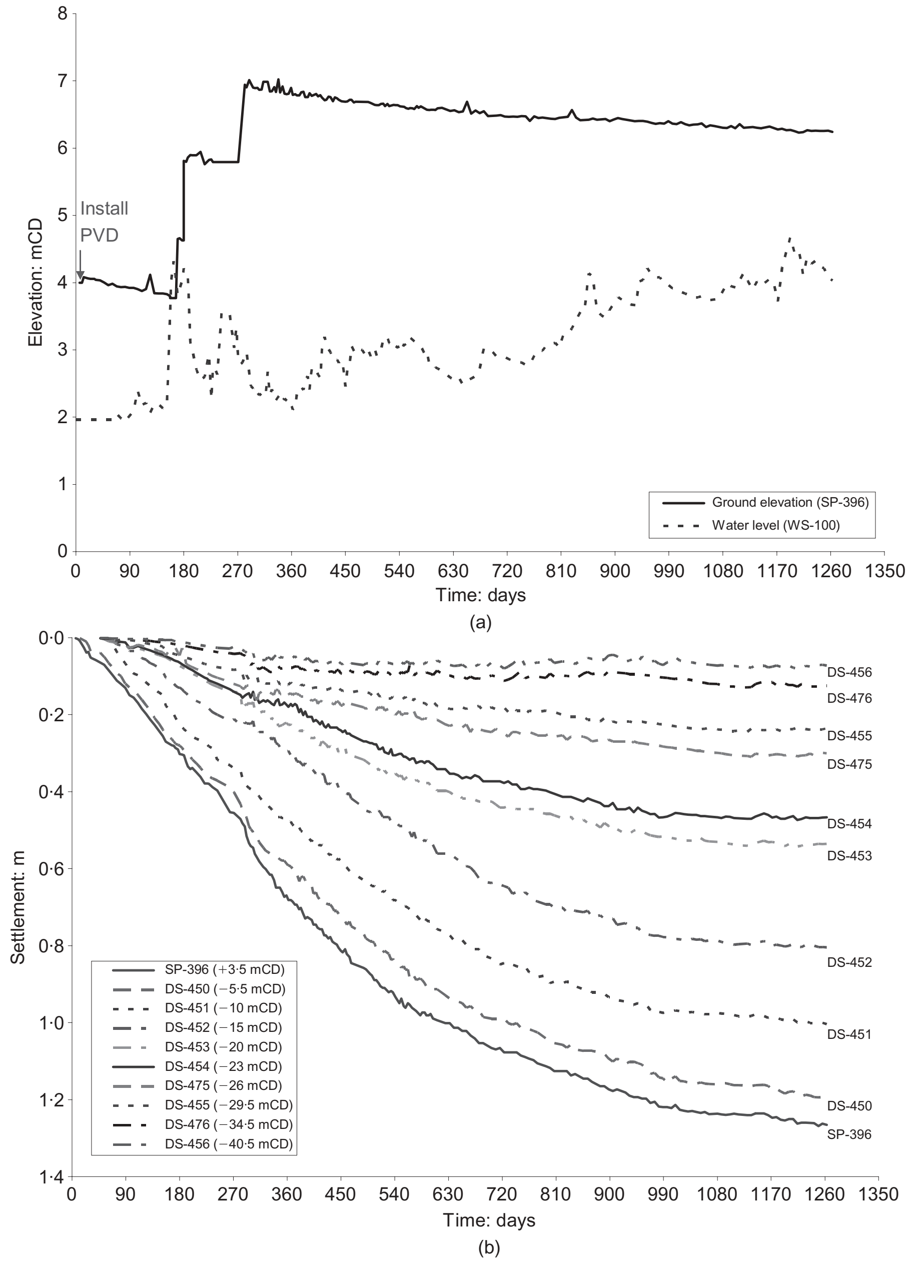

Fig. 6. Field settlement results of settlement gauges for A2S-72 (2·5 m × 2·5 m): (a) elevation; (b) settlement

installed in a separate borehole at different elevations of the marine clay sub-layers. This enables measurement of the magnitude of deformation of these sub-layers. A PVC pipe extension is provided for the deep settlement gauges to eliminate the effect of downdrag onto the rod of the gauges. Field settlement monitoring data can be used to ascertain the settlement of the reclaimed fill from the time of initial installation. These data can be analysed by the Asaoka and hyperbolic methods to predict the ultimate settlement of the reclaimed land under the surcharge fill. Back-analysis of the data will also enable the coefficient of consolidation for horizontal flow to be closely estimated. Factors that affect prediction by the Asaoka method are the assessment period after surcharge placement, and the time interval used for the analysis (Bo *et al.*, 1999; Arulrajah *et al.*, 2003). Prediction by the hyperbolic method is affected by the assessment period after surcharge placement (Bo *et al.*, 1999; Arulrajah *et al.*, 2003).

Pneumatic and vibrating-wire electric piezometers were installed to monitor the dissipation of excess pore pressures of the marine clay under the reclaimed fill load. The piezometers were installed in individual boreholes at various predetermined elevations in the marine clay, in the same instrument clusters as the water standpipes and settlement gauges. The pneumatic and electric piezometers indicate similar measurements for piezometric elevation and excess pore water pressures. Installation of piezometers at the same elevations as the deep settlement gauges allowed correction of the piezometer tip due to large strain settlements of the marine clay under the reclaimed fill. Factors that affect the analysis of piezometers include assessment period, hydrogeologic boundary conditions, settlement of piezometer tip and reduction of initial imposed load due to the submergence effect (Bo *et al.*, 1999, 2003).

Field instrument monitoring was carried out at regular intervals so that the degree of improvement could be

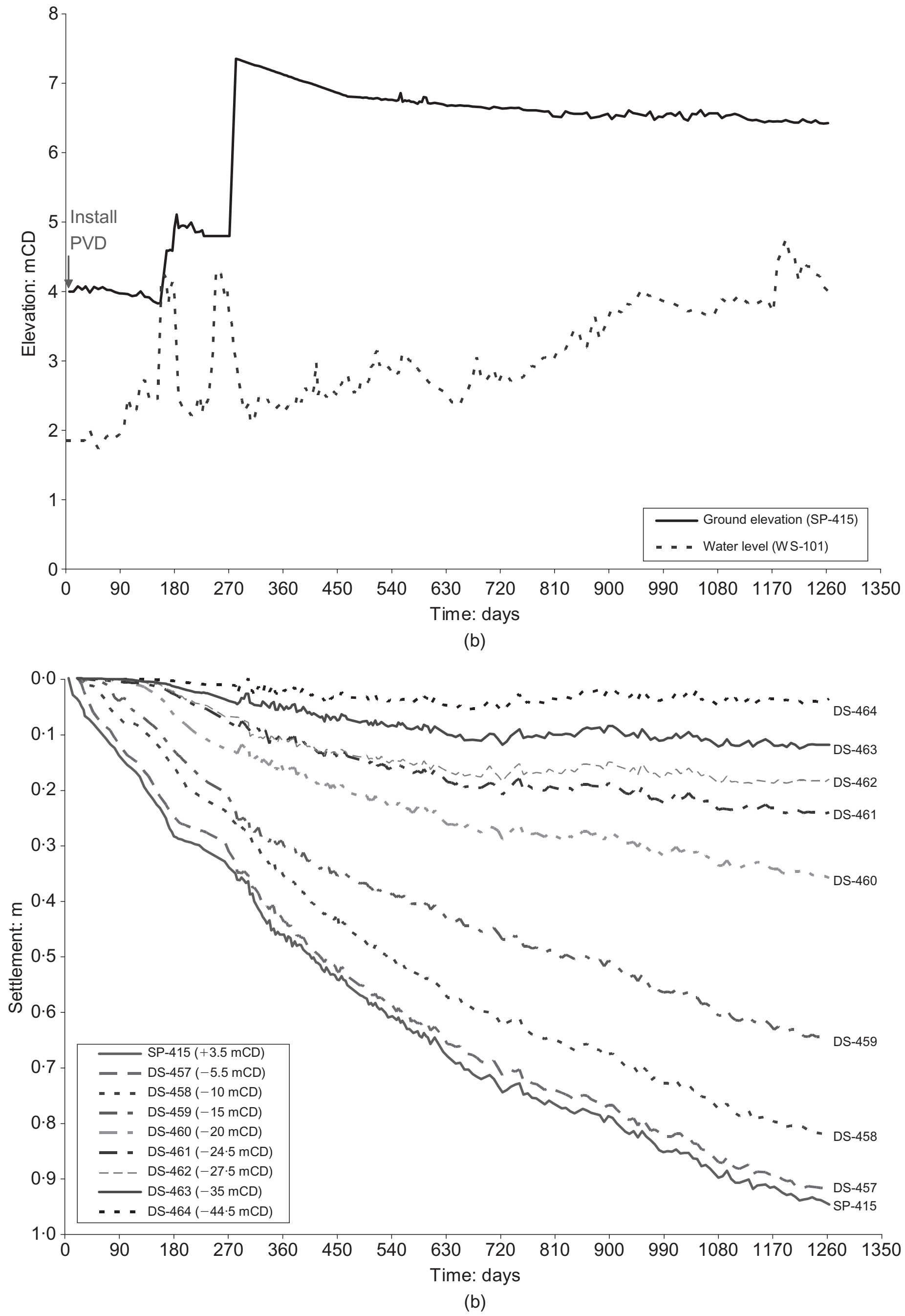

Fig. 7. Field settlement results of settlement gauges for A2S-73 (3·0 m × 3·0 m): (a) elevation; (b) settlement

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. At other times the instruments was usually monitored once a week.

Assessment of field settlement gauges

The Asaoka and hyperbolic methods enable accurate predictions to be made of the ultimate settlement of marine clay. The Asaoka method also enables the coefficient of consolidation due to horizontal flow to be back-analysed. These methods are frequently used in the assessment of degree of improvement of marine clays under reclaimed fills.

Asaoka method

Asaoka (1978) has suggested a procedure modified for application to consolidation problems with vertical drains using the Barron (1948) solution for pure radial drainage. The Asaoka procedure generates a straight line only if the soil behaviour fulfils the assumptions of Terzaghi's theory of one-dimensional consolidation. The use of the Asaoka method for the assessment of the degree of consolidation of marine clays with vertical drains in land reclamation projects has been described by Choa *et al.* (1981), Bo *et al.* (1997, 1999, 2003) and Arulrajah *et al.* (2003).

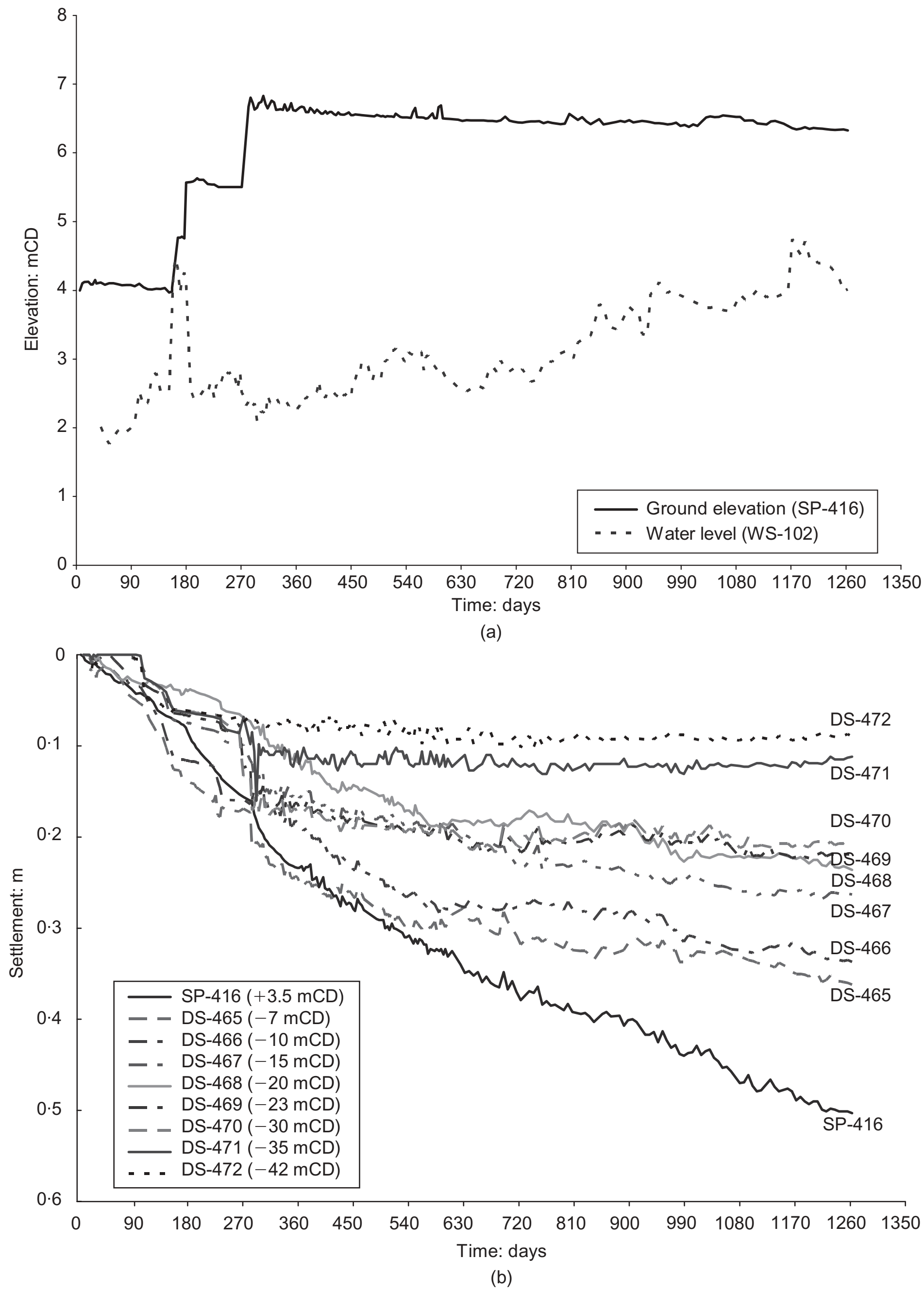

Fig. 8. Field settlement results of settlement gauges for A2S-74 (no drains)

In the Asaoka analysis procedure, the time–settlement curve of the settlement gauge is first plotted. A series of settlement values $s_1, s_2, \ldots, s_n$ is selected, such that s_n is the settlement at time n and the time interval $\Delta t = (t_n - t_{n-1})$ is constant. The next step is to plot the points (s_{n-1}, s_n). These points should lie on a straight line defined as

$$s_n = s_o + \beta s_{n-1} \tag{1}$$

where s_o and β are two constants that depend on the selected time interval, Δt.

The ultimate settlement can then be predicted at the intercept of this line and a 45° line. The constant β represents the slope of the constructed straight line, and it can be related to the coefficient of consolidation due to horizontal flow by

$$C_h = \frac{d_e^2 F(n) \log_e \beta}{8 \Delta t} \tag{2}$$

where d_e is the diameter of the equivalent soil cylinder and $F(n)$ is the drain spacing factor.

Hyperbolic method

In the hyperbolic method, the relationship between consolidation settlement and time is postulated to approach a hyperbolic curve defined as

$$\frac{t}{s} = c + mt \tag{3}$$

This is a straight line in a plot of t/s against t. The equation

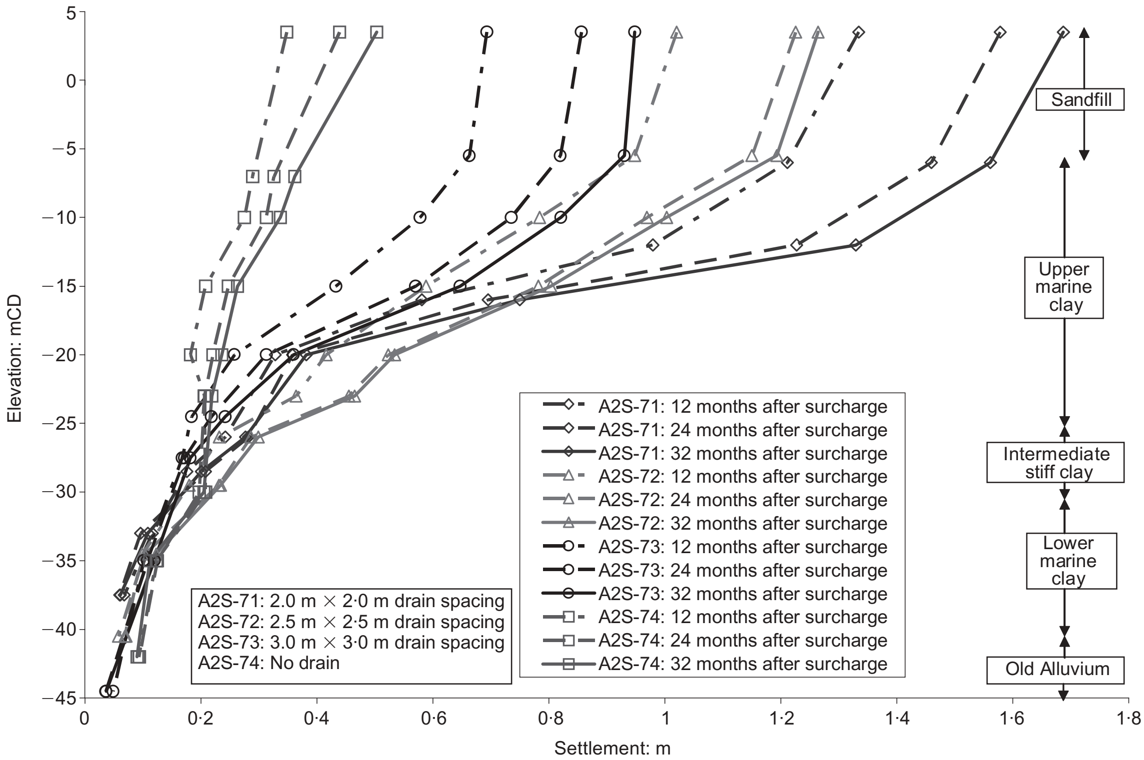

Fig. 9. Comparison of field settlement isochrones between sub-areas at pilot test site

shows that the ultimate settlement is given by $1/m$, which is the inverse of the slope. The use of the hyperbolic method to assess the degree of consolidation of marine clays with vertical drains in land reclamation projects has been described by Choa *et al.* (1981), Bo *et al.* (1997, 1998) and Arulrajah *et al.* (2003). The hyperbolic method is also useful in tracing the loading history of ground improvement works. Changes in the loading sequence will appear as deviations from the hyperbolic line, which can be easily detected (Tan, 1995). A degree of consolidation of at least 60% should be attained by the foundation soil in order for the constants c and m to be estimated for cases of combined vertical and radial drainage (Tan, 1995).

Tan (1995) stated that good estimates of the total primary settlement can be obtained from the inverse slope ($1/m$) multiplied by the theoretical slope factor (α) for cases of combined vertical and radial drainage. The factor α used in the assessment is based on the method proposed by Tan (1995). Ultimate settlement is defined as follows:

$$\text{Ultimate settlement} = \alpha\left(\frac{1}{m}\right) \quad (4)$$

Degree of consolidation of settlement gauges

From measured settlement and predicted ultimate settlement, the degree of consolidation can be estimated:

$$U = \frac{S_t}{S_{\text{ult}}} \quad (5)$$

where S_t is the settlement at time t, S_{ult} is the ultimate primary settlement predicted by the Asaoka or hyperbolic methods, and U (%) is the degree of consolidation.

Analyses of settlement gauges

Figure 4 compares the settlement plate results between the various sub-areas in the pilot test site. The A2S-71 (2·0 m × 2·0 m) sub-area records the highest magnitude and rate of settlement as compared with the other sub-areas, owing to its closer drain spacing. The A2S-74 (no drains) sub-area, on the other hand, records the lowest magnitude and rate of settlement.

The vast improvement of the sub-areas treated with vertical drains compared with the sub-area with no drains is clearly evident in the figure: the closer the vertical drain spacing, the higher the corresponding magnitude of settlement. Sub-area A2S-71, with the closest drain spacing, shows the highest settlement readings, whereas the untreated sub-area A2S-74 shows the least. This indicates that the vertical drains are functioning as per their requirements.

The magnitudes of settlement of sub-areas A2S-71, A2S-72, A2S-73 and A2S-74 are shown in Figures 5, 6, 7 and 8 respectively.

Figure 9 compares the field settlement isochrones for the various sub-areas at various durations after surcharge. The settlement gauges that were installed 0·5 m beneath the vertical drain platform level in the reclamation sand and the deep settlement gauges that were installed at the top surface of the compressible marine clay gave similar readings for magnitude and rate of settlement. This indicates that the settlement contribution of the sandfill layer is minimal, as would be expected. The deep settlement gauges that were installed in the different sub-layers indicate decreasing settlement with depth, as would also be expected.

The settlement gauges indicate increasing settlement in the marine clay with increase in surcharge duration. The marine clay is observed to be softer and with higher compression parameters in the upper layer. The settlement gauges installed in the very deep underlying dense sand layer indicate minimal settlement with increasing surcharge duration, which is expected. The settlement isochrones confirm that the sub-area with the closest drain spacing registers the highest settlements. The settlement isochrones indicate a trend of decreasing settlement for the deeper

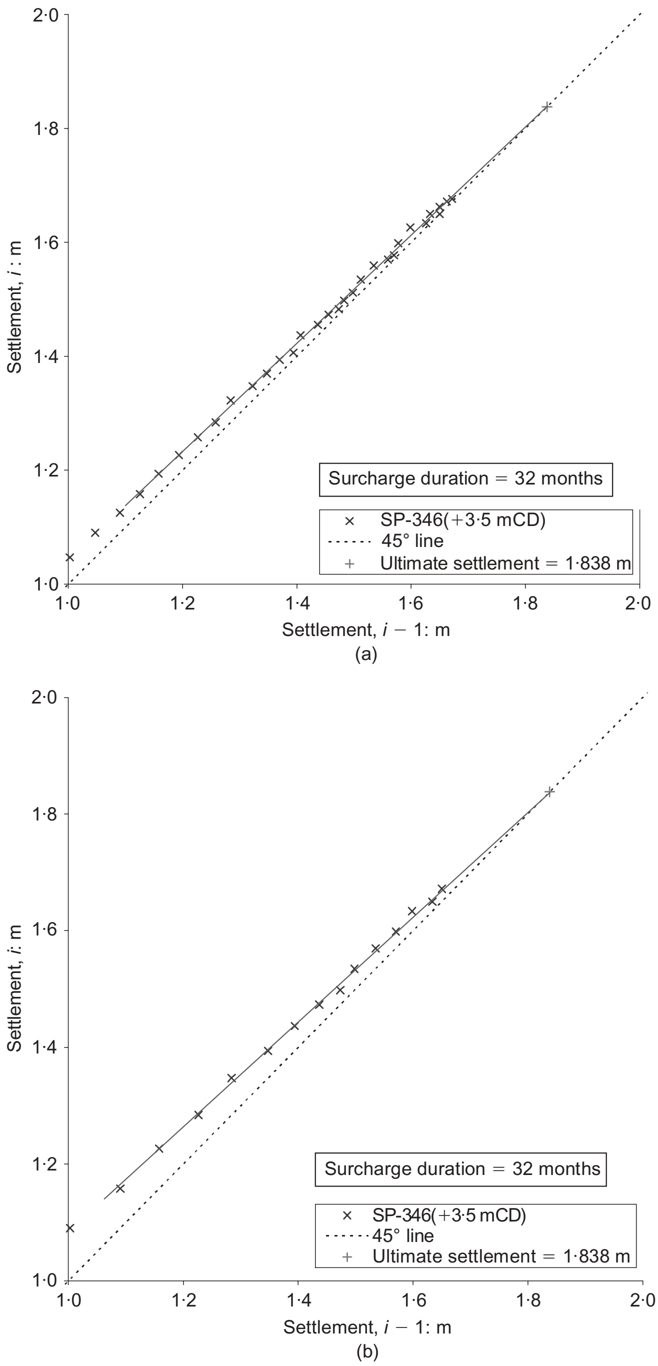

Fig. 10. Asaoka plot for A2S-71 (2·0 m × 2·0 m) at time interval of: (a) 28 days; (b) 56 days

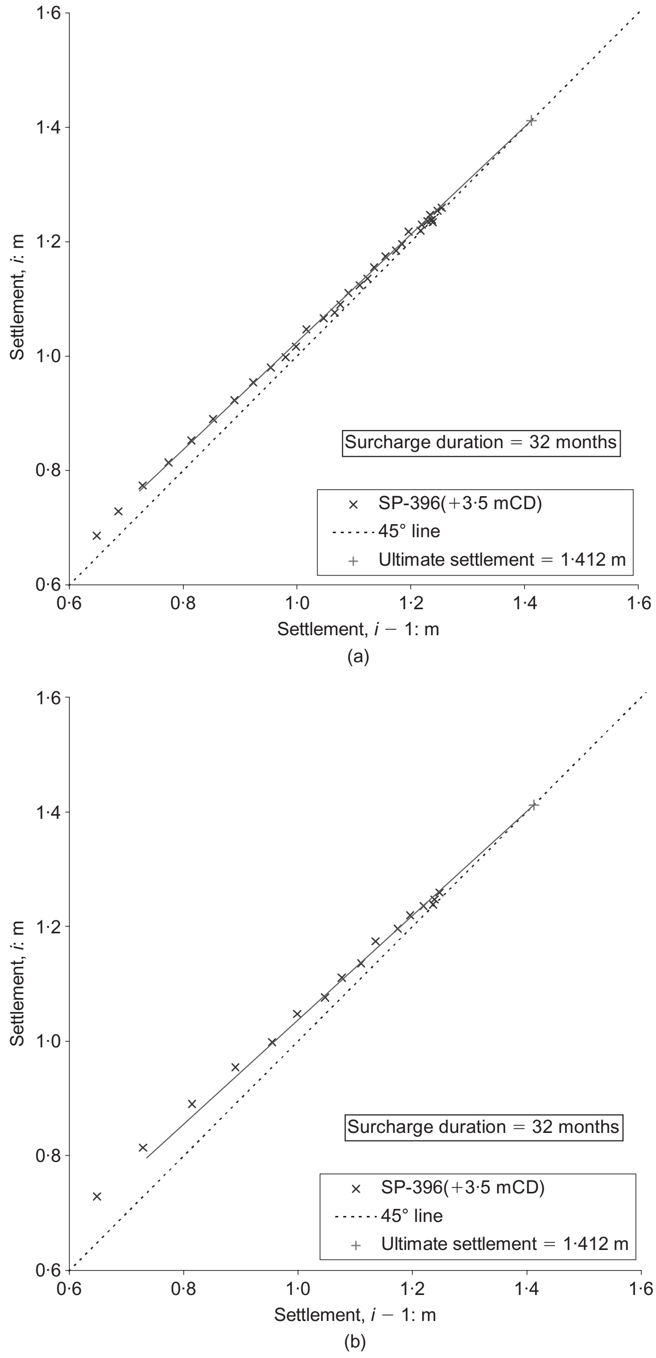

Fig. 11. Asaoka plot for A2S-72 (2·5 m × 2·5 m) at time interval of: (a) 28 days; (b) 56 days

settlement gauges, which is due to the marine clay increasing in density, stiffness, strength, and the compression parameters decreasing with depth. Minimal settlement is recorded in the hard old alluvium layer. Plotting settlement isochrones is a useful means of checking whether the settlement gauges for the clusters are functioning properly.

The settlement gauges in the pilot test site were analysed by the observational method by means of the Asaoka and hyperbolic method predictions. Arulrajah *et al.* (2003) have discussed the factors affecting prediction by these two methods. They stated that, for the Asaoka method, as the time interval increases, a cut-off time interval is obtained after which increasing time intervals would converge to the same magnitude of ultimate settlement. The selection of a smaller time interval than that of the cut-off time interval for the Asaoka method will result in a higher magnitude of ultimate settlement and correspondingly a lower degree of consolidation. However, the use of increasing time intervals would be restricted by the number of data points available to assess the best-fit line. Arulrajah *et al.* (2003) have also stated that the C_h value back-analysed by the Asaoka method is dependent on the time interval used for the prediction. Furthermore the C_h value predicted by the Asaoka method decreases and converges to the actual value as increasing time intervals are used in the back-analysis. Arulrajah *et al.* (2003) recommend that, for the hyperbolic method, a longer assessment period should be used in the prediction as the magnitude of ultimate settlement increases

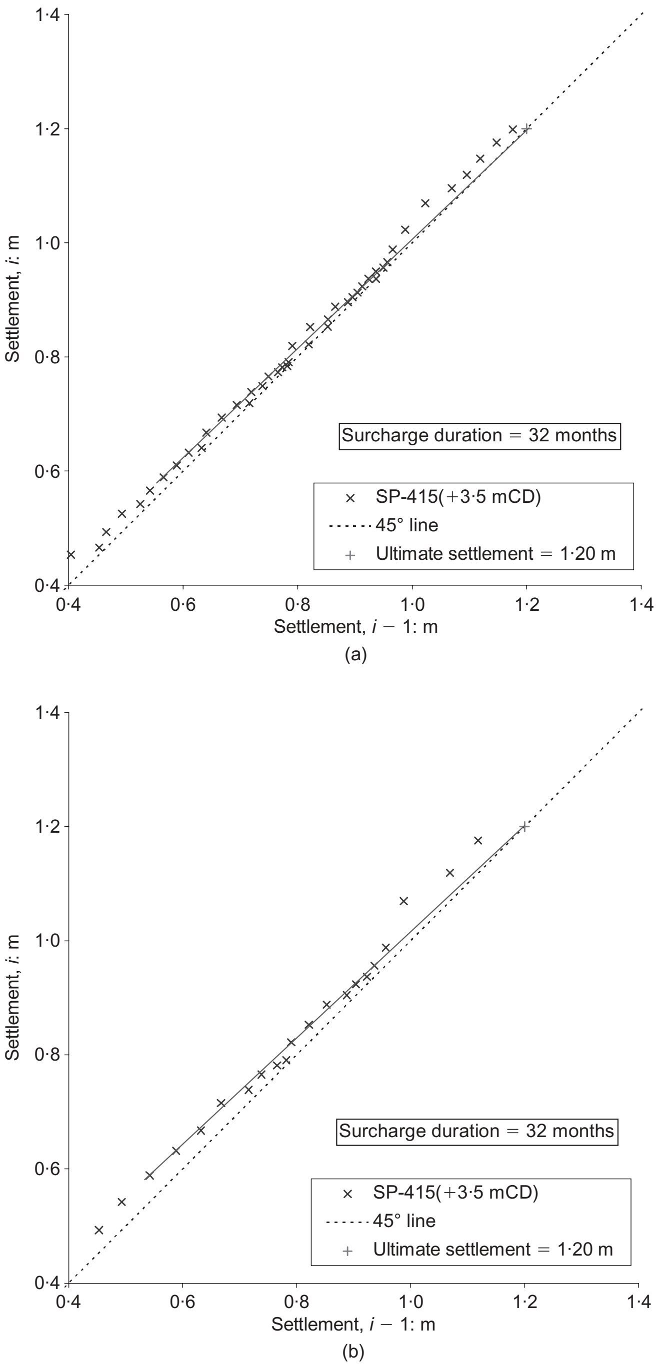

Fig. 12. Asaoka plot for A2S-73 (3·0 m × 3·0 m) at time interval of: (a) 28 days; (b) 56 days

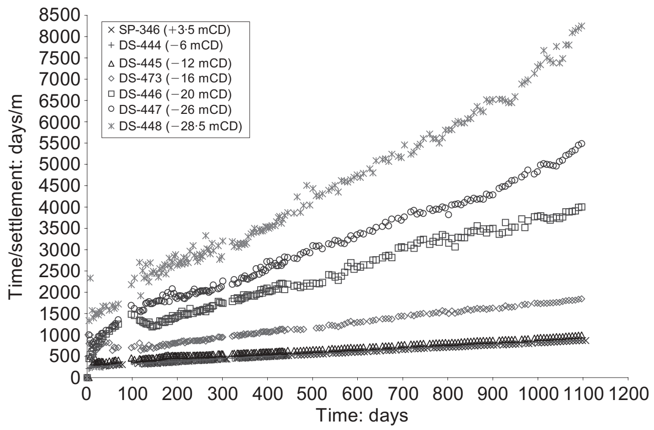

Fig. 13. Combined hyperbolic plot of settlement gauges for A2S-71 (2·0 m × 2·0 m)

and subsequently the degree of consolidation decreases as a longer assessment period is used.

Relatively large time intervals of 28 and 56 days have been used in the Asaoka predictions in this paper, following the recommendations of Arulrajah *et al.* (2003), for which the cut-off time interval was ascertained to be 28 days. The Asaoka and hyperbolic predictions have also been carried out 32 months after surcharge placement. Based on the ultimate settlements obtained from the Asaoka and hyperbolic predictions, the degrees of consolidation of the marine clay for the vertical drain treated sub-areas were subsequently computed.

Figures 10–12 show the Asaoka plot predictions at time intervals of 28 and 56 days for the settlement plates at the A2S-71, A2S-72 and A2S-73 sub-areas of the pilot test site. Figs 13 and 14, 15 and 16, and 17 and 18 show respectively the combined and typical hyperbolic plots for the settlement gauges at A2S-71 (2·0 m × 2·0 m), A2S-72 (2·5 m × 2·5 m) and A2S-73 (3·0 m × 3·0 m).

Normally, for the same surcharge and the same thickness of clay, the same amount of ultimate settlement is obtained after a long time. However, in the pilot test site, there are variations in the final predicted settlements, for various reasons. It is apparent that the A2S-71 sub-area has the highest level of intermediate marine clay layer. In addition, higher excess pore pressures were recorded in the A2S-71 and A2S-74 (no drains) sub-areas, which indicates a lower effective stress compared with the other sub-areas. Furthermore, settlement of the sub-areas prior to the installation of instruments will also result in variations in the settlement measured after installation of instruments.

Assessment of piezometers

Pneumatic piezometers were installed in the same clusters and close to the same elevation as the settlement gauges, to enable correction of the piezometer tip due to large strain settlement. Water standpipes were installed in the clusters so as to measure the static water level at these locations and hence ascertain the excess pore water pressures of the piezometers.

The piezometers indicate measurements for piezometric head. They are utilised to measure the pore pressure in the soil. Regular monitoring was carried out to measure the piezometric head together with static water level, so that changes of excess pore pressure due to additional load and hence the degree of consolidation could be computed. The method of computation of the average degree of consolidation is defined as

$$U = 1 - \frac{U_t}{U_{\mathrm{i}}} \qquad (6)$$

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 ($\Delta\sigma'$). Piezometers were installed at different elevations so that the average degree of consolidation for the whole

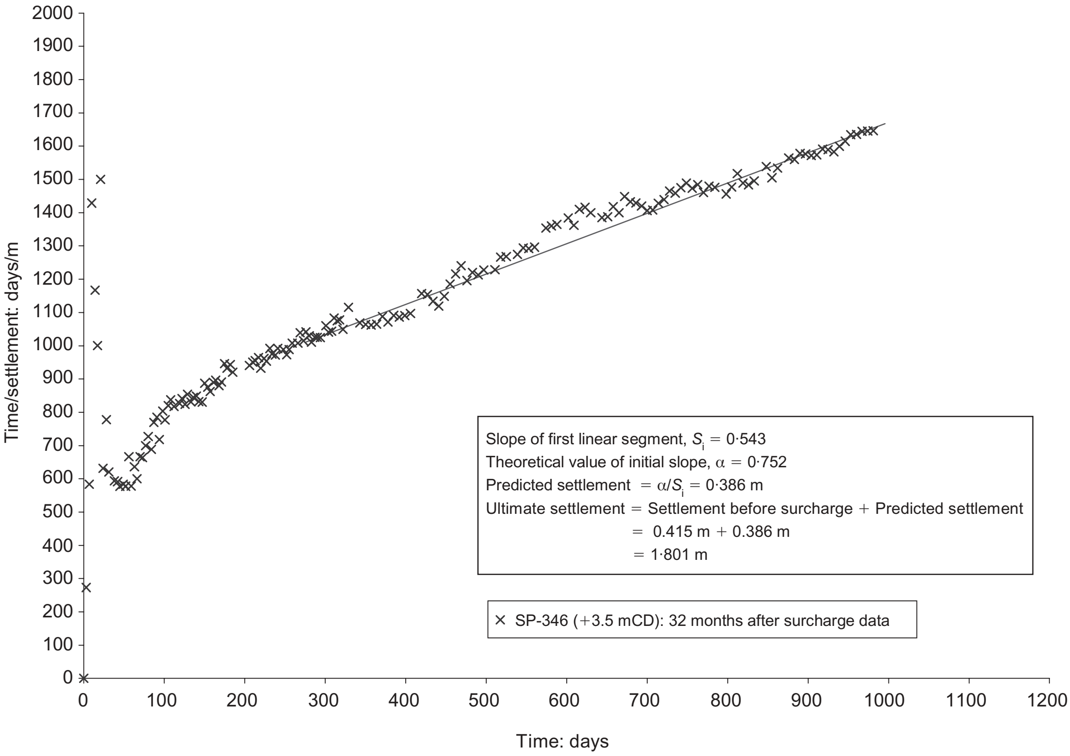

Fig. 14. Hyperbolic plot for A2S-71 (2·0 m × 2·0 m) after surcharge duration of 32 months

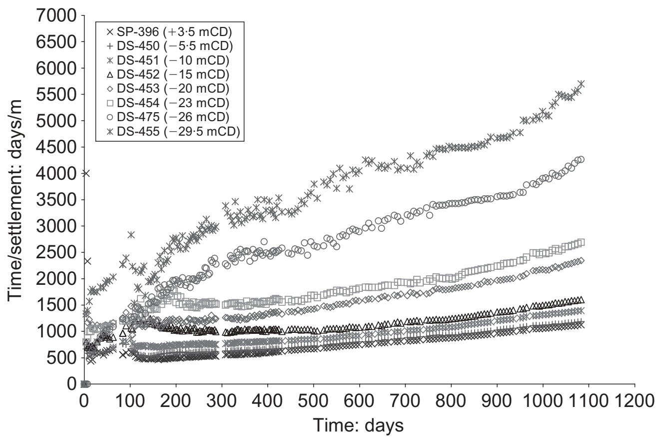

Fig. 15. Combined hyperbolic plot of settlement gauges for A2S-72 (2·5 m × 2·5 m)

compressible unit as well as that of each of the sub-layers could be determined.

Owing to the large strain settlements at the site, all raw piezometer readings were corrected to account for the new elevation of the piezometer at each monitoring due to the settlement of the piezometer tip. The settlement of the adjacent deep settlement gauges in the cluster at about the same respective elevation was used to adjust 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.

Back-analysis of coefficient of consolidation

From field pore pressure measurements, the coefficient of consolidation due to horizontal flow can be back-analysed. The first step is to determine the degree of consolidation at the particular time using equation (6). Then the non-dimensional time factor, T_h, has to be determined using the following equation:

$$U_r = 1 - \exp\frac{-8T_h}{F(n)} \tag{7}$$

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, and $F(n)$ is the vertical drain factor, which is given by

$$F(n) = \left(\frac{n^2}{n^2-1}\right)\log_e(n) - \left(\frac{3n^2-1}{4n^2}\right) \tag{8}$$

where n is the drain spacing ratio $= d_e/d_w$: $d_e = 1{\cdot}13$ times the drain spacing for square pattern, and 1·05 times the drain spacing for triangular pattern; $d_w = [2(a+b)]/\pi$, where a is the drain width and b is the drain thickness.

The 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).

Total time method:

$$C_h = \frac{T_h d_e^2}{t} \tag{9}$$

Incremental time method:

$$C_h = \frac{T_{h2} - T_{h1}}{t_2 - t_1} d_e^2 \tag{10}$$

Analyses of piezometers

The piezometer monitoring data for all the sub-areas have been corrected to account for the settlement of the piezometer tip. All the piezometers indicate a marked increase in piezometric elevations and excess pore water pressures during the surcharge placement at around the 120 day mark.

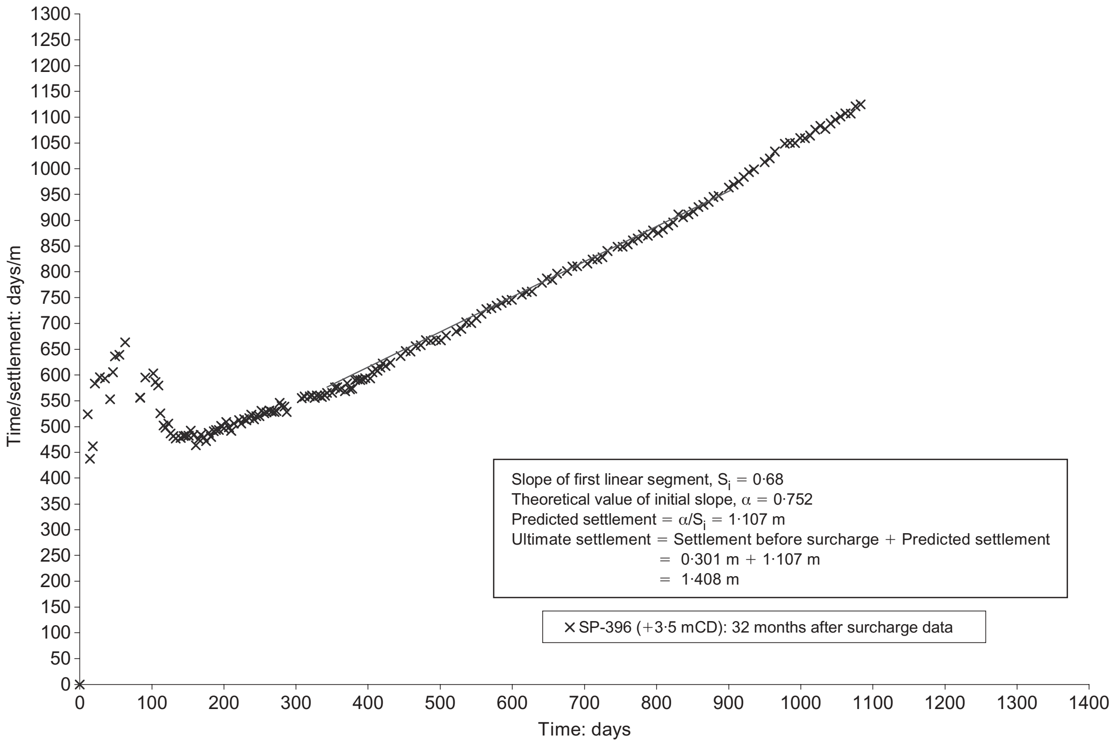

Fig. 16. Hyperbolic plot for A2S-72 (2·5 m × 2·5 m) after surcharge duration of 32 months

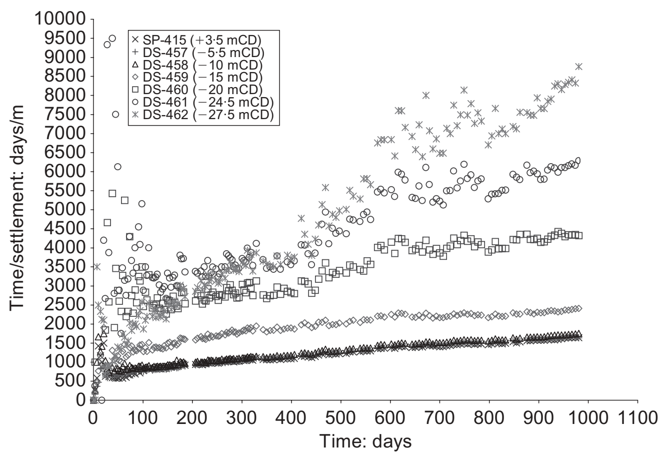

Fig. 17. Combined hyperbolic plot of settlement gauges for A2S-73 (3·0 m × 3·0 m)

This is followed by a gradual dissipation of the excess pore water pressures during the surcharge period in the sub-areas with vertical drains, which indicates an increasing degree of consolidation of the marine clay over time. The no drains area also indicates this trend, but to a far lesser extent.

At approximately the 1170 day mark, some piezometers pick up a slight rise in piezometric elevation and excess pore water pressures, which is attributable to surcharge placement at areas adjacent to or close to these sub-areas. The piezometers are noted to be sensitive to the surcharge placement operations and the loading pressure bulbs of these adjacent areas. Damage to piezometers is indicated by an extremely rapid increase in certain readings of piezometric elevation and excess pore water pressure. A sudden loss of signal could be attributable to damage from moving machinery.

The piezometer elevations and excess pore water pressures for the four sub-areas (A2S-71, A2S-72, A2S-73 and A2S-74) are shown in Figs 19, 20, 21 and 22 respectively. Higher excess pore pressures were recorded in the A2S-71 and A2S-74 sub-areas, which indicates a comparatively lower effective stress than in the other two sub-areas. Fig. 23 compares the excess pore pressure isochrones between the sub-areas 32 months after surcharge. Non-uniform variation of the excess pore pressure with elevation is due to slight differences in the installed location of the piezometer from the vertical drains, as well as the presence of thin sand lenses (so-called microlayers).

Figure 24 compares the degree of consolidation between the sub-areas 32 months after surcharge. Rapid dissipation of excess pore water pressure with time is clearly evident in the sub-areas treated with vertical drains, compared with the sub-area with no drains. The sub-area with the closest vertical drain spacing is, in general, found to register the highest degree of consolidation at a particular elevation. Some exceptions to this are found at certain elevations: this could be due to slight variations of the soil profiles between the various sub-areas. Furthermore, the presence of sand seams in the marine clay will increase its permeability and enable the excess pore water pressure in it to drain relatively rapidly. Piezometers installed close to the reclamation sand boundary near the top of the marine clay are found to register reducing excess pore water pressure with time and thus a higher degree of consolidation, which is due to their being installed close to the drainage boundary. Piezometers installed close to the dense sand layer at the bottom of the marine clay are also found to register a reducing excess pore water pressure with time and thus a higher degree of consolidation, confirming that there is bottom drainage of excess pore water pressure into the permeable sand layer. Evidently, from the findings in the

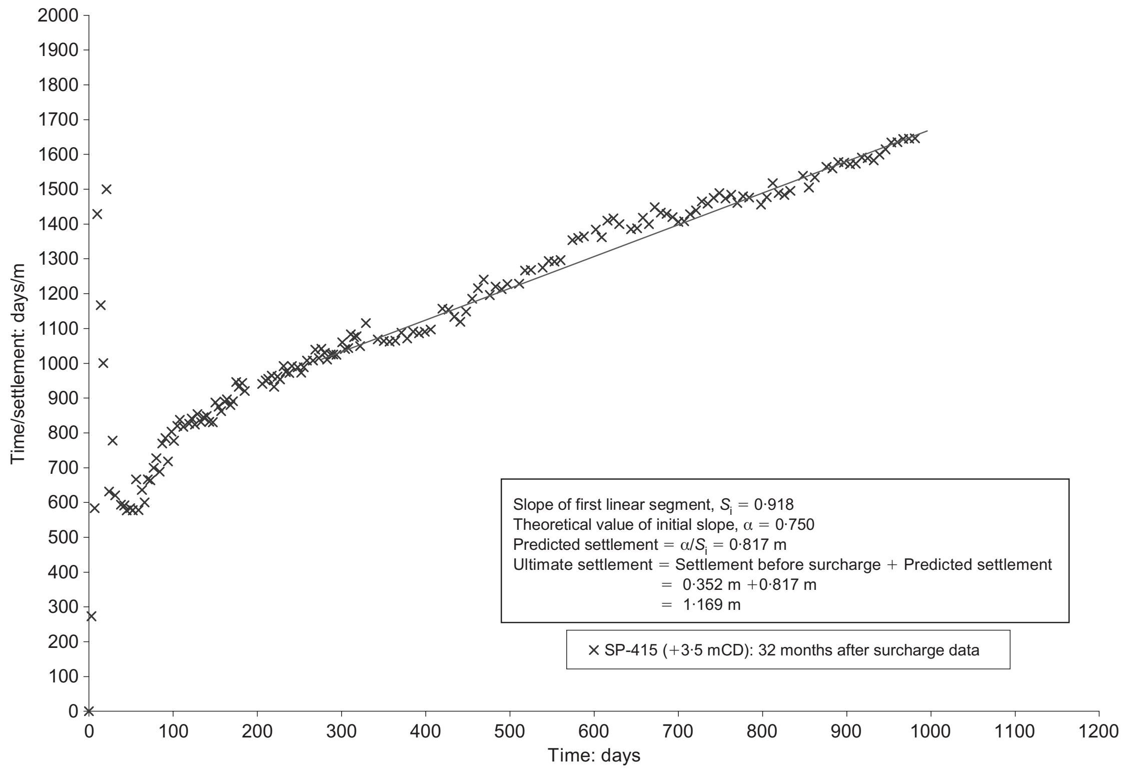

Fig. 18. Hyperbolic plot for A2S-73 (3·0 m × 3·0 m) after surcharge duration of 32 months

figures, the degree of consolidation is highest for the sub-area with the closest vertical drain spacing and lowest for the no drains sub-area.

Comparison of observational methods

Table 2 summarises the comparison of degree of consolidation and back-analysed C_h between the settlement plates and piezometers at the various sub-areas 32 months after surcharge, obtained by the observational methods. The degree of consolidation of the sub-areas treated with vertical drains is observed to be far greater than that of the no drains sub-area.

Results and discussions

The Asaoka method indicates that, at the end of the surcharging period of 32 months, the sub-area with the closest vertical drain spacing (A2S-71: 2·0 m × 2·0 m) has achieved a degree of consolidation of 91·8%, whereas that with the widest vertical drain spacing (A2S-73: 3·0 m × 3·0 m) has achieved a degree of consolidation of 79·0%.

The hyperbolic method indicates that, at the end of the surcharging period of 32 months, sub-area A2S-71 has achieved a degree of consolidation of 93·7%, whereas sub-area A2S-73 has achieved a degree of consolidation of 81·1%.

The piezometer indicates that, at the end of the surcharging period of 32 months, sub-area A2S-71 has achieved a degree of consolidation of 86·2%, whereas the untreated sub-area (A2S-74) has achieved a degree of consolidation of only 37·0%.

The ultimate settlements and degrees of consolidation as obtained by the Asaoka and hyperbolic methods are found to converge, and to be in excellent agreement after the surcharge period of 32 months. The degree of consolidation predicted by the hyperbolic method is found to be slightly higher than that by the Asaoka method. The piezometer indicates a lower degree of consolidation than the field settlement predictions. This can be attributed to the non-linearity of the stress–strain behaviour of soil (Mikasa, 1995).

The C_h values of the marine clay back-calculated by the Asaoka and piezometer methods after 32 months of surcharge placement are found to be in good agreement. They both indicate that the back-analysed C_h value is lowest for the sub-area with the closest vertical drain spacing (A2S-71: 2·0 m × 2·0 m) and highest for the sub-area with the furthest vertical drain spacing (A2S-73: 3·0 m × 3·0 m). This can be attributed to the higher degree of smear effect at locations with closer drain spacing.

The main factor accounting for the lower C_h values back-calculated from field settlement measurements is the smear effect incurred by the insertion of the mandrel during the installation of vertical drains. For soft marine clay the smear effect can be quite significant at locations equipped with vertical drains (Chu *et al.*, 2002). Bo *et al.* (2000) have reported that the permeability of soil in the smear zone could be reduced by one order of magnitude or to the horizontal hydraulic conductivity of the remoulded clay as a result of smearing. When drains are installed at close spacing the back-calculated C_h values will generally be greatly influenced by this smear zone (Chu *et al.*, 2002).

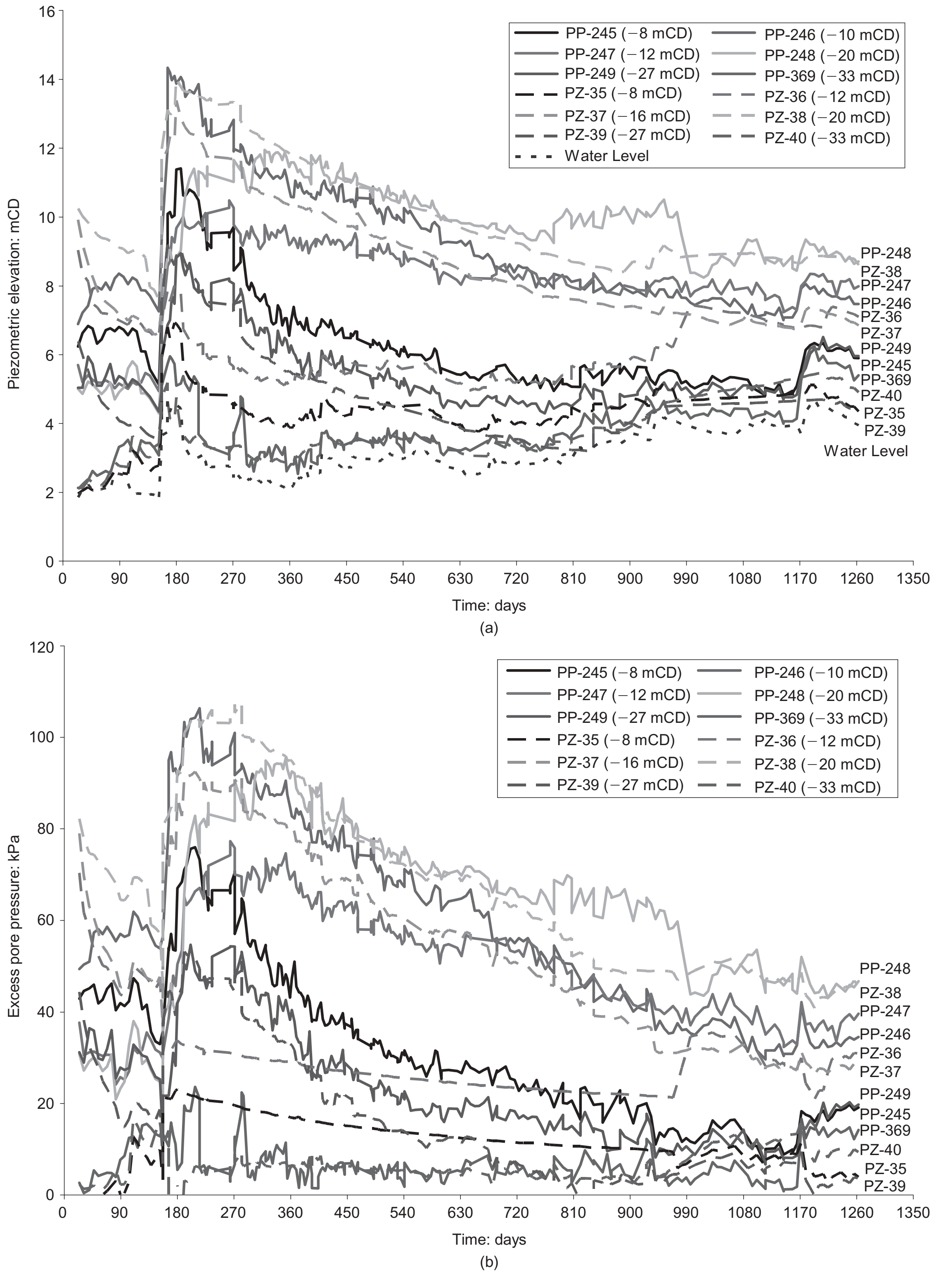

Fig. 19. (a) Piezometric elevations and (b) excess pore water pressures for A2S-71 (2·0 m × 2·0 m)

Conclusions

The magnitude of settlement is highest in sub-area A2S-71, which has the closest vertical drain spacing (2·0 m × 2·0 m), and lowest in sub-area A2S-74 (no drains). Increased settlement and increased consolidation are obtained with closer vertical drain spacings. Similarly, the excess pore water pressure dissipates more rapidly in sub-areas with closer spacing of vertical drains. This indicates that the vertical drains installed in the project are performing to improve the soil drainage system.

Relatively large time intervals of 28 and 56 days have been used in the Asaoka predictions in this paper following the recommendations of Arulrajah *et al.* (2003), for which the cut-off time interval was ascertained to be 28 days. The selection of the time interval to be used in the Asaoka method is of importance in the assessment of the degree of consolidation.

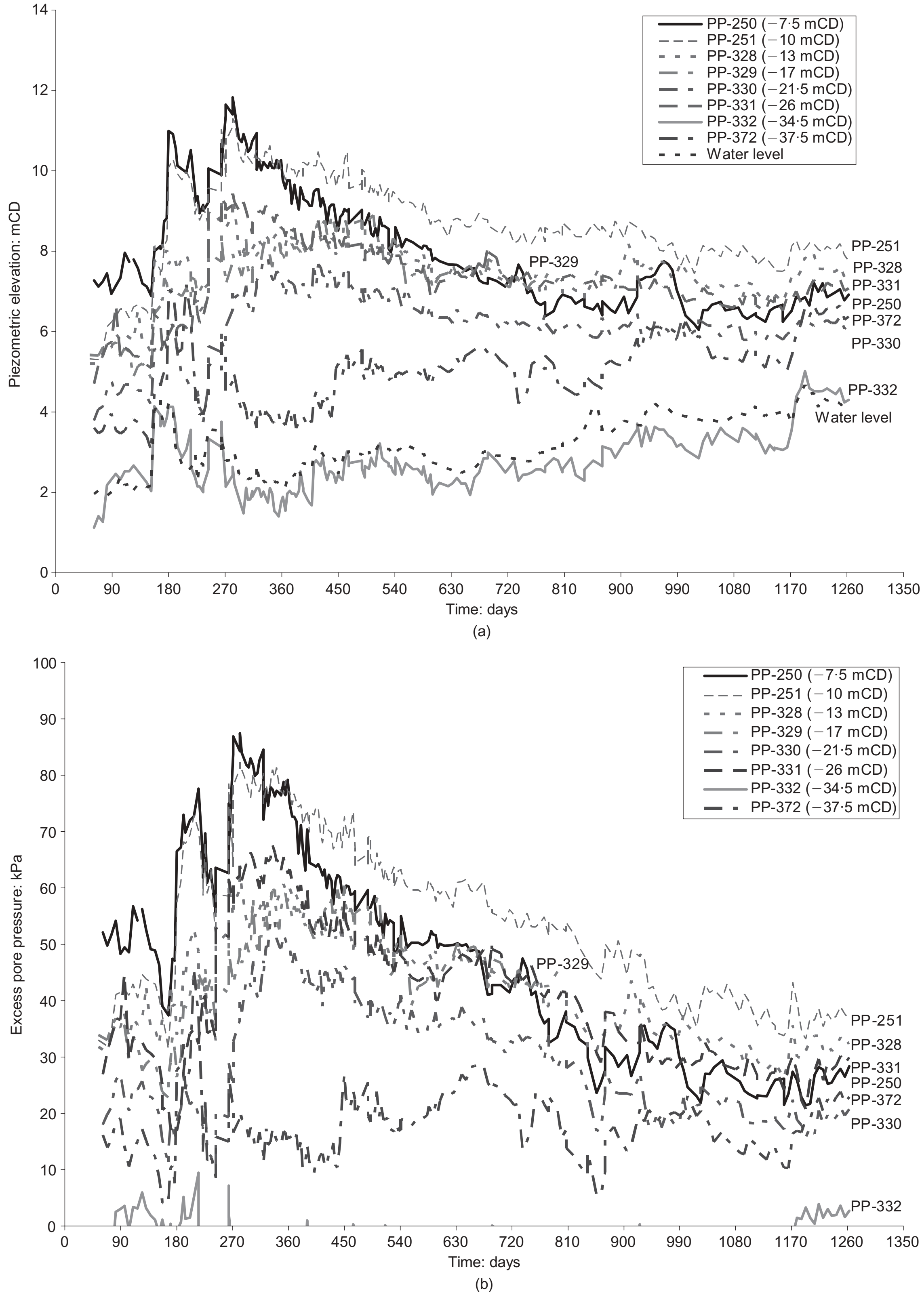

Fig. 20. (a) Piezometric elevations and (b) excess pore water pressures for A2S-72 (2·5 m × 2·5 m)

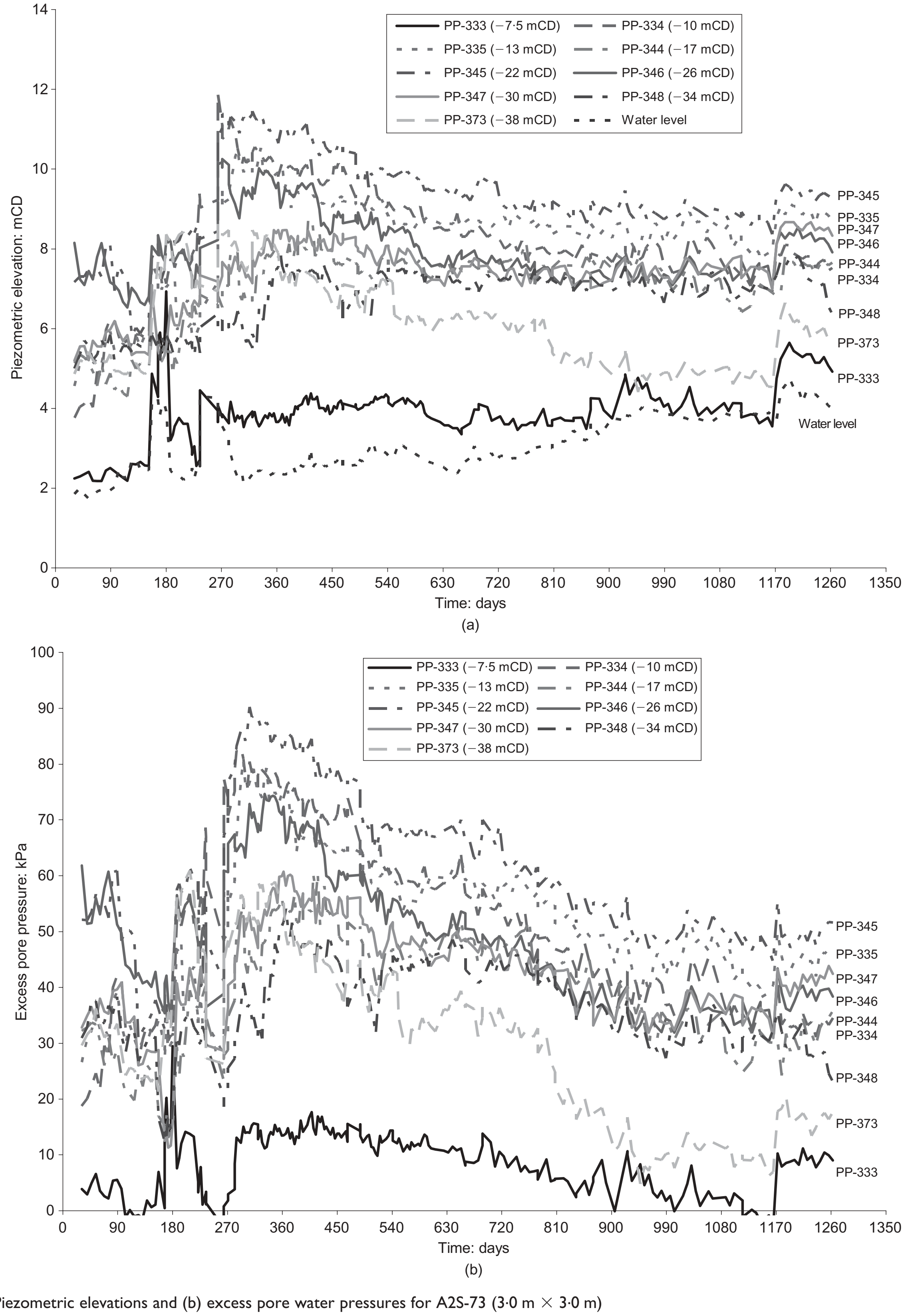

Fig. 21. (a) Piezometric elevations and (b) excess pore water pressures for A2S-73 (3·0 m $\times$ 3·0 m)

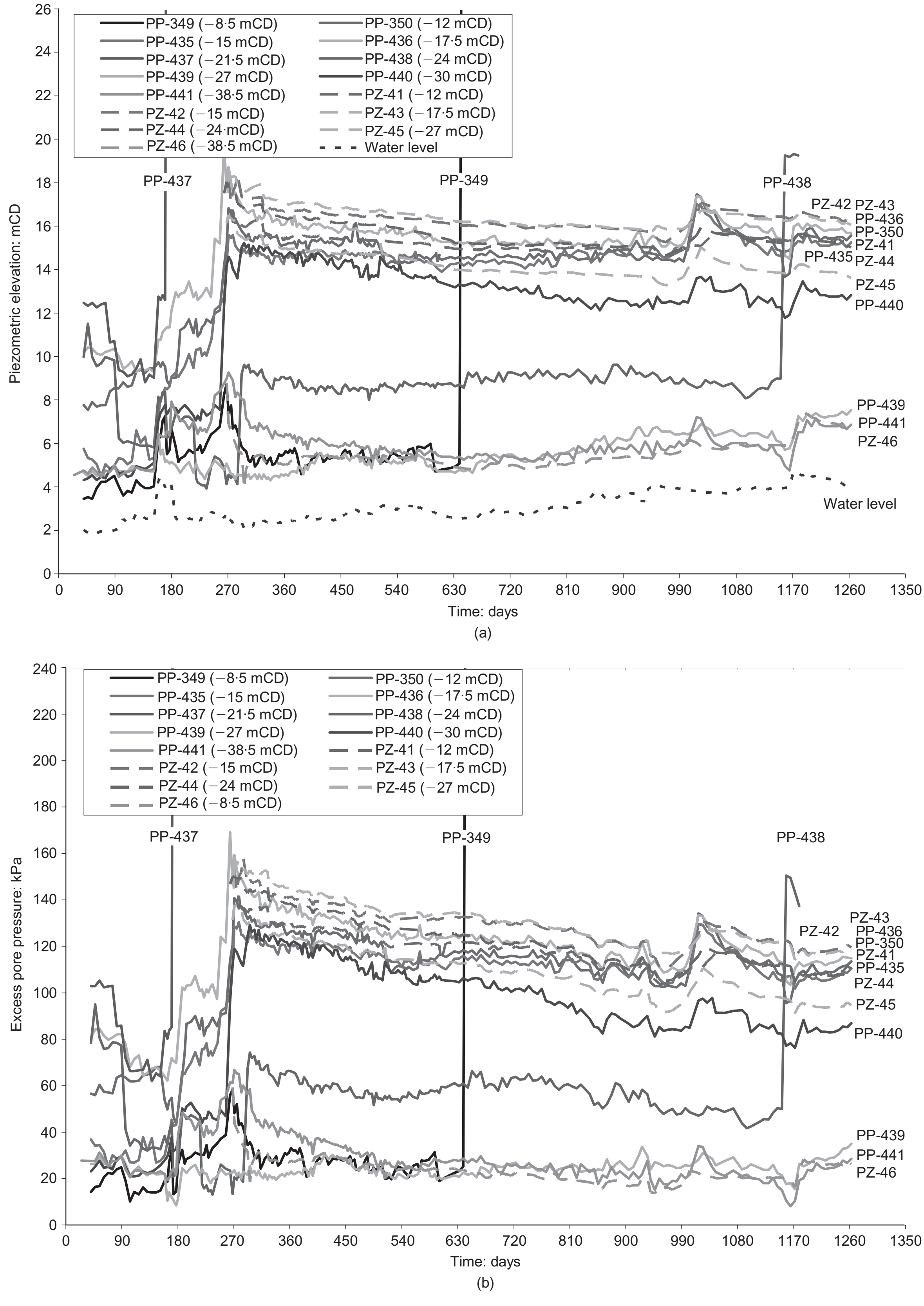

Fig. 22. (a) Piezometric elevations and (b) excess pore water pressures for A2S-74 (no drains)

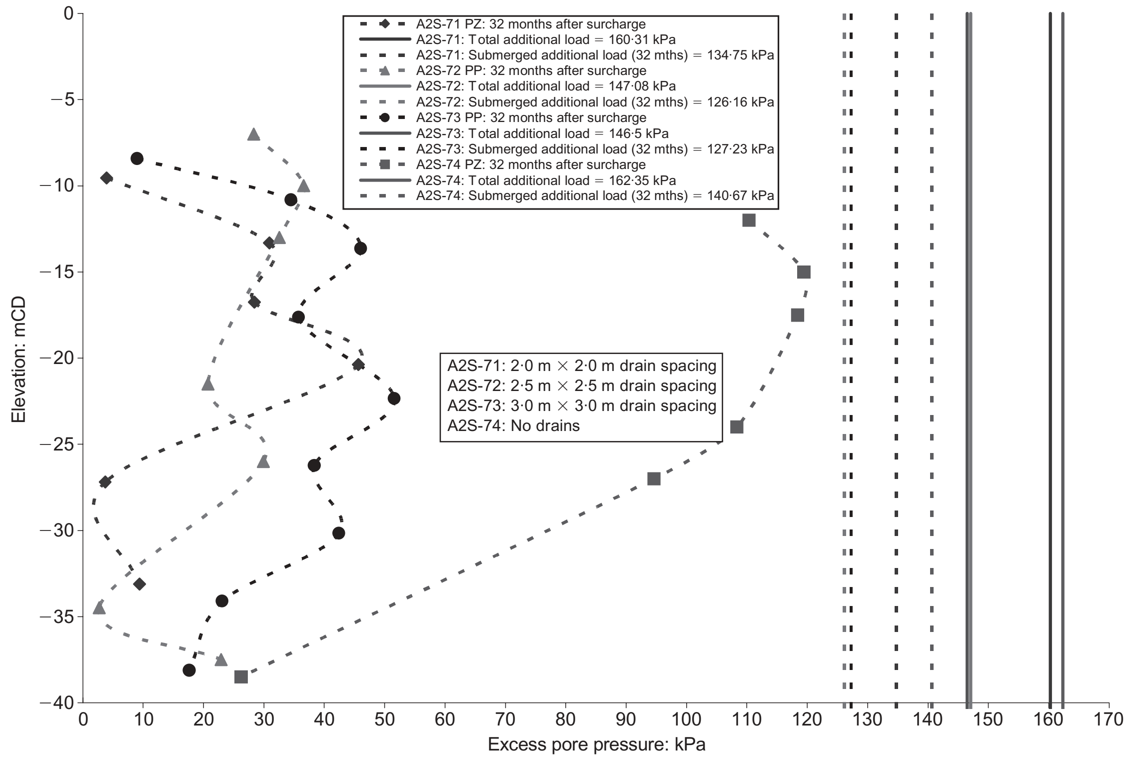

Fig. 23. Comparison of piezometer excess pore pressure isochrones between sub-areas 32 months after surcharge

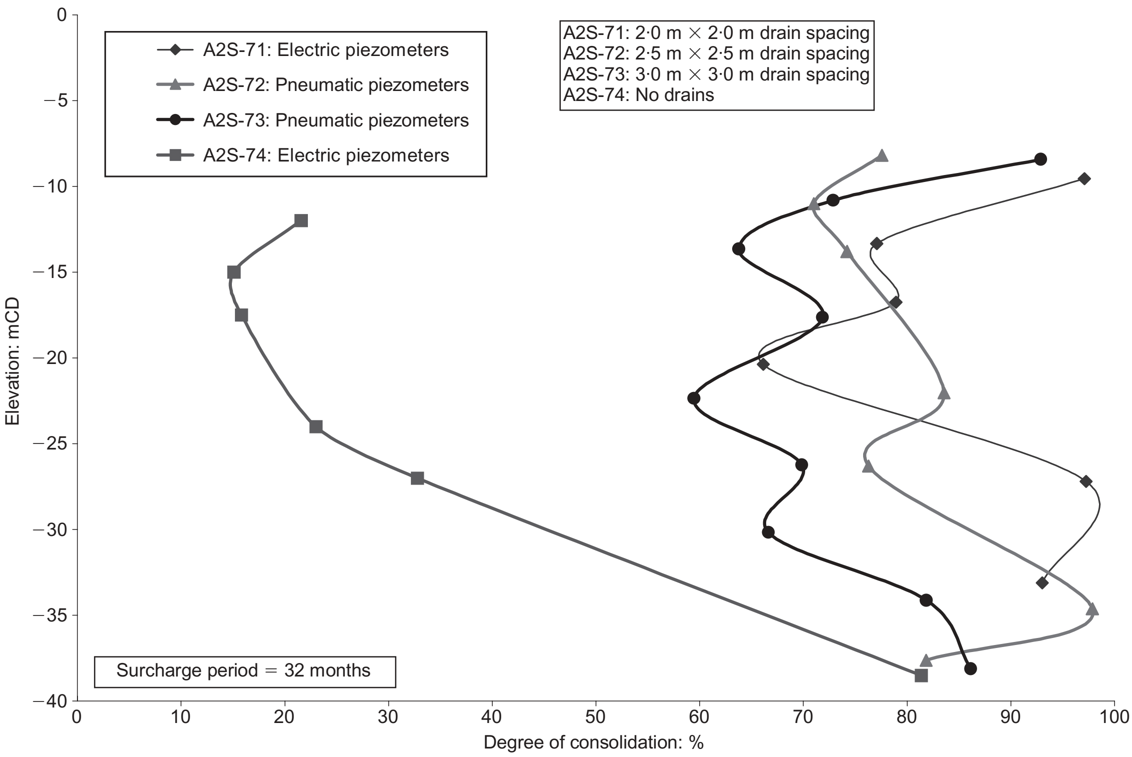

Fig. 24. Comparison of degree of consolidation between sub-areas 32 months after surcharge.

For the hyperbolic method an assessment period of 32 months was used in the prediction of ultimate settlement and subsequently the degree of consolidation. This long assessment period was used as the magnitude of ultimate settlement increases and subsequently the degree of consolidation decreases as a longer assessment period is used.

The ultimate settlement and degree of consolidation obtained by the Asaoka and hyperbolic methods is found to converge to be in excellent agreement with each other after the surcharge period of 32 months. The degree of consolidation predicted by the hyperbolic method is found to be slightly higher than that of the Asaoka method.

Table 2. Comparison of Asaoka, hyperbolic and piezometer methods 32 months after surcharge (41·9 months of monitoring)

Sub-area	Drain spacing	Comparison	Asaoka	Hyperbolic	Piezometer
A2S-71	2·0 m × 2·0 m	Ultimate settlement: m	1·838	1·801	–
		Settlement to date: m	1·687	1·687	–
		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 m × 2·5 m	Ultimate settlement: m	1·412	1·408	–
		Settlement to date: m	1·264	1·264	–
		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 m × 3·0 m	Ultimate settlement: m	1·200	1·169	–
		Settlement to date: m	0·948	0·948	–
		Degree of consolidation, *U*: %	79·0	81·1	73·1
		Back-analysed C_h: m^2/year	2·20	–	2·23
A2S-74	No drains	Degree of consolidation, *U*: %	–	–	37·0

For the piezometer method an assessment period of 32 months was used in predicting the degree of consolidation. Correction for settlement of the piezometer tip is of particular importance for determination of the excess pore water pressures and subsequently the degree of consolidation of marine clay under reclamation fills.

The piezometer indicates a lower degree of consolidation than field settlement predictions. This can be attributed to the non-linearity of the stress–strain behaviour of soil (Mikasa, 1995). Similar findings have been reported by Bo *et al.* (1999).

The C_h values back-calculated by the Asaoka and piezometer methods 32 months after surcharge placement are found to be in good agreement. Both methods indicate that the back-analysed C_h value of the marine clay is lowest for the sub-area with the closest vertical drains spacing (A2S-71: 2·0 m × 2·0 m) and highest for the sub-area with the widest vertical drain spacing (A2S-73: 3·0 m × 3·0 m). This can be attributed to the higher degree of smear effect at locations with closer drain spacing.

Acknowledgements

The authors are most grateful to Dr A. Vijiaratnam, the former chairman of SPECS Consultants (Singapore) Pte Ltd, for his encouragement and full support in the submission of these findings.

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Discussion contributions on this paper should reach the editor by 1 April 2005