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Soil disturbance analysis due to vertical drain installation

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Abstract

The installation of drains creates a disturbed region known as a smear zone where the change in the clay structure affects the horizontal permeability and compressibility. The parameters required to characterise the smear effect are the extent of the smear zone and the ratio of the horizontal coefficient of permeability in the undisturbed zone and in the smear zone. Only limited studies have been carried out on different aspects of soil disturbance due to driving vertical drains and its effects on the subsequent consolidation. In this paper the disturbed zone around a rectangular mandrel was characterised using soil samples obtained from the soft clay layer at various locations beneath an embankment built at Ballina, Australia, where vertical drains were installed. By determining the change in the coefficient of permeability, the water content and volume compressibility across the smear zone, the effects of soil disturbance on consolidation due to the installation of drains can be quantified using the available numerical model.

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Soil disturbance analysis due to vertical drain installation

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The installation of drains creates a disturbed region known as a smear zone where the change in the clay structure affects the horizontal permeability and compressibility. The parameters required to characterise the smear effect are the extent of the smear zone and the ratio of the horizontal coefficient of permeability in the undisturbed zone and in the smear zone. Only limited studies have been carried out on different aspects of soil disturbance due to driving vertical drains and its effects on the subsequent consolidation. In this paper the disturbed zone around a rectangular mandrel was characterised using soil samples obtained from the soft clay layer at various locations beneath an embankment built at Ballina, Australia, where vertical drains were installed. By determining the change in the coefficient of permeability, the water content and volume compressibility across the smear zone, the effects of soil disturbance on consolidation due to the installation of drains can be quantified using the available numerical model.

Notation

c_c	gradient of compression line of reconstituted soil
c_h	coefficient of consolidation for horizontal drainage (m^2/d)
c_k	permeability index
d_e	diameter of influenced zone (m)
e	void ratio
$e_{iD(ICL)}$	void ratio on isotropic compression line (ICL) at the intercept of line AB and the isotropic compression line
e_{SC}	void ratio of undisturbed soil at yield stress
e_{SD}	void ratio of partially disturbed soil at yield stress
H	thickness of clay (m)
K	ratio of horizontal permeability of the undisturbed soil to that of the soil–drain interface
k_h	coefficient of horizontal permeability (m/s)
k_{hi}	coefficient of horizontal permeability in undisturbed zone (m/s)
k_v	coefficient of vertical permeability (m/s)
k_0	coefficient of horizontal permeability at soil–drain interface (m/s)
m_v	coefficient of volume compressibility (m^2/kN)
n	ratio r_e/r_w
r	distance from centre of drain (m)
r_e	radius of influenced zone (m)
r_m	radius of mandrel (m)
r_s	radius of smear zone (m)
r_w	radius of drain well (m)
$S(t)$	settlement at a given time (m)
s	ratio r_s/r_w
T_h	dimensionless time factor
t	time (d)
U_h	degree of consolidation
$u(t)$	excess pore-water pressure (kPa)
w	water content
w_{max}	maximum water content
γ_w	unit weight of water (kN/m^3)
ε	volumetric strain
μ	function of n, s, k_{hi}, k_0
σ_v	vertical applied effective stress (kPa)

1. Introduction

Consolidation by prefabricated vertical drains (PVDs) has been a popular method for ground improvement projects because it reduces the drainage path and accelerates consolidation (Bo *et al.*, 2003; Indraratna *et al.*, 2005, 2012). Slender PVDs are normally encased with a steel mandrel and driven into soft clay using a hoist. The penetration and subsequent removal of the steel mandrel disturbs the surrounding soil and creates a smear zone. The lateral permeability and compressibility of the clay inside the smear zone is changed because the installation process alters the structure of the clay, which adversely affects consolidation (Indraratna and Redana, 1998).

The classical solution for vertical drains by Barron (1948) was extended by Hansbo (1981) to incorporate smear and well resistance. Chai and Miura (1999) stated that the extent of the smear zone and the ratio between the lateral coefficient of permeability in the undisturbed zone and in the smear zone are the main aspects which characterise the smear zone. The extent of the smear zone can be determined either by variations in the permeability or water content along the radial distance (Indraratna and Redana, 1998; Sathananthan and Indraratna, 2006). Onoue *et al.* (1991) conducted laboratory experiments on remoulded Boston Blue clay samples, from which they suggested a three-zone model based on the distribution of the coefficient of horizontal permeability around the vertical drain. Using large-scale consolidation tests with reconstituted alluvial clay, Indraratna and Redana (1998) concluded that the ratio between the vertical and horizontal permeability approached unity in the smear zone, and the radius of that smear zone is four to five times the equivalent radius of the drain. Sharma and Xiao (2000) performed similar experiments and reported that the radius of the smear zone was about four times the radius of the mandrel used and its permeability was about 1·3 times lower than the surrounding undisturbed region. Using cavity expansion theory, Ghandeharioon *et al.* (2010) demonstrated that a conical shape of the smear zone would be more realistic than an assumed cylindrical shape. However, an equivalent cylindrical shape could still provide the same consolidation response based on the equivalent area method and it was concluded that the radius of the smear zone is about 3·1 times the equivalent radius of the mandrel. By measuring the hydraulic head loss, Hird and Moseley (2000) investigated the characteristics of layered soil consisting of alternative layers of kaolin and sand, and derived a smear zone about 1·6 times the radius of the drain, based on the pore pressure distributions. Sathananthan and Indraratna (2006) derived the extent of the smear zone in reconstituted Moruya clay (New South Wales), based on the water content reduction, as being 2·5 times the equivalent diameter of the mandrel. Walker and Indraratna (2007) showed that the smear zone overlaps when the drain spacing is closer, below which consolidation cannot be accelerated any further. Basu and Prezzi (2007) incorporated a transition zone between a completely remoulded smear zone and undisturbed zone into a radial consolidation theory.

All the laboratory experiments mentioned above were carried out using reconstituted soil samples. Burland (1990) and Leroueil and Vaughan (1990) stated that the behaviour of in situ soil can differ from its remoulded state due to its distinctive structure, because, when a remoulded sample is prepared, its in situ structure is completely destroyed. Furthermore, all the above studies were carried out using scaled down model vertical drains to simulate actual field conditions. In the field, PVDs are installed at much higher rates (up to 1 m/s) than those in laboratory conditions, and the in situ soil is subjected to an extended period of shearing because the PVDs are much longer. Therefore, establishing accurate smear zone characterisation under laboratory conditions is difficult, and the implications of these installation procedures compared to actual field installation are often not well documented. Using monitored settlement data of an embankment, where vertical drains were installed using two different sizes of mandrels, Bergado *et al.* (1991) observed a higher settlement and faster rate of consolidation in the area where the smaller mandrel was used. Rujikiatkamjorn *et al.* (2013) proposed a conceptual model that captured the effects of soil structure by performing undisturbed large-scale testing, and suggested a three-zone model around the vertical drain, but a characterisation of the smear zone in relation to actual field conditions was not included in their study.

In the present paper, the smear zone characteristics stemming from actual drain installation in the field were assessed using the variations of the coefficients of permeability, water content and compressibility. Undisturbed samples were collected around the drain and a series of oedometer tests was performed. The aim of this research was to investigate and establish a more realistic extent of soil disturbance due to drain installation and propose a suitable technique for field conditions, which enables the extent of smear zone to be estimated.

2. Site characteristics

For this study, clay samples were extracted from a site in Ballina, New South Wales. The site is close to the Pacific Highway, which runs along the east coast of Australia between Sydney and Brisbane. The site is situated in a low-lying flood plain that consists of highly compressible and saturated clays. The subsoil conditions are relatively uniform throughout the site, and consist of a 0·2 m thick layer of organic materials which contain decomposing organic matter, underlain by a 1 m thick, sandy clayey silt alluvium crust. Silty clay with a high-plasticity, dark grey, estuarine deposit was encountered from 1·5–9·5 m deep, followed by 5 m thick, fine-grained sand layer underlain by a stiff layer of Pleistocene clay. Some basic soil properties are given in Table 1. Geotechnical characteristics of Ballina clay have been studied and already reported by Indraratna *et al.* (2012). The soil can be classified as a high-plasticity clay (CE) according to the Unified Soil Classification System.

3. Prefabricated vertical drain installation and recovery of undisturbed samples

Prefabricated vertical drains were installed at this site using an 80 t excavator equipped with 20 m long steel mandrel. The wick drains were 100 mm wide, 3 mm thick, and the cross-section of the mandrel was 120 mm × 60 mm. A rectangular shoe (140 mm long × 90 mm wide × 1 mm thick) was used to anchor the end of each drain at the desired depth. Drains were installed in a square

Properties	Values
Liquid limit, LL: %	98
Plastic limit, PL: %	32
Plasticity index, PI	66
Specific gravity, G_s	2·58
Water content: %	94·7
Void ratio, e	2·44
Wet unit weight: kN/m^3	16·5

Table 1. Soil properties of Ballina clay

pattern 1·2 m apart, to a depth of 15 m, at approximately 1·5 m/s. Before the drains were installed, vibrating wire piezometers and horizontal push-in pressure gauges were installed at various depths to measure the response during installation. A cross-section of a typical instrumentation plan is shown in Figure 1.

To characterise the smear zone, two types of installation patterns were adopted: single-drain installation (W1 and W2) and multi-drain installation (W3). With the single-drain installation (single-drain case), a vertical drain was installed and the soil samples were collected from around the drain (Figures 2(a) and 2(b)). With multiple-drain installation (multi-drain case), 14 wick drains were installed in two rows, in a square pattern at a spacing of 1·2 m, and then samples were collected from between the drains to investigate the possibility of an overlapping smear zone (Figure 2(c)).

After installation, samples of undisturbed soil were recovered immediately from depths between 2·5 to 2·95 m below the 600 mm thick working platform. The sample collection was

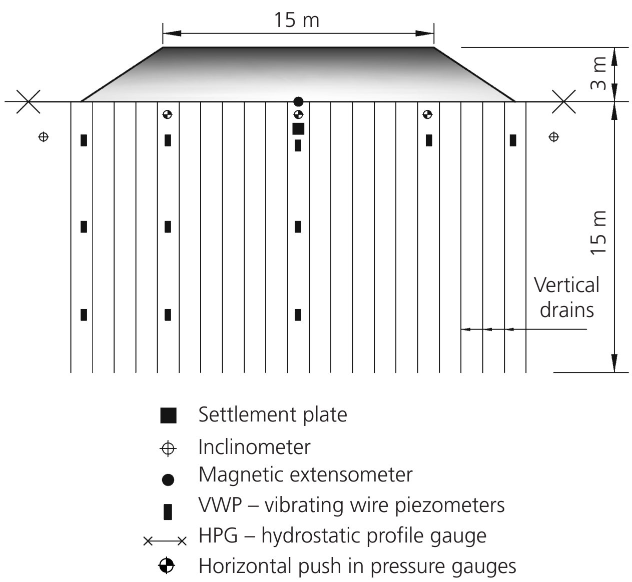

Figure 1. Typical cross-section of embankment with instrumentation layout

completed within 30–45 min after PVD installation. Shelby tube samplers (50 mm diameter and 450 mm long) were used to extract the in situ samples. The outside diameter of the tube that enters the soil during sampling was 49·4 mm and the inside diameter of the tube was 47·8 mm. Therefore, an area ratio of the sampler tube was 6·88%, which is clearly less than the recommended value of 10% (Hvorslev, 1949) still followed in practice worldwide. For this study, it was imperative to use small diameter sampling tubes, which could then be fitted exactly to oedometer apparatus without further disturbing the sample. Owing to the restricted space and the low shear strength of soil, it was not feasible to obtain the block samples at 2 m depth. For W1 and W2, 11 samples of undisturbed soil were collected, but to minimise disturbance adjacent to the sample formed by previous extraction, a space between each sampling location of at least 300 mm was maintained (see Figures 2(a) and 2(b)). For W3, ten samples were collected and their locations are presented in Figure 2(c). The holes were pre-bored to the desired depth and then the tube was pushed into the ground using a hydraulic system mounted on a truck and by applying a steady, uninterrupted force to ensure continuous uniform motion. When the tube reached the desired level, after a few minutes, it was rotated and slowly withdrawn at a uniform speed as recommended by Hvorslev (1949). Immediately after each tube was extracted from the ground it was cleaned with a wet cloth and sealed with two layers of paraffin wax and a plastic cap at end of the tube to prevent any loss of moisture. The tubes were then wrapped in a shock-absorbing bubble wrap sheet and transported and stored in a room at low temperature (10°C) and with 95% humidity, to prevent any moisture loss before being tested in the laboratory.

4. Experimental programme

The moisture content of each sample was measured immediately after they arrived at the laboratory. Specimens close to the end of the tube (30 mm) were discarded before the inner specimens were extracted to conduct moisture content tests. The tubes were re-sealed with wax and stored in the humidity room. Oedometer tests were performed using the specimens extracted vertically and horizontally from each sampling tube. The former were used to investigate the variations of vertical compressibility and the latter were mainly used to investigate the change in horizontal permeability. According to Indraratna *et al.*, 2012, undrained shear strength of the soil at the relevant depth of sampling is approximately 5 kPa. Owing to adhesion between the clay and the tube, and the relatively small diameter of the tube, extracting the whole length of the sample would create more soil disturbance, especially to the soil adjacent to the tube wall; therefore, to prepare the vertical specimen, the tube was cut into a 20 mm length. To minimise disturbance, the tube was held securely and a pipe cutter, which did not generate heat during cutting, was used to cut along the surface of the tube. Once the tube was cut around its circumference, the soil was trimmed with a thin wire. The 20 mm high specimen was fitted directly onto an oedometer ring for a consolidation test. The vane shear test was conducted before and after sample preparation, and it was demonstrated that the

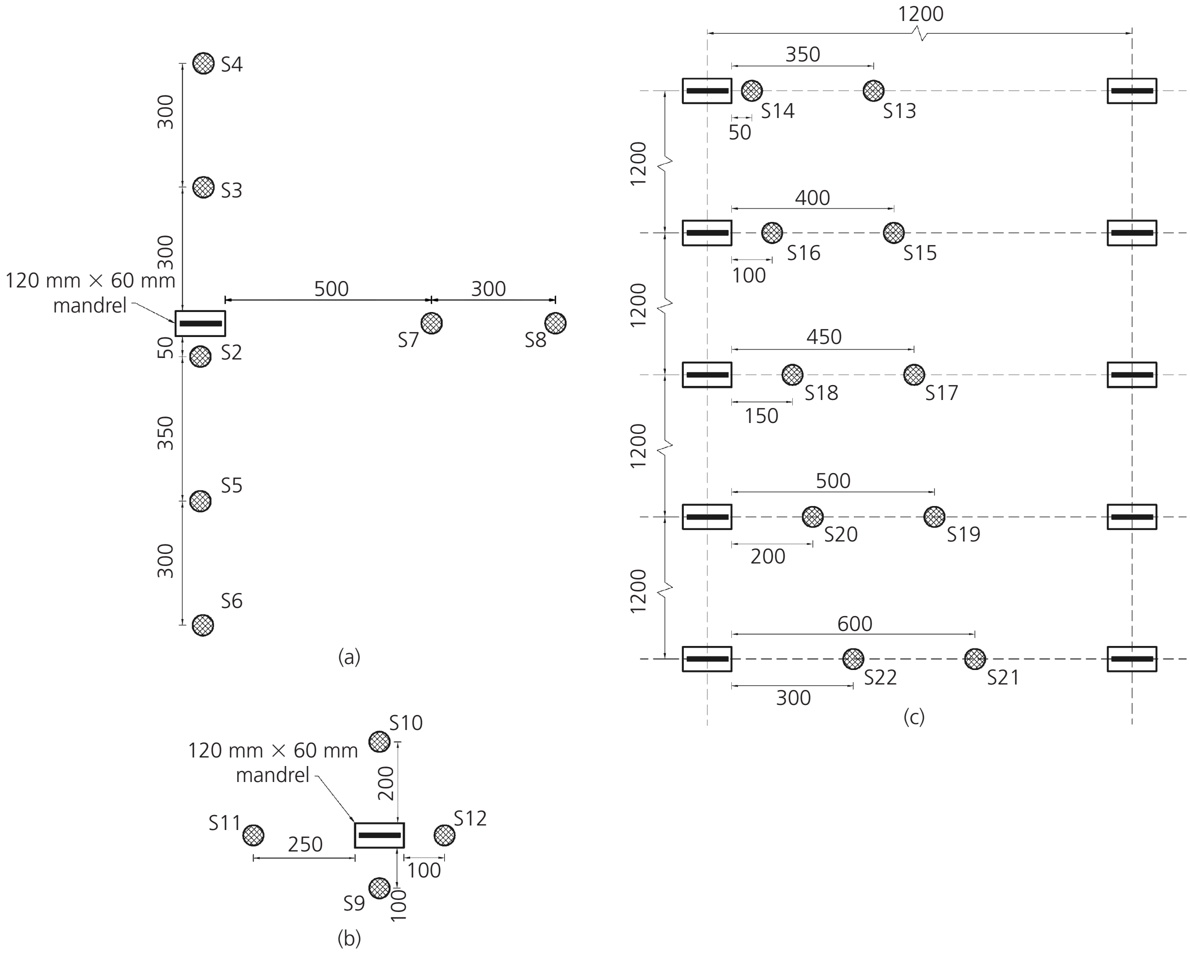

Figure 2. Sampling locations for single drain installation: (a) W1; (b) W2; multi-drain installation; (c) W3 (dimensions in mm)

corresponding shear strengths were similar, thereby confirming that the sample preparation had not caused any significant disturbance. An initial seating stress of 3·4 kPa was applied to the specimen and each loading increment was applied for 1 d, and the loading was doubled until it reached 218·7 kPa. To prepare a horizontal specimen, the 75 mm long sample was cut and extracted using the same technique. A horizontal sample was carefully trimmed to fit a 42·1 mm diameter, thin-wall oedometer ring and was later subjected to a consolidation test (ASTM D2435/D2435M-1 (ASTM, 2011)).

5. Test results and analysis

5.1 Characterisation of smear zone: permeability and water content perspective

The extent of the smear zone created by drain installation can be obtained by assessing the variation of compressibility, permeability and water content along the radius from the PVDs. Figure 3(a) shows the variation of water content along the radial distances for the single-drain and multi-drain cases. The natural moisture content before installation at a depth 2·5–2·9 m was approximately 93–95%. This means that the water content gradually increased up to 89–90% and then remained relatively constant. Disturbance due to the rapid movement of a rigid inclusion, such as a steel mandrel in soft clay, leads to fabric remoulding, which is not caused by the moisture reduction. More information on the disturbance and moisture reduction has been discussed by Sathananthan and Indraratna (2006) and Rujikiatkamjorn *et al.* (2013). At a distance more than 400 mm away from the drain, the moisture content is almost unaffected by installation in the case of a single drain, but with multi-drain installation, an overlapping smear zone is evident because the water contents were less than those in the case of a single drain by approximately 4%. Since the dimensions of the mandrel were 140 mm × 90 mm, which is equivalent to a mandrel diameter of 126·6 mm, the diameter of the disturbed zone due to drain installation was about 6·3 times the equivalent mandrel diameter. Figure 3(b) shows the normalised reduction in the water content, that is, $(w_{\max} - w)/w_{\max}$ in relation to the radius normalised by the equivalent mandrel radius, together with the laboratory data by Sathananthan and Indraratna (2006), where $w_{\max}$ and w are

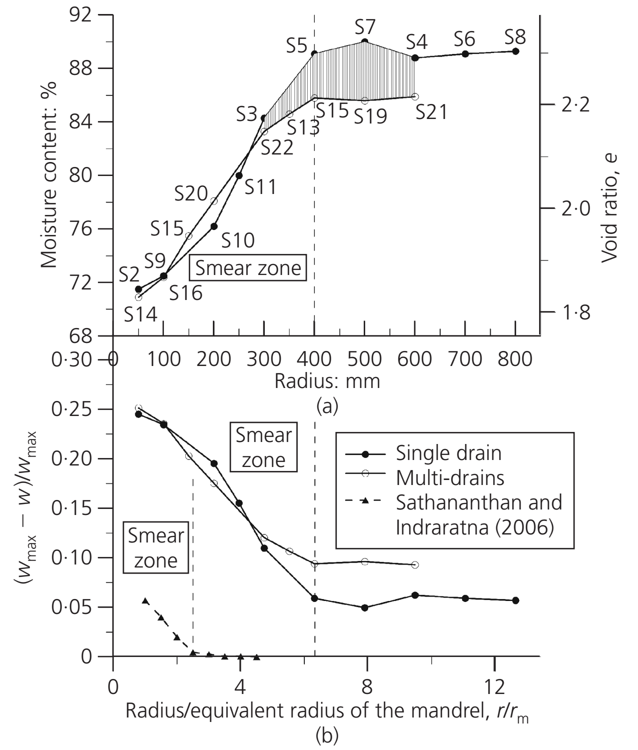

Figure 3. (a) Variation of moisture content along the distance away from the drain. (b) Variation of normalised moisture content reduction with normalised distance with equivalent mandrel radius for both single-drain and multi-drain cases

the maximum water content and the water content at a given location, respectively. Plots are generally similar, but the extent of the smear zone and the reduction in water contents seem to be larger than those based on laboratory data from large-scale reconstituted samples tested by Sathananthan and Indraratna (2006), who estimated the diameter of the smear zone to be 2·5 times the equivalent mandrel diameter.

The variations in the void ratio along the radial distance are shown in Figures 4(a) and 4(d), and they reveal a similar trend to the variation in the water content shown previously in Figure 3. Variations in the lateral permeability along radial locations are presented in Figures 4(b) and 4(e) for both cases. The Casagrande log time method was used to derive the coefficient of consolidation in the horizontal direction (c_h) from samples extracted horizontally, and Terzaghi's one-dimensional theory was used to back-calculate the horizontal permeability values (k_h). In fact the lateral permeability was almost constant beyond 400 mm away from the drain, but it decreased towards the drain. The lateral permeability in the case of multi-drains also confirmed the possibility of an overlapping smear zone, because the permeabilities at a given location more than 300 mm away were less than those obtained from the single-drain case. At least three samples at a given location were tested to confirm the soil properties. To characterise the smear zone, normalised permeability defined as the ratio between the horizontal permeability (k_h) to the horizontal permeability of the undisturbed zone ($k_{h(\text{undisturbed})}$) is plotted in Figures 4(c) and 4(e). This shows that the value of the normalised permeability ratio decreased swiftly with the radial distance close to the drain boundary (highly disturbed zone), whereas the change in normalised permeability became minimal further away from the drain. Irrespective of the pressure applied, all the curves are confined within a relatively narrow band, clearly defining the extent of the smear zone. These data revealed that the normalised lateral permeability ratio within the smear zone varied from 0·2 and 1 (an average of 0·6), and further away from the drain the $k_h/k_{h(\text{undisturbed})}$ ratio approached unity for the single drain, but it decreased to 0·9 for the case of multi-drains. In general, the variations in the moisture content, void ratio and permeability indicated that the smear zone was about 6·3 times greater than the equivalent dimension of the mandrel, a result that was higher than those obtained in previous laboratory studies. It is therefore evident that, in field conditions, the soil can be subjected to more disturbance when longer vertical drains are installed, because the soil can experience a longer shearing period during installation. The samples tested in this study was limited only to 2 m depth – the location of the soft clay layer, which was subjected to significant shearing during mandrel driving. Therefore, the focus was on the disturbance of this relatively shallow, soft clay layer. However, it has been observed that the extent of smear zone is considerably less at deeper layers when the clay becomes stiffer and at higher confining pressure with depth. The analogy of pile driving in relation to mandrel intrusion is useful to further clarify the concept (Gavin *et al.*, 2010).

5.2 Characterisation of the smear zone: perspective of soil compressibility

When vertical drains are being installed, the in situ structure of natural soil can be altered, affecting its compressibility, apart from its permeability and void ratio. Rujikiatkamjorn *et al.* (2013) have provided a framework from which it is possible to capture the degree of disturbance using the concept of the variation of the void ratio due to destructuring during compression (Figure 5). Based on the change in the void ratio of partially disturbed soil at each respective point of maximum yield stress along the yield points line AB, the defined degree of disturbance (DD) due to soil destructuration can be quantified as follows

1. $$\mathrm{DD} = 1 - \left(\frac{e_{\mathrm{SD}} - e_{\mathrm{id(ICL)}}}{e_{\mathrm{SC}} - e_{\mathrm{id(ICL)}}}\right)$$

where e_{SD} is the void ratio of the partially disturbed soil at yield stress, e_{SC} is the void ratio of the undisturbed soil at yield stress and $e_{\mathrm{id(ICL)}}$ is the void ratio on the isotropic compression line (ICL) at the intercept of line AB and the ICL.

Figures 6 and 7 present the compression curves for vertical and horizontal samples respectively, and they show that the soil becomes increasingly disturbed towards the drain as the adjacent

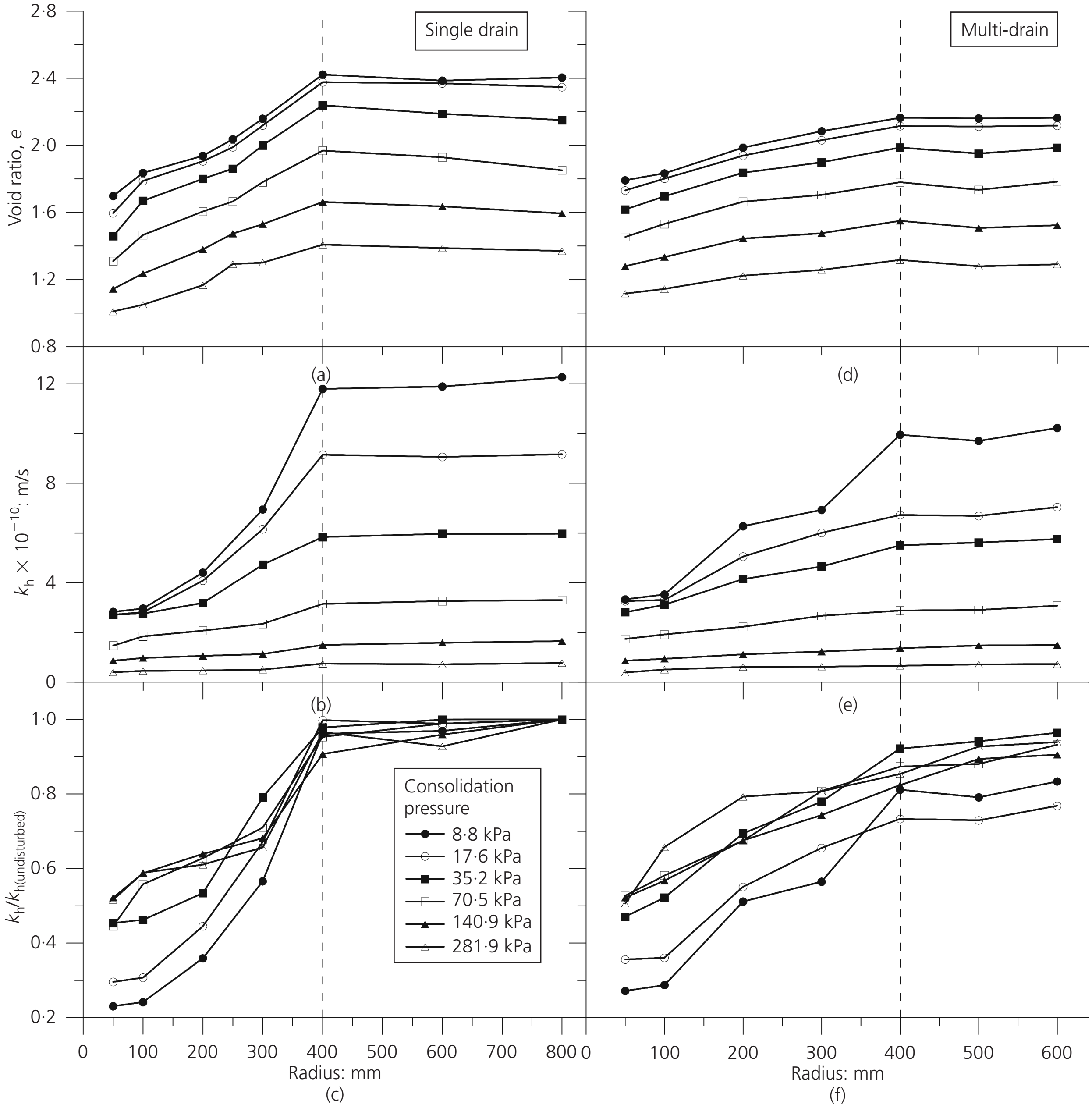

Figure 4. Variations of void ratio, permeability and normalised permeability along the distance away from vertical drain for both single-drain and multi-drain cases

soil experiences severe remoulding due to installation. The undisturbed stress profile was generated from a soil sample extracted further away from the vertical drain (more than 3 m), using the same sample preparation method. If the sample disturbance due to the sampling and extraction method had been significant, then there would not have been any visible change in the pre-consolidation pressure. However, the results show that the pre-consolidation pressure is notably reduced close to the drain. Here the compression curves for the multi-drain case at the drain influence zone (600 mm away from the drain) are generally lower than those for the single-drain curves, a result that may be attributed to the effects of installing adjacent vertical drains. This was also detected by field instrumentation, where the in situ pore pressures and total lateral pressures increased by 3–5 kPa, but they still returned to their original in situ state 6–18 h after installation. These minimum values were observed because the instruments were installed at the influence zone of the drain.

The degree of disturbance based on Equation 1 against the normalised radius is shown in Figure 8, and reveals there was a

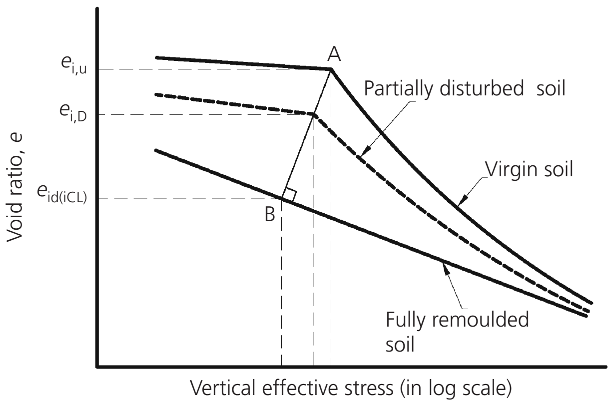

Figure 5. Concept to assess the degree of soil disturbance

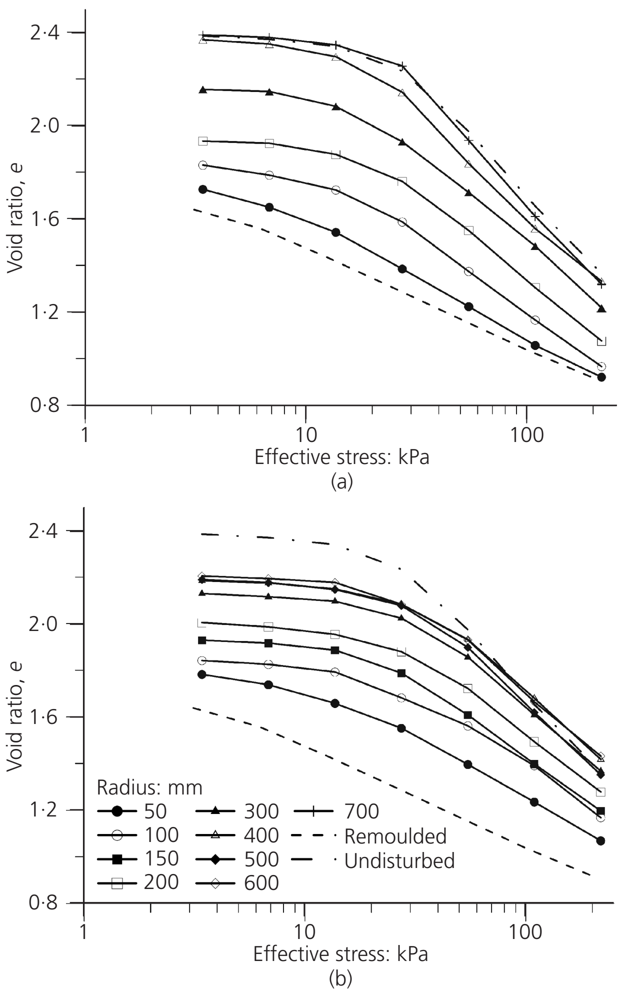

Figure 6. Compression curves for vertical samples: (a) single-drain case; (b) multiple-drain case

higher degree of disturbance for the surrounding soil adjacent to the drain. The degrees of disturbance for the vertical samples in the relatively undisturbed region were 10·4% and 24·1% for single-drain and multi-drain cases, respectively, while the degrees

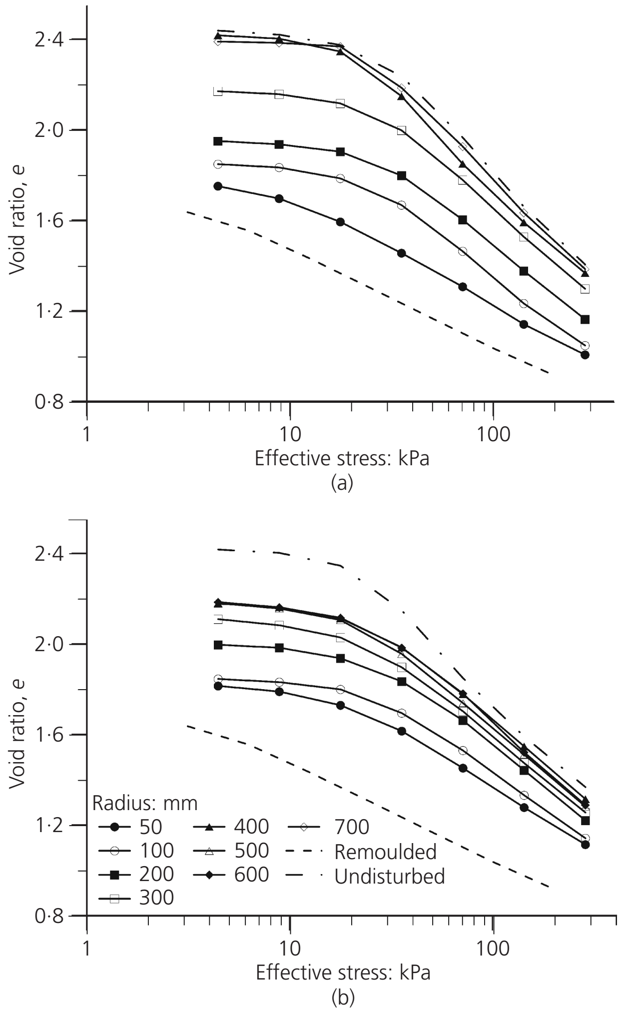

Figure 7. Compression curves for horizontal samples: (a) single-drain case; (b) multiple-drain case

of disturbance for the horizontal samples in the relatively undisturbed region were 4·1% and 30·6% for single-drain and multi-drain cases, respectively. The degrees of disturbance 50 mm away from the drain were 89·4% and 79·7% for single-drain and multi-drain cases, respectively. Compared to the laboratory results by Rujikiatkamjorn *et al.* (2013), these degrees of disturbance were higher because the soil was subjected to a longer period of installation.

5.3 Effect of drain installation on soil anisotropy

Anisotropy can develop in soft clays during the deposition period and can be preserved unless they are disturbed (Leroueil and Vaughan, 1990). According to Larsson (1981) and Tavenas *et al.* (1983), marine clay exhibits very little or no anisotropy. It was expected that compressibility and permeability anisotropy would be altered during the installation of vertical drains. In relation to one-dimensional consolidation, volume compressibility anisotropy can be defined as the ratio of the coefficient of volume compressibility obtained from a horizontal specimen to that

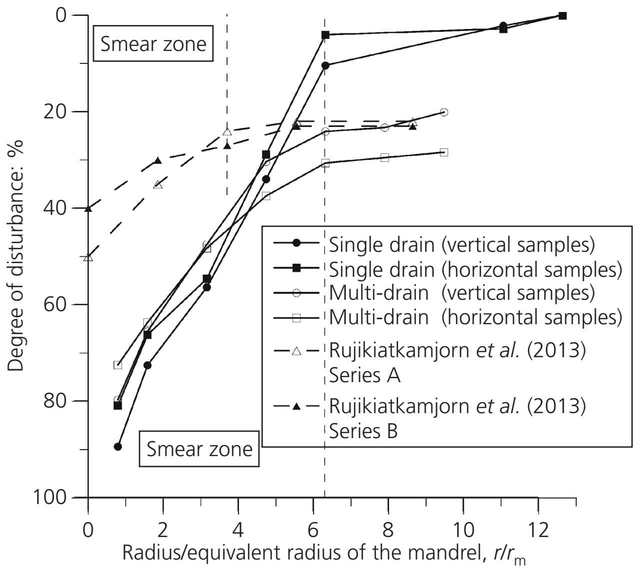

Figure 8. Degree of disturbance

obtained from a vertical specimen at the same location. Permeability anisotropy can be defined in the same manner as volume compressibility anisotropy. Figure 9 presents the volume compressibility anisotropy and permeability anisotropy some distance away from a vertical drain at an effective stress of 24–54 kPa. For this site, the degree of anisotropy of volume compressibility and permeability for the undisturbed soil was 1·2 and 1·1, respectively. The volume compressibility anisotropy obtained from the single-drain case was higher than that for the multi-drain case, although these values diminished when approaching the close vicinity of the drain. A similar trend was also observed for permeability anisotropy.

5.4 Practical implications

To demonstrate the effects of installation on consolidation, a radial consolidation theory that captures the linear smear zone, proposed by Walker and Indraratna (2007), was adopted. A linear variation was selected not only for simplicity but also because it captured the variation of soil properties within the smear zone reasonably well. Figure 10 presents the unit cell together with variations in linear permeability in the smear zone.

The degree of consolidation (U_h) can be expressed as

2a. $$U_h = \exp\left(\frac{-8T_h}{\mu}\right)$$

2b. $$T_h = \frac{c_h t}{d_e^2}$$

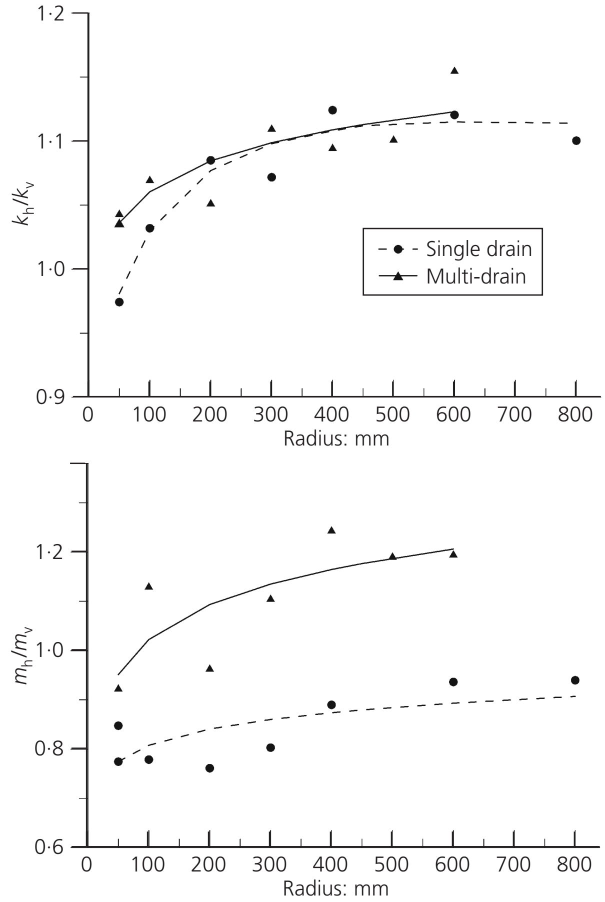

Figure 9. Volume compressibility anisotropy and permeability anisotropy along the distance away from vertical drain

2c. $$c_h = \frac{k_{hi}}{m_v \gamma_w}$$

2d. $$\mu = \ln\left(\frac{n}{s}\right) - \frac{3}{4} + \frac{K(S-1)}{(S-K)}\ln\left(\frac{s}{K}\right)$$

2e. $$K = \frac{k_{hi}}{k_0}$$

2f. $$n = \frac{r_e}{r_w}$$

2g. $$s = \frac{r_s}{r_w}$$

where T_h is the time factor, r_s is the radius of the smear zone, r_w

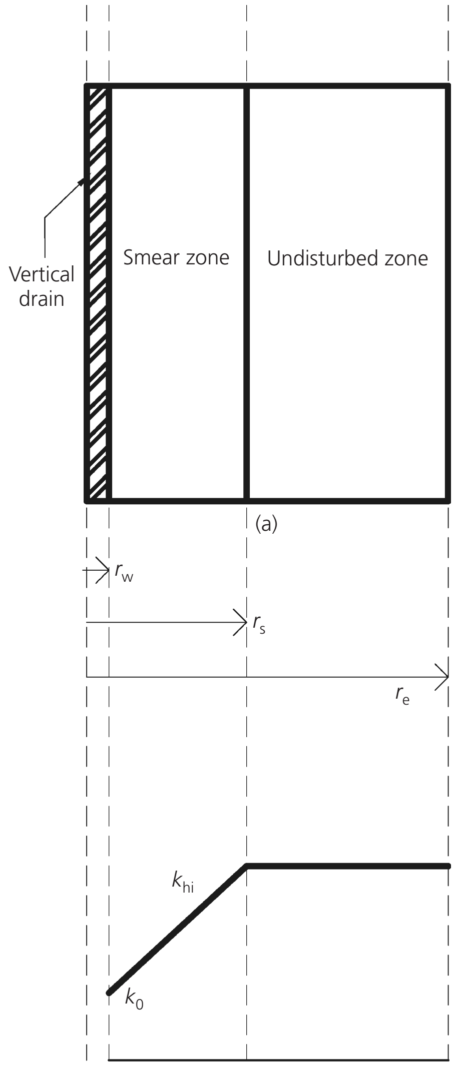

Figure 10. (a) Cross-section of unit cell with vertical drain and (b) permeability variation

is the equivalent radius of the vertical drain, r_e is the radius of the influence zone, k_{hi} is the coefficient of horizontal permeability in the undisturbed zone, k_0 is the coefficient of horizontal permeability at the soil–drain interface, c_h is the coefficient of consolidation in the horizontal direction, m_v is the average coefficient of volume compressibility from the vertical samples and γ_w is the unit weight of water.

Settlement ($S(t)$) at a given time (t) can be obtained based on

$$3. \quad S(t) = U_h m_v \Delta\sigma_v H$$

Excess pore pressure ($u(t)$) at a given time (t) can be determined based on

$$4. \quad u(t) = U_h \Delta\sigma_v$$

where $\Delta\sigma_v$ is the vertical applied effective stress and H is the soil thickness.

Based on the field observation, the most appropriate parameters for the analysis were taken as: $r_s = 400$ mm, $r_e = 678$ mm, $r_w = 51{\cdot}5$ mm, $\Delta\sigma_v = 29{\cdot}1$ kPa, $H = 15$ m.

The following three cases were examined: case A (single-drain case), case B (multi-drain case) and case C (ideal case: no smear). The parameters are tabulated in Table 2. Figure 11 presents the variation of the degree of consolidation and the associated excess pore pressure and settlements based on the three cases. As expected, the consolidation rate based on case C was the highest, followed by case B and case A. In case B, the lower coefficient of compressibility led to a higher rate of consolidation than case A. In terms of associated settlement calculation, owing to the installation effect, all three cases resulted in different values of the ultimate settlement, but case C yielded the highest ultimate settlement. The final settlement is independent of the drainage type (radial or vertical or both), but directly related to the compressibility parameter (m_v or c_c), effective stress increment and the clay thickness, and any change in magnitude of the compressibility parameter due to disturbance will affect the final settlement. The unit cell analyses showed that, by including the variations in compressibility and permeability due to the degree of disturbance, a more realistic prediction of consolidation can be obtained. The performance of this embankment is currently being monitored, but the observation data will not be available until the end of 2014. Variations in the properties of soil due to drain installation should also be considered during design, apart from the variations in the soil permeability.

6. Conclusion

The effects of vertical drain installation on soil permeability and compressibility were investigated using samples obtained from a soft clay site in Ballina, NSW. The variations of compressibility and permeability in the vertical and horizontal directions were

Parameter	Single-drain case A	Multi-drain case B	Ideal drain case C
k_{hi}: $\times 10^{-10}$ m/s	7·97	6·88	7·97
k_0: $\times 10^{-10}$ m/s	2·96	2·96	7·97
m_v: m^2/kN	0·00290	0·00188	0·00336
n	13·165	13·165	13·165
s	7·767	7·767	7·767
K	2·696	2·329	1·000
c_h: m^2/d	0·00242	0·00323	0·00209

Table 2. Soil parameters used for analysis

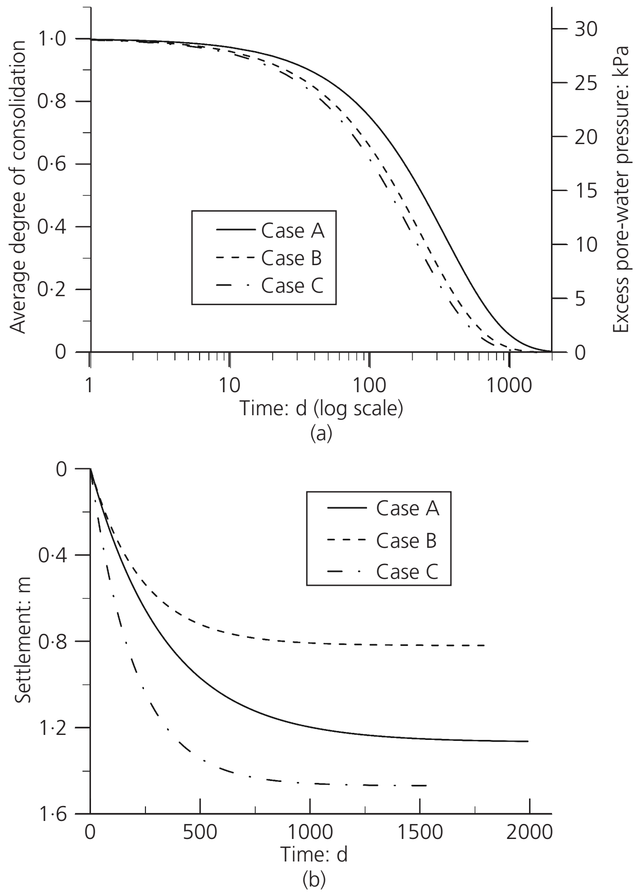

Figure 11. (a) Excess pore pressure predictions and degree of consolidation; (b) comparison of vertical displacements

obtained using a standard oedometer test. The extent of the smear zone can be explained on the basis of either the variations of normalised permeability, soil compressibility, or a change in the water content. It can be seen that the water content gradually increased in the smear zone and then remained relatively constant. However, at a distance greater than 400 mm away from the drain, the moisture content was almost unaffected by installation for the single-drain case. The samples taken for both single-drain and multi-drains cases were from the same area, where the clay was homogeneous within a close proximity. Therefore, the effect of spatial variation can be ignored here. Further, from Figure 3(a) it is evident that the water content is almost the same within a distance of 400 mm. However, beyond the smear zone in the multi-drain case, water contents and horizontal soil permeability further decreased in comparison to those obtained from undisturbed samples, supporting the existence of overlapping smear. The water contents in this region were less than in the single-drain case by approximately 4%. Similar trends were also observed in the variation of permeability and void ratio. These observations can be attributed to a probable overlapping smear zone where the permeabilities or water content at a given location greater than 300 mm away were less than those obtained from the single-drain case. In all these methods, the radius of the smear zone was about 6·3 times the equivalent mandrel radius, which was larger than that observed in the laboratory using reconstituted specimens. Volume compressibility and permeability anisotropy also provided similar trends because the degree of anisotropy changed significantly close to the drain, as was expected. It was also evident that, in field conditions, the soil can be subjected to a higher degree of disturbance when longer vertical drains are installed. The compression curves revealed that the soil became increasingly disturbed towards the drain as the soil adjacent to the drain experienced severe remoulding due to installation.

The numerical analyses showed that, by including the unit cell variations in compressibility and permeability due to the degree of disturbance, a more realistic prediction of the degree of consolidation could be obtained. In disturbed soil the permeability, coefficient of consolidation and compression characteristics, including compressibility and pre-consolidation pressure, were adversely affected. Therefore, based on these findings, the variation of the soil properties due to drain installation must be taken into account during design, apart from the variations of soil permeability. These variables significantly affected the rate of settlement and dissipation of excess pore pressure, so it is suggested as the basis of this study that these parameters should be assessed using undisturbed samples obtained at different distances from the vertical drains.

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