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Pore pressure based method to quantify smear around a vertical drain

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Abstract

Radial consolidation testing of Ballina clay (New South Wales, Australia) was carried out using a large-scale consolidometer 650 mm in diameter. In this study, the characteristics of the smear zone were evaluated on the basis of hydraulic gradient changes derived from the measured excess pore pressure data in the radial direction. The extent of the smear zone determined using this technique is compared with past approaches, where the variations in water content and lateral permeability were adopted to evaluate smear. The approach proposed herein based on the change of hydraulic gradient coincides with the previous two methods, and the smear zone could be established at almost 2.5 times the effective mandrel diameter. A good agreement is also found between the theoretical radial consolidation predictions, after incorporating the smear zone characteristics and the measured time-settlement curve. The proposed method for the determination of smear zone extent can be carried out during consolidation with minimum disturbance to soil, provided a sufficient number of pore pressure transducers are installed. It also eliminates the need for a number of soil samples and high-quality soil sampling technique after the installation of the drain.

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Pore pressure based method to quantify smear around a vertical drain

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Radial consolidation testing of Ballina clay (New South Wales, Australia) was carried out using a large-scale consolidometer 650 mm in diameter. In this study, the characteristics of the smear zone were evaluated on the basis of hydraulic gradient changes derived from the measured excess pore pressure data in the radial direction. The extent of the smear zone determined using this technique is compared with past approaches, where the variations in water content and lateral permeability were adopted to evaluate smear. The approach proposed herein based on the change of hydraulic gradient coincides with the previous two methods, and the smear zone could be established at almost 2.5 times the effective mandrel diameter. A good agreement is also found between the theoretical radial consolidation predictions, after incorporating the smear zone characteristics and the measured time–settlement curve. The proposed method for the determination of smear zone extent can be carried out during consolidation with minimum disturbance to soil, provided a sufficient number of pore pressure transducers are installed. It also eliminates the need for a number of soil samples and high-quality soil sampling technique after the installation of the drain.

KEYWORDS: consolidation; ground improvement; laboratory tests; permeability; pore pressures; settlement

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NOTATION

d_e	diameter of soil cylinder dewatered by a drain
d_m	equivalent diameter of mandrel
d_s	equivalent diameter of smear zone
k_h	horizontal permeability in the undisturbed zone
$k_h(r)$	horizontal permeability at radius r
k_s	horizontal permeability in the smear zone
k_v	vertical permeability
l	drain length
m_v	coefficient of volume compressibility
r	radius
r_e	radius of unit cell
r_m	equivalent radius of mandrel
r_s	radius of the smear zone
r_w	radius of the drain
t	time
U	average degree of consolidation
u	excess pore water pressure at the location (r, z) at time t
w	water content
w_{max}	maximum water content
γ_w	unit weight of water
κ	ratio of undisturbed permeability to permeability at the drain/soil interface

INTRODUCTION

Prefabricated vertical drains (PVD) remain to be one of the most popular methods of soft soil improvement. It is well known that the installation of PVD causes a disturbed zone around them, which is known as the smear zone, where the properties of the clay are changed, such that the lateral permeability is significantly decreased, thereby increasing

the time for consolidation. Hansbo (1960) observed that drain installation could cause a change in pore water pressure dissipation especially in the smear zone but no method to determine its extent was proposed. The smear (disturbed) zone can be usually characterised using either the variation in soil permeability or the moisture content (Onoue *et al.*, 1991; Sharma & Xiao, 2000; Sathananthan & Indraratna, 2006). Bergado *et al.* (1991) also describe a back-calculation method to determine the smear zone extent by curve fitting laboratory consolidation tests. These techniques often require careful small specimen extraction from the smear zone to conduct oedometer testing, from which the change in the coefficient of permeability can be obtained. At least two test specimens are required (i.e. to determine the smear and to obtain the consolidation curve). The coefficient of permeability is a function of the pore water pressure gradient at a given location. Therefore, the existing techniques of determining the coefficient of permeability using small specimens obtained from various locations are considered to be an indirect approach to characterise smear zone.

In this paper, a different approach to establish the smear zone is proposed, based on measured excess pore pressure dissipation trend as this can be a more practical solution if sufficient piezometers are provided in the field, and there is no need for extensive soil sampling for evaluating permeability and water contents after the drains are installed. Further, this technique allows both smear zone evaluation and consolidation analysis to be conducted using the same soil sample. The smear zone is evaluated by considering the change of hydraulic gradient towards the vertical drain. The smear zone estimation is then compared with the past methods of quantifying smear based on the observed variation of water content and the lateral permeability coefficient (k_h). Moreover, the predicted consolidation curve incorporating the smear effect is compared with the observed time–settlement data. The past methods of evaluating the permeability ratio (k_h/k_v) and water content variation for quantifying smear take a considerable amount of

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field sampling and laboratory efforts, whereas the proposed technique of examining the radial derivative of hydraulic gradient to establish the zone of smear can be executed swiftly, if an adequate number of piezometers can be provided in the field.

EXPERIMENTAL SET-UP AND PROCEDURE

A large-scale radial drainage consolidometer (650 mm diameter $\times$ 450 mm height) was used in this study (Fig. 1(a)). The experimental procedures are explained elsewhere by Ghandeharioon *et al.* (2010). The clay sample was extracted from a low-lying flood plain consisting of highly compressible and saturated estuarine clay from the coastal town of Ballina, NSW, from a depth of 2 m. It is a dark grey, silty and highly plastic clay with a specific gravity of 2.6 and a natural water content of 94%. The liquid limit, plastic limit and plasticity index were 98, 32 and 66%, respectively. It is noteworthy that the natural water content is close to the liquid limit. The geotechnical properties of Ballina clay can be found in a previous study by Indraratna *et al.* (2015). The clay was first sieved to remove any oversize particles of soil and large sea shells and other relics of marine environment. The clay was then mixed with distilled water to form a slurry where the water content was ~ 1.4 times the liquid limit. The slurry was then poured into the cell with mild vibration to expel all trapped air. Subsequently, the sample was pre-consolidated under an initial stress of 20 kPa at controlled temperature and humidity conditions in the geotechnical laboratory. A PVD (100 mm $\times$ 4 mm) was installed using a mandrel (115 mm $\times$ 10 mm). The equivalent diameter of the drain (66.2 mm) was determined based on the method proposed by Atkinson & Eldred (1981). Seven miniature pore

pressure transducers were placed in a staggered arrangement (Fig. 1(b)) radially around the drain (i.e. 15, 30, 45, 60, 100, 150, 200 mm from the centreline), and 100 mm above the bottom of the cell. Surface settlement was measured using a linear variable differential transformer. The water content along the specimen radius was measured after installing the central drain. Finally, an additional load of 60 kPa was applied onto the sample throughout this post pre-consolidation period. Given that the oedometer-determined yield stress of this soil is 31 kPa (Geng *et al.*, 2012), the resulting settlement on application of this total stress followed the normally consolidated line.

DETERMINATION OF SMEAR ZONE

Based on the dissipation of pore water pressure, the following method is proposed to determine the variation of the coefficient of permeability within the smear zone. The governing equation for excess pore pressure dissipation in a saturated soil considering both vertical and radial drainage can be expressed by (Barron, 1948)

$$\frac{\partial u}{\partial t} = \frac{k_v m_v}{\gamma_w} \left(\frac{k_h(r)}{k_v} \left(\frac{\partial^2 u}{\partial r^2} + \frac{\partial u}{r \partial r} \right) + \frac{\partial^2 u}{\partial z^2} \right) \quad (1)$$

where u is the excess pore water pressure at location (r, z) at time t ; m_v is the coefficient of volume compressibility; γ_w is the unit weight of water; k_v is the vertical permeability coefficient assumed to be unchanged and $k_h(r)$ is the horizontal permeability at radius r .

The vertical permeability of the sample ($k_v = 5 \times 10^{-10}$ m/s) and the coefficient of volume compressibility ($m_v = 0.0066$ m²/kN) were determined using the consolidation

Fig. 1. Detailed schematic diagram of the large consolidometer: (a) vertical cross-section and (b) horizontal cross-section showing the locations of pore water measurement. LVDT, linear variable differential transformer

curve obtained from a large-scale consolidometer without a vertical drain, but under the same loading conditions. In addition, small oedometer samples cored horizontally were used to measure the horizontal permeability in the undisturbed zone, following the method suggested by Indraratna & Redana (1998). It was found that the uniform horizontal permeability (k_h) was 1.11×10^{-9} m/s. Based on the boundary condition of free drainage at the drain and the top and the bottom of the sample, equation (1) can be discretised using the finite difference technique. For a given pore pressure dissipation curve at a known radial location at a given depth, the normalised horizontal permeability – that is, ratio $k_h(r)/k_v$ at any radius r can then be established using either a quasi-linear or parabolic relationship (Walker & Indraratna, 2006).

RESULTS AND DISCUSSION

The predictions of normalised pore water pressure (u/σ_0) using equation (1) with the data measured at different radii are shown in Fig. 2, where u is the excess pore water pressure and σ_0 is the applied pressure. Note that the gradient or rate of pore water dissipation increases when the measurements are closer to the drain. The variations of normalised lateral permeability (k_h/k_v), the normalised water content ($(w_{\max} - w)/w_{\max}$) and the pore pressure

Fig. 2. Excess pore pressure dissipation (measured and calculated) at different locations

gradient (equation (2)) are plotted in Fig. 3, where $w_{\max}$ and w are the maximum water content and the water content at a given location, respectively. The normalised lateral permeability increases from 1.6 at $r = 15$ mm ($r/r_m = 0.38$) to 2.2 at $r = 100$ mm ($r/r_m = 2.5$), and it is almost unaffected beyond 100 mm, thus demarcating the undisturbed zone. The trends for both indices are similar, in that the boundary of the smear zone is close to 100 mm, which is about 2.5 times the mandrel radius (r_m) and 3.1 times the drain radius (r_w). The extent of the smear zone obtained by the proposed method has been validated with that obtained from the moisture content measurement. This also agrees with the values provided earlier by Sathananthan & Indraratna (2006) for a soft estuarine clay from the eastern coast of NSW (town of Moruya), where they reported the radius of the smear zone as being about 2.5 times the equivalent mandrel radius.

The trend of excess pore pressure dissipation towards the vertical drain where smear effects are expected to be prominent is also examined in this study. Based on equation (1) for a given depth z and a time t , the radial derivative of excess pore pressure – that is, (du/dr) is plotted in Fig. 3(c) for both cases of ‘with smear’ and ‘without smear’, the latter being the theoretical plot based on Barron (1948), while the former is plotted using the experimental data. Observing that (a) the variation of k_h along the radial direction would converge to the constant horizontal permeability in the undisturbed zone and (b) du/dr is inversely proportional to the horizontal permeability when the vertical permeability is constant in the unit cell, the plots of du/dr for both cases (i.e. ‘with smear’ and ‘without smear’) can be used to determine the smear zone the intersection of these two curves. Based on the proposed method, Fig. 3(c) gives the smear zone size to be close to $r/r_m = 2.5$. Moreover, using the normalised water content criterion proposed by Sathananthan & Indraratna (2006), Fig. 3(b) further verifies that this value lies in the proximity of $r/r_m = 2.5$. The results thus show that the radial distance ($r = 100$ mm, $r/r_m = 2.5$) demarcates the boundary of the smear zone, beyond which the change in permeability is marginal – that is, the permeability is unaffected by the drain installation. The smear zone established using the aforementioned method falls well within the theoretical drain influence zone where the value of du/dr changes significantly (Fig. 3), beyond which only vertical flow may be significant. Table 1 summarises the smear zone characteristics from previous studies. It contains values of k_h/k_s and whether it is the average or minimum value at the drain interface is denoted by superscript ‘*’ (average) or ‘†’ (minimum). This information has been provided for comparison purposes so as to benchmark the current results as compared with the available literature. It can be seen that the measured values of this study are in conformity with those reported in the past.

So far, only the pore pressure data near the smear zone have been used to establish its characteristics, so to validate these findings, the results were used in conjunction with the consolidation theory, while considering the vertical and horizontal drainage (Carrillo, 1942). The average degree of consolidation (U) based on settlement can be given by

$$U_t = 1 - \sum_{m=1}^{\infty} \frac{8}{(2m+1)^2 \pi^2} \times \exp \left(- \left[\left(\frac{2m+1}{2} \right)^2 \pi^2 \frac{k_v t}{m_v \gamma_w l^2} + \frac{8}{\mu m_v \gamma_w d_e^2} \right] \right) \quad (2)$$

As proposed by Walker & Indraratna (2006, 2007), the values of μ can be determined based on whether the

Fig. 3. Variations of permeability and normalised water content away from the centre: (a) permeability; (b) normalised water content; and (c) pore pressure gradient

Table 1. Extent of the smear zone and permeability as reported in the literature

Source	r_s/r_m	k_h/k_s
Barron (1948)	1.6	3*
Hansbo (1981)	1.5	3*
Bergado <i>et al.</i> (1991)	2	N/A
Onoue <i>et al.</i> (1991)	1.6	3*
Almeida & Ferreira (1993)	1.5–2	3–6*
Indraratna & Redana (1998)	4	1.15†
Chai & Miura (1999)	2–3	N/A
Hird & Moseley (2000)	1.6	3*
Sharma & Xiao (2000)	4	1.3†
Sathananthan & Indraratna (2006)	2.5	1.3†
Current study	2.5	1.3†

r_s , radius of the smear zone; r_m , the equivalent mandrel radius; k_s , horizontal permeability in the smear zone; k_h , horizontal permeability in the undisturbed zone.

*Average k_h/k_s .

†Minimum k_h/k_s at the drain interface.

variations in permeability are linear or parabolic, therefore

$$\mu_L = \ln\left(\frac{n}{s}\right) - \frac{3}{4} + \frac{\kappa(s-1)}{s-\kappa} \ln\left(\frac{s}{\kappa}\right) \quad \text{for linear variation} \quad (3)$$

$$\mu_P = \ln\left(\frac{n}{s}\right) - \frac{3}{4} + \frac{\kappa(s-1)^2}{s^2 - 2\kappa s + \kappa} \ln\left(\frac{s}{\sqrt{\kappa}}\right) - \frac{s(s-1)\sqrt{\kappa(\kappa-1)}}{2(s^2 - 2\kappa s + \kappa)} \quad (4)$$

$$\ln\left(\frac{\sqrt{\kappa} + \sqrt{\kappa-1}}{\sqrt{\kappa} - \sqrt{\kappa-1}}\right) \quad \text{for parabolic variation}$$

where $n = r_e/r_w$, $s = r_s/r_w$, $\kappa = k_h/k_s$, k_h is the undisturbed horizontal coefficient of permeability, k_s is the minimum horizontal coefficient of permeability in the disturbed zone, κ is the ratio of undisturbed permeability to permeability at the drain/soil interface, l is the drain length, d_e is the diameter of soil cylinder dewatered by a drain, d_s is the

Fig. 4. Comparison between the measured and calculated average degree of consolidation by settlement for different smear profiles

diameter of the smear zone and d_w is the equivalent diameter of the drain. The values of other parameters based on Fig. 3 are as follows: $n=9.84$, $s=1.51$, $\kappa=1.31$, $k_h=1.11 \times 10^{-9}$ m/s and $k_v=5 \times 10^{-10}$ m/s

Figure 4 presents a comparison between the predictions of degree of consolidation based on the measured settlement using equation (2) for different permeability profiles for the smear zone in relation to laboratory data. The predictions based on the variations in permeability are in acceptable agreement with the measured data. As expected, the highest rate of consolidation occurs in the case of 'no smear', followed by the parabolic, linear and the constant permeability ($k_h=8 \times 10^{-10}$ m/s) case. The experimental data agrees well with the parabolic case for most part of the consolidation process; however, during the initial consolidation process the linear case shows a better match. It can be seen that apart from the size of smear zone, the variation of soil permeability within the smear zone plays an important role in correctly capturing the actual consolidation response.

CONCLUSION

In this study, the extent of the smear zone for remoulded Ballina clay was determined graphically using the excess pore pressure (u) data, and then identifying the radial distance (r) at which the two curves for (du/dr) (i.e. with smear and without smear) intersect. The size of the smear zone based on this approach was ~ 2.5 times the equivalent mandrel diameter, and this was in very good agreement with the smear zone established using the two past methods based on the variations of lateral permeability and water content. When the size of the smear zone and the variation of k_h within the smear zone were incorporated, the time-settlement predictions were in excellent agreement with the measured consolidation data. Considering that the previous approaches involve extensive soil sampling and laboratory effort, the proposed technique should be verified with the field data, if an adequate number of piezometers can be provided in the field.

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