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Research Paper

On permeability matching to simulate pore pressure measurements

Rohan T.R. Walker [a,*], Richard Kelly [b]

[a] Centre for Geomechanics and Railway Engineering, University of Wollongong, NSW 2522, Australia
[b] Chief Technical Principal, Geotechnical SMEC – Australia & New Zealand Division Level 1, 154 Melbourne St, South Brisbane, QLD 4101, Australia

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ABSTRACT

Matching average degree of consolidation is a common approach to convert unit cell solutions for vertical drains to two and three-dimensional calculations. These techniques facilitate efficient computation and have been shown to accurately model settlement of the system. However, pore pressures are usually measured at the location of maximum pore pressure. This article demonstrates that use of permeability matching techniques theoretically results in different maximum pore pressures than in unit cells. Some guidance for the magnitude of the difference is provided as a rule of thumb to assist analysts judge the accuracy of their modelling compared with pore pressure measurements.

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1. Introduction

Using two dimensional plane strain analysis to model the three dimensional reality of vertical drain improved ground is not new [1]. Square and triangular drain installation patterns along with rectangular PVD are converted to equivalent circles for axisymmetric unit cell analysis. Circular drains and influence areas are converted to plane strain drain walls such that through judicious choice of geometric and permeability values the axisymmetric and plane strain consolidation rates are matched on average. A number of matching procedures have been developed ([2–12]) with overviews of many of the methods presented in [1,13].

Pore pressure measurements are usually made at the nominal location of maximum excess pore pressure. Despite developers of the matching procedures showing differences between axisymmetric and plane strain pore pressure distributions ([3–5,9]), usually an analyst directly compares the output of 2D or 3D computations with the measurements. Russell et al. [14] has explicitly warned against such a direct comparison. This article explores more deeply that the maximum pore pressure obtained from 2D and 3D calculations using permeability matching techniques is different from that obtained using a unit cell approach. There is no doubt that plane strain matching procedures can be successfully employed ([15]) but we emphasise that pore pressure outputs from the calculations cannot be directly compared with measurements.

Though not explored herein, it is noted that when comparing pore pressure predictions with measurements allowances may need to be made for: fluctuating groundwater levels (tidal/flooding/seasonal); clogged/malfunctioning piezometers; settlement of piezometers.

2. Equal strain consolidation equations

Assuming equal strain conditions (horizontal sections remain horizontal) with Darcian, horizontal only flow, the strain rate, $\dot{\varepsilon}$, in a unit cell (see Fig. 1) for both axisymmetric and plane strain consolidation depends on the average excess pore pressure, $\bar{u}$, according to:

$$\dot{\varepsilon} = \frac{k_h}{\gamma_w}\eta(\bar{u} - u_w) \tag{1}$$

where k_h is a reference value of horizontal permeability, usually the undisturbed permeability value; u_w is the pore pressure in the drain (i.e. negative for vacuum); γ_w is unit weight of water. The η, or 'eta' term in is a lumped parameter that depends on the permeability distributions and geometry of the unit cell:

$$\eta = \frac{2}{r_e^2\mu} \tag{2}$$

r_e is the drain influence radius (or B, influence width in plane strain). The horizontal permeability distribution (see Fig. 1) leads to the dimensionless μ parameter. Many expressions have been developed for μ: [16–19,19–22]. Despite laboratory and field evidence that smear zone permeability changes gradually with distance from the drain ([23–27]) the simple formulations of a

* Corresponding author.
E-mail addresses: rtrwalker@gmail.com (R.T.R. Walker), DrRichard.Kelly@smec.com (R. Kelly).

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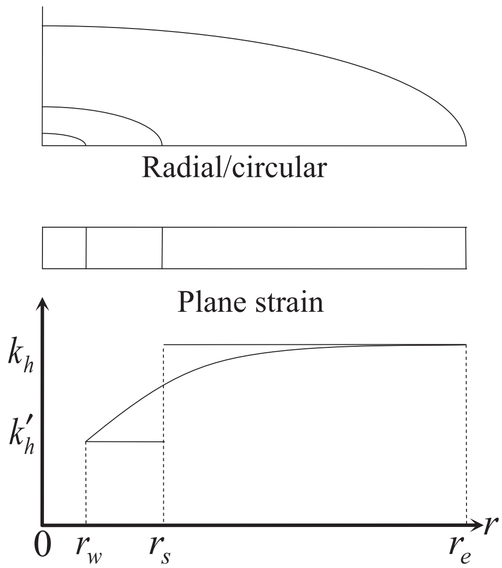

Fig. 1. Smear zone permeability in unit cell.

constant smear zone permeability are most commonly used. Appendix A contains μ expressions for single smear zones with constant permeability; the plane strain expressions account for zero or finite width drains. Solving Eq. (1) with the constitutive relationship $\dot{\varepsilon} = -m_v\dot{\bar{u}}$ leads to Hansbo's [18] consolidation equation $\bar{u} = \bar{u}_0 \exp(-\eta c_h t)$.

To achieve the same average strain rates between different models we simply use Eq. (1) to equate the relevant strain rates. For axisymmetric to plane strain conversion (assuming equal vacuum $u_{w,a} = u_{w,p}$):

$$\frac{k_p}{B^2\mu_p} = \frac{k_a}{r_e^2\mu_a} \tag{3}$$

where subscripts $_a$ and $_p$ designate axisymmetric and plane strain parameters respectively and the '$_h$' for horizontal permeability has been omitted. The μ parameters depend on drain spacing ratio $n = r_e/r_w = B/b_w$, smear zone size ratio $s = r_s/r_w = b_s/b_w$, smear zone permeability ratio $\kappa = k_h/k_{h,s}$. The choice of plane strain permeability, drain wall spacing and smear zone properties is arbitrary provided the relationship in Eq. (3) holds. Various expressions for the μ term have been derived. Appendix A contains axisymmetric and plane strain μ terms for constant permeability in the smear zone as well as ideal drains with no smear zone. These μ terms are not new in of themselves but are recast in simplified forms.

While satisfying Eq. (3) will match the average excess pore pressure, the pore pressure distributions differ. For equal strain conditions with Darcian flow the pore pressure can be expressed in general:

$$u = \frac{\bar{u} - u_w}{\mu + \mu_w}(f(\alpha) + \mu_w) + u_w \tag{4}$$

where $\alpha_a = r/r_w$, $\alpha_p = b/b_w$ or if $b_w = 0$ $\alpha_p = b$. Appendix A has expressions for axisymmetric and plane strain $f(\alpha)$, for constant smear zone permeability as well as no smear zone.

Provided Eq. (12) holds then $\bar{u}_a = \bar{u}_p$, taking equal vacuum pressures in the drain ($u_{wa} = u_{wp}$) the ratio between axisymmetric to plane strain pore pressure is:

$$\frac{u_a - u_w}{u_p - u_w} = \frac{f_a + \mu_{wa}}{f_p + \mu_{wp}}\frac{\mu_p + \mu_{wp}}{\mu_a + \mu_{wa}} \tag{5}$$

Ignoring vacuum and well resistance Eq. (5) reduces to:

$$\frac{u_a}{u_p} = \frac{f_a}{f_p}\frac{\mu_p}{\mu_a} \tag{6}$$

Thus, the ratio between pore pressure at a point in an axisymmetric unit cell and a point in a plane strain unit cell will be a constant, provided the average excess pore pressure is equal. Fig. 2 shows some axisymmetric and plane strain pore pressure distributions (Eq. (4)) for various plane strain and axisymmetric smear zone size ratios (s_p and s_a) and permeability ratios (κ_p and κ_a). No axisymmetric to plane strain matching is involved in Fig. 2, however, any dashed line could be an attempt to model any of the solid lines. Of note is the higher pore pressure at the periphery of the influence zone in plane strain. If a modeler is expecting the maximum pore pressures directly from their plane strain analysis to match that in the field they will be disappointed. Including a smear zone in plane strain reduces the difference between $u_{\max,a}$ and $u_{\max,p}$. Further reductions are possible if the plane strain smear zone permeability is very low.

In the field piezometers are usually installed midway between vertical drains at two to four different depths. Thus the measured pore pressures are expected to correspond to pore pressures at the periphery of an axisymmetric unit cell (i.e. the maximum u at $\alpha = n$). This ignores the small differences expected between square/triangular and circular influence areas. We now investigate how the maximum pore pressure modelled in 2D/3D differs from that in the field depending on the choice of modelling parameters. We consider three common approaches: (1) drains in a 2D plane strain analysis are modelled with line elements with no smear zone; (2) as per case (1) but with an explicit smear zone; (3) 3D analysis with no smear zone.

3. Case 1 – 2D plane strain, line element drains with no smear,

If modelling an embankment with vertical drains in 2D plane strain then it is conceivable that for each layer of soil in the model there could be four material types: (1) soil beyond the embankment toe unaffected by vertical drains with permeability k_h; (2) undisturbed soil at the periphery of a vertical drain influence area with k_{hp}; (3) smear zone with $k_{hp,s}$; and (4) the drain itself with k_w. Especially when performing parametric analysis modifying many material models can be time consuming.

To limit the number of material models and avoid small mesh discretization within drains and smear zones, vertical drains are commonly modelled as 1D line elements with no smear zones. Also the plane strain drain spacing, B, is chosen to fit the graphical user interface's snap-to grid spacing (often multiples of 0.5 m). Evaluating Eqs. (6), (12b), and (18b) for the above case of $s_p = \kappa_p = 1$, $\alpha_p = \alpha_a = n$, $s_0 = 0$ yields $f_p = 1$, $\mu_p = 2/3$ so:

$$\frac{u_{\max,a}}{u_{\max,p}} = \frac{2}{3}\frac{f_a}{\mu_a} \tag{7}$$

The axisymmetric to plane strain pore pressure ratio for this case is independent of the plane strain drain spacing. Fig. 3 shows the pore pressure ratio for various axisymmetric smear arrangements. As a rule of thumb for $n > 20$ $u_a/u_p \approx 0.7$. For close drain spacing or with large diameter drains (e.g. stone columns) it is recommended to calculate u_a/u_p based on the formulas.

4. Case 2 – Explicit smear zone in plane strain

Figs. 2 and 3 indicate that without a smear zone the plane strain excess pore pressure distribution is not a good fit for the axisymmetric distribution (despite average values being equal). Including an explicit smear zone improves the distribution match but we are faced with choosing three of the four parameters, k_p, B, s, and κ to

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