Finite element analysis of self-boring pressuremeter tests in over-consolidated clay

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ABSTRACT

Self-boring pressuremeter (SBPM) tests are widely used in site investigations, due to their distinct advantage to measure the shear stress-strain-strength properties of the suroundingsoil with minimum disturbance. The measured pressuremeter curve can be interpreted using analytical solutions based on the long cylindrical cavity expansion theory with relatively simple constitutive models. However, SBPM tests are strongly affected by the soil behavior and details of installation procedure. In addition, the derived parameters for clays (e.g. undrained shear strength, and shear modulus) are affected by a number of state variables such as overconsolidation ratio, and stress level. In this paper, SBPM tests are investigated using finite element analysis and the MIT-S1 model, to consider complex soil behavior more realistically. SBPM tests in K_0-consolidated Boston Blue Clay at different OCRs are simulated in axial symmetric and plain strain conditions, consistent with the assumptions used in analytical solutions. The derived undrained shear strength from both contraction and expansion curves are compared with theoretical values from stress-strain curves, to evaluate the reliability of the derived parameters from the SBPM tests.

Keywords: pressuremeter tests; finite element analysis; soil behaviour.

1. Introduction

The pressuremeter test (PMT) has the distinct advantage to measure the shear stress-strain-strength properties of the surrounding soil in the field. In principle, the PMT is a practical realization of a cylindrical cavity expansion, and the measured data can be used to obtain important engineering properties such as the undrained shear strength of clay, and deformation modulus (Baguelin et al. 1972; Bellotti et al. 1989; Clarke 1996; Palmer A. C. 1972; Wroth 1984). However, the disturbance that occurs during device installation can cause considerable differences between properties interpreted from actual PMT and those from the ideal cavity expansion (Prapaharan et al. 1990). The self-boring pressuremeter (SBPM) has the minimum disturbance to the surrounding soil (Windle and Wroth 1977; Wroth and Hughes 1973), and is now a well-established site investigation tool for use in a wide variety of soils (Benoit and Clough 1986; Clough and Denby 1980; Schnaid et al. 2000; Wroth 1984).

Analytical solutions have been derived for the SBPM tests based on the cavity expansion and contraction theories using relatively simple constitutive models (Gibson and Anderson 1961; Jefferies 1988). As more realistic soil behavior and boundary conditions are taken into account, analytical treatment becomes exceedingly difficult to handle.

In the paper, the SBPM tests are evaluated using finite element analysis and the MIT-S1 model (Pestana and Whittle 1999), to consider more realistic soil behaviour. The analyses are conducted undrained for clay, same as those assumed in the analytical studies. The computed results are interpreted following the procedure suggested by those analytical studies, and the interpreted soil properties are compared with known values from element tests. Particular focus is on the effects of OCR on the derived undrained shear strength of clay from expansion and contraction curves.

2. Interpretation of the SBPM tests in clay

Analytical interpretation of the SBPM tests have been developed based on the long cylindrical cavity expansion from a finite radius and assumed constitutive models for soils (Gibson and Anderson 1961; Ladanyi 1972; Palmer A. C. 1972; Prévost and Höeg 1975). The SBPM is assumed to expand under conditions of axial symmetry and plane strain in the axial direction, so that all variables are functions of radius only, reducing the problem to a single dimension.

Gibson and Anderson (1961) interpreted the SBPM tests in clay based on elastic-perfectly plastic Tresca model.

The initial expansion of the SBPM takes place elastically at a stiffness of $2G$ from the lift-off point $(0,\sigma_{h0})$ to the yield point $(s_u/2G,\sigma_{h0}+s_u)$. The shear modulus is defined as $G=\tau/\gamma=\tau/2\varepsilon_\theta$, where $\gamma=2\varepsilon_\theta$ is the engineering shear strain. At this stage the soil at the SBPM surface is just brought to yield, and thereafter a zone of plastically deforming soil extends outwards from the SBPM.

The volume changes in SBPM tests start from σ_{h0}, and the expansion curve for plastic loading can be theoretically expressed in eq. (1), using the volumetric strain $\Delta V/V$ at the deformed state.

$$p = \sigma_{h0} + s_u \left[1 + \ln\left(\frac{G}{s_u}\right) + \ln\left(\frac{\Delta V}{V}\right) \right] \quad (1)$$

The form of eq. (1) suggests that the plastic phase of SBPM results should lie on a straight line in the $(p-\sigma_{h0}) \sim \ln(\Delta V/V)$ plot with a gradient equal to the undrained shear strength (s_u). This method is still popular for interpreting SBPM tests in clay, partly due to its reliance on the large strain portion of the test which is less affected by soil disturbance.

The unloading part of the self-boring pressuremeter tests were found more reliably than the initial loading part which is sensitive to the soil disturbance during the installation process. The small strain cavity unloading solution given by Jefferies (1988) can be expressed in eq. (2) using the maximum radius $R_{\max}$ and maximum pressure $p_{\max}$ of SBPM at the start of unloading.

$$p = p_{\max} - 2s_u \left[1 + \ln\left(\frac{G}{s_u}\right) + \ln\left(\frac{R_{\max}}{R} - \frac{R}{R_{\max}}\right) \right] \quad (2)$$

Similar to the method using eq. (1), the form of eq. (2) suggests that the undrained shear strength can be derived from the slope of the $(p - p_{\max}) \sim \ln(R_{\max}/R - R/R_{\max})$ plot at relatively large contraction cavity strain.

3. Description of the MIT-S1 model

3.1. Model description

The MIT-S1 (Pestana and Whittle 1999) is a generalised effective stress model to describe the rate-independent behaviour of uncemented soils over a wide range of confining pressures and densities. The model inherits the incrementally linearized elastoplastic framework used by the MIT-E3 (Whittle and Kavvadas 1994), but introduces significant changes in the geometry of the bounding surface and hardening laws, and a new framework of compression behaviour to unify the modelling of clays and sands (Pestana and Whittle 1995).

The model was implemented into Abaqus™ through a user-specified subroutine (UMAT) using an automatic explicit substepping algorithm with error controls, following the integration procedure in Dong (2023).

3.2. Element tests in the bedding plane

The MIT-S1 model has been extensively evaluated for the K_0-consolidated resedimented Boston Blue Clay (BBC) with different initial overconsolidation ratios (Pestana et al. 2002), including the triaixal tests, plain strain tests, and simple shear tests. However, the soil behavior in SBPM tests are more relevant to the plane strain compression tests in the bedding plane which is more or less isotropic.

Fig. 1 shows the computed stress path and stress-strain behaviour of K_0-consolidated undrained plane strain compression tests of BBC in the isotropic bedding plane at five different OCRs, with the initial vertical preconsolidation effective stress $\sigma'_{vc} = 100kPa$. For normally consolidated and lightly over consolidated states (OCR =1, 2), the shear strength shows initial softening and then minor hardening features, whereas the heavily overconsolidated clay (OCR =4, 8, 16) exhibits strong hardening behaviour.

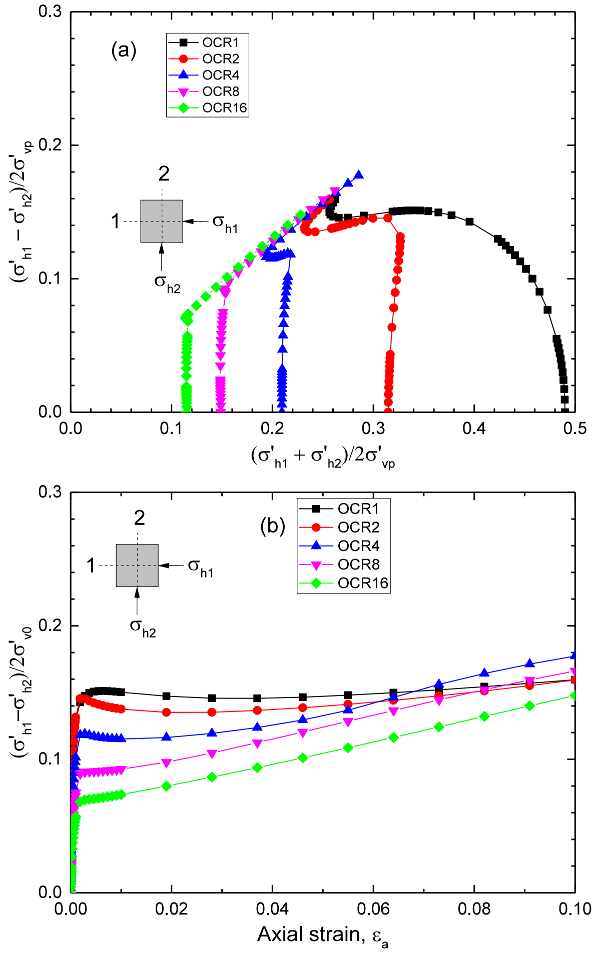

Figure 1. Simulated (a) stress path and (b) stress-strain behaviour of the K_0-consolidated plane strain compression (PSK0C) tests of BBC in the isotropic bedding plane with different OCRs

4. Finite element model

Finite element analyses have been conducted using Abaqus™ (v2020) to simulate the SBPM tests, and the axial symmetric model is shown in Fig. 2. The SBPM is 80mm in diameter, and a radial displacement is applied on the left boundary for cavity expansion or contraction. Two horizontal boundaries are constrained in the vertical direction to achieve plane strain condition, and the insitu total horizontal stress σ_{h0} is maintained on the right side for equilibrium. Displacement boundary condition is applied at the cavity for expansion and contraction. Eight-noted quadrilateral elements are used for the soil to achieve more accurate results. Small permeability value (10^{-10} m/s) and short test duration (1 second) are applied to maintain the undrained condition.

The analysis procedure closely follows the SBPM tests. The initial effective stress and pore water pressure in the ground is set up in the geostatic step. The SBPM membrane is then expanded to a specified cavity hoop strain level $\Delta R/R_0 = 20\%$ at constant rate, and then is contracted to a small residual cavity pressure.

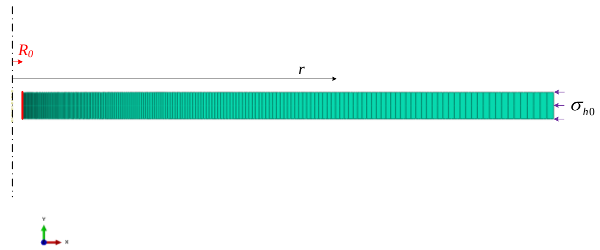

Figure 2. Finite element model for the SBPM tests

5. Result interpretation

Fig. 3(a) shows the computed expansion and contraction curves from tests in K_0-consolidated BBC with 5 different OCRs (1, 2, 4, 8, and 16) at the initial vertical effective stress $\sigma'_{v0} = 100kPa$. The effect of OCR on the test results is evident. Fig. 3 (b) shows the coresponding stress-strain curves at the cavity boundary during both expanion and contraction, which is consistent with Fig. 1 (b).

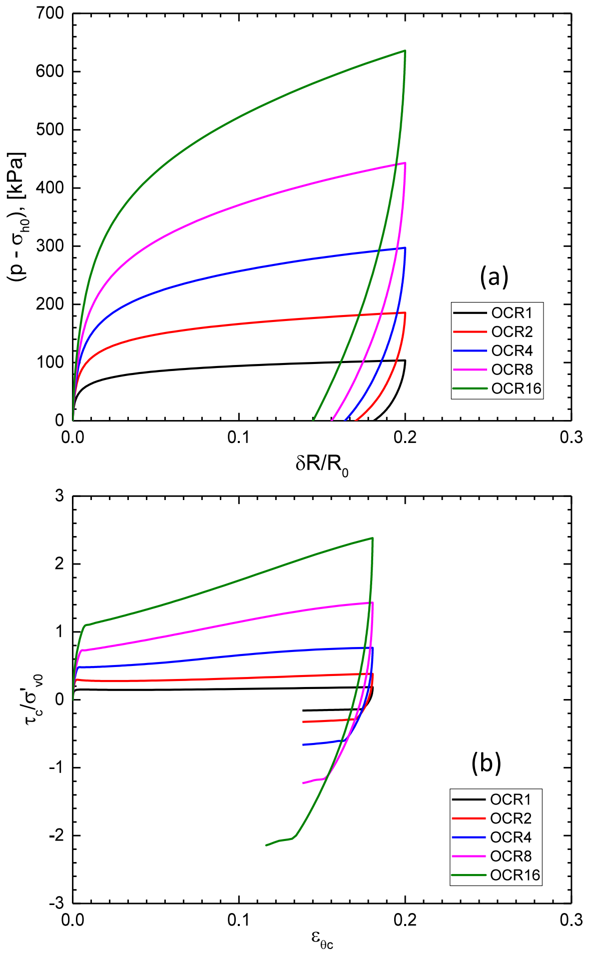

Figure 3. Computed (a) SBPM expansion and contraction curves, and (b) stress-strain curves at cavity boundary in K_0-consolidated BBC at different OCRs

The slope of the interpreted expansion curves in Fig. 4 (a) varies with the cavity strain level for heavily overconsolidated clay (e.g. OCR= 4, 8, 16), due to the strong nonlinear stress-strain relation and hardening behaviour shown in Fig. 3 (b). The slope at large strain level is used to derive the undrained shear stregnth, s_u. Similarly, the undrained shear strength can also be derived from last part of the contraction curve in Fig. 4 (b) which involves the reversal loading.

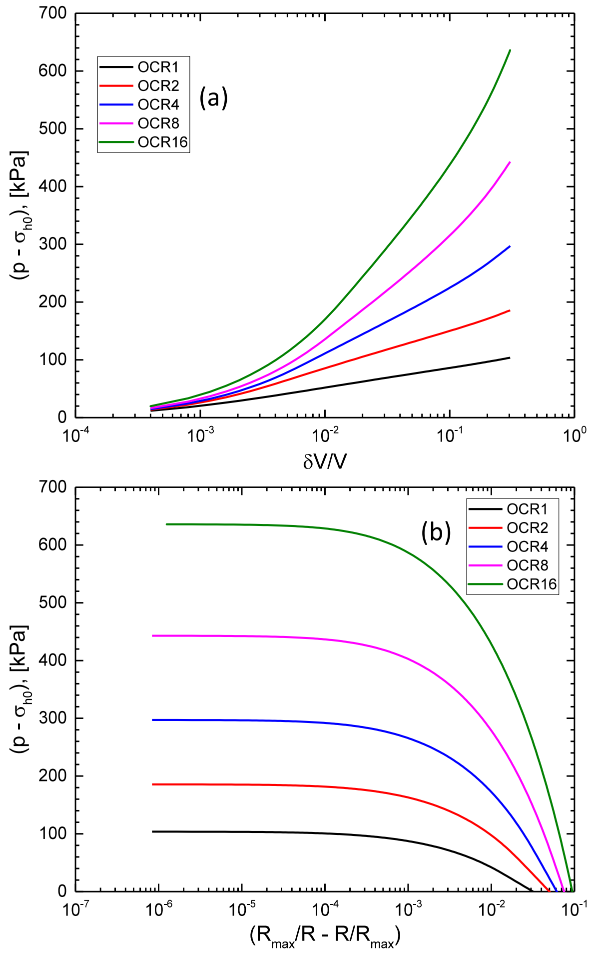

Figure 4. Interpreted SBPM (a) expansion and (b) contraction curves in K_0-consolidated BBC at different OCRs

Fig. 5 shows the derived undrained shear strength from both expansion and contraction curves in Fig. 4, together with the theoretical values from the stress-strain curves at the end of expansion in Fig. 3 (b). Although the strength derived from the expansion curves are close to the theoretical values at different OCRs, the derived strength from contraction curves are below the theoretical values for high OCRs. This is because the shear strength at the reversal loading is smaller than the strength at the end of expansion, as shown in Fig. 3 (b). This implies that although the derived shear strength from SBPM tests reflects the soil behaviour, the undrained shear strength is a state variable and is affected by the strain level. This can also explains the uncertainties of using insitu tests to derive the undrained shear strength parameters.

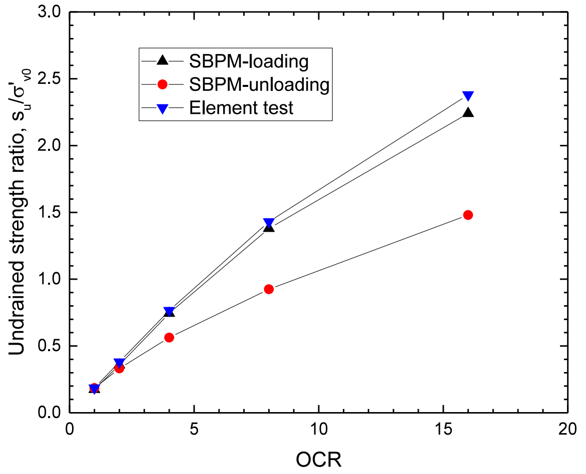

Figure 5. Evaluation of derived strength parameters

6. Conclusions

The SBPM tests in clay have been evaluated using finite element analysis and the MIT-S1 model, following the suggested procedure from analytical solutions. General conclusions are drawn for future applications:

- The analytical solutions derived from simple elasto-perfectly plastic soil models may have limitations to represent realistic soil behavior, but the suggested procedures to interpret the test results are useful to evaluate the numerical analysis with advanced soil models.
- The soil behavior in the bedding plane which the SBPM tests are conducted, can be different from those in the depositional plane due to anisotropy. The derived parameters are expected to differ from those from more common tests (e.g. triaxial, and simple shear) in the depositional plane.
- The undrained shear strength derived from the SBPM tests in clay are affected by the nonlinear stress-strain relations of undrained clay at different OCRs.

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