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TECHNICAL NOTE

A practical geometry correction for interpreting pressuremeter tests in clay

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INTRODUCTION

Analysis of the pressuremeter has typically been based on the one-dimensional expansion of a cylindrical cavity by assuming that, for usual pressuremeter geometries with aspect ratios of about six, end effects are negligible and the pressuremeter can be treated as infinitely long. However, work by Borsetto, Imperato, Nova & Peano (1983) and Houlsby & Carter (1993) has indicated that this is a poor assumption. The effect of finite pressuremeter geometry must be considered during interpretation if realistic ground properties are to be derived.

There is no disagreement about the importance of a finite geometry correction, but there is no such consensus about the magnitude of the correction. In particular, Houlsby & Carter proposed that, based on their finite element studies, the effect of finite geometry was readily approximated by modifying the true undrained strength by as much as 40%. However, application of their proposed correction factors does not recover the theoretical $L/D = \infty$ load–displacement curve (Fig. 1).

The Authors have repeated the core analyses of Houlsby & Carter using a public domain finite element code which is substantially more accurate than that previously reported, thereby eliminating one possible error. Also, the analyses were extended to include the contraction phase of the self-bored pressuremeter (SBP) tests to minimize uncertainty in recovered properties.

Like Houlsby & Carter, the Authors use the numerical results to develop a finite geometry correction, but, unlike them, show that the correction factors recover the input soil parameters (referred to here as the 'true' parameters) within a defined certainty. Broadly, s_u can be recovered with an uncertainty of about $\pm 5\%$ and I_r can be recovered to an uncertainty of about $\pm 20\%$. The accuracy with which σ_{h0} can be recovered is approximately $\pm 2\%$.

CORRECTION FACTOR

For a given radial displacement, compared with an infinitely long cylinder and all else being considered equal, the finite pressuremeter length increases the cavity pressure. The increased cavity pressure can be represented as a correction factor applied to the expansion relationship predicted by the assumption $L/D = \infty$, as indicated in Fig. 2.

Defining this correction as β gives

$$[\psi - \sigma_{h0}]_{L/D=\infty} = \beta[\psi - \sigma_{h0}]_{L/D=n} \tag{1}$$

or, applying the cavity expansion theory at an instant in a test, gives

$$s_{u(\mathrm{true})} = \beta s_{u(L/D=n)} \tag{2}$$

where n is the geometric factor of the SBP, which is typically 6 for many commercial devices; all else remains fixed. In this Technical Note, correcting SBP data by β is referred to as an overshoot correction. This is the approach proposed, but not used, by Houlsby & Carter (1993).

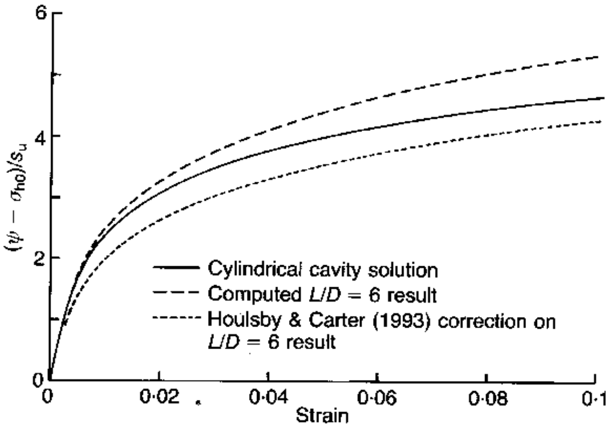

Fig. 1. Pressure versus strain for $I_r = 200$

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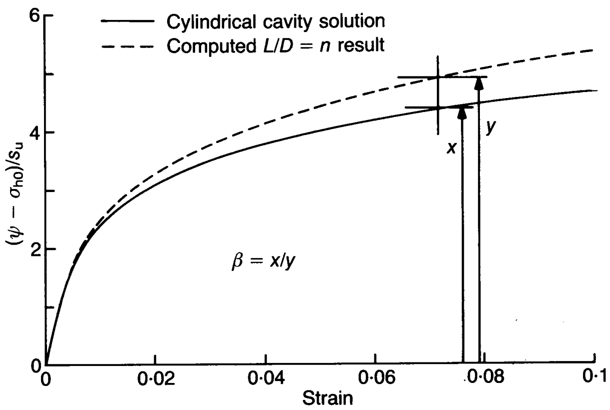

Fig. 2. Definition of overshoot correction

β is not truly a constant but varies with strain during a single test. There is a distortion as well as a simple scaling, and this is why the correction factors of Houlsby & Carter do not recover a reasonable estimate of the true ground response.

PRESSUREMETER IDEALIZATION

In order to compare the effect of the aspect ratio on the theoretical behaviour of a cylindrical cavity, the closed form solution of Gibson & Anderson (1961), expanded to include unloading behaviour by Jefferies (1988) and independently by Houlsby & Withers (1988) has been used. The theory is explained in these papers and so only a summary of the results in presented here. The soil is considered to be undrained (and therefore incompressible), linear elastic–perfectly plastic, and to obey the Tresca yield criterion with an associated flow rule. Therefore the pressure–strain behaviour of the pressuremeter is defined completely by the undrained shear strength s_u and shear modulus G. The pressure applied to the pressuremeter membrane is denoted as ψ and, using small strain theory, the tensile hoop strain at the pressuremeter surface by $\varepsilon = (a - a_0)/a_0$, where a_0 and a are the initial and current pressuremeter radii.

The theoretical analysis of an SBP test has been considered in five discrete parts, using the small strain solution for numerical convenience, (see equations (3)–(13)). Real tests will be analysed using large strain theory as reported by Jefferies (1988) and Houlsby & Withers (1988). Correction factors remain unchanged. The five parts are as follows.

(*a*) *Perfect self-boring in an isotropic material.* It has been assumed that the pressuremeter is installed without any disturbance to the soil.

(*b*) *Initial elastic expansion*

$$\Delta\sigma_r = 2G\varepsilon \tag{3}$$

$$\Delta\sigma_\theta = -\Delta\sigma_r \tag{4}$$

$$\psi = \sigma_{h0} + 2G\varepsilon \tag{5}$$

At yield

$$\psi = \sigma_{h0} + s_u \tag{6}$$

$$\varepsilon = s_u/2G = 1/2I_r \tag{7}$$

(*c*) *Plastic expansion*

$$\psi = (\sigma_{h0} + s_u) + s_u \ln (2I_r\varepsilon)] \tag{8}$$

(*d*) *Elastic contraction*

$$\psi = \psi_{max} - 2G\varepsilon \tag{9}$$

At yield

$$\psi = \psi_{max} - 2s_u \tag{10}$$

$$\varepsilon = \varepsilon_{max} - s_u/G \tag{11}$$

(*e*) *Plastic contraction*

$$\varepsilon^* = \varepsilon_{max} - \varepsilon \tag{12}$$

$$\psi = \psi_{max} - 2s_u[1 + \ln (I_r\varepsilon^*)] \tag{13}$$

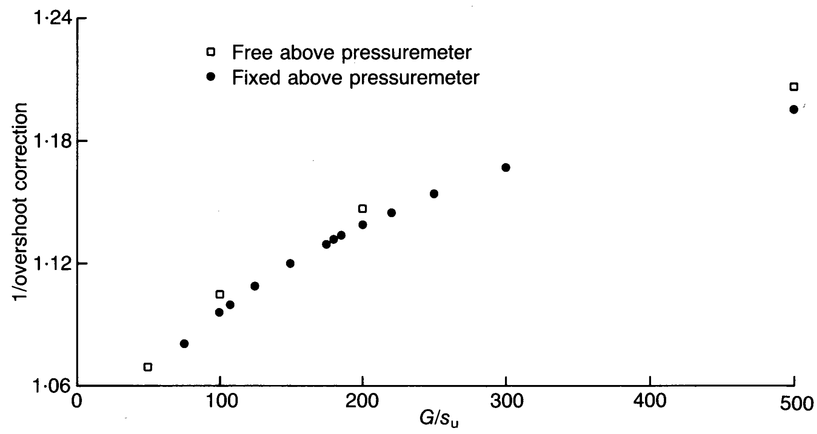

Fig. 3. Effect of fixity on the difference between measured and theoretical pressuremeter pressure

The soil is assumed to have a coefficient of earth pressure at rest K_0 of unity. This is not an important assumption for the one-dimensional analysis. However, acceptance of the importance of L/D for real situations suggests that K_0 may have more effect than has previously been considered.

In order to look more closely at correction factors for finite length SBP tests in clay, numerical simulations were produced for infinitely long and $L/D = 6$ pressuremeter idealizations using an adaptation of a University of Manchester finite element code. This code is available in the public domain (Smith & Griffiths, 1988) and the visco-plastic solution method results in a maximum error in computed response of an infinite cylinder of less than 0·35% for a range of I_r of 50–500.

The pressuremeter was modelled using eight-noded quadrilateral elements with symmetry assumed at mid-height. Meshes of 20 by 20 and 30 by 30 were used to ensure that the solution was independent of mesh size. The effect on the central pressuremeter deflexion of changing the fixity above the pressuremeter from fully fixed (no separation between the pressuremeter and the soil above the membrane) to fully free (no change in stress at the interface between the pressuremeter and the soil above the membrane) was less than 1% of the theoretical solution (Fig. 3). Both idealizations are incorrect, but encompass the real boundary conditions. Modelling results assuming no fixity above the pressuremeter are now presented.

MODELLING RESULTS

The results of the six simulations used to generate the overshoot correction are shown in Table 1 and Fig. 4. The difference between the theoretical and modelled solutions is shown to increase with both I_r and applied strain. At an I_r of 75 the correction factor β varies from 0·952 to 0·926 between $\varepsilon = 5\%$ and $\varepsilon = 10\%$. At the maximum value of $I_r = 500$, above that typically encountered in practice, β varies from 0·867 to 0·837 at $\varepsilon = 5\%$ and $\varepsilon = 10\%$. Hence, s_u may be overestimated in terms of an overshoot error by up to 20% if a correction is not applied.

Table 1. Overshoot error β from finite length ($L/D = 6$) simulations

I_r	β		
	5%	7%	10%
75	0·9524	0·9399	0·9259
100	0·9412	0·9282	0·9130
150	0·9259	0·9111	0·8937
200	0·9130	0·8971	0·8789
300	0·8936	0·8761	0·8577
500	0·8673	0·8504	0·8368

This increase in error with strain implies that the standard interpretation method of deriving s_u by plotting ψ against ln (ε) would exacerbate this effect and result in even higher correction factors; this is the difference between the correction factors computed here and those reported by Houlsby & Carter (1993).

L/D CORRECTION

In the iterative forward modelling (IFM) approach, the true soil parameters are guessed and the theoretical response for these parameters is computed. Comparison of the guessed theoretical results with test data is used to improve the guess, the procedure being iterated several times to give a good estimate of the true ground properties. The guessed properties are explicit at every step and so it is simple to apply an L/D correction factor to these guesses during IFM.

When plotted against ln (I_r) the values of β from Table 1 approximated parallel straight lines (Fig. 5). The overshoot error β during loading was therefore approximated by the function

$$\beta = 1{\cdot}241 - 0{\cdot}05[\ln (I_r \varepsilon)] \qquad (14)$$

where ε is given as a percentage.

The value of β used in the IFM was determined

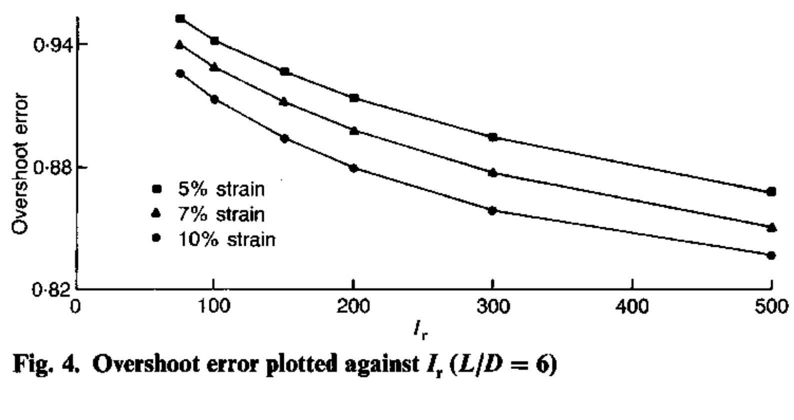

Fig. 4. Overshoot error plotted against I_r ($L/D = 6$)

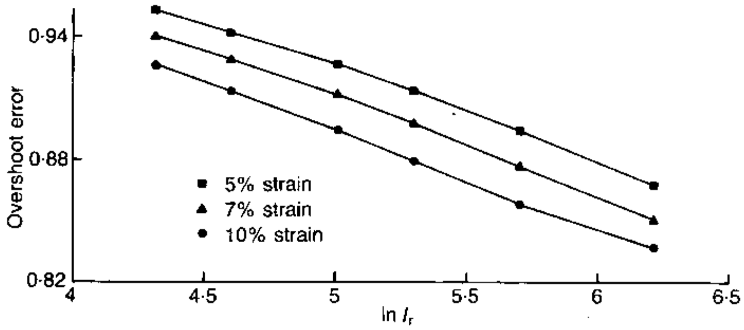

Fig. 5. Overshoot error plotted against ln (I_r)

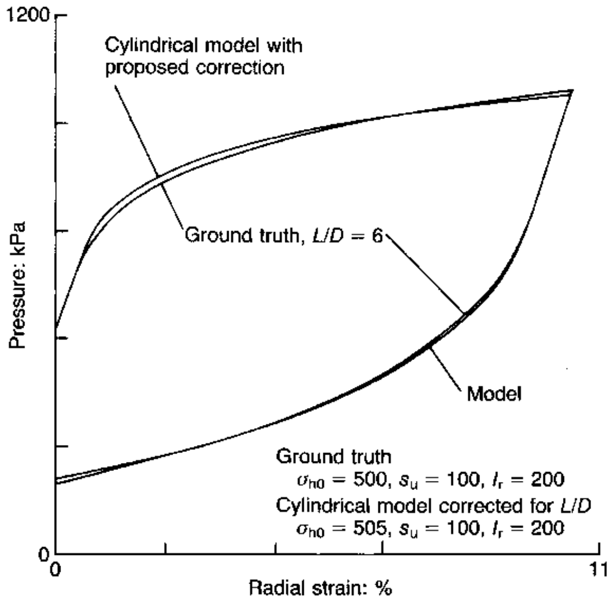

Fig. 6. Fit of cylindrical cavity theory to data with $L/D = 6$ using proposed correction

from equation (14) by using a strain value equal to 2/3 of the maximum strain applied, i.e. $\varepsilon = 2\epsilon_{max}/3$). This strain value was chosen because most analysts tended to average out the errors about this point. With the correct parameters input into IFM this correction resulted in a good fit to the strength at 2/3 of the maximum strain, but the resulting curve fit was too stiff. A correction was therefore applied to I_r

$$I_{r\,(L/D=6)} = 0{\cdot}9\beta I_{r(\text{true})} \tag{15}$$

An additional correction was also applied to σ_{h0}. Fits to the data, both with and without any corrections applied, resulted in a systematic bias towards too high a horizontal stress. The correction applied to the horizontal stress was given by

$$\sigma_{h0\,(L/D=6)} = \sigma_{h0\,(\text{true})} + 0{\cdot}1 s_{u\,(L/D=6)} \tag{16}$$

The effect of correcting the SBP response is indicated in Fig. 6. The corrections applied result in a

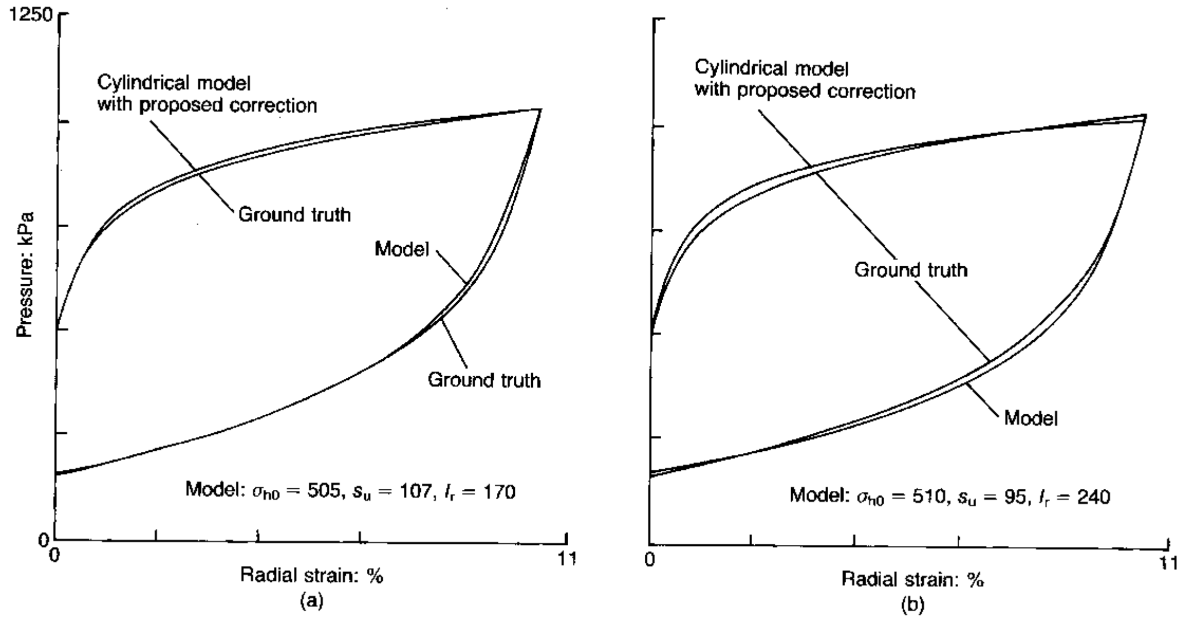

Fig. 7. Uncertainty in recovered ground truth: (a) s_u overestimated; (b) s_u underestimated

good match between the simulated data and the derived solution.

UNCERTAINTY

SBP tests, like other in situ tests, present an inverse problem in the determination of the soil parameters from the measured data. With an inverse problem there is always some uncertainty associated with parameter extraction, and the SBP is no different from this general rule. An advantage of the IFM procedure is that this uncertainty may be determined by exploring the limits at which the image match breaks down to any sensible interpreter.

The uncertainty associated with the L/D correction is shown in Fig. 7. There is always the possibility of getting only one of either s_u or I_r incorrect, but the greatest uncertainty occurs when each parameter is uncertain but in the opposite sense. This condition is shown in Fig. 7(a) where s_u is underestimated and I_r is overestimated; the opposite possibility is shown in Fig. 7(b). In both Figs 7(a) and 7(b) the modelled behaviour is sensibly different from the best achievable (Fig. 6). The deviations of properties interpreted using Figs 7(a) and 7(b) from the known ground truth are thus an estimate of the uncertainty with which properties may be inferred from the SBP, given perfect knowledge of the constitutive model and using the proposed correction for L/D effects. Fig. 7 shows the uncertainty in undrained strength to be about $\pm 5\%$. The rigidity is rather more difficult to distinguish by eye and has a correspondingly larger uncertainty of about $\pm 20\%$. There is apparently a further bias in σ_{h0} of about 1–2% over that already removed by equation (16). Generally σ_{h0} may be recovered unbiased to about this accuracy. However, within this range individual interpreters may systematically bias their interpretations of σ_{h0} too high or too low (here the bias is high).

CONCLUSIONS

The results of the finite element modelling of a pressuremeter with $L/D = 6$ (the geometry of self-bored pressuremeters that are commonly available) indicate errors in the value of s_u derived from the cylindrical expansion theory which depend on I_r and ε_{max}. These errors may be approximated by equations (14), (15) and (16) for s_u, I_r and σ_{h0} respectively, and the IFM method of analysis used to recover the true ground properties. True ground strength s_u may be recovered to an uncertainty of about $\pm 5\%$ and ground rigidity I_r to an uncertainty of about $\pm 20\%$. The in situ horizontal stress σ_{h0} may be recovered to $\pm 2\%$, although individual interpreters may impart a systematic bias within this range.

NOTATION

- a current pressuremeter radius
- a_0 initial pressuremeter radius
- D diameter of pressuremeter
- G elastic shear modulus
- I_r rigidity index G/s_u
- L length of pressuremeter
- s_u undrained shear strength
- β overshoot correction factor
- ε tensile hoop strain
- ψ pressure applied to soil by pressuremeter
- σ_{h0} in situ horizontal stress
- σ_r radial stress
- σ_θ hoop stress

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