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# The myth of the finite pressuremeter geometry correction

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## Introduction

Soil strength and stiffness properties are obtained from pressuremeter tests using analyses that depend on solutions for the expansion of an infinitely long cylindrical cavity. Real pressuremeters have length to diameter ratios between 3 and 10. Studies using finite element methods have indicated that this finite pressuremeter geometry leads to significant over-estimation of the shear strength. This paper tests the finite element results and shows that they do not predict the shear stress-strain response observed in real tests in the field. The conclusion is that end effects associated with finite pressuremeter geometry are of negligible significance for the derivation of material strength.

## Background

Several papers have reported on the consequences of finite pressuremeter geometry for the derivation of material strength and stiffness parameters. Two of the more recent are considered here, Houlsby & Carter (1993) and Shuttle & Jefferies (1995).

Houlsby & Carter (1993) present the results of simulated undrained pressuremeter tests in a finite element model of simple elastic/perfectly plastic soil. The simulated tests were run for differing length to diameter ratios, depths below ground level and for common values of rigidity index in the model soil.

Gibson & Anderson (1961) give the solution for an undrained cylindrical expansion in simple elastic/perfectly plastic soil. For a current radius $a$ at the cavity the total pressure $P$ being applied is

$$P = P_0 + S_u \left\{ 1 + \ln\left[ \left( I_r \right) \left( 1 - \left( \frac{a_0}{a} \right)^2 \right) \right] \right\} \qquad \ldots [1]$$

where $P_0$ is the cavity reference pressure
$I_r$ is the rigidity index $G/S_u$
$G$ is the shear modulus
$S_u$ is the undrained shear strength
$a_0$ is the initial radius of the cavity

The Houlsby & Carter tests indicate that the smaller the length to diameter ratio, the greater the stress that must be applied to achieve a given plastic deformation. The difference in stress is expressed as a correction factor whose magnitude depends on a number of variables.

The corrections given in Houlsby & Carter are derived by following conventional engineering practice. The finite element tests are plotted in terms of total pressure against the natural log of the current volumetric strain and the slope of the most linear part of this plot gives the undrained shear strength directly. Houlsby & Carter take the slope between 2% and 5% cavity strain and express the correction factor as the ratio of the derived shear strength to the input shear strength. The choice of strain range is important because the effective length to diameter ratio reduces as the diameter of the plastic zone increases, so that other strain ranges give different results.

The conclusion of Houlsby & Carter is that the undrained shear strength is greatly affected by finite pressuremeter geometry. It is reported that a pressuremeter with a length to diameter ratio of 6 in material with a rigidity index of 200 would over-estimate the shear strength by more than 20%. The strain dependent nature of this error is acknowledged but not quantified because it is accounted for by the specified working method.

Shuttle & Jefferies (1995) repeats some of the work of Houlsby & Carter using different finite element code. Similar results are obtained although this is not immediately obvious from the manner in which the data are presented.

The consequences of finite geometry are expressed in Shuttle & Jefferies as an overshoot correction $\beta$ where *at an instant* in a test:

$$S_{\mathrm{u(true)}} = \beta S_{\mathrm{u(measured)}} \qquad \text{...[2]}$$

$\beta$ is related to the rigidity index and is strain dependent, being a function of the current diameter of the plastic zone. Shuttle & Jefferies give the following approximation for $\beta$ :

$$\beta = 1.241 - 0.05[\ln(I_r \epsilon_c)] \qquad \text{...[3]}$$

where $\epsilon_c$ is cavity strain in %

$\beta$ is used within the context of a curve comparison procedure where $S_u$ is an input parameter for generating a theoretical curve to fit as closely as possible the full measured curve. For a pressuremeter test in material with a rigidity index of 200, the effect of $\beta$ is less than 10% at 5% cavity strain.

Both studies provide corrections for pressuremeters with a length to diameter ratio (L/D) of 6 (the ratio for a Cambridge Self Boring Pressuremeter) in material with a rigidity index typical of what might be discovered in London clay (Table 1).

### Table 1 - Variation of $S_{u(measured)}$ / $S_{u(true)}$ for L/D of 6 at about 5% cavity strain

| | Source of Data | Method | $I_r = 100$ | $I_r = 200$ | $I_r = 500$ |
|---|---|---|---|---|---|
| [1] | Houlsby & Carter (1993) | [a] | 1.152 | 1.248 | 1.420 |
| [2] | Shuttle & Jefferies (1995) | [b] | 1.062 | 1.095 | 1.153 |
| [3] | Shuttle & Jefferies (1995) | [a] | 1.174 | 1.278 | 1.389 |
| [4] | Houlsby & Carter (1995) | [a] | 1.149 | 1.246 | 1.415 |

*Notes:*
Method [a] - produce a plot of total pressure against Ln volumetric strain and take the slope between 2% and 5% cavity strain.
Method [b] - calculate the overshoot correction $\beta$ .

At first sight there seems to be conflict about the magnitude of the correction between the two studies, but the difference is due to how the simulated tests are interpreted. If equations [1] and [3] are combined, then Shuttle & Jefferies 'geometry affected' pressuremeter tests can be derived. If these tests are then interpreted using the method specified by Houlsby & Carter, correction factors similar to those reported by Houlsby & Carter are obtained. This has been done here, and is shown in the third row of Table 1. Later work by Shuttle (quoted in Houlsby & Carter 1995) along these lines gives results even closer to those reported by Houlsby & Carter (1993) - compare rows one and four of Table 1.

For the purposes of this paper the Shuttle & Jefferies overshoot correction described by equation [3] is the most convenient way to access the finite geometry results but the table indicates that the two sets of simulated tests produce similar data. Alternative ways of utilising that data give different corrections.

## The comparison with field tests

It is not possible to test the magnitude of the corrections from field data. However if the predictions of the finite element studies are valid then the strain dependent nature of the finite geometry effect will give pressuremeter shear stress curves that show a strain hardening response. The degree of this response will depend on a number of factors, but for a given pressuremeter the significant variable will be the rigidity index.

Presenting the finite element results on semi log axes masks the extent of strain hardening behaviour. The effect is better demonstrated by drawing the shear stress versus strain curve using the subtangent or Palmer (1972) method. Figure 1 is an example.

A pressure versus strain curve for an infinite length pressuremeter was created using equation [1] with a rigidity index of 200, an undrained shear strength of 1 and a cavity reference pressure of 0. An overshoot correction $\beta$ was derived for every increment of strain using a version of equation [3] optimised for an $I_r$ value of 200, and the corresponding pressure versus strain curve for a pressuremeter with a length to ratio diameter of 6 was derived. These curves were then analysed by the subtangent method to give the data plotted in Figure 1.

The infinite length data gives the simple elastic/perfectly plastic form assumed by the Gibson & Anderson solution. However an obvious strain hardening response is apparent in the curve for the finite length pressuremeter.

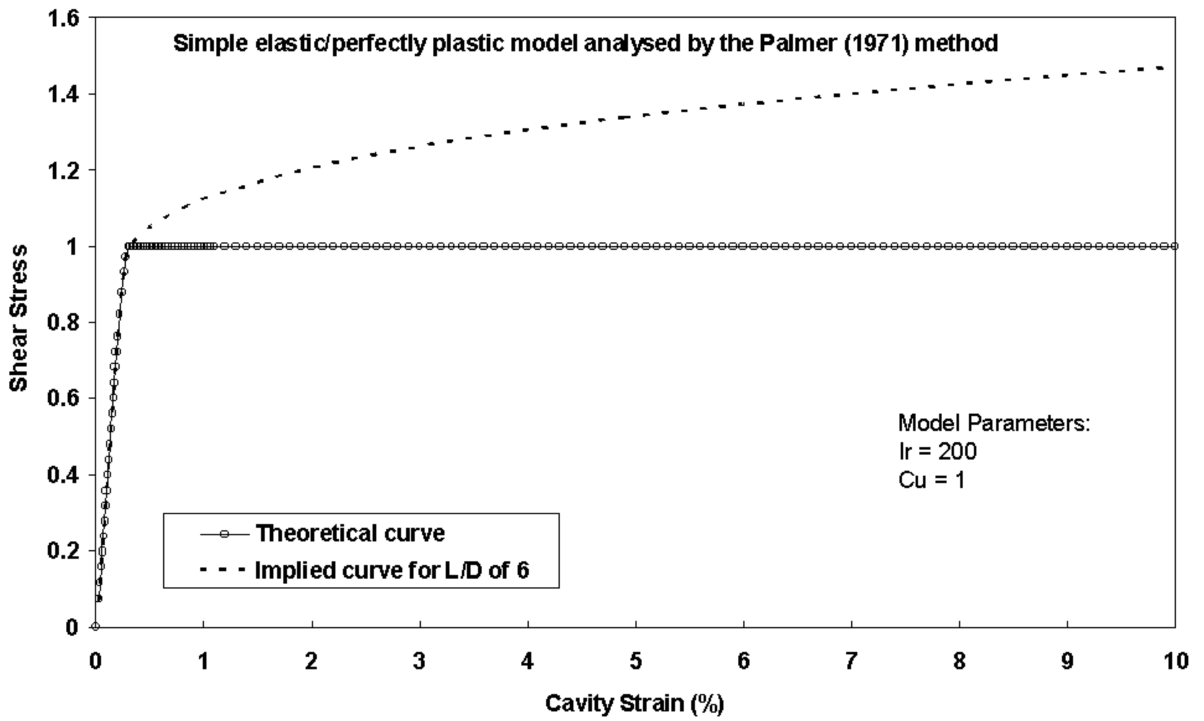


*Fig. 1 The subtangent analysis applied to the finite length problem*

If the finite element results are relevant then tests in the field must show this response but they do not. Figure 2 is the shear stress:strain response derived from four self bored pressuremeter (SBP) tests in the same borehole in London clay. The instrument has a length to diameter ratio of 6. The tests lie between 10 and 17 metres below ground level. These tests have been chosen because of their freedom from defects such as obvious cracking at large strain which would be indicated by apparent strain softening. They are good examples of pressuremeter tests in the material for which the Gibson & Anderson analysis was developed. The data has been normalised by the derived shear strength to make the curves comparable with the data in figure 1, and the finite length pressuremeter data from figure 1 is also plotted in figure 2.

There are difficulties using conventional spreadsheet facilities to calculate the local slope of measured pressure:strain curves but the scatter here is reasonably small and the shapes of the curves are clear. There is no evidence of apparent shear stress increasing with strain, if anything the reverse. There are some indications of a peak strength near the origin up to 1.2 times the ultimate strength, and some signs that the pressuremeter curves have been affected by the taking of unload/reload cycles.

Figure 3 shows the same data plotted in terms of total pressure versus the natural log of the volumetric strain. In this example the total pressure has been normalised by subtracting the reference pressure $P_0$ before dividing by the derived shear strength. The pressure scale starts from 1, in effect the yield stress, so that only the plastic loading is seen and the intercept on the strain axis gives $\ln(1/I_r)$. The intercept on the normalised pressure axis gives the limit pressure in the form of the so-called pressuremeter constant (6.3 for an $I_r$ of 200).

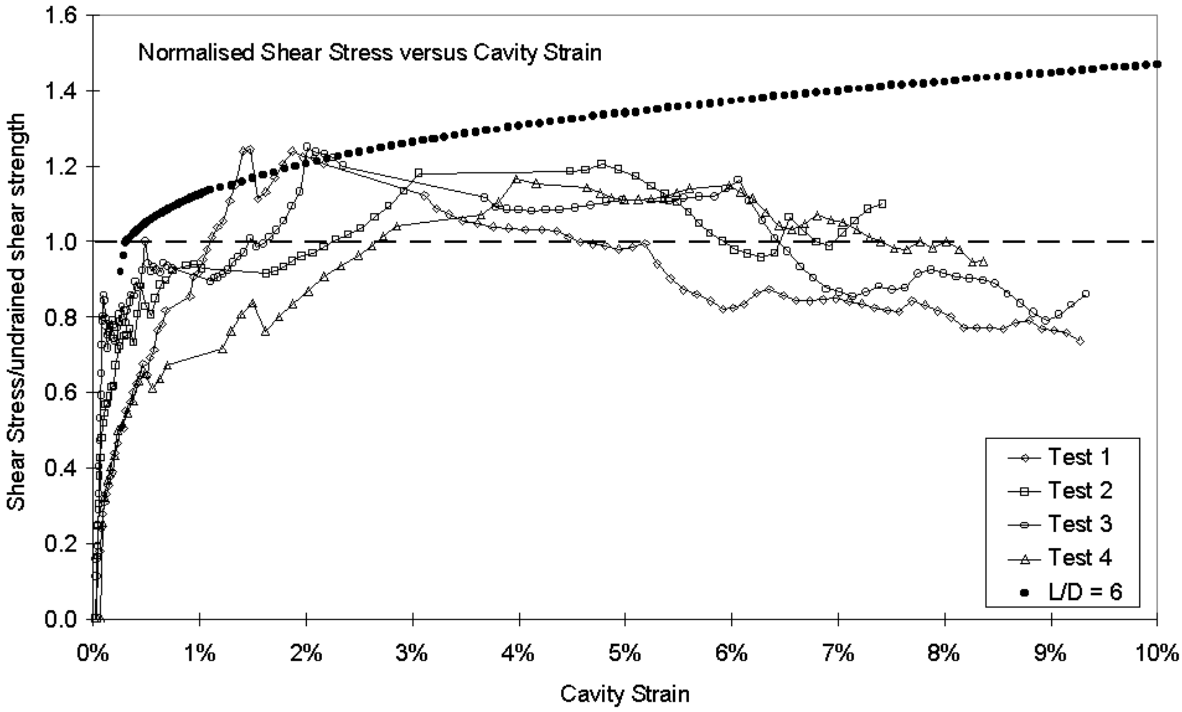


*Fig. 2 Subtangent analysis of four SBP Tests in London clay*

Although short sections of the field data do indicate some local strain hardening, a glance along the plotted points especially at large strain shows that the assumption of perfect plasticity is not unreasonable. The local strain hardening is due to the influence of unload/reload cycles on the loading curve, and is a transitory effect. This is indicated by the manner in which a line projected back through the points at large strain passes close to the initial points near the yield stress. The shear stress:strain response predicted for a length to diameter ratio of 6 and an $I_r$ of 200 is quite different.

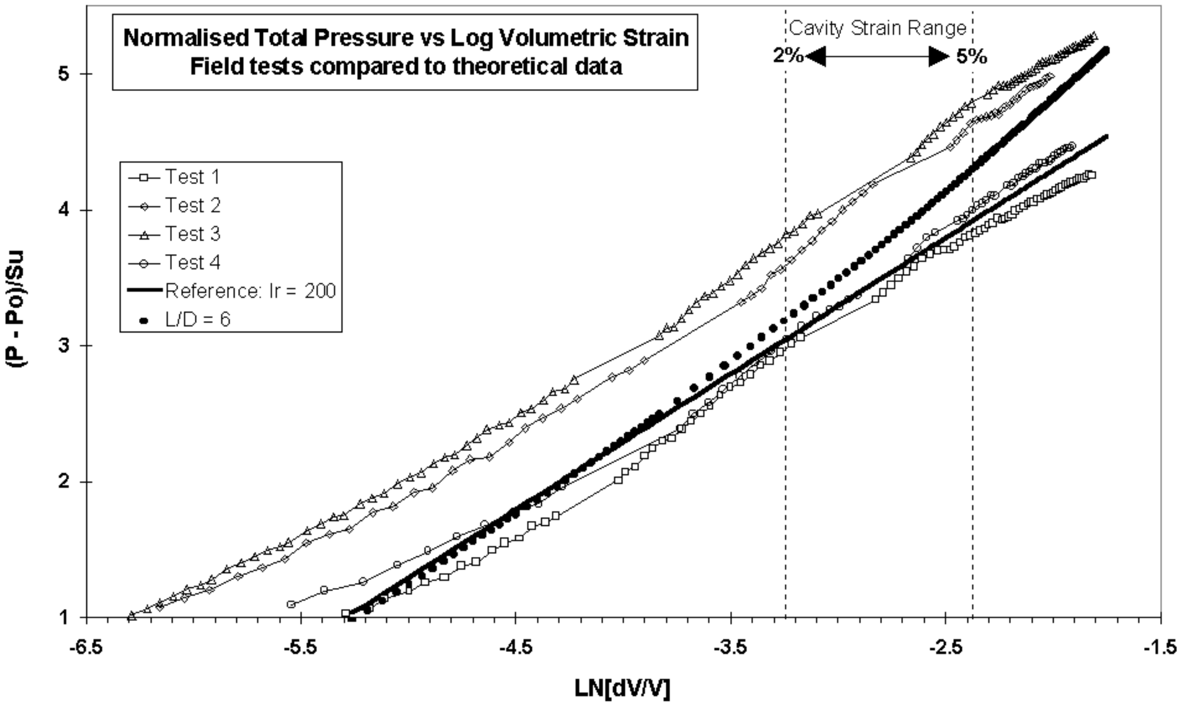


*Fig. 3 Gibson & Anderson style analysis applied to the same data plotted in figure 2*

## Conclusion

An attack on the validity of the finite geometry correction based on the absence of a strain hardening response might seem indirect, not to say superficial, but it is fundamental. There is no special magic about the length to diameter ratio of the instrument - it is the length to diameter ratio of the expanding cavity that is significant. Because this ratio is reducing all the time the test is in progress, the strain hardening response is a necessary sign that a correction is needed. Conversely, as demonstrated here, the absence of such behaviour is sufficient evidence by itself to show that there can be no important error in the pressuremeter estimates of shear strength due to end effects.

The finite element tests are not wrong - indeed, some effort has been expended demonstrating that different researchers using different code obtain similar data. However as far as tests in real soil are concerned, the results of the finite element tests are irrelevant. Although this conclusion comes from a handful of field tests from one type of instrument in one type of soil it is strongly suspected that other pressuremeters in other soils are much less affected by finite geometry than has been supposed. The evidence from field tests in sand, for example, is that the angle of internal friction determined at the initial yield is usually similar to the value derived at the end of the test at about 10% cavity strain. Although this author has little experience of the Ménard pressuremeter, inspection of the examples of such tests in the papers by Gibson & Anderson and by Palmer show no evidence of strain hardening. Indeed, it is difficult to imagine how these two classic analyses for undrained strength could have been demonstrated if the corrections for end effects are of the magnitude suggested by the finite element tests.

It is not difficult to think of reasons why the finite element results are misleading. The finite element soil is described by a linear elastic characteristic. Real soils invariably have a non-linear elastic response. The consequences for the test are dramatic. Non-linear stiffness means that in the expanding cavity, soil that is yielding is conditioned by a significantly lower stiffness than soil which is behaving elastically. The ‘ends’ of the expanding cavity where a small axial component might be expected are much stiffer than the linear elastic model suggests.

It is possible to imagine circumstances where end effects could be demonstrated. Clean sand of uniform particle size rained into a calibration chamber might respond in a manner that approximates to linear elastic. Tests in such material (Fahey 1980), do show some measurable affect due to pressuremeter length to diameter ratios but it is by no means clear that strength is over-estimated.

Outside of this contrived situation, non-linear elastic behaviour probably compensates for the influence of end effects. The ‘myth’ in the title of this paper refers as much to the model as it does to the concept.

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