Finite Element Analysis of Pressuremeter Tests in Soil

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SUMMARY. A finite element analysis is carried out for the self-boring pressuremeter tests in clay. The main objective of this study is to quantify possible effects of finite length of the pressuremeter on soil parameters derived from the tests. It has been concluded that serious overestimation of the strength parameters of clay may be deduced by applying the Gibson and Anderson method to field pressuremeter tests. A new interpretation procedure is therefore proposed to eliminate effects due to the simple assumptions used in the conventional interpretation method.

1. INTRODUCTION

In the early stage of development of pressuremeters, the results of pressuremeter tests were interpreted by means of empirical expressions to give parameters for design such as allowable bearing capacity factors and moduli for allowable settlement. The first fundamental interpretation of an expansion test was published by Gibson and Anderson (1961) in which the pressuremeter was considered to be infinitely long so that the deformation of the surrounding soil was assumed to be in conditions of axial symmetry and plane strain. The interpretation was developed for both undrained expansion tests in clay and expansion tests in cohesionless soils, for which the soil is assumed to behave elastically until failure occurs at a constant effective stress ratio and with no volume change.

As far as the undrained expansion is concerned, Palmer (1972) has also developed a method which can be used to interpret pressuremeter tests without a prerequisite assumption of stress-strain relationship for the soil being tested. However this approach has been found to be very sensitive to the disturbance of the soil caused by installation, and the resulting uncertainty about the reference strain. By comparison, it is generally accepted that the original Gibson and Anderson analysis is preferable in deriving undrained shear strength as recommended by Mair and Wood (1987). Although the Gibson and Anderson analysis has been widely used to interpret self-boring pressuremeter tests in clay, it is also recognised that it often leads to overestimation of undrained strength.

The literature contains several well-documented reports of tests on clays with the self-boring pressuremeter. Results indicate important disagreement with the results of good laboratory tests or other in-situ tests. It is the Authors belief that these disagreements may be largely due to the influence of the finite length of the pressuremeter. Although the analyses assume an infinitely long pressuremeter, a typical length to diameter ratio is about six. Yu (1990) has recently carried out a comprehensive study of the influence of finite length for various pressuremter tests in both clay and sand. In his study, a two-dimensional finite element analysis was used to simulate pressuremeter tests, which are then back-analysed using the conventional cavity expansion solutions. This paper will concentrate on the influence of finite length for self-boring pressuremeter tests in clay. The pressuremeter tests are analysed using a novel two-dimensional finite element formulation, which is particularly suitable for axisymmetric problems (Yu, 1991; Yu et. al., 1991).

2. NUMERICAL MODELLING OF PRESSUREMETER TESTS

In this paper, the self-boring pressuremeter was assumed to be installed deep into the ground without any disturbance and the initial soil stress state was assumed unchanged by the installation of the pressuremeter. To isolate effects due to the finite length of the pressuremeter from possible numerical errors due to the non-linear solution algorithm, a calibration calculation with an infinitely long pressuremeter was carried out for each pressuremeter test with a finite length of probe. Figure 1 shows a mesh for real pressuremeter calculations which consists of 288 modified 6 node triangular elements and the mesh with a plane strain condition in the vertical direction was used to model infinitely long pressuremeters. Care was taken in designing these meshes so that possible regions with higher stress gradients have a higher density of elements. The pressuremeter membrane was modelled by 6 elements and boundary conditions used in calculations are shown in Figure 1.

A fixed ratio of the total height of mesh to half length of the pressuremeter has been used and different length to diameter ratios are obtained by multiplying the vertical coordinate of all meshes by a certain factor. The material behaviour of the infinite medium was simulated by a correcting layer for which the continuum properties and the correcting layer properties are related by an elastic solution (Yu, 1990).

3. ANALYSIS OF PRESSUREMETER TESTS

3.1 Parameters for the Analysis

In order to quantify the effects due to the finite length of pressuremeter probes, numerical simulations of self-boring pressuremeter tests in clay have been carried out using the axisymmetric finite element method developed by the author (Yu, 1991). The soil mass has been idealised as an

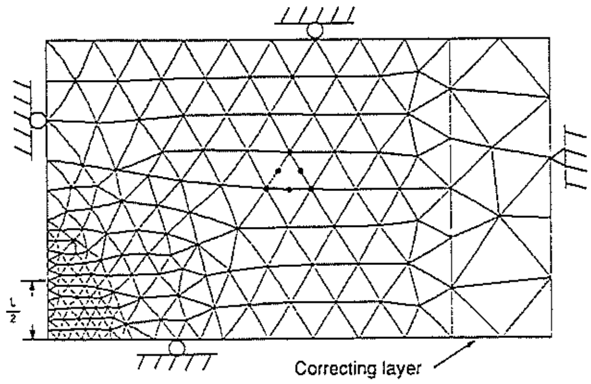

Figure 1: Finite element mesh used for simulation of pressuremeter tests

elastic-perfectly plastic medium which obeys the von Mises yield criterion and deforms under constant volume conditions. Pressure controlled 'quick' expansion tests were simulated and each test was continued to a cavity strain $\epsilon = 10\%$ for centre of pressuremeter membrane. Effects due to finite stiffness of membrane are ignored in this study.

Table 1 summarises all values of the key parameters varied in the numerical simulations. An isotropic initial stress state with zero value for all stress components was assumed.

Table 1 Numerical tests of self-boring pressuremeter in clay

$\frac{L}{D}$ \ I_r	50	100	200	300	500
4	F8	F12	F16	F20	F4
6	F7	F11	F15	F19	F3
8	F6	F10	F14	F18	F2
∞	F5	F9	F13	F17	F1

Figure 2 shows a typical set of results of numerical simulations of the self-boring pressuremeter test in clay. The pressure-expansion curve from each numerical simulation was interpreted as if it were derived from a real field test, using the standard technique proposed by Gibson and Anderson. The shear modulus G has been derived from the initial pressure-expansion curve over the range $\psi = 0 \rightarrow s_u$, which is the elastic range for the Tresca material. For the von Mises material used in this study, the elastic range is expected to be even larger than that for the Tresca model. With respect to determination of shear strength, two approaches were recommended by Mair and Wood (1987). The plot of ψ against $\ln \epsilon_v$ is usually used to define s_u, which can either be estimated from the slope of the curve or the extrapolated limit pressure at $\frac{V-V_0}{V} = 1$. As pointed out by Mair and Wood, strengths obtained with the limit pressure method appear to be less sensitive to the assumed reference conditions, and hence less sensitive to disturbance associated with installation of the pressuremeter. Both of these approaches have been used to derive undrained shear strength from the expansion curve for comparisons. In order to investigate possible effects of using different volumetric strain definitions, two different ways of deriving it namely, $\epsilon_v = 2\ln(\frac{a}{a_0}), \epsilon_v = \ln(\frac{V}{V_0})$ were used, where a, a_0 are the current and initial radius of the middle point of the pressuremeter membrane and V, V_0 are the current and initial pressuremeter volumes respectively. A least squares method was used to find the slope in deriving the shear strength. Two different strain ranges measured by strain magnitude of the middle point of the membrane (i.e. $\epsilon_c = 2 \rightarrow 5\%$ and $\epsilon_c = 2 \rightarrow 10\%$) were chosen for deducing the undrained shear strength so that the analysis may be objective and possible effects due to different strain ranges used for deriving the undrained shear strength could be quantified.

When the undrained shear strength is estimated from the limit pressure by extrapolation, the so-called Menard limit pressure is used for interpretation. The Menard limit pressure is defined as the pressure at which $\frac{V}{V_0} = 2$, corresponding to $\frac{a}{a_0} = \sqrt{2}$. The choice of Menard limit pressure instead of the true limit pressure at which $\frac{V}{V_0} = \infty$ allows the interpretation to be made using the two different volumetric strain definitions described earlier. In determining the effects due to finite length of pressuremeters, we need to investigate the ratio of limit pressures of pressuremeter tests with an infinitely long probe and those with a finite length. The following expression was assumed:

$$\psi_{lm} = s_u^l(1 + \ln(\frac{G}{s_u^l})) \qquad (1)$$

where ψ_{lm} denotes the Menard limit pressure, which is found by extrapolating the expansion curve in the range $\epsilon_c = 5 \rightarrow 10\%$, and s_u^l represents the undrained shear strength corresponding to the Menard limit pressure. After obtaining ψ_{lm} for each pressuremeter test, equation (1) can be used to derive s_u^l using a Newton-Raphson solution scheme.

3.2 Numerical Results

The derived undrained shear strengths for each pressuremeter test are summarised in Table 2 and Table 3. Table 4 shows the derived shear moduli. For all the cases, $s_{utc} = 1.0$ is used which corresponds to a plane strain undrained shear strength of $\frac{2}{\sqrt{3}}$. The derived values of plane strain undrained shear strength from the numerical analyses of the pressuremeter tests with an infinitely long probe are found to be in good agreement with the actual shear strength used in the analysis. The maximum error is found to be less than about 2%. This evidence suggests that the performance of the numerical method used in the analysis is very satisfactory. It is also necessary to note that in Table 4 the actual values of shear moduli used in the analysis are equal to the values of rigidity index (i.e. $I_r = \frac{G}{s_{utc}}$) listed in the Table because a value of unity for s_{utc} is used in the calculation.

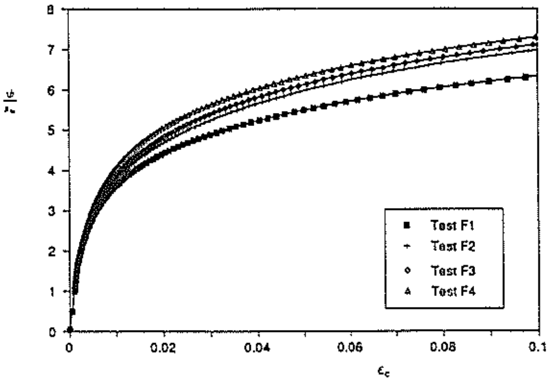

Figure 2: A typical set of results for numerical simulations of the self-boring pressuremeter test in clay

Table 2 The derived shear strength for self-boring pressuremeter test in clay using loading slope

$\frac{L}{D}$	I_r	50		100		200		300		500	
	ϵ_c	2 − 5%	2 − 10%	2 − 5%	2 − 10%	2 − 5%	2 − 10%	2 − 5%	2 − 10%	2 − 5%	2 − 10%
4	s_{uv}	1.3227	1.3506	1.3546	1.3673	1.3625	1.3686	1.3582	1.3653	1.3563	1.3627
	s_{uc}	1.3434	1.4057	1.4312	1.4553	1.4530	1.4430	1.4307	1.4172	1.3947	1.3884
6	s_{uv}	1.2692	1.3055	1.3141	1.3330	1.3390	1.3583	1.3518	1.3668	1.3624	1.3705
	s_{uc}	1.2514	1.3077	1.3297	1.3777	1.4042	1.4309	1.4264	1.4358	1.4269	1.4217
8	s_{uv}	1.2329	1.2776	1.2883	1.3017	1.3046	1.3328	1.3261	1.3510	1.3478	1.3648
	s_{uc}	1.2144	1.2582	1.2648	1.3123	1.3404	1.3842	1.3798	1.4130	1.4125	1.4264
∞	s_{uv}	1.1488	1.1707	1.1676	1.1777	1.1666	1.1787	1.1689	1.1793	1.1697	1.1814
	s_{uc}	1.1555	1.1744	1.1664	1.1769	1.1666	1.1784	1.1686	1.1790	1.1695	1.1812

In general it can be seen that the use of conventional one dimensional cavity expansion theory to pressuremeter tests with finite length of probes tends to overestimate both shear strength and shear moduli. When the volumetric strain is defined by twice central strain of the membrane, the overestimation of shear moduli was found to be negligible even for the pressuremeter tests with a length/diameter ratio of 4. Significant overprediction of shear moduli was observed, however, when the volumetric strain is calculated from the actual volume of the pressuremeter membrane. As far as undrained shear strength is concerned, the numerical results suggest that the overestimation due to the finite length/diameter ratio, using the approach of deriving undrained shear strength from the slope of logarithmic plot of expansion curve, largely depends on the rigidity index of the soil. The rigidity index is defined as ratio of shear modulus to undrained shear strength. By comparison, it is interesting to note that the effect on undrained shear strength due to pressuremeter geometry, using the approach of deducing undrained shear strength from the limit pressure, are relatively independent of the rigidity index. The following sections are devoted to examining the variation of the length/diameter ratio effects with different parameters for the pressuremeter tests.

Table 3 The derived shear strength for self-boring pressuremeter test in clay using limit pressure

$\frac{L}{D}$	I_r	50	100	200	300	500
4	s^l_{uv}	1.2857	1.3099	1.3096	1.3091	1.3104
	s^l_{uc}	1.2689	1.3045	1.3022	1.3005	1.3073
6	s^l_{uv}	1.2270	1.2478	1.2692	1.2734	1.2808
	s^l_{uc}	1.1938	1.2303	1.2545	1.2598	1.2762
8	s^l_{uv}	1.1690	1.2057	1.2363	1.2395	1.2483
	s^l_{uc}	1.1363	1.1779	1.2072	1.2260	1.2483
∞	s^l_{uv}	1.0395	1.0491	1.0798	1.0844	1.0938
	s^l_{uc}	1.0474	1.0491	1.0745	1.0844	1.0923

Table 4 The derived shear moduli for self-boring pressuremeter test in clay

$\frac{L}{D}$	I_r	50	100	200	300	500
4	G_v	58.5628	116.8647	233.4681	350.0718	583.2787
	G_c	49.8962	99.5284	198.7926	298.0567	496.5849
6	G_v	55.0649	109.8705	219.4812	329.0920	548.3132
	G_c	48.9956	97.7274	195.1905	292.6537	487.5797
8	G_v	53.4678	106.6770	213.0952	319.5133	532.3491
	G_c	48.8132	97.36259	194.4609	291.5592	485.7556
∞	G_v	48.1071	95.9503	191.6364	287.3225	478.6946
	G_c	48.5762	96.8885	193.5128	290.1371	483.3856

3.3 Effects of Length to Diameter Ratio

The effects of length to diameter ratio on derived soil properties may be examined in detail by considering the case where the rigidity index is equal to 100. The ratio of derived parameters from pressuremeter tests with an infinitely long membrane to derived parameters from pressuremeter tests with a finite length of membrane was used to measure the effects of finite length.

The variation of the effects on stiffness, due to the finite length of pressuremeter probe, with length to diameter ratio is shown in Figure 3. It can be seen that the membrane end effects for the case when volumetric strain is calculated from the volume of the pressuremeter are more significant than the case when volumetric strain is assumed to be twice the central strain of the membrane. For the pressuremeter tests with a length to diameter ratio of 6, the overestimation of shear modulus is about 13% when the volumetric strain is calculated from volume of pressuremeter.

As far as the shear strength is concerned, different ways of deriving the strength were distinguished. The variation of the effects due to finite length of pressuremeter with length to diameter ratio is shown in Figure 4 to Figure 5 for different ways of calculating the volumetric strain. It can be seen that the effects of finite length of the pressuremeter increases when the length to diameter ratio decreases.

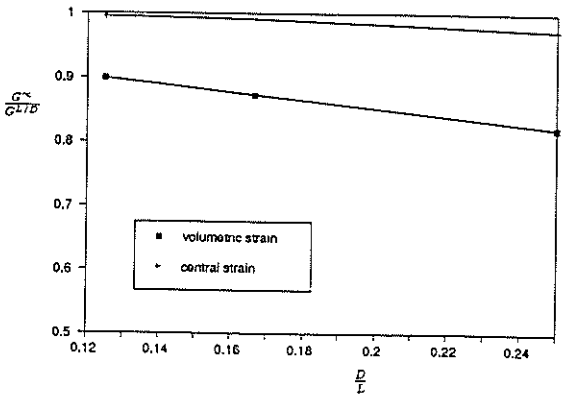

Figure 3: Effects on shear modulus due to length to diameter ratio

3.4 Effects of Soil Rigidity Index

Five different values of rigidity index, denoted by I_r, have been used in the numerical calculations so that the possible effects due to variation of rigidity index on the derived soil properties may be fully quantified. To isolate the effects of rigidity index from the effects due to different length to diameter ratios, the case when the length to diameter ratio is equal to 6 was chosen to highlight the importance of rigidity index.

From Table 4, it is easily noticed that the variation of effects on shear modulus, due to the finite length of pressuremeter probes, with rigidity index is very small, and could be neglected in practice.

The numerical results of the effect on undrained strength due to finite length of pressuremeters for the case when length to diameter ratio is equal to 6 are shown in Figure 6 to Figure 7 for two different ways of deriving the volumetric strain used in the analysis. It can be seen that the ratio of the derived undrained shear strength for pressuremeter tests with an infinitely long probe to the derived shear strength for the pressuremeter tests with a length to diameter ratio of 6 is less than unity for all cases.

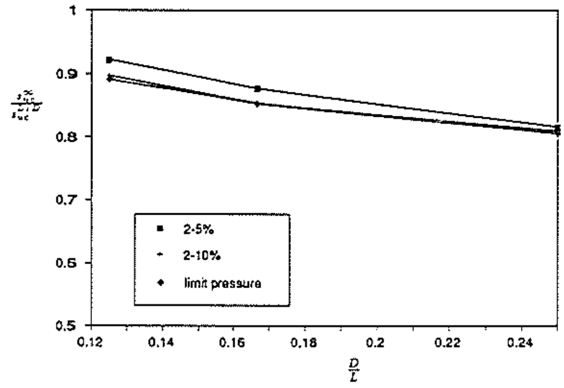

Figure 4: Effects on strength due to finite length using central strain

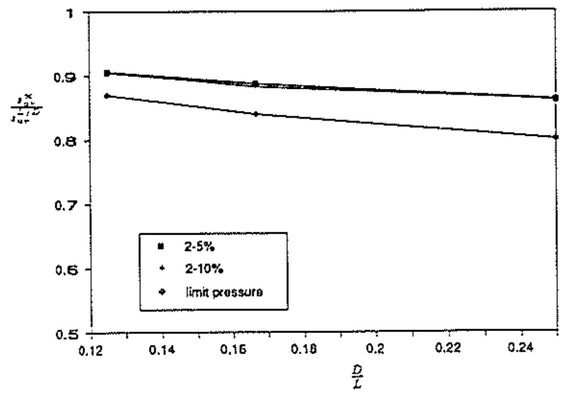

Figure 5: Effects on strength due to finite length using volumetric strain

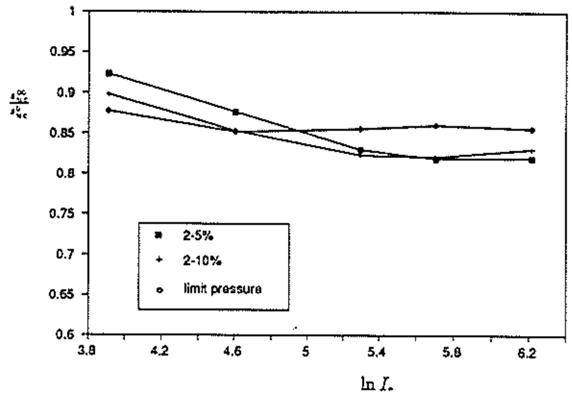

Figure 6: Variation of finite length effects on strength with rigidity index using central strain

It suggests that the use of the conventional one dimensional interpretation method for the real pressuremeter tests with a finite length tends to overestimate the 'true' undrained shear strength. It is interesting to see that the effects due to finite length are relatively independent of the rigidity index if the undrained shear strength is derived from the limit pressure. The average overestimation of undrained shear strength for this case is about 15%. For the case when the undrained shear strength is deduced from the slope of pressuremeter expansion curve, the finite length effects increase with the rigidity index.

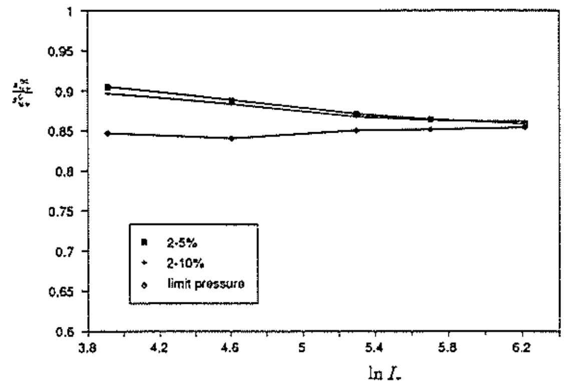

Figure 7: Variation of finite length effects on strength with rigidity index using volumetric strain

4. RECOMMENDED INTERPRETATION PROCEDURE

The analysis presented above has illustrated clearly the danger of applying an undrained shear strength profile obtained from self-boring pressuremeter tests using the conventional Gibson and Anderson method. By using the numerical results, a correction may be made to the pressuremeter test results to account for the finite length effects.

A value of 6 for length to diameter ratio may be used to represent the geometry of the self-boring pressuremeter which has been widely used in practice (e.g. the Cambridge self-boring pressuremeter). Hence only numerical results for the pressuremeter tests with a length to diameter ratio of 6 are considered in the following discussion. Of course, the same argument may be used for self-boring pressuremeter tests with a different length to diameter ratio.

For self-boring pressuremeter tests in clay, the effects on derived undrained shear strength due to the finite length of the probe depends on the approach used to derive the undrained shear strength. As was mentioned earlier, when the undrained shear strength is estimated from the limit pressure, the finite length effect is relatively independent of the rigidity index and the average overestimation of the undrained shear strength was found to be about 15%. This suggests that when the undrained shear strength is obtained from the limit pressure approach, the finite length effects may be accounted for by multiplying the derived strength by a factor of 0.85.

On the other hand, if the undrained shear strength is estimated from the pressuremeter expansion slope, it is necessary to distinguish the two different strain definitions used in presenting the pressuremeter expansion curve. When the undrained shear strength is obtained from the plot of pressure against the volumetric strain, the following expression may be used to represent the finite length effects on the derived strength:

$$\frac{s_{uv}^{\infty}}{s_{uv}^{6}} = 0.971 - 0.0185 \ln I_r \qquad (2)$$

If the undrained shear strength is estimated from the plot of pressure against the membrane central strain, the finite length effect was found to be slightly dependent on the strain ranges used in the interpretation. In general, the use of the membrane central strain could lead to a slightly more overestimation of the undrained strength due to finite length of pressuremeters.

Equation (2) may be used to improve the conventional Gibson and Anderson method in deriving the undrained shear strength from the pressuremeter test results.

With respect to the shear modulus, it was found that the effect on shear modulus due to finite length is negligible when the shear modulus is derived from the initial curve in the plot of pressure against membrane central strain. However, if the plot of pressure against volumetric strain is used to estimate the shear modulus, the finite length effect was found to be quite significant. The overestimation of the shear modulus due to the finite length may go up to 13%. It suggests that the derived shear modulus from the plot of pressure against volumetric strain for the pressuremeter test results needs to be multiplied by 0.87 in order to eliminate the effect due to pressuremeter geometry.

5. CONCLUSION

One of the major advantages of the pressuremeter test is the possibility of evaluating accurate soil parameters from the test data. In the past a simplified one-dimensional cavity expansion theory has been used to reduce the pressuremeter test data to give design parameters. The cavity expansion theory involves important assumptions about the material behaviour and pressuremeter geometry. In this paper, the two-dimensional finite element formulation was used to assess the effects of pressuremeter geometry on derived soil parameters.

For the self-boring pressuremeter tests in clay, it was found that use of the conventional Gibson and Anderson method for the field pressuremeter test tends to overestimate the undrained shear strength and shear modulus. It is interesting to note that the overestimation of the shear modulus, when derived from the plot of the pressure against central membrane strain, is negligible. As far as the shear strength is concerned, the numerical results suggest strong dependence of the finite length effects on rigidity index when the undrained shear strength is derived from the loading slope. By contrast, when using the limit pressure to obtain the undrained shear strength, the finite length effects have been found to be relatively independent of the rigidity index of the soil.

Based on numerical results, an improved procedure for obtaining soil parameters from pressuremeter tests in clay has been proposed to eliminate effects of using the simple assumptions in the conventional interpretation methods.

6. ACKNOWLEDGEMENT

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