

Interpretation of selfboring pressuremeter tests using a curve fitting approach

R.P.Cunha

Department of Civil Engineering, University of Brasília, Brazil

R.G.Campanella

Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada

ABSTRACT: This paper presents the concept of interpreting selfboring pressuremeter testing curves by using a curve fitting approach, which is seldom used nowadays to derive soil parameters from this in-situ testing tool. This approach has the great advantage of easily establishing useful soil data even when testing curves are initially disturbed. It has been found, however, that the quality of the soil parameters predicted by the curve fitting approach is also dependent on factors other than the initial conditions of the soil, like the ability of the idealized cavity expansion model to simulate the pressuremeter expansion process and the strain range of curve fitting. Thus, this paper addresses the strain range factor and gives some general guidelines for the interpretation of selfboring pressuremeter testing curves with the curve fitting approach.

1 INTRODUCTION

Since Menard's pioneering work there have been major developments in the pressuremeter, especially in the 70's and 80's. These developments can be subdivided into areas of pressure and strain measurement, probe insertion, analytical and numerical interpretation and new types of pressuremeter. The selfboring pressuremeter was devised to eliminate the disturbance problems caused by the preboring method adopted for the Menard pressuremeter.

With the selfboring method to minimize disturbance the test results can be properly analyzed in the light of cavity expansion theories, where the initial conditions are well established. However, Hughes (1973) demonstrated in the laboratory with the X-ray technique that even under "perfect" selfboring conditions a disturbance of at least 0.5 % of the pressuremeter radius can be induced in sand. Thus, when selfboring in-situ an even higher disturbance percentage can be expected.

The current traditional methodology of analysis, well discussed by many authors (Benoit and Clough 1986, Findlay 1991 and others), is extremely sensitive to any disturbance "built into" the testing curve. Therefore, the disturbance affect set up during the selfboring pressuremeter installation may limit the usefulness of this tool, at least in sands. In order to overcome this aspect, emphasis is placed on the development of improved ways of interpreting the data which are less sensitive to disturbance. The

presentation of this less sensitive interpretation approach, and its usefulness in interpreting both disturbed and undisturbed testing curves are demonstrated using field examples and are given next.

2 CURVE FITTING OF TESTING CURVES

The curve fitting approach basically consists in the comparison of the field testing curve with some idealized pressure expansion testing curve based on some sort of constitutive model, as demonstrated by Figure 1. The idealized model curve can be interactively changed by changing the input parameters that constitute its rheological relationships. This is carried out until a "match" or "fitting" between this model curve and the field one is established.

The closer the rheological relationships and assumptions of the adopted cavity expansion model are to the real shearing phenomena, the closer will be the agreement of the idealized curve with respect to the field one (assuming no disturbance). As well, the lower the number of input model parameters, the easier and faster will be the curve fitting. In this respect, Figure 1 illustrates a curve fitting example in which only 3 parameters of the adopted model (σ_h or effective lateral stress, G_i or shear modulus and ϕ or friction angle) are varied during the curve fitting.

The curve fitting concept is not new in the pressuremeter technology, although it is almost

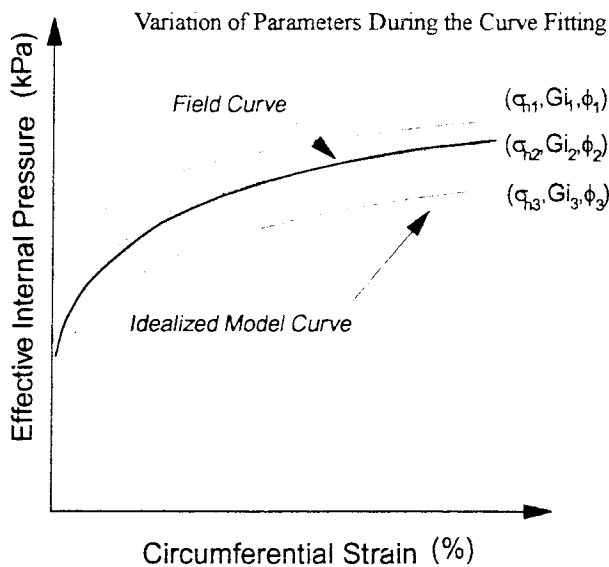


Figure 1. Curve fitting interpretation methodology

ignored nowadays to derive soil parameters in clays or sands. In clays it was initially postulated by Arnold (1981), although the deployment of this approach wasn't clear at that time. Some time later, Jefferies (1988) suggested an "image-matching" procedure to derive the soil parameters, due to recent advances in terms of data acquisition and processing systems for the pressuremeter in the late 80's. Those initial ideas allowed Hughes (1989) (personal communication) to develop the curve fitting approach with tests in sands, and to advocate it afterwards. Research emphasis was then placed on this subject by the University of British Columbia (UBC), culminating with several Ph.D. theses (Sully 1991 and Cunha 1994) in the early 90's.

Based on Cunha's work with the UBC selfboring pressuremeter installation, testing and interpretation procedures in a particular granular research site close to UBC it was found that the strain range of curve fitting between the field and model curves is of importance. This is the case principally with slightly disturbed testing data, which is almost the rule when testing in granular sites. In order to illustrate this aspect some pressuremeter data is presented and discussed next.

3 STRAIN RANGE OF CURVE FITTING

The data presented herein was obtained during an extensive field testing programme in the UBC research site called "Laing Bridge South", for which details can be found in Bertok (1987). This data was interpreted by a new cavity expansion model (Cunha 1994), although any of the existing cavity expansion models in literature for drained materials

could be used for this purpose. Since the emphasis of this paper is not placed on theoretical aspects of the modeling itself, but rather on the concept of test interpretation and its refinements, it is felt that the usage of such a model does not hamper the conclusions yet to be drawn.

The analysis is carried out with both undisturbed as well as disturbed testing data, trying to cover all possible classes of pressuremeter testing curves which are obtained in the field. The chosen set of data originates from test soundings 8 m apart at the site, and are related to the same (5.3 m) depth.

3.1 Undisturbed Testing Curve

Typical selfboring pressuremeter tests are expanded to cavity (circumferential in sands) strains in the range of 10%. Under the traditional interpretation methodology only the last loading points obtained within this testing range are used to define the slope in the log-log graph, hence the friction angle. This is so because it is argued that the initial stages of expansion can be considerably affected by the disturbance generated prior to the test. Following this same reasoning, it may be also argued that if the approach followed by full-displacement pressuremeter tests is adopted for the selfboring pressuremeter, with a testing stage carried out to a considerably higher circumferential strain, then it will be possible to predict truly undisturbed soil parameters from the interpretation of the latter stages of the field data.

In order to assess this hypothesis a series of curve fitting interpretations were carried out with an undisturbed field curve. This curve had its quality assessed by the visual quality assessment criteria put forward by Robertson (1982), and was expanded to a circumferential strain around 20%. The fitting ranges chosen for the match of both field and analytical (model) curves varied from 0 to 5%, 5 to 10%, 10 to 15% and above 15% as demonstrated by the top plot of Figure 2.

The interpretation analysis varied the parameters σ_h , G_i and ϕ during the fitting, and adopted the constant values of 34° and 0.25 for the constant-volume friction angle and the Poisson's coefficient, respectively. These latter values were experimentally obtained in drained triaxial tests with undisturbed samples of this site.

Figure 2 also shows the curve fit results (predicted parameters) for each of the chosen strain ranges, rendering the following comments:

1. The predicted soil parameters are not unique and depend on the range of match adopted during fitting. Nevertheless, for curve fittings between 0 to 5% or 5 to 10% the same idealized curve suffices to represent the measured experimental

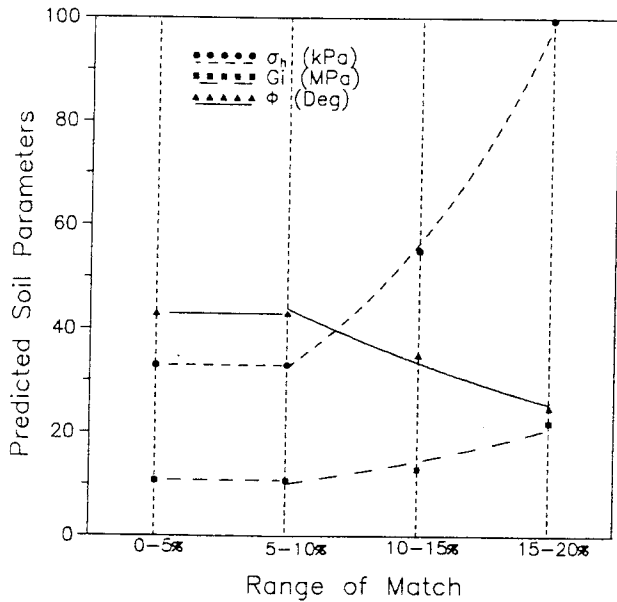
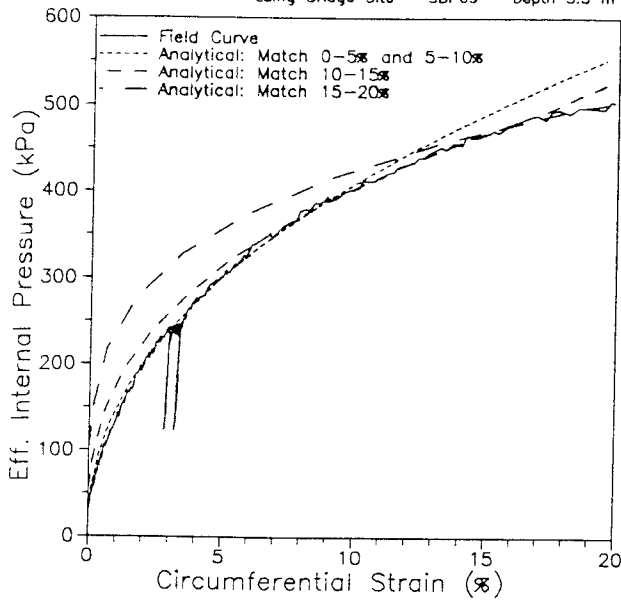


Figure 2. Fitting analyses and results on undisturbed testing curve

data. The same set of predicted soil parameters are obtained in this range. For curve fittings above $\approx 10\%$ it is not possible to obtain a unique set of predicted parameters. The higher the range adopted for fitting (above $\approx 10\%$), the higher are the differences between the predicted set of parameters and the parameters obtained with the fitting of the initial part of the experimental curve;

2. The predicted parameters from the curve fitting between 0 and 10% ($\phi = 43^\circ$, $\sigma_h = 33$ kPa and $G_i = 11$ MPa) are consistent with the expected values for this site, based on geotechnical / geological results discussed by Cunha (1994);

3. The predicted soil parameters for the curve match above $\approx 10\%$ do not seem to be realistic. The predicted effective lateral stresses appear to be extremely overestimated (consider, for instance, that the effective vertical stress at this depth is around 60 kPa). The predicted friction angles appear to be extremely underestimated. This is so because friction values below the constant volume angle are predicted, suggesting a contractive behavior during shear rather than dilatant. However, a fully contractive behavior was not observed in the triaxial laboratory tests with the undisturbed samples of this site.

The findings above suggest that for undisturbed selfboring testing curves meaningful parameters from the fitting approach can be solely obtained if the match is carried out with the initial loading points of the testing curve, between 0 to $\approx 10\%$ (circumferential strain). This finding is directly in opposition to the common belief that only the latter stages of the testing curve are useful for the interpretation analysis, but agrees with the usual practice of expanding selfboring pressuremeters to cavity strains up to around 10%.

Perhaps the information experimentally measured for circumferential strains above $\approx 10\%$ is influenced by external factors that are not considered in the existing cavity expansion models. Indeed, two possible factors are prone to hamper the interpretation analysis at these high strain levels, as follows:

1. End Effects: The UBC selfboring has an expanding section only 6 diameters (12 radii) long and it is unlikely that a plane strain solution will be applicable for strains much larger than 10%. Given the possible non-cylindrical shape of the plastic zone at these latter stages, a compromise between the cylindrical and the spherical cavity expansion theory would have to be developed for the interpretation analysis.

2. Strain Softening of the Sand: The typical shear behavior of the sand at a constant confining pressure was discussed by Vaid et al (1980). Over a considerable range of strain, both initially loose and dense samples undergo volume expansion, and at very large shear strains tend to approach an ultimate strength and critical void ratio, at which the sand shears with no change in volume or stress.

In the latter stages of the test the expansion also takes place with the imposition of very high levels of shear stress and strain in the sand surrounding the cavity. Based on the experimental sand behavior previously mentioned, it may be possible to speculate that during this stage an annulus of sand at critical state conditions will be developed between the cavity wall and the elasto-plastic boundary.

In this case the expansion process can be understood as the expansion of a two-layered system, composed of an inner layer shearing at

constant volume conditions encompassed by an outer (plastic) layer where dilative volume change takes place. The response of this critical state annulus of sand has a dominant effect on the measured testing response at the latter stages of expansion. Thus, if reliable soil parameters are sought with curve fitting interpretation at high strain levels, then the cavity expansion model has to be modified to account for the strain softening of the sand. Failure to do so results in the prediction of unrealistically high σ_h 's and low ϕ 's, such as those presented in Figure 2.

3.2 Disturbed Testing Curve

Disturbance affects the shape of the testing curve, and consequently should also influence the final set of predicted soil parameters.

In order to assess the likely influence of disturbance on the predicted parameters another series of curve fitting interpretations was carried out. For this purpose a disturbed field curve was selected. The disturbed characteristics of the chosen curve are assessed based on the following evidence:

1. The shape of the curve does not follow the "high quality standards" put forward by Robertson (1982) with his visual quality assessment criteria. This is, however, circumstantial evidence of the disturbed characteristics of this field curve;

2. The chosen curve came from the test sounding SBP19, at a depth of 5.3 m in the testing site. This particular sounding consisted of 2 insertion trials at the same borehole. The first trial was carried out up to 5.7 m at a high penetration rate, resulting in the plugging of the cutting shoe to an extent of 70 % of its sectional area. This invariably disturbed the surrounding sand up to ≈ 6 m deep. This is strong evidence of the disturbed characteristics of this particular field curve.

The interpretation analysis was conducted similarly as before, but in this case a higher number of fitting ranges were selected for the interpretation analyses. The fitting ranges chosen for the match of both field and analytical curves varied from 0 to 3 %, 3 to 6 %, 4 to 7 %, 5 to 8 %, 6 to 9 %, 7 to 10 % and 9 to 10 %. Given the previous findings the interpretation analysis was carried out up to a circumferential strain of ≈ 10 %.

Figure 3 shows the chosen field curve and the obtained results. The top plot presents the fitting between both field and idealized analytical curves. For clarity, only 3 analytical curves are shown. The bottom plot shows the predicted parameters for each fitting case.

For this disturbed testing curve the following comments apply:

1. The quality of curve fitting is excellent in either the initial or in the latter stages of the field

curve. This does not mean that the predicted soil parameters (for each of the fitting cases) are equally reliable;

2. As for the undisturbed testing curve the parameters obtained are not unique, and depend on the range of fitting. Nevertheless, for each of the predicted parameters, the variation with the range of curve fitting "levels off" for matches at the latter stages of the test (close to 10 %). For curve fittings in the initial ranges of the test, from 0 to ≈ 5 % it is not possible to obtain a unique set of predicted parameters;

3. The predicted parameters for curve fittings between ≈ 5 % and 10 % (average $\phi = 44.2^\circ$,

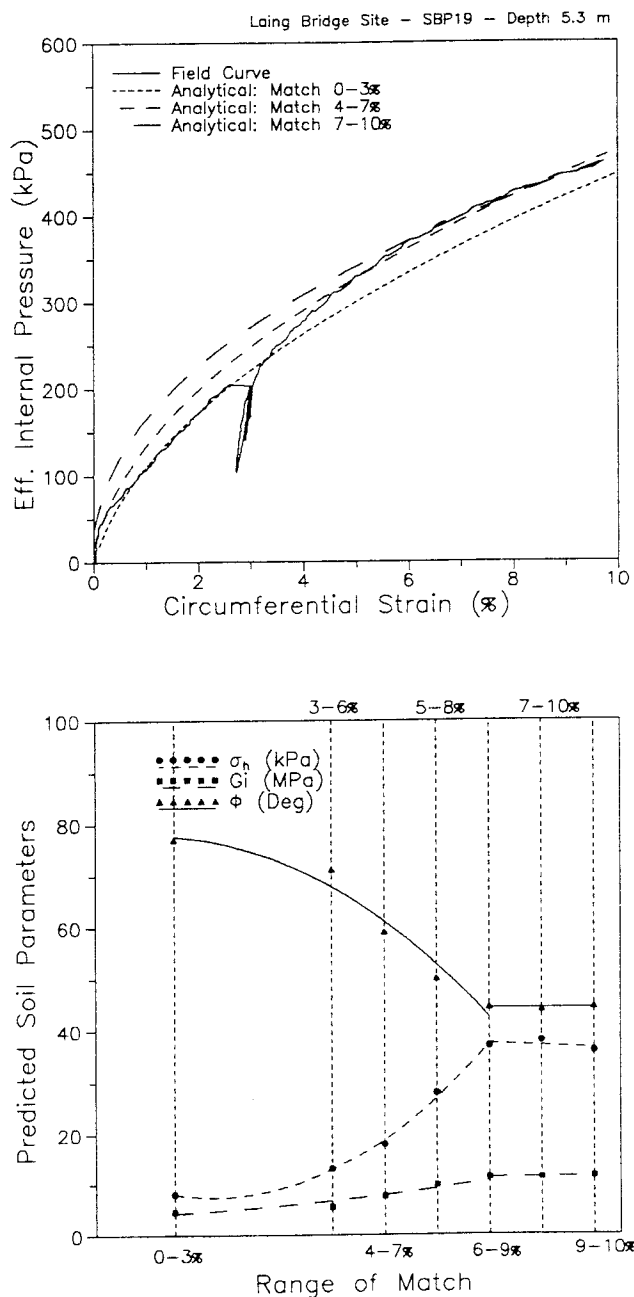


Figure 3. Fitting analyses and results on disturbed testing curve

$\sigma_h = 37$ kPa and $G_i = 11.3$ MPa) agree well with the parameters obtained with the fitting interpretation of the initial stages of the undisturbed curve;

4. The predicted soil parameters for the curve fitting in the initial stages of the field test do not seem to be realistic. This observation was also given with the results of the analysis carried out in the latter stages (beyond 10 %) of the undisturbed curve. With the disturbed curve, however, it appears that overestimated friction angles (above 50°) and underestimated effective lateral stresses (below 20 kPa) were predicted.

The findings above suggest that for disturbed selfboring testing curves meaningful parameters from the fitting approach can be solely obtained if the fitting is solely carried out with the latter stages (above $\approx 5\%$ and below 10 %) of the field curve. This is caused by the fact that disturbance affects the initial shape of the testing curve, reducing its "roundness". At the latter stages of this same curve, below a circumferential strain of approximately 10 %, the effects of disturbance are decreased and may be even erased.

Basically when disturbance is generated during the selfboring process an annulus of disturbed and loose soil is formed around the probe. The diameter of this annulus is unknown and will depend on the degree of disturbance generated prior to the testing stage. The response of this speculated annulus of soil influences the measured response of the test. The expansion process, therefore, can be also understood as the cavity expansion in a two-layered system, one looser close to the probe's shaft and another denser around this first layer. The selfboring testing curve will initially follow the path defined by the looser (disturbed) annulus of sand, therefore reducing its initial smooth "roundness". As the plastic zone grows in the latter stages of expansion (beyond $\approx 5\%$), the effects of the disturbed annulus on the measured response are continuously decreased. This results from the fact that a larger zone of undisturbed soil starts to be encompassed by the expanding plastic zone. Hence, the measured cavity response at the latter stages of expansion predominantly reflects the shearing response of this undisturbed zone of soil.

However, even if the disturbance on the testing curve is erased beyond circumferential strains above $\approx 10\%$ other factors start to dominate (as noted before) hampering the fitting interpretation analysis.

4 CONCLUSIONS

The interpretation methodology presented herein allows the prediction of reliable soil parameters for either undisturbed or disturbed data in sands. This represents an advance in relation to the traditional

interpretation methodologies, that could only be applied in perfectly undisturbed selfboring pressuremeter curves. Nevertheless, the reliability of the predicted soil parameters may be expected to be directly proportional to the quality of the testing curve. For undisturbed or slightly disturbed testing curves the reliability of the predicted parameters is high. For disturbed curves the reliability of the parameters is somewhat reduced. As a general rule, for either undisturbed or disturbed data the curve fitting should be carried out in the latter stages of expansion (between $\approx 5\%$ to $\approx 10\%$).

As a final comment, it shall be noted that, with the aforementioned interpretation methodology, it is also possible to obtain a good indication of fundamental soil parameters from prebored or Ménard pressuremeter test results, as long as the curve fitting can be applied between 5 and 10 % strain. Reasonably reliable deformation and strength parameters have already been obtained with Ménard pressuremeter tests in the residual (unsaturated) porous clay of Brasília, as presented by Ortigao et al (1996).

ACKNOWLEDGEMENTS

The authors acknowledge the support given by both the Brazilian (CNPq) and the Canadian (NSERC) Research Councils for this research, and the field equipment and electronic help given by Mr. Scott Jackson and Harald Schremp.

REFERENCES

- Arnold, M. 1981. An empirical evaluation of pressuremeter test data. *Canadian Geotechnical Journal*, 18: 455-459.
- Benoit, J. and Clough, G.W. 1986. Self-boring pressuremeter tests in soft clay. ASCE, *JGED*, 112, (1): 60-78.
- Bertok, J. 1987. Settlement of embankments and structures at Vancouver International Airport. *Canadian Geotechnical Journal*, 24: 72-80.
- Cunha, R.P. 1994. Interpretation of selfboring pressuremeter tests in sands. *Ph.D. Thesis*, Dep. of Civil Engineering, University of British Columbia
- Findlay, R.C. 1991. Use of the 9-arm self-boring pressuremeter to measure horizontal in situ stress, stress anisotropy, and stress-strain behavior in soft clay. *Ph.D. Thesis*, Dep. of Civil Engineering, University of New Hampshire.

- Hughes, J.M.O. 1973. An instrument for in situ measurement in soft clays. *Ph.D. Thesis*, Dep. of Civil Engineering, University of Cambridge.
- Jefferies, M.G. 1988. Determination of horizontal geostatic stress in clay with self-bored pressuremeter. *Canadian Geotechnical Journal*, 25: 559-573.
- Ortigao, J.A. R., Cunha, R.P. and Alves, L.S. 1996. In situ tests in Brasília porous clay. *Canadian Geotechnical Journal*, 33: 189-198.
- Robertson, P.K. 1982. In-situ testing of soil with emphasis on its application to liquefaction assessment. *Ph.D. Thesis*, Dep. of Civil Engineering, University of British Columbia.
- Sully, J.P. 1991. Measurement of in situ lateral stress during full-displacement penetration tests. *Ph.D. Thesis*, Dep. of Civil Engineering, University of British Columbia.
- Vaid, Y.P., Byrne, P.M. and Hughes, J.M.O. 1980. Dilation rate as a measure of liquefaction resistance of saturated granular materials. *Soil Mechanics Series 43*, Dep. of Civil Engineering, University of British Columbia.