CPT data in relation to a general model for the undrained behaviour of homogeneous Swedish clays

Rolf Larsson, Helen Åhnberg and Hjördis Löfroth
Swedish Geotechnical Institute, Linköping, Sweden

ABSTRACT: The evaluation of undrained shear strength and preconsolidation pressure from CPT data in fine-grained soils is largely empirical. The evaluation is normally based on comparisons between the CPT data and results from other tests, such as triaxial tests, direct simple shear tests etc. Test results in Swedish clays indicate that the net cone resistance is primarily governed by the horizontal preconsolidation pressure. Assuming that this is the case, the different empirical correlations between net cone resistance and (1), the preconsolidation pressure from oedometer tests, (2) the undrained shear strength from tests with different modes of shear, are in line with what can be expected with consideration to the general soil model for the behaviour of Swedish clays. This model has been elaborated using results from laboratory tests to describe, among other things, how the undrained shear strength varies with preconsolidation pressures, overconsolidation ratio, and the mode of undrained shear.

1 INTRODUCTION

The cone penetration test, CPT, has become a useful tool for evaluating the undrained shear strength and estimation of the preconsolidation pressure in clays in Sweden. A number of theories has been presented for the evaluation of shear strength from the CPT data, but the evaluation is still largely empirical. Different empirical relations have been proposed depending on what mode of undrained shear is referred to and what shear strength test has been used as reference in obtaining the empirical relations. This paper discusses the factors that govern the results and how CPT data relate to the general model for undrained behaviour of homogeneous Swedish clays.

2 GENERAL BEHAVIOUR OF SWEDISH HOMOGENEOUS CLAYS IN UNDRAINED CONDITIONS

The general behaviour of Swedish homogeneous clays has been extensively studied at the Swedish Geotechnical Institute (SGI) and Chalmers University of Technology (e.g. Sällfors 1975; Larsson 1977, 1981). A model has been developed for natural Swedish clays in which the yield surfaces of these clays are defined by four border lines: two representing the Mohr-Coulomb shear failure lines, and two representing the preconsolidation pressures in the vertical and horizontal directions, as shown in Fig. 1. The horizontal preconsolidation pressure is the product of the vertical preconsolidation pressure, σ'_c, and the coefficient of earth pressure at rest in normally consolidated conditions, K_{0NC}.

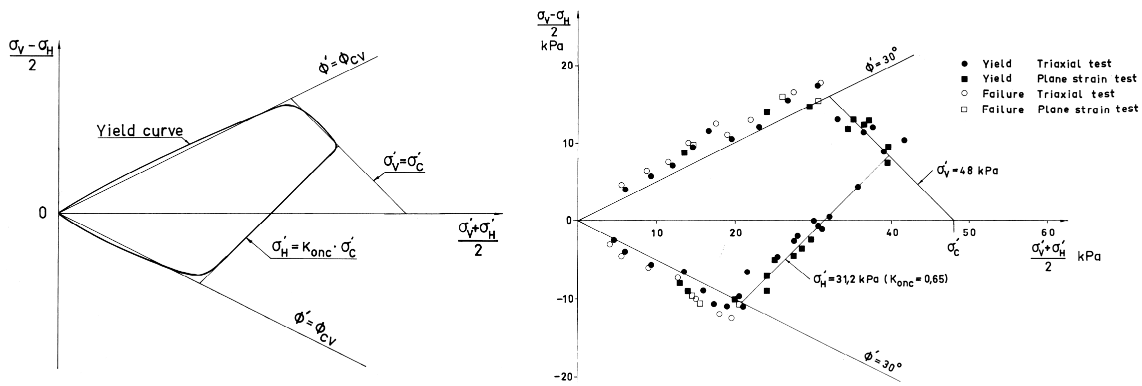

Fig. 1. General model for yield surfaces in Swedish clays and experimental verification of a yield surface. (Larsson 1977, 1981)

The model shown in Fig.1 has been further extended to be valid also for rotated principal stresses (e.g. Larsson and Sällfors 1981).

The typical effective friction angle in the Swedish clays is 30°, and the undrained shear strength of normally consolidated and slightly overconsolidated clay (OCR 1-1.5) in active shear (corresponding to triaxial and plane strain compression tests), $c_{u,active}$, can be approximated as:

$$c_{u_{active}} \approx \frac{\sigma'_c}{3} \tag{1}$$

The corresponding passive shear strength (corresponding to triaxial and plane strain extension tests) can be approximated as:

$$c_{u_{passive}} \approx \frac{K_{0_{NC}}\sigma'_c}{3} \tag{2}$$

For normally and slightly overconsolidated soils that have consolidated under a major vertical stress and a minor horizontal stress, and in which the major stress is then rotated by an angle α, the undrained shear strength can be estimated as:

$$c_{u_\alpha} \approx \frac{\sigma'_c(\cos^2\alpha + K_{0_{NC}}\sin^2\alpha)}{3} \tag{3}$$

A number of field and laboratory investigations were performed in the early 70s to evaluate the coefficient of earth pressure at rest in inorganic Scandinavian clays (e.g. Bjerrum and Andersen 1972; Massarsch et al. 1975; Larsson 1975). Data from the studies are plotted in Fig. 2. The results indicated that K_{0NC} may be estimated as:

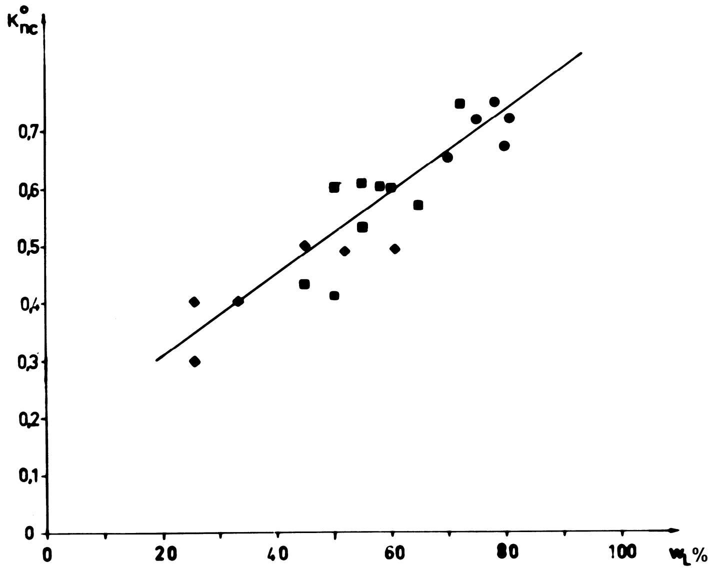

Fig. 2. Coefficient of earth pressure at rest in normally consolidated Scandinavian clays as a function of liquid limit. (After Larsson 1977)

$$K_{0_{NC}} \approx 0.31 + 0.71(w_L - 0,2) \qquad (4)$$

where w_L is the liquid limit of the clay.

Combining equations (2) and (3) with equation (4) thus gives:

$c_{u_{passivee}} \approx \sigma'_c(0,056 + 0,237 w_L)$ in passive shear, and (5)

$c_{u_{direct\ simple\ shear}} \approx \sigma'_c(0,125 + 0,178 w_L)$ in direct simple shear, where the shear surface is horizontal and the major stress theoretically acts in a direction deviating 60° from the vertical. (6)

Data have been compiled from triaxial tests and direct simple shear tests on normally consolidated and slightly overconsolidated Swedish clays. Although there is considerable scatter in the data, the general pattern of the strength values normalised against the vertical preconsolidation pressures conforms well to the pattern predicted by the model, as shown in Fig. 3.

Unloading from the normally consolidated state results in a reduction of shear strength, and the normalised undrained shear strength in overconsolidated soils is usually written as:

$c_u = a\, \sigma'_c\, OCR^{\,b-1}$ or $c_u = a\, \sigma'_v\, OCR^{\,b}$ (e.g. Jamiolkowski et al. 1985) (7)

where *OCR* is the overconsolidation ratio and σ'_v is the effective vertical stress. The factor 'a' corresponds to the relation between the undrained shear strength and the vertical preconsolidation pressure for normally consolidated soil in the particular mode of loading, equations (1, 5, 6), and the factor 'b' normally varies between 0.7 and 0.9 with an average of 0.8 in Swedish clays.

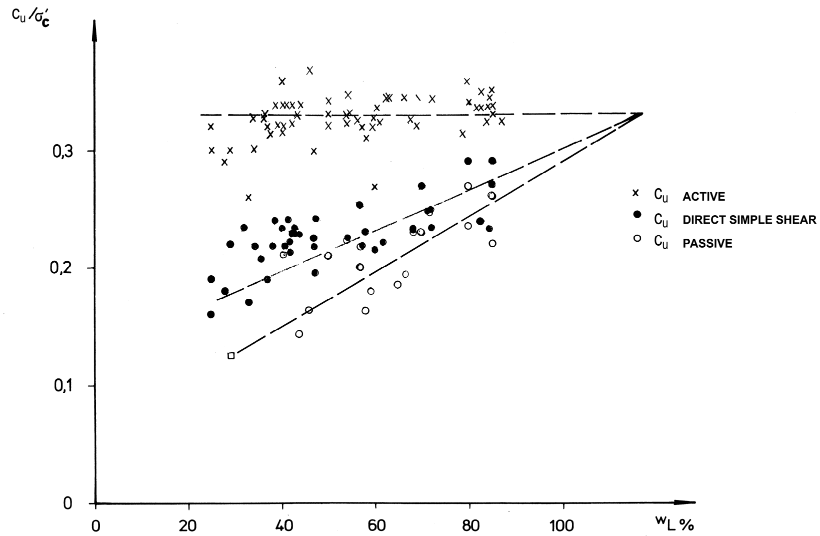

Fig. 3. Undrained shear strength in normally consolidated inorganic Scandinavian clays as a function of preconsolidation pressure and liquid limit. (After Larsson et al. 2007)

3 EVALUATION OF THE CPT WITH CONSIDERATION OF YIELD STRESSES

There are a number of approaches to analyse the CPT data in a theoretical way including bearing capacity theory, cylindrical or spherical cavity expansion theory, strain path analyses and finite element analyses, (e.g. Yu 2004). However, a significant shortcoming in the currently available analyses is that they typically do not account for yield stresses, anisotropy and rate effects. The evaluation of soil parameters from the CPT data is thereby still largely empirical.

A CPT probe increases the total vertical and horizontal stresses at the cone tip during probe advancement. In undrained and fully saturated conditions, the soil can not be compressed and is mainly displaced outwards. The increasing total stresses result in increasing effective stresses and increasing pore pressures. According to most soil models and practical experience (e.g. Sällfors 1975), the effective stress can reach, but not exceed, the preconsolidation pressure in undrained conditions.

Both the vertical and horizontal stresses can be expected to increase during cone advancement, but in the normal case, where the horizontal preconsolidation pressure is lower than the vertical, the development of pore pressure and effective stresses is likely to be governed by the horizontal preconsolidation pressure. The corresponding undrained shear strength would then be the passive shear strength. The horizontal preconsolidation can be expected to be reached around the cone, and as a result, the effective stress condition around the cone can be expected to be governed almost solely by the horizontal preconsolidation pressure, regardless of the overconsolidation ratio in the surrounding soil mass. Possible exceptions are very heavily overconsolidated soils.

4 EXPERIENCE WITH CPTS IN SWEDISH CLAYS

An extensive investigation regarding the use of the CPT data for the evaluation of properties in normally consolidated and slightly overconsolidated Swedish clays was performed by Larsson and Mulabdic´ (1988). Together with data from the literature, the results formed the basis for evaluating the preconsolidation pressure and undrained shear strength of Swedish clay (Larsson 1995, 2007). The results were compared to preconsolidation pressures obtained from oedometer and active triaxial tests, and to undrained shear strengths as determined by active triaxial tests, direct simple shear tests, and field vane shear tests. After applying an empirical correction the field vane shear tests should yield approximately the same values as the direct simple shear tests (e.g. Larsson et al. 2007).

Both preconsolidation pressure and undrained shear strength are normally evaluated from CPT data using the net cone resistance, q_t-σ_v, (i.e. total corrected cone resistance minus total vertical stress). The parameters are evaluated by dividing the net cone resistance by appropriate cone factors. The comparisons yielded the empirical correlations:

$$\sigma'_c \approx \frac{q_t - \sigma_{v0}}{1.21 + 4.4 w_L} \tag{8}$$

$$c_{u_{active}} \approx \frac{q_t - \sigma_{v0}}{3{,}6 + 13{,}2 w_L} \tag{9}$$

$$c_{u_{direct\ ssimple\ shear}} \approx \frac{q_t - \sigma_{v0}}{13{,}4 + 6{,}65 w_L} \tag{10}$$

In another study, comprehensive investigations were performed to evaluate the soil properties in Swedish clay slopes created by erosion, and where the stability had earlier been improved by excavations at the crests (Larsson and Åhnberg 2003, 2005). These investigations were performed in homogeneous clays where the overconsolidation ratios ranged from just over 1 behind the slope crest up to 100 at the toe of the slope.

Regardless of the overconsolidation ratio, the data indicated a similar relationship between vertical preconsolidation pressure and net cone resistance as previously found for normally and only slightly overconsolidated soils. This meant that there was no reduction in the net cone resistance with unloading and increasing OCR similar to the decrease in undrained shear strength that should occur according to the general model and the laboratory tests in the investigation. Therefore, an extra correction for overconsolidation ratio was introduced in the evaluation of undrained shear strength of overconsolidated clays from CPT data:

$$c_u = \frac{q_t - \sigma_{v0}}{N_{kt(\alpha)}} \left(\frac{OCR}{1{,}3} \right)^{b-1} \tag{11}$$

where $N_{kt(\alpha)}$ is the empirical relation for evaluation of the particular undrained shear strength (active, direct simple shear etc.) in normally and slightly overconsolidated soil, and the factor 1.3 is used as the average overconsolidation ratio for which the factors $N_{kt(\alpha)}$ were evaluated.

5 THE RESULTS OF THE CPTS IN RELATION TO THE GENERAL MODEL

The results of the CPTs in terms of net cone resistance have shown a clear relation with the vertical preconsolidation pressure. However, the relation is strongly dependent on the liquid limit. Considering the theoretical yield stress approach, the horizontal preconsolidation pressure σ'_{ch} can be expected to govern the net cone resistance in undrained conditions. Combining equations (4) and (8) gives

$$\sigma'_{ch} \approx \frac{(q_t - \sigma_{v0})(0,31 + 0,71(w_L - 0,2))}{1.21 + 4.4 w_L} \tag{12}$$

For liquid limits between 20% and 80%, which is the normal range for inorganic clays in Sweden, equation (12) yields an almost constant relation with an average of

$$\sigma'_{ch} \approx \frac{q_t - \sigma_{v0}}{6.55} \tag{13}$$

Fig. 4.

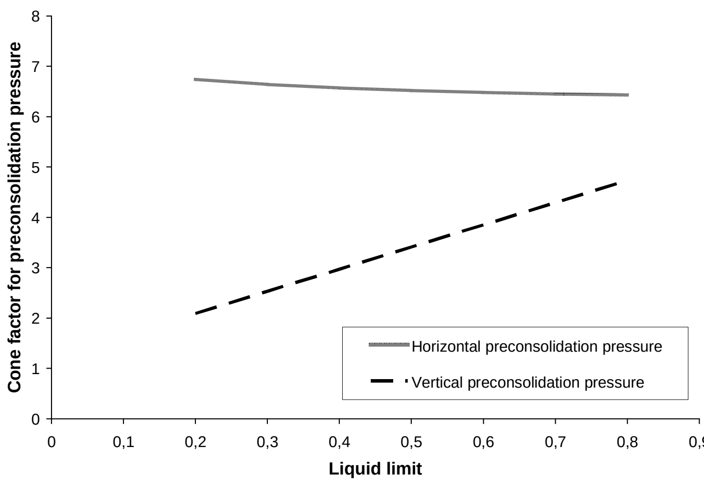

Fig. 4. Empirical cone factor for vertical preconsolidation pressure and estimated cone factor for horizontal preconsolidation pressure. (After Löfroth 2008)

A laboratory investigation was performed by Löfroth (2008) to examine the effect of preconsolidation on CPT data. The results from the laboratory CPTs scattered too much to ascertain whether the best correlations were obtained using the mean isotropic stresses or the horizontal stresses. Nevertheless, they indicated that the horizontal preconsolidation strongly affected the net cone resistance, and that the overconsolidation ratio had little influence on the results.

Thus, there are strong indications that the net cone resistance can be linked directly to the horizontal preconsolidation pressure, and consequently, that the governing undrained shear strength in the CPT should correspond to the passive shear strength. The observation that overconsolidation does not significantly affect the results implies that in order to make the evaluation compatible with data from triaxial tests, plane strain tests and direct simple shear tests, a correction like that in equation (11) should be used.

Assuming that the net cone resistance is governed solely by the horizontal preconsolidation pressure, the passive undrained shear strength could be evaluated by combining equations (2) and (13), which gives an almost constant cone factor for this strength of 19.7.

$$c_{u_{passive}} \approx \frac{q_t - \sigma_{v0}}{19.7} \tag{14}$$

Using equation (14) and the relations between the strengths obtained at different modes of loading given by the general soil model, equations (1,5,6), makes it possible to estimate what cone factors should then be used when relating the CPT data to the shear strength in triaxial compression and in direct simple shear. The resulting cone factors correspond well to those found empirically from direct comparisons of results from CPTs and laboratory tests, equations (9) and (10), as shown in Fig. 5. If the net cone resistance is linked directly to the horizontal preconsolidation pressure in the soil, this together with the general soil model for Swedish clays thus largely explains the various cone factors obtained in these soils.

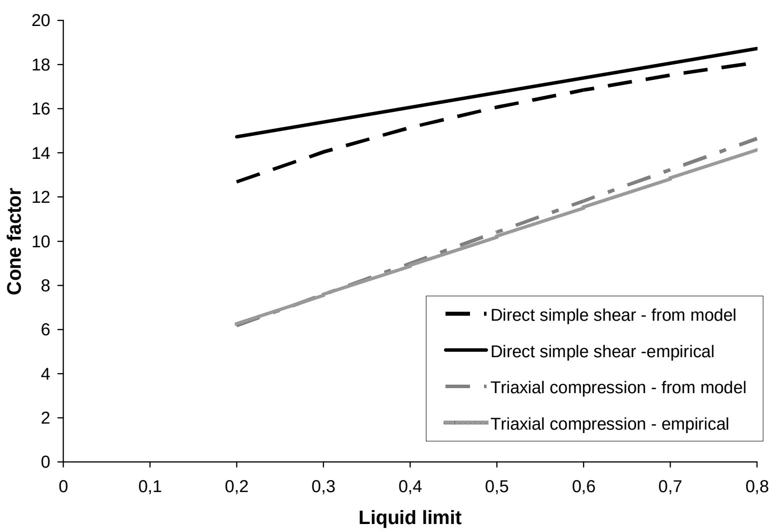

Fig. 5. Empirical and estimated cone factors for evaluation of undrained shear strength in direct shear and triaxial compression.

6 CONCLUSIONS

The data obtained from a large number of investigations using CPTs in Swedish clays have, when analysed within the framework of the general model for the behaviour of these clays, shown that:

- There are strong indications that the net cone resistance in homogeneous, low permeable clays is governed by the preconsolidation pressure in the horizontal direction.
- An assumption that the net cone resistance is governed by the horizontal preconsolidation pressure alone largely supports the various cone factors used for evaluating undrained shear strength and preconsolidation pressure.

The Swedish clay model is generally only applicable to Swedish clays. However, an assumption that the net cone resistance is governed by the horizontal preconsolidation pressure may be helpful to explain other local correlations.

Approaches used to derive material parameters in clay from CPT data should take into account yield surfaces, limitations of the effective stresses, and shear strength anisotropy.

Further basic research with CPTs in clays with carefully controlled stress histories and stress conditions is desired.

REFERENCES

Bjerrum, L and Andersen, K. (1972). In situ measurement of lateral pressures in clay. *Proceedings of the Fifth European Conference on Soil Mechanics and Foundation Engineering, Madrid 1972*, Vol. 1, pp. 23-28.

Jamiolkowski, M., Ladd, C.C., Germaine, J.T. and Lancelotta, R. (1985). New developments in field and laboratory testing of soils. Theme Lecture. *Proceedings, Eleventh International Conference on Soil Mechanics and Foundation Engineering, San Francisco 1985*, Vol. 1. pp 57-153.

Larsson, R. (1975). Measurement and calculation of horizontal stresses in clay. Geotechnical department, Chalmers University of Technology, Gothenburg.

Larsson, R. (1977). Basic behaviour of Scandinavian soft clays. *Swedish Geotechnical Institute, Report* No. 4. Linköping.

Larsson, R. (1981). Drained behaviour of Swedish clays. *Swedish Geotechnical Institute, Report* No. 12. Linköping.

Larsson, R. (1995). The CPT-test. *Swedish Geotechnical Institute, Information* No. 15E. Linköping. (Revised in 2007)

Larsson, R. (2007). CPT-sondering. *Swedish Geotechnical Institute, Information* No. 15. Review 2007. Linköping. (In Swedish)

Larsson, R. and Mulabdić, M. (1991). Piezocone tests in clay. *Swedish Geotechnical Institute, Report* No. 42. Linköping.

Larsson, R. and Sällfors, G. (1981). Hypothetical yield envelope at stress rotation. *Proceedings of the Tenth International Conference on Soil Mechanics and Foundation Engineering, Stockholm 1981*, Vol. 1, pp. 693-696.

Larsson, R., Sällfors, G., Bengtsson, P.-E., Alén, C., Bergdahl, U. and Eriksson, L. (2007). Evaluation of Shear Strength in cohesive Soils. *Swedish Geotechnical Institute, Information* No 3, Linköping. (In Swedish – Updated version of Information No 3 from 1984 with English version No 3E , also published in a shorter version in *ASTM Geotechnical Testing Journal* , Vol. 10, No. 3, 1987.)

Larsson, R. and Åhnberg, H. (2003). Long-term effects of excavations at crests of slopes. *Swedish Geotechnical Institute, Report* No. 61. Linköping.

Larsson, R. and Åhnberg, H. (2005). On the evaluation of undrained shear strength and preconsolidation pressure from common field tests in clay. *Canadian Geotechnical Journal*. Vol. 42, No. 4, pp. 1221-1231.

Löfroth, H. (2008). Undrained shear strength in clay slopes – Influence of stress conditions – A model and field test study. Thesis. Chalmers University of Technology, Department of Civil and Environmental Engineering, Division of Geo Engineering, Geotechnical Engineering, Gothenburg.

Massarsch, R., Holtz, R.D., Holm, D.G. and Fredriksson, A. (1975). Measurement of horizontal in situ stresses. *ASCE Specialty Conference on In Situ Measurements of Soil Properties. Raleigh, North Carolina, June 1-4, 1975*, Vol. 1, pp. 266-286.

Sällfors, G. (1975). Preconsolidation pressure of soft, high-plastic clays. Thesis, Chalmers University of Technology, Department of Geotechnical Engineering, Gothenburg.

Yu, H.S. (2004). In situ soil testing: from mechanics to interpretation. *Proceedings, Geotechnical and geophysical site characterization 2, ISC 2, Porto*, Vol. 1, pp. 3-38.