# Influence of the stress conditions on the piezocone shear strength – results from a model test study

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ABSTRACT: This paper presents results from piezocone tests in a study focusing on the influence of the horizontal stresses on the undrained shear strength measured with both piezocone and field vane shear tests in clay, with special reference to clay slopes. The influence of the horizontal stresses was studied by model tests with a mini piezocone in large triaxial cells. The shear strength evaluated in the model tests has been compared with an empirical equation that describes how the undrained shear strength varies with preconsolidation pressure and overconsolidation ratio and with results from direct simple shear tests. In addition, the undrained shear strength at the toe of a slope has been predicted based on the results of the model tests together with piezocone tests above the crest of the slope.

## 1 INTRODUCTION

Evaluation of the undrained shear strength in clay from CPT's has, in Sweden, to a great extent been based on empirical relationships that were found for the stress distribution valid for horizontal ground and normally consolidated or slightly overconsolidated soil (Larsson & Mulabdic'1991). The relationship between the effective horizontal and effective vertical stresses then correspond to $K_{0(NC)}$ conditions. For these conditions the results from laboratory tests and CPT's generally show good agreement. However, different studies (e.g. Kurup et al. 1994) indicate that, when the relations between horizontal and vertical stresses differ from those in normally consolidated soil, e.g. at the toe of a slope, also the relations between CPT's and laboratory tests differ. This indicates the influence of the horizontal stresses on the undrained shear strength determined by the piezocone test. Also theoretical analyses of the piezocone test using bearing capacity methods, cavity expansion methods, strain path methods, and finite element methods or a combination of these methods, (e.g. Vesic', 1975, Teh & Houlsby, 1991, Yu et al., 2000) indicate that the net cone resistance and correspondingly the undrained shear strength evaluated from this parameter should be governed by, either the horizontal stresses, or both the horizontal and the vertical stresses.

To correct for the effect of stress induced anisotropy, a correction factor as a function of the plasticity of the clay has been introduced for field vane tests (e.g. Bjerrum, 1973). The correction factors used in Sweden, until today, are a function of the liquid limit of the clay and were proposed by Larsson et al., (1984). These correction factors have recently been revised to include an extra correction factor for overconsolidation (Larsson et al., 2007). The evaluation of undrained shear strength from CPT's also varies with liquid limit and overconsolidation ratio.

This paper presents results of piezocone tests in a study initiated to provide a better understanding of how the results from the piezocone and the field vane shear test are influenced by the horizontal stresses, with special reference to the stress conditions in clay slopes. In this study model tests with a mini piezocone and a mini vane in large triaxial cells were carried out together with complementary tests in the field (Löfroth, 2008).

## 2 SCOPE OF THE TESTS

The model tests were conducted in order to study the effects of the ratio between effective horizontal and vertical stresses ($K = \sigma'_h/\sigma'_v$) on the undrained shear strength as determined with piezocone tests under controlled conditions. For each stress condition, model piezocone tests were conducted and the cone resistance and penetration pore pressure were measured. In order to control the stress history of the clay specimens, each specimen was consolidated for stresses above its natural vertical and horizontal preconsolidation pressures. As a result, a new and well defined stress history for each specimen was created.

All samples in the model tests were taken from the upper part of the soil profile under the dry crust, at a test site in the Partille municipality (east of Gothenburg), in the west part of Sweden. From the top of the eroded slope to the river bottom, the difference in height is about 12 m. The soil at the test site consists of post glacial and glacial clay to more than 35 m depth. The clay is medium sensitive and high plasticity with liquid limits and water contents between 60 and 75%. The overconsolidation ratio is about 1.3 above the crest and about 2.5 at the toe of the slope. The undrained shear strength of the clay at the crest of the slope varies between about 11 kPa at the top to about 36 kPa at 30 m depth.

### 2.1 *Equipment*

To carry out the model tests, two types of triaxial cells were designed and built (Löfroth, 2008). The first type was used to consolidate clay specimens for isotropic stress conditions and for conditions with larger horizontal stress than vertical stress (K>1). The second type was used to consolidate clay specimens for isotropic stress conditions or for stress conditions with larger vertical stress than horizontal stress (K<1). The cells were designed for specimens with a height of 280 mm and a diameter of 126 mm. A mini piezocone from Fugro Engineers BV was used in the model tests. The piezocone has a cone area of 100 mm$^2$ (diameter of 11.3 mm), a friction sleeve and a pore pressure transducer with a filter just behind the shoulder of the tip.

## 2.2 *Test series*

From the start, the intention was to carry out model tests for stress conditions equal to those in the passive and active zones of the slope, as well as for horizontal ground. The tests should also be carried out at stress conditions corresponding to two different stress levels in the ground. The stress conditions in the model tests that were intended to correspond to the lowest stress level are presented in Table 1 and shown in a s-t stress diagram in Figure 1. The induced preconsolidation stresses for these tests were: $\sigma'_{cv}$ = 119 kPa, $\sigma'_{ch}$ = 77 kPa, $K_{0(NC)}$ = 0.65.

Table 1. Consolidation stresses for the model tests corresponding to the lowest stress level.

| Test | Effective vertical stress | Effective horizontal stress | $K_0$ |
|---|---|---|---|
| 7-1 | 85 | 68 | 0.8 |
| 7-2 | 34 | 68 | 2.0 |
| 7-3 | 34 | 34 | 1.0 |
| 7-4 | 85 | 34 | 0.4 |

The model tests corresponding to the highest stress level were given stress conditions about 1.5 times higher than the lower stress level.

After the first test series was completed, it was decided to complement with two isotropically consolidated test series with induced isotropic preconsolidation pressures corresponding to the vertical preconsolidation pressure at the lowest stress level and the highest level respectively. The isotropic model tests corresponding to the lowest stress level had test conditions given in Table 2 and are included in Figure 1.

Table 2. Consolidation stresses for the isotropic model tests corresponding to the lowest stress level.

| Test | Effective vertical stress | Effective horizontal stress | $K_0$ | OCR |
|---|---|---|---|---|
| ISO 1 | 34 | 34 | 1.0 | 3.5 |
| ISO 2 | 85 | 85 | 1.0 | 1.4 |
| ISO 3 | 119 | 119 | 1.0 | 1.0 |

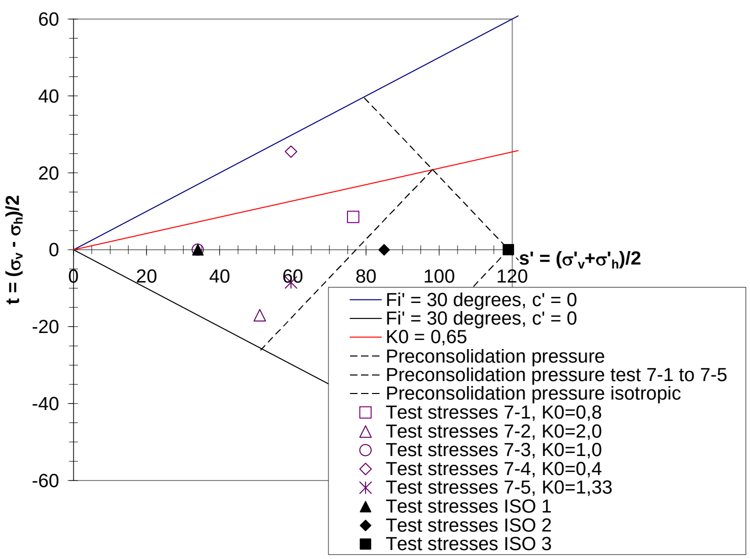

Figure 1. Consolidation stresses for tests 7-1 to 7-4 and ISO1 to ISO3.

## 2.3 *Test procedure*

To reach the preconsolidation stresses corresponding to the two stress levels for the $K_{0(NC)}$-consolidated tests, the consolidation was carried out in four steps. For the fourth consolidation step, the time - deformation curve was plotted and the time for 100 % consolidation was evaluated according to the Casagrande method. When 100 % consolidation had been reached unloading to the final consolidation stresses was carried out in one step. These stresses were applied for 1-2 days in most cases and the total heave was noted. The isotropically consolidated tests were preconsolidated and unloaded in the same way but using two consolidation steps instead of four.

One piezocone test was carried out in the centre of one specimen to 120 mm depth and a direct simple shear test was carried out on a sample taken out in the centre of the remaining part of the specimen. The piezocone equipment was calibrated just before the tests in each testing round and then again directly after the tests. After the tests, samples were taken from the outer parts of the specimens for routine analyses.

# 3 RESULTS OF THE PIEZOCONE MODEL TESTS

Evaluation of the undrained shear strength from piezocone tests is normally made using the equation:

$$c_u = \frac{q_T - \sigma_{v0}}{N_{kt}} \tag{1}$$

The cone factor $N_{kt}$ varies depending on what shear strength it is referred to, i.e. the active shear strength, the shear strength at direct simple shear or some other case. In this study ($q_T$-$\sigma_{v0}$) has been normalised against the horizontal preconsolidation pressure, the vertical preconsolidation pressure and the mean preconsolidation pressure. To see the effect of the overconsolidation ratio (OCR), the normalised net cone resistance has been plotted versus the horizontal, vertical and mean overconsolidation ratio.

To compare these relations with the empirical equation that directly or indirectly describes how the undrained shear strength varies with preconsolidation pressure and overconsolidation ratio (e.g. Ladd et. al., 1977 and Jamiolkowski et al., 1985):

$$\frac{c_u}{\sigma'_{cv}} = a \cdot OCR_v^{b-1} \tag{2}$$

it is necessary to include the cone factor, $N_{kt}$. In the empirical curves in the diagrams, $c_u$ in the equation has thus been multiplied by $N_{kt}$. The empirical relation of $N_{kt}$ corresponding to the shear strength at direct simple shear for Swedish slightly overconsolidated clays has been used:

$$N_{kt} = 13.4 + 6.65 \cdot w_L \tag{3}$$

where $w_L$ is the liquid limit in decimal numbers (Larsson & Mulabdic, 1991). The value of $w_L$ is chosen to be some mean value of $w_L$ for the model tests which gives $N_{kt} \approx 17$.

In the empirical Equation 2 the empirical values of 0.22 for the *a*-factor for direct simple shear and 0.8 for the *b*-factor have been applied. The choice of these values were supported by results from direct simple shear tests on specimens consolidated for effective stresses 2.5 times the natural preconsolidation pressure and then unloaded to various OCRs according to the SHANSEP procedure (Ladd & Foot, 1974). The evaluated factors *a* and *b* were then 0.22 and 0.81 respectively, i.e. very close to the empirical values. The empirical relation is based on a normalisation of the undrained shear strength against the vertical preconsolidation pressure and it has been converted to be valid for a normalisation against the horizontal preconsolidation pressure or the mean preconsolidation pressure.

Analysing the results from the piezocone tests, the scatter of the data is rather great and consequently the significance of the relations is low for all the piezocone plots. Trying to detect any correlation, the plots with the net cone resistance normalised against the horizontal, vertical and mean preconsolidation pressure, each plotted versus the horizontal, vertical or mean OCR respectively have been compared. Figure 2 shows the net cone resistance normalised against the horizontal preconsolidation pressure and plotted against the horizontal OCR.

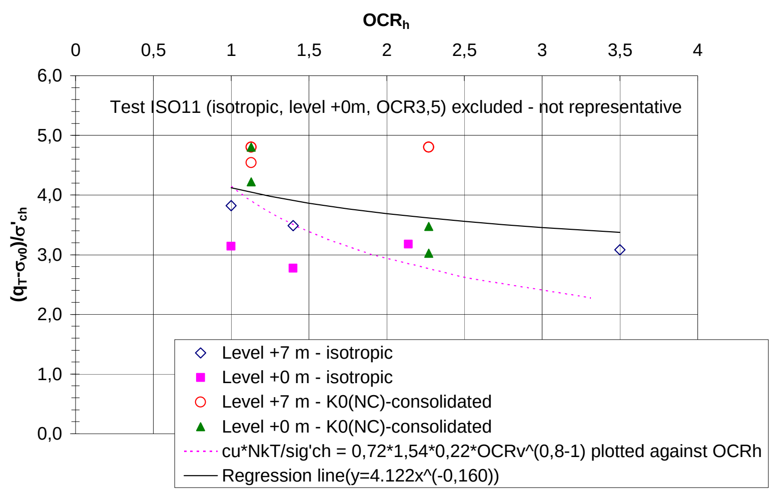


Figure 2. The net cone resistance normalised against the horizontal preconsolidation pressure and plotted against the OCR in the horizontal direction.

In all the plots, the empirical equation shows a larger decrease with OCR than the results from the piezocone tests, which indicates that unloading has a greater influence on the direct simple shear test results than on the piezocone test results. However, based on the results alone, it is not possible to ascertain whether it is the horizontal, the vertical or the mean preconsolidation pressure that has the most influence on the net cone resistance. This is because of the low significance and the difficulties to distinguish the type of plot that best correlates with the empirical equation. However, according to the above mentioned theories (see Section 1) the net cone resistance should be governed by, either the horizontal stresses, or both the horizontal and the vertical stresses. Consequently, normalisation against the horizontal or the mean preconsolidation pressure should give the best correlation, as was also the case in this study.

It may be possible to estimate the influence of the vertical or the horizontal preconsolidation pressure using empirical data from earlier studies. Combining the relation found by Larsson (1977),

$$K_{0NC} = 0.31 + 0.71(w_L - 0.2) \quad (4)$$

with the relation by Larsson & Mulabdic, (1991),

$$\frac{q_T - \sigma_{v0}}{\sigma'_{cv}} = 1.21 + 4.4 \cdot w_L \quad (5)$$

gives an expression for the relation between the net cone resistance and the horizontal preconsolidation pressure

$$\frac{q_T - \sigma_{v0}}{\sigma'_{ch}} = \frac{1.21 + 4.4 \cdot w_L}{0.31 + 0.71 \cdot (w_L - 0.2)} \quad (6)$$

In Figure 3 the net cone resistance is normalised against the vertical preconsolidation pressure and the horizontal preconsolidation pressure respectively and plotted versus the liquid limit using Equations 5 and 6. It is clearly seen that there is hardly any change in the net cone resistance normalised against the horizontal preconsolidation pressure with the liquid limit, whereas the net cone resistance normalised against the vertical preconsolidation pressure is strongly dependent on the liquid limit. This indicates that the net cone resistance is primarily dependent on the horizontal preconsolidation pressure and appears to be a more or less direct function of this.

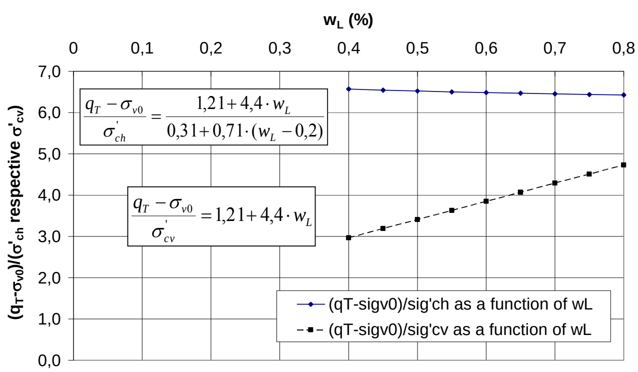


Figure 3. The net cone resistance normalised against the horizontal preconsolidation pressure and the vertical preconsolidation pressure respectively and plotted versus the liquid limit.

## 4 ANALYSIS OF FIELD TESTS BASED ON THE MODEL TESTS

Based on the results of the model tests and the stress conditions in the slope, the undrained shear strength at the toe of the test site slope have been predicted (Löfroth, 2008). The field tests performed far behind the crest of the slope was used as reference as they correspond to almost horizontal ground conditions. From the results of the model tests the best correlations found for undrained shear strength and stress history were used, which is the regression line for the net cone resistance normalised against the horizontal preconsolidation pressure and plotted against the horizontal

OCR (Figure 2). In the analysis procedure, the results from piezocone tests behind the crest of the slope plotted against depth and corrected with regard to the liquid limit were normalised against the horizontal preconsolidation pressure. This normalised field shear strength was used to calibrate the model test regression line to the field tests, i.e. to give the right starting point for the "field test" regression curve. Based on the horizontal preconsolidation pressure and the horizontal OCR at the toe the undrained shear strength at the toe of the slope was then calculated.

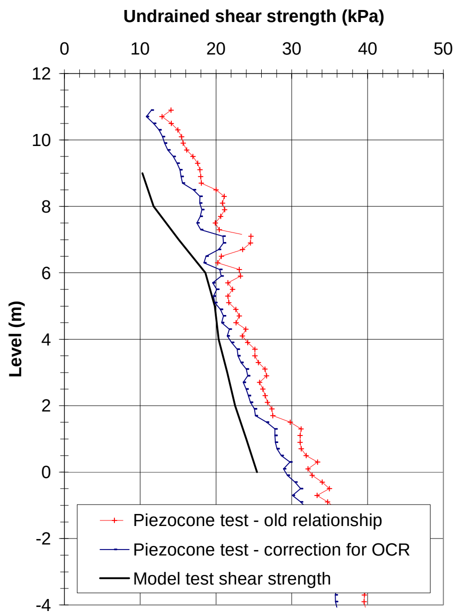


Figure 4. Undrained shear strength calculated from the model piezocone test results compared with calculated field piezocone test results.

In Figure 4 the undrained shear strength calculated from the model tests is compared with the undrained shear strength calculated from the field tests with the relationships based on normally consolidated and slightly overconsolidated soils (Larsson & Mulabdic' 1991) and the undrained shear strength calculated with the relationships, which have an extra correction for overconsolidation (Larsson & Åhnberg 2003). It can be seen that the undrained shear strength calculated from the model tests is considerably lower than the undrained shear strength based on the relation without correction for overconsolidation. This indicates that there is a need for an extra correction for overconsolidation. That it is also lower than the undrained shear strength based on the relation with correction for overconsolidation indicates that this correction should possibly be even greater than in the proposed relationship with correction for overconsolidation. However, as the model test data show quite a large scatter this conclusion is only tentative.

## 5 CONCLUSION

From the results of the model piezocone tests alone, it is not possible to distinguish with certainty if it is the horizontal or mean preconsolidation pressure that has the largest influence on the net cone resistance. The influence of the horizontal and vertical preconsolidation pressures may however, be distinguished using also empirical data from other studies. The prediction of undrained shear strength at the toe of a slope based on the model tests imply that there is a need for an extra correction for overconsolidation and that a correction based in the usual way on the vertical overconsolidation ratio gives a fairly good correspondence with the adapted model test results.

## 6 ACKNOWLEDGEMENTS

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