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THE IMPACT OF LARGE EXCAVATIONS ON SHEAR STRENGTH IN CLAY AND SLOPE STABILITY

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ABSTRACT

Construction in clay areas with natural slopes prone to landslides and slope failures is an engineering challenge. To improve the safety in slopes, the general way, is to modify the slope geometry by reducing the active forces (excavation) or increasing resisting load (backfilling). In practice the reduction of effective stress affects the undrained shear strength in clay. The stress related reduction of undrained shear strength after large excavations in soft clay in western Sweden, has been analysed by advanced laboratory testing at different stress levels. The reduction in shear strength results in changes to safety factors in slope stability analyses.

Undrained shear strength in clay is dependent on stress history and can be calculated empirically using effective stress, over consolidation ratio and liquid limit. To accurately predict how undrained shear strength changes with stress level, site-specific constants (a & b) need to be evaluated. A series of direct simple shear tests at different stress states have been performed for this purpose on undisturbed clay samples. The pre-consolidation pressure and liquid limit varies for the clay samples tested. With site-specific constants evaluated from laboratory testing, undrained shear strength could be empirically calculated for different stress states and compared to the results from direct simple shear test with corresponding effective overburden stress.

Results indicate a good correlation between the empirically calculated value of undrained shear strength and the results received from direct simple shear tests at different stress states. The empirical relations and laboratory tests indicate that the effect of reduced undrained shear strength is larger near the surface and decreases with depth. For stability analysis, the changes in undrained shear strength from excavation can be modelled with the SHANSEP-model, which is an effective stress-based model.

Keywords: slope stability, soft clay, SHANSEP.

BACKGROUND

Trollhätte Canal in western Sweden is 82 km long, 10 km is a dug and blasted canal, while the rest is in the Göta River. The difference in level along the route is 44 meters and is managed by six canal locks. These locks are to be replaced due to aging infrastructure. In Lilla Edet this entails a new lock parallel to the old lock and a large excavation in the existing soft clay slope. Construction in clay areas with natural slopes prone to landslides and slope failures is an engineering challenge. To improve the safety of the slopes, the general way historically was to modify the slope geometry by reducing the active forces (excavation) or increasing resisting load (backfilling). In this project, the main approach to reshape the slopes around the new lock, is large excavations. Excavations contribute to a stress reduction and in practice this could lead to a reduction in undrained shear strength in soft clay.

This article aims to describe the changes in shear strength due to large excavations in clay and the impact on the factor of safety in clay slopes. The study is based on planed excavations in existing

natural soft clay slopes along Göta river in western Sweden.

THEORY

During 1970 Ladd, Et al (1974) and Ladd, Et al (1977) presented a method, The Stress History and Normalized Soil Engineering Property, which is a tool for estimating the in situ undrained properties of a clay. The characteristics of cohesive soils can be evaluated based on empirical observation from testing. Cohesive soil samples exhibit similar strength and stress-strain characteristics when tests were normalized regarding consolidation stress (Ladd et al 1974 & Ladd et al 1977).

According to empirical experience from triaxial tests and direct simple shear (DSS) tests, the undrained shear strength varies depending on the over consolidation ratio (OCR), effective stress and liquid limit. The variation in shear strength can be evaluated by the expression

$$c_u = a \cdot \sigma'_v \cdot OCR^b \quad (1)$$

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Alt.

$$c_u = a \cdot \sigma'_v \cdot OCR^{b-1} \quad (2)$$

(Ladd et al. 1977, Jamiolkowski et al. 1985)

In formulas (1) and (2) respectively, a and b are material constants and can be evaluated from triaxial tests and DSS tests. The mode of loading determines the factor a . Results from active triaxial tests presented by Larsson (1980) indicate that factor a is about 0.33 in Swedish clays. However, from DSS tests factor a has been found to vary with the liquid limit where the average value is approximately 0.22. The factor of b has been presented to normally vary between 0.75 and 0.85 in both DSS tests and triaxial tests (Jamiolkowski, 1985).

Based on the above expressions the SHANSEP model was presented by Ladd et al. (1977) and Jamiolkowski et al. (1985). By establishing the stress history, performing a series of DSS tests with varying OCR and using the relationship between normalized parameters and OCR, the profile of undrained shear strength can be evaluated. Swedish soft clays can normally be normalized in relation to the natural preconsolidation pressure (Löfroth, 2008).

To avoid damaging the structure in the Swedish soft clays, the DSS tests are reconsolidated just below the in situ preconsolidation pressure. The sample is then unloaded to reach an evaluated OCR, which affects the results in undrained shear strength. (Löfroth, 2008).

ANALYSES AND LABORATORY TESTING

In Sweden, to obtain the undrained shear strength in soft clay, the direct simple shear (DSS) test is normally used (Svahn, 2015). In this study DSS tests were used to determine the undrained shear strength at different stress states in soft clay, with the aim to analyse the impact of large excavations on the shear strength in natural clay slopes. Samples from three different locations with different depths were used. All DSS tests were performed in accordance with standard test procedures were samples initially reconsolidated for stresses close to the preconsolidation pressure ($0.85 \cdot \sigma'_{cv}$). After reconsolidation, the samples were unloaded to the in situ vertical stress or selected vertical stress evaluated from different magnitude of excavations and unloading. Shearing with a constant rate of deformation (0.1 mm/h) was performed. For the selected vertical stress an unloading corresponding to 2, 4 or 6 m excavation was tested.

The results from the DSS tests with different stress states were used to evaluate the site-specific factor a and b . By plotting the normalized undrained shear strength against OCR, the equation from the regression line presents the factor a and b , as shown in the equation in Figure 1. Figure 1 presents laboratory testing from one

sample point. The blue points represent all the test results with vertical stress state deviant from in situ due to unloading of the soil. The red points represent the result from actual in situ stress state from sample depth 7, 9, 12 and 14 m. For this specific sample point $a = 0.26$ and $b = 0.75$ could be evaluated.

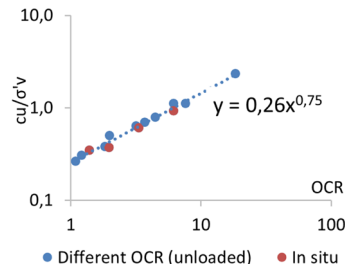


Figure 1 Results from direct simple shear tests with different OCR for one sample point

The same procedure was performed for all three sample locations in the Lilla Edet area. In each sample point, 2 to 3 depths were tested between 7 to 12 m deep. The relation between a normalized undrained shear strength and OCR was analyzed, as shown in Figure 2. All the results from DSS tests with different stress states and sample depths resulted in factor $a = 0.26$ and $b = 0.77$.

A minor change in b was observed when analyzing only one sample point compared to the entire area. In comparison with previous studies, it can be observed that factor b falls within the expected range (Jamiolkowski, 1985). Factor a for this specific site deviates slightly from earlier studies conducted in Sweden by Larsson (2003). Factor a is normally lower than 0.22 for low-plasticity clays, and higher for high-plasticity clays. At this site the clay samples have shown a liquid limit of approximately 60% which indicates a high-plasticity clay. Empirical values for the factor in clay regarding liquid limit can be evaluated by the expression

$$a \approx 0.125 + 0.205w_L/1.17 \quad (3)$$

(Larsson et al., 2007)

The observed value of the a factor acquired from testing is reasonable for this site.

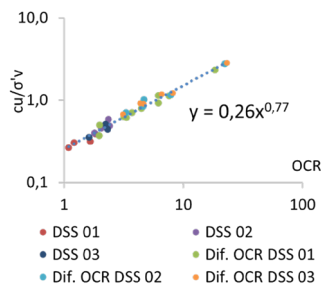


Figure 2 Results from all direct simple shear test with different OCR

RESULTS OF UNDRAINED SHEAR STRENGTH

Laboratory testing resulted in values of undrained shear strength at different stress states. The obtained result of undrained shear strength for each stress state in one sample point is plotted against the elevation in Figure 3 (Cu DSS). Three different stress states are plotted, corresponding to 2, 4, and 6 meters of unloading. Furthermore, input for factors a and b in the empirical equation could be evaluated from several direct simple shear (DSS) tests at different samples and stress levels. Results show that factor a varies between 0.26 and 0.27, and factor b varies between 0.75 and 0.77.

A comparison was made between the obtained test results of undrained shear strength at different levels of unloading (excavations) and the empirically calculated undrained shear strength. The empirical undrained shear strength was calculated with the expression presented by Ladd et al. 1977, Jamiolkowski et al. 1985 using the evaluated factors a and b . In the expression an effective stress (σ'_v) representing 2, 4 and 6 meters of unloading (excavation) was used. Additionally, the empirical in situ undrained shear strength was calculated from oedometer tests. The comparison is presented in Figure 3.

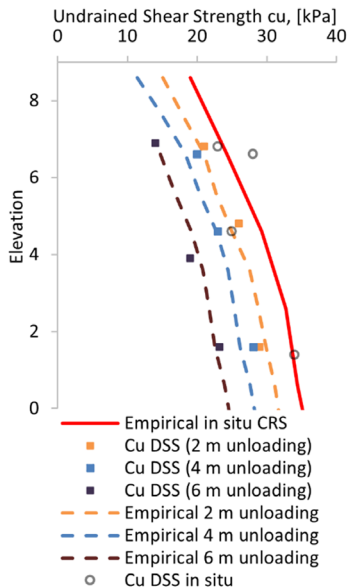


Figure 3 Results from empirically calculated undrained shear strength at different stress levels in comparison with actual results from DSS test at different stress levels for one sample point

The results in Figure 3 shows a strong correlation between the results from unloaded DSS tests and the empirically calculated shear strength

based on preconsolidation pressure (σ'_p) and overconsolidation ratio (OCR). To calculate changes in effective stresses and OCR, insight regarding pore pressures, both in-situ and after exocavation, is crucial. In Figure 3 a hydrostatic pore pressure 1 meter underneath the excavation level has been used to calculate effective stresses after unloading.

SLOPE STABILITY ANALYSIS

Stability analyses were performed using Geostudio SLOPE/W with a SHANSEP material model. SHANSEP is a stress state-based model that uses input data from the relationship between effective stress and undrained shear strength. Figure 4 represents the input data for the calculation from a specific section with 3, 6 and 9 meters of excavations. In a normal slope stability analysis (total stress model), the model uses the black line value of undrained shear strength. However, in the analysis considering the effects of unloading, all four lines with different undrained shear strengths related to effective stresses are used. As a result, the factor of safety decreases from 1.13 to 1.07 when considering the reduction in shear strength, approximately a 5% difference. Results indicate a direct correlation between the lowering of undrained shear strength and the lowering of factor of safety.

In the process of evaluating the input for the SHANSEP model the pore pressure is of great importance for the effective stress. The effective stress, in turn, affects the shear strength in the model. This means that the obtained undrained shear strength at a certain stress state can be directly linked to pore pressure conditions in each specific calculation section.

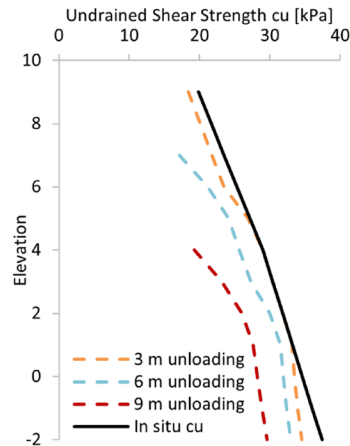


Figure 4 Input data to slope stability analysis.png

CONCLUSION

Results indicate a good correlation between the calculated value of undrained shear strength and the results received from direct simple shear tests at different stress states. The relations and laboratory tests indicate that the effect of reduced undrained shear strength is larger near the surface and decreases with depth. For stability analysis, the changes in undrained shear strength from excavation can be modelled with the SHANSEP-model, which is an effective stress-based model. Results from stability analyses indicate a direct correlation between the effects of lowering the undrained shear strength and the factor of safety.

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