Design of cut-and-cover tunnel in quick clay based on CPTU and laboratory tests

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ABSTRACT: The Norwegian Public Roads Administration plans to build a new major highway between Trondheim and Stjørdal in Central Norway. The tunnel passes under an urbanized area, where a more than 20 m deep excavation will be made in soft and sensitive soil. The soil conditions in the area consist mainly of a top layer of fill and debris materials over partly soft and very sensitive (quick) clay. The ground investigations included amongst others CPTU and retrieval of undisturbed block samples. In the laboratory, anisotropically consolidated, compression (CAU_C) and extension (CAU_E) triaxial tests, direct shear tests (DSS) and continuous consolidation tests (CRS) were carried out to provide comparison for the interpreted CPTU data.

1 INTRODUCTION

The Norwegian Public Roads Administration (NPRA), Central Region shall establish a new highway (Euro-route 6) between the municipalities of Trondheim and Stjørdal in Central Norway. The consulting company Multiconsult was at an early stage engaged to pre-design a part of this highway system in Trondheim city, the so-called Dayzone west section. This section will partly be built as a"cut-and-cover" – tunnel, continuing eastwards in a rock tunnel.

The planned section requires a deep excavation in quick clay, 22.5 to 30 m wide and 20 m deep at the most. To reduce deformations and maintain sufficient safety against bottom heave in the building pit, a design with internally strutted sheet pile walls and soil stabilization with jet pile ribs or lime cement columns beneath the excavated level was suggested in the pre-design phase. The sheet pile wall is designed with a base depth of maximum 9 m beneath the bottom of the building pit. The final design of the excavation will be made in a joint process between the NPRA and a consortium of contractors and engineering consultants. The final design will not be similar to the solutions presented herein.

2 GROUND CONDITIONS AND PERFORMED INVESTIGATIONS

The ground conditions in the project area consist mainly of a top layer with fill masses and debris, above partly sensitive silt and clay. In general, the stratification can be subdivided in 5 layers, see Multiconsult (2007a, b, c) and NPRA (2007 a, b) for a more complete and detailed description and soil data. The top fill is continuous along the whole road section. In the northernmost part of the ”cut-and-cover”-tunnel, a sand layer is encountered, whereas silt or silty soils have been found in most of the section. Deeper down, clay is encountered, which in the southern part is classified as quick clay. The quick clay is increasing in thickness towards the entrance of the rock tunnel. Some of the highly sensitive materials have a composition closer to silt, but is classified as quick clay herein due to their low remoulded shear strength and high sensitivity. The depth to the rock surface varies over the area, with the rock surface sloping from south to north along the tunnel section.

The field investigations comprised various types of soundings: 6 rotary pressure soundings, 38 total soundings (rotary pressure sounding combined with drilling 3 m into the rock surface), 18 piezocone penetration tests (CPTUs), undisturbed soil sampling using piston sampling and Sherbrooke block sampling, installation of piezometers (3 locations, a total of 4 piezometer probes). The sampling was carried out in 5 locations using a standard Geonor ϕ54 mm piston sampler, with a total of 55 cylinders. The Norwegian Geotechnical Institute (NGI) performed 2 boreholes with the Sherbrooke ϕ250 mm block sampler (boreholes 809 and 823). A total of 8 block samples in the depth interval of 6 – 24 m were obtained, including both silts and quick clays.

Multiconsult carried out laboratory tests on the ϕ54 mm cylinder samples, whereas NGI carried out laboratory tests on the block samples. The latter samples were transported to NGI in Oslo in private cars to reduce the impact of sample disturbance during transport as much as possible.

The extensive test programme in the laboratory included standard index testing, anisotropically consolidated, compression (CAU_C) and extension (CAU_E) triaxial tests, direct shear tests (DSS) and continuous consolidation tests using the CRS test procedure. Results from previous investigations in the area have also been examined and used as supplementary data.

3 SOIL SAMPLING AND PARAMETER INTERPRETATION FROM LABORATORY TESTS

Soil sampling should normally provide a basis for identification of the sampled soils and determination of mechanical properties. The latter requires samples of satisfactory quality with a minimum of sample disturbance, truly reflecting the in situ strength and stiffness properties of the materials. In Norway, the sample quality is presently divided into three classes, according to the guidelines issued by the Norwegian Geotechnical Society (NGF), depending on a rough classification of the sample disturbance: Undisturbed samples (Class 1), disturbed samples (Class 2) and remoulded samples (Class 3). This classification is now being changed into five Quality classes, complying with the new Eurocode 7 and the ISO CEN standard on soil sampling. However, neither the Eurocode 7 nor the NGF classification systems introduce objective criteria for division between the five Quality classes.

Normally, the ϕ54 mm Geonor piston sampler is used to produce samples in the best quality classes, obtaining satisfactory results in clays and fine silts. This requires that the sampling equipment is well maintained and designed, and that recommended procedures are followed in the sampling operations, both in the field, during transport and handling in the laboratory.

The Sherbrooke block sampler, described by Lefebvre & Poulin (1979), is a specially developed sampler for retrieval of ϕ250 mm x 300 mm intact soil samples. The method is used occasionally in commercial projects in Norway, more frequently in research. It is particularly useful where other sampling methods fail to give samples of sufficient quality, particularly in lean, sensitive clays. The block sampling operations require a special soil auger for pre-drilling of a ϕ400 mm pilot hole, into which the sampler is lowered. The borehole is usually cased and filled with a support fluid. Before sampling, the borehole has to be cleaned and smoothened by a flat auger, otherwise the soil debris may interfere with the rotation of the sampler and influence the geometry and quality of the soil block.

After insertion of the sampler down to the sampling level, it is rotated slowly in the borehole. By this, the cutting knives mounted in front of the three hollow legs carve a trench along the periphery of the sampler, and a cylindrical block is formed as the sampler advances deeper. The debris is removed by drilling fluid, flushing through the hollow legs. After carving the block to its complete length, the sample is released from the surrounding soil. This is done by pushing the knives into the bottom of the soil block, triggered by a blow on a release spring mounted on top of the sampler. The sampler is then slowly rotated to shear off the block completely. The sampler is then hoisted slowly to the surface, while the soil block is resting on the three cutting knives. The sample has no confinement other than the drilling liquid supporting it during this process. Arriving at the surface, the sample is cleaned, lifted over to a base plate and sealed by PVC foil and wax before transport to the laboratory.

4 INTERPRETATION OF SOIL PARAMETERS FROM CPTU

In this project, results from CPTU profiles are used to interprete and evaluate strength and stiffness parameters, as well as stress history and preconsolidation stress. The presentation herein concentrates however only on interpretation of the undrained shear strength.

4.1 *Local correlations*

In the interpretation of undrained compression shear strength (s_u^C), local correlations are made with the measured strength from CAU_C triaxial tests on block samples. By performing CPTU and block samples in the same borehole locations, a local correlation between results from CPTU and CAU_C tests was established. For the fine grained, soft and sensitive soils encountered in this project, the undrained shear strength was derived from pore pressure based correlations, since the relative influence of errors is believed to be less for the pore pressure than for the cone resistance. The undrained shear strength is hence determined as:

$$s_u^C = \frac{\Delta u}{N_{\Delta u}} \qquad (1)$$

where, Δu = $u_2 - u_o$, recorded excess pore pressure
$N_{\Delta u}$ = pore pressure cone factor

Results from previous investigations on high quality block samples shows that the cone factor $N_{\Delta u}$ increases approximately linearly with increasing pore pressure ratio, B_q, e.g. Lunne at al (1997a). The pore pressure ratio B_q is defined as:

$$B_q = \frac{\Delta u}{q_n} \qquad (2)$$

where, q_n = net cone resistance

In the design evaluations, the excavation was divided in different sections, based on ground conditions and required support level. Two different approaches were used in the interpretation of CPTU results. First, local CPTU correlations were used for quick clay, clay and silty materials, respectively. For all materials, the following general correlation was introduced for interpretation of s_u^C:

$$N_{\Delta u} = C_1 + C_2 \cdot B_q \qquad (3)$$

The constant C_1 = 1, whereas C_2 = 7.5 in the quick clay and C_2 = 9.0 in clay and silt layers, were used. These values are in good agreement with the previously proposed empirical values by Lunne et al (1997a). As a second approach, interpretation of CPTU, using the more recent correlations presented by Karlsrud et al (2005), were also carried out. The latter method separates between correlations for high and low sensitivity (threshold value S_t = 15), and depends on overconsolidation ratio (OCR) and plasticity (I_p).

The interpreted results from the two boreholes with block sampling are shown in Figure 1. The two different approaches show very good agreement in the quick clay for depths larger than about 7 m, shown in Figure 1a.

It should be mentioned that Norwegian practice introduces a reduction in interpreted shear strength of 15 % on the peak shear strength, when results or correlations are based on block samples. This is due to the brittle nature of block samples often seen in laboratory tests.

Approaching the rock surface, the interpretation of the undrained shear strength from CPTU becomes somewhat uncertain. Figure 1a shows this effect from 20 – 21 m depth below the terrain level, where both pore pressure and cone resistance decreases in the CPTU profile. This results in a reduction of s_u^C, using the B_q- related interpretations, both for pore pressure and cone resistance based correlations. It is assumed that this behaviour may be caused by the prevailing drainage or pore pressure conditions approaching the rock surface, probably due to an artesian pore pressure effect. The soil in this area also contains thin seams and layers of sand that may influence the CPTU records.

Due to a lack of good samples in this depth, only one passive triaxial test is available for comparison. Based on the results from this triaxial test, along with common values of anisotropy ratios, the results indicate that the shear strength is increasing with depth even for depths close to the rock surface, also in borehole CPTU 823.

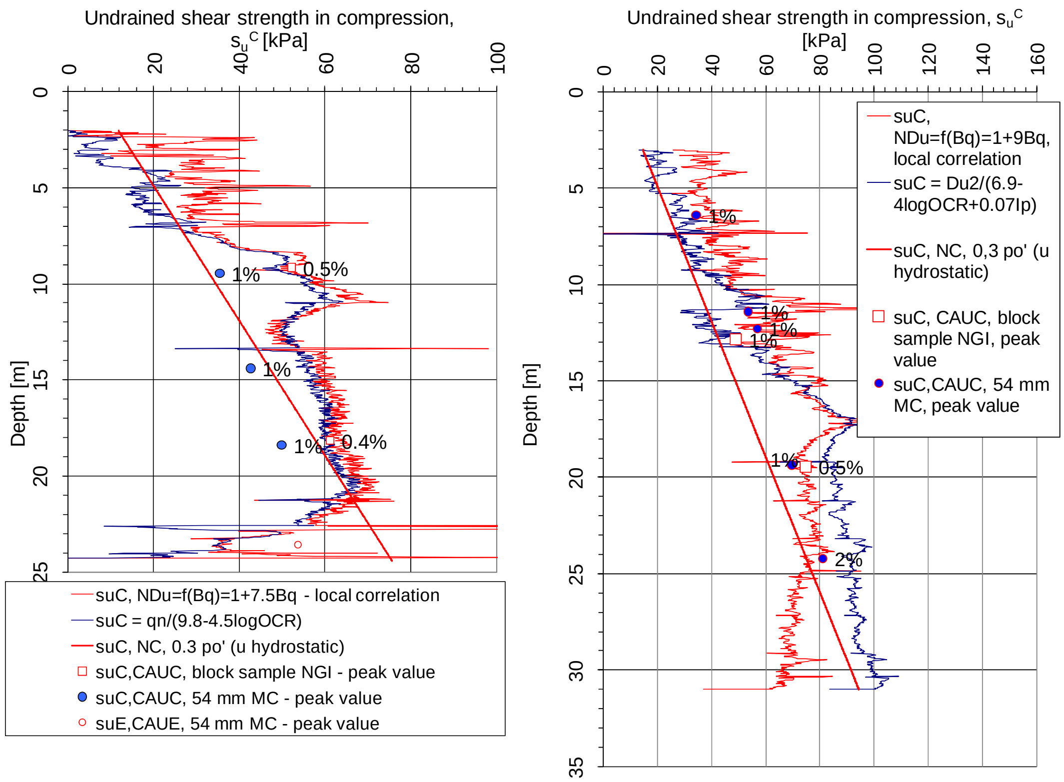

Figure 1. Interpreted s_u^C in borehole 823 (quick clay) to the left and borehole 809 (silt and clay at larger depths) to the right.

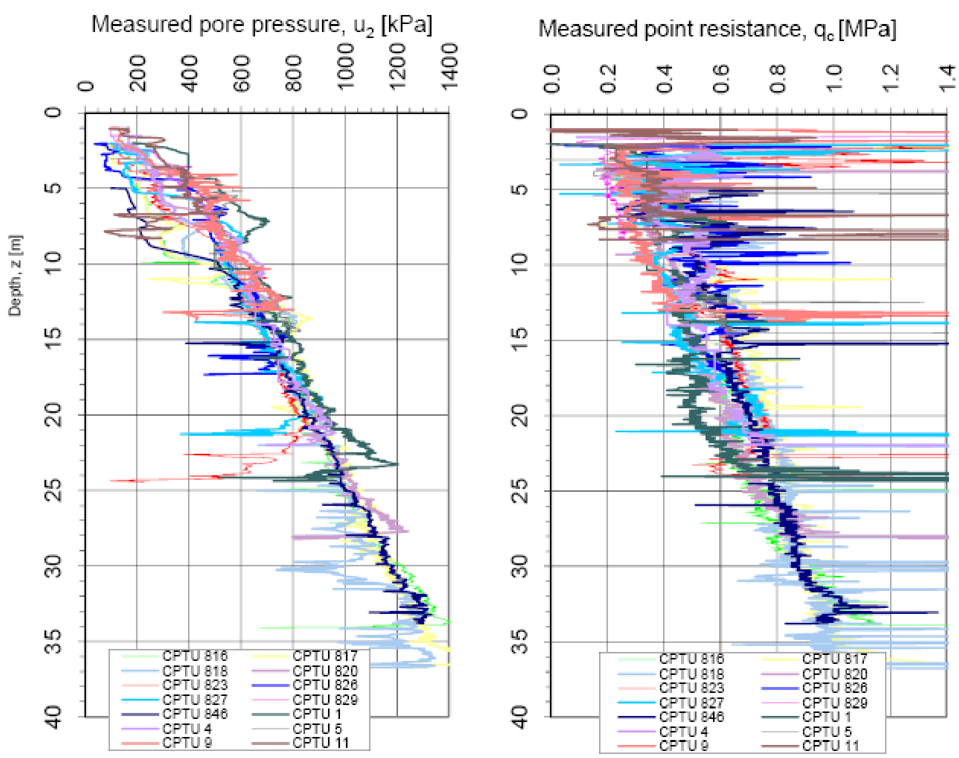

Figure 2. Variations in measured pore pressure (left), and cone resistance (right) in quick clay.

4.2 *Variations in shear strength within the quick clay zone*

The variations in ground conditions over the area are well documented through the performed CPTUs. Figure 2 shows the recorded pore pressure and cone resistance for the section with quick clay. The results show a relatively large variation in recorded values of the cone resistance. However, as shown in Figure 2, the variation in measured pore pressure is significantly less than the measured cone resistance for the quick clay/clay layer below approximately 10 m depth. Accordingly, these variations also results in variations of the interpreted strength for the quick clay layer.

5 COMPARISON AND DISCUSSION OF RESULTS

Interpretation of parameters is based on CPTU soundings and sample series from block sampling and ϕ54 mm piston samples. In design, special emphasis is put on tests carried out on block samples, together with interpretation of strength and stiffness parameters from CPTU. The CPTU-profiles are also used to extrapolate the data from local block samples to other parts of the soil profiles where block sample results are not available. The results from laboratory tests on block samples and CPTU were subsequently used as input to numerical analyses of the support structures, such as FEM-analyses.

5.1 *Evaluation of sample quality*

The evaluation criteria based on volumetric strain ε_{vol} (Andresen & Kolstad (1979)) and change in void ratio Δe (Lunne et al (1997b)) during consolidation were introduced for classification of sample quality in the tests. Special tests and CPTU interpretations indicate that the overconsolidation ratio OCR is less than 2, except for borehole 809 between 6.4 and 6.5 m depth.

In general, sample specimens taken by ϕ54 mm piston sampler were somewhat disturbed and placed in Quality class 2-4, according to the classification given by Lunne et al (1997b). The highest Quality class (Class 1) was obtained for 3 of the 8 triaxial tests on block samples. These samples range in quality from Class 1 to Class 3, representing very good to poor quality. The poorest sample quality was obtained for the deepest sample in the quick clay layer (Borehole 823, ca. 18 m depth). This may partly be explained by the poor soil properties of the quick clay and the large sampling depth. Moreover, the effective stress level at this depth may have been overestimated due to the possible presence of artesian pore pressure, causing too high consolidation stresses applied on triaxial test specimens.

The results from block samples show a brittle behaviour at failure for undrained tests on high quality samples, where the strain level at peak strength is about 0.5 %. The tests performed on ϕ54 mm piston samples show considerably softer behaviour, caused by a higher degree of sample disturbance. The determination of the characteristic undrained shear strength profile is hence mostly based on results from block samples and CPTU. To ease the comparison, the strength values are presented as peak values or strength values at 1-2 % axial strain level, if the test does not reveal a distinct maximum peak value. The strain levels used are included in Figure 1. The strength values presented herein should not be considered as design values for the project.

5.2 *Comparison between shear strength from CPTU and laboratory tests*

Figure 1 shows interpreted undrained shear strength for boreholes 809 and 823, where block sampling was carried out. Interpretation of the CPTU-results is based on $N_{\Delta u}$, determined from empirical correlations with B_q and the laboratory parameters I_p, S_t and OCR. The correlations are all based on active (compression) triaxial tests (CAU_C) on block samples as described in Section 3. For the final determination of the cone factor $N_{\Delta u}$ in this project, a local correlation with CAU_C triaxial strength data from block samples was made, see Section 4. These local correlations gave cone factors in good agreement with values reported by Lunne et al (1997a) and Karlsrud et al (2005). The values are also in good agreement with the range in values of this factor from analytical approaches. The interpreted undrained shear strength values for laboratory tests on the silty soils plot somewhat higher than the corresponding values interpreteted from CPTU. This is not an uncommon observation and may be caused by sample disturbance and compaction of the loose silt during sampling and consolidation in the triaxial tests.

Values for the anisotropic shear strength are taken from various shear tests on the block samples for three different conditions (s_u^C, s_u^{DSS} and s_u^E). The relationships between the soil strength are frequently used in geotechnical engineering, and are normally determined from an empirical database, based on a high number of tests. Values obtained in this project are reported in Table 1.

Table 1. Recorded values of anisotropy ratio from block samples.

	Borehole 809		Borehole 823	
	D=12.85m Silty clay	D = 19.45m Clay	D = 9.15m Quick clay	D = 18.15m Quick clay
Direct shear tests, s_u^{DSS}/s_u^C	0.76	0.56	0.58	0.62
Extension tests, s_u^E/s_u^C	0.42	0.29	0.28	0.23

The anisotropy ratios for the quick clay are generally somewhat lower than previously reported values based on ϕ54 mm piston samples. More data is however needed to say that this is characteristic for block samples of quick clay. In this project, very small values of the plasticity (I_p = 5 - 8 %) were measured for quick clay and silt. This is typical for marine lean and sensitive clay in this region of Norway. In general, the ratios between direct, extension and compression modes of the s_u – values reduces in value for reducing values of the plasticity. In this context, the findings in this project represent extreme conditions in the result database. Further research and systematic studies are however necessary to extend the database for such ground conditions.

6 CONCLUSIONS

In this paper, special emphasis has been put on interpretation of the undrained shear strength from CPTU and the results from laboratory tests on block samples, both with respect to testing in compression, extension and direct shear modes. The results have been used to develop local correlations between recorded data from CPTU and interpreted shear strength parameters from laboratory triaxial tests on block samples, including anisotropy effects.

Correlations between parameters interpreted from CPTU and laboratory test results generally require good sample quality. In this project, the combination of sensitive clays and sampling beyond 20 meters depth made undisturbed sampling very challenging. This may explain why samples obtained by the ϕ54 mm piston sampler generally were somewhat disturbed. Most of the block samples showed excellent or satisfactory quality, and were thus in much better shape than the piston samples.

Experiences in this high risk project show that CPTU is a very good method to provide reliable soil parameters, particularly if local correlations between high quality laboratory tests and CPTU data can be made.

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