Undrained shear strength and compression properties of Swedish fine-grained sulphide soils

Propriétés de résistance au cisaillement non drainée et de compression des sols sulfatés à granulométrie fine en Suède

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ABSTRACT

In this paper recently finished and on-going research of strength and deformation properties of Swedish fine-grained sulphide soils is presented. In the paper, some selected test results from the finished project are presented and recommendations are given for determination and evaluation of undrained shear strength of sulphide soils. A short description of the characteristics of the particular type of sulphide soil is also given. The overall purpose of the recently started research project is to improve the possibilities to predict long term settlements of structures founded on sulphide soils.

RÉSUMÉ

Des recherches actuelles sur les propríétés de résistance et de déformation des sols sulfatés à granulométrie fine en Suède sont présentées dans ce papier. Aussi, quelques résultats d´essais sélectionnés d´un projet. Il y a aussi des recommandations sur la détermination et l´évaluation de la résistance au cisaillement non drainée des sols sulfatés. Une description courte des caractères distinctifs des sols sulfatés particuliers. L´objectif général de la recherche projet récemment démarré est d´amélioré la possibilité de prédire le tassement structure fondé sur le sol sulfaté.

Keywords : sulphide soils, fine-grained, organic, iron sulphide, undrained shear strength, compression, creep, settlements, geotechnical engineering

1 INTRODUCTION

Fine-grained sulphide soils are common along the north-eastern coast line of Sweden, a distance of about 900 km, Figure 1. Sulphide soils are in general very compressible, susceptible to creep deformations and show normally low undrained shear strength. Furthermore, a sulphide soil may cause negative environmental impact by acidation and chemical impact if it is subjected to oxygen at e.g. excavation or lowering of ground water table, Mácsik (1999). At foundation engineering works it is striven to, for environmental or/and economic reasons, to use the sulphide soil as foundation instead of excavating it. By sulphide soils is in this paper meant the unique type of sulphide soils found in the coastal areas around the Gulf of Bothnia in north-eastern Sweden, Figure 1.

Description and classification of geotechnical properties of sulphide soil has been problematic due to a lack of an established unified system for this. The evaluation methods developed for other Swedish fine-grained soils have in general shown poor relevance for sulphide soil, Westerberg and Mácsik (2003). The research previous conducted, concerning geotechnical properties, has been relatively limited.

In this paper some results are presented from a recently finished research project concerning geotechnical classification and undrained shear strength of sulphide soil (Larsson et al., 2007a). Furthermore, a recently started research project dealing with compression properties and settlement predictions in sulphide soil is presented.

2 CHARACTERISTICS OF SULPHIDE SOILS

The sulphide soils described in this paper, Figure 1, are not soils with uniform properties, but properties like grain size distribution, water content, and density varies as for other fine-grained soils with location and often with depth.

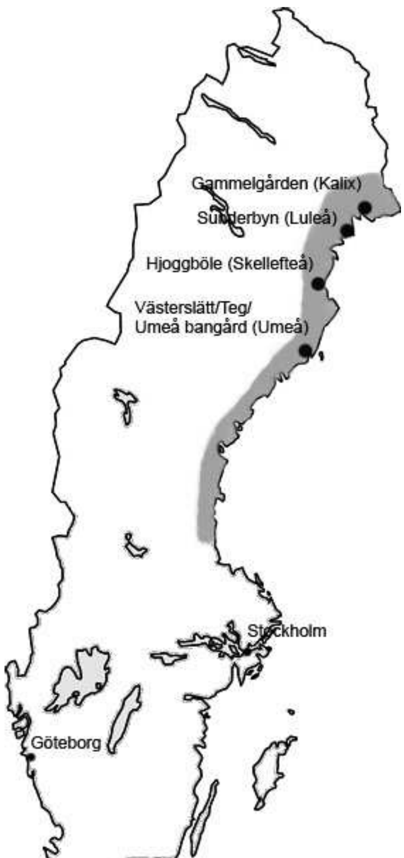

Figure 1. The approximate location of sulphide soils (shaded area) in north-eastern Sweden and the location of the test sites.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-72

However, typical ranges for properties are total sulphur content 0.1-2% of dry weight, total iron content 2-5% of dry weight, organic content 2-7% of dry weight, water content 50-80%, and bulk density 1.4-1.6 t/m^3. The undrained shear strength is typically 10-20 kPa, but can vary between 5 and 40 kPa. The fine-grained sulphide soil is typically an organic silt – organic silty clay, and is in cases with organic contents above 6% denoted as silty or clayey gyttja. Due to the varved structure of sulphide soils the values of different properties may vary (significantly) between centimeter thick layers, which should be considered when planning and conducting tests.

The sulphide soils are normally coloured black or varved with black bands and the black colour comes from the iron sulphide (FeS), Figure 2. The sulphide soils have a distinct odour of hydrogen sulphide (H_2S). If sulphide soil gets in contact with oxygen (air), it will gradually change colour from black to grey/brown, as a result of oxidation of iron sulphide (FeS) and pyrite (FeS_2) taking place, Figure 2. For sulphide soils the structure is often relatively porous and the voids between the mineral grains and clay particles are filled with pore water, organic material and iron sulphide (Pusch, 1973; Eriksson et al., 2000).

Deposits of sulphide soils may be found with depths over 20 m. They are typically normally consolidated or only slightly overconsolidated, and often there is artesian ground water pressure in the coarser layers beneath.

The sulphide soils at the Gulf of Bothnia, have been formed as sediments at river mouths and outside the coast in the special environment prevailing at the time for sedimentation, Mácsik (1994). The water in which the sulphide soil was sedimented was brackish/sweet and the environment was typically deficient in oxygen. The environment prevented a complete decomposition of the organic material in the sediments. Such environments exist also today and new sulphide soil sediments continue to be formed.

Sulphide soils of various types can be found in other parts of the world, e.g. in coastal regions of northern Finland, Japan, Australia and Vietnam. However, they normally differs significantly in composition and properties compared to the particular type found in north-eastern Sweden.

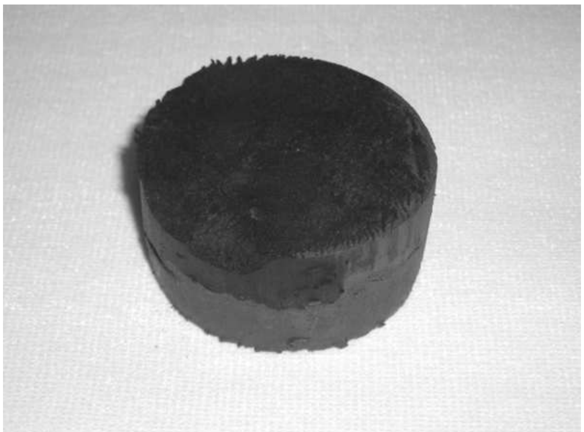

Figure 2. Sample of homogeneous black coloured sulphide soil which shows oxidation and belonging colour change at the shaft surface.

3 UNDRAINED SHEAR STRENGTH

3.1 *Test site Gammelgården*

In the now finished research project, Larsson et al. (2007a), the undrained shear strength was investigated at six different sites, Figure 1. The undrained shear strength was determined in situ by CPTs and field vane tests and in laboratory by direct simple shear tests, triaxial tests and fall-cone tests. The reference test for determination of undrained shear strength was the direct simple shear test. In figure 3, the undrained shear strength at Gammelgården is presented. The soil at this test site has a relatively high clay content (varies between 23 and 35% of dry weight) for a Swedish sulphide soil. In the figure is shown evaluation according to Swedish practice for inorganic clays correcting for the liquid limit (denoted clay eva; Larsson et al., 2007b), and the new proposed method for evaluation and correction for sulphide soil (denoted sulphide eva; Larsson et al. 2007a). For the test site at Gammelgården, the differences in undrained shear strength for the two evaluation methods are significant but numerically not very large. As expected, due to structural and stress anisotropy, significantly higher undrained shear strength is obtained in triaxial tests compared to direct simple shear tests. For the triaxial tests, the undrained shear strength was about 11% higher when tested at soil temperature compared to room temperature (not shown in Figure 3).

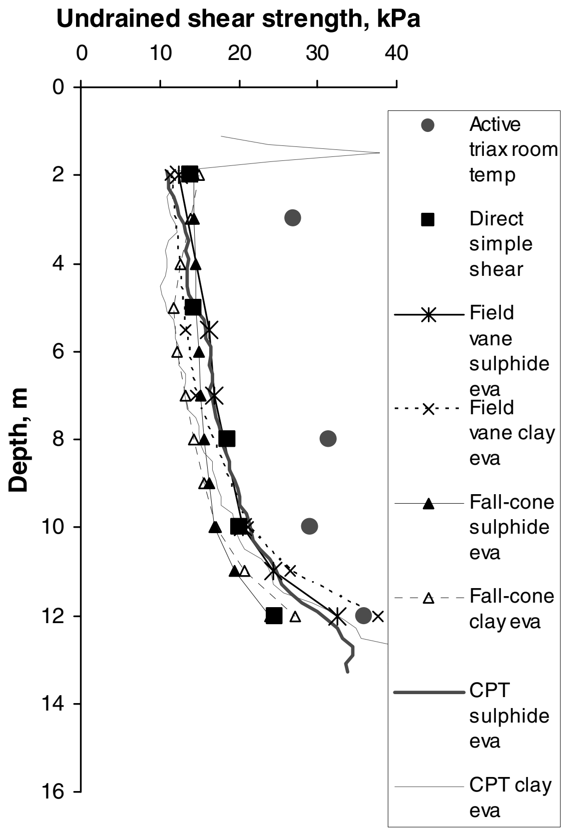

Figure 3. Undrained shear strength in Gammelgården evaluated by different test methods.

Figure 4 presents bulk density and water content from the soil profile in Gammelgården. The relatively low bulk density is related to the relatively high organic content (4,5-6% of dry weight). The liquid limit is slightly higher than the water content, and have maximum values around 180% and 160% at 5 m depth, decreasing with depth to about 85% and 75% respectively at 12 m depth. The organic content is slightly lower than the sum of the total content of iron and sulphur. The soil in Gammelgården is classified as organic sulphide clay / clayey sulphide gyttja.

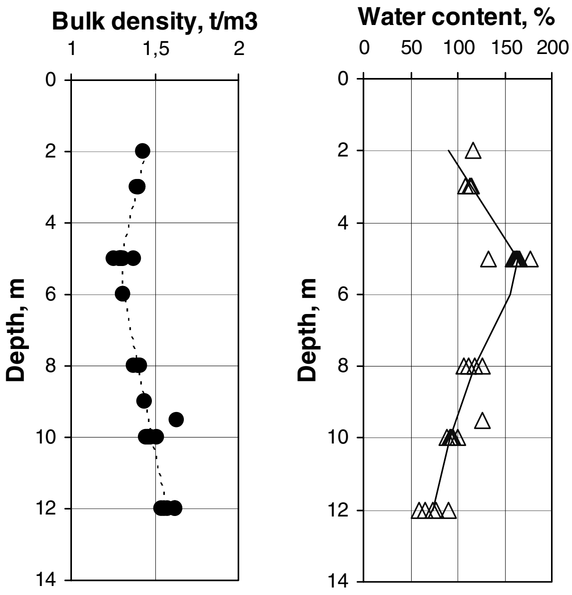

Figure 4. Bulk density and water content in Gammelgården, determined values and estimated variations with depth.

3.2 *Normalised undrained shear strength*

Results of normalised undrained shear strength from direct simple shear tests conducted on samples from the test sites investigated by Larsson et al. (2007a) is shown in Figure 5.

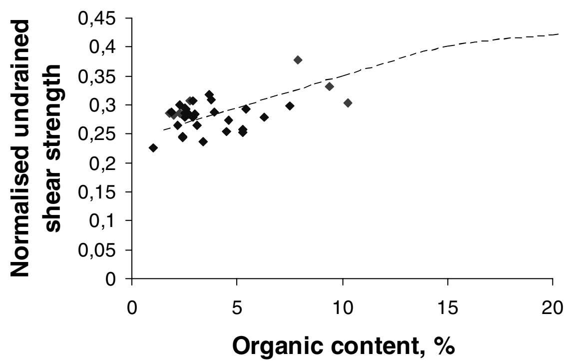

Figure 5. Normalised undrained shear strength, factor *a*, versus organic content for direct simple shear tests. The dotted line shows corresponding relation for organic clay-gyttja according to Larsson (1990).

In Figure 5 the factor *a* is presented as a function of organic content. The undrained shear strength is expressed as

$$c_u = a\sigma'_c OCR^{-0,2} \tag{1}$$

where c_u is the undrained shear strength, σ'_c is the preconsolidation pressure, and *OCR* is the overconsolidation ratio. The normalised undrained shear strength factor *a* shows a clear relation to the organic content (but no correlation with the liquid limit or the clay content). For sulphide soils the organic content seems, as for other organic soils or organic mineral soils, to largely govern the strength properties, Figure 5.

4 RESEARCH ON COMPRESSION PROPERTIES

4.1 *Background*

Today, there is insufficient knowledge and tools how to, with reasonable accuracy, predict settlements including long term settlements of sulphide soils. Experience has shown that the developed and measured settlements caused by a structure often deviate (significantly) from those predicted. Most often the measured settlements are larger, but sometimes they are smaller. Creep settlements of sulphide soils may go on for decades and long term settlements may be substantial and cause severe damages of structures like roads, rail roads and buildings. The large long term settlements are related to the relatively porous structure of sulphide soils, Eriksson (1992).

4.2 *Research project*

In a recently started (autumn 2008) research project compression properties, and in particular creep behaviour, of sulphide soils is studied. The overall purpose of the project is to improve the possibilities to predict long term settlements of structures founded on sulphide soils. The project includes laboratory investigations of compression (including creep) behaviour, field measurements of settlements and pore pressures caused by structures, and development of models for prediction of settlements. The research project will be conducted in conjunction with on-going and planned new constructions of rail roads and roads in north-eastern Sweden.

5 CONCLUSIONS

In this paper results of conducted research of undrained shear strength on fine-grained sulphide soils from the Gulf of Bothnia in north-eastern Sweden are presented.

To be classified as sulphide soil and be investigated and have the test results corrected according to the recommendations given in Larsson et al. (2007a), the soil shall be found along the coast line of the Gulf of Bothnia, contain visible amounts of iron sulphide and have an organic content of at least 1-2%.

For soils classified as sulphide soils the measured values from fall-cone tests and field vane tests should be corrected by a factor 0,65 according to

$$c_u = 0{,}65\tau_{k,v} \tag{2}$$

where c_u is undrained shear strength, and $\tau_{k,v}$ uncorrected strength value of fall-cone tests and field vane tests respectively. This means that the undrained shear strength should not, as for other fine-grained Swedish soils, be corrected for the liquid limit.

For soils classified as sulphide soils, the results from CPTs should be evaluated using a cone factor of 20 for determination of undrained shear strength according to

$$c_u = \frac{q_t - \sigma_{v0}}{20}\left(\frac{OCR}{1{,}3}\right)^{-0,2} \tag{3}$$

where q_t is total cone resistance, σ_{v0} total overburden pressure and *OCR* overconsolidation ratio.

If the undrained shear strength is critical, supplementary direct simple shear tests should be conducted. When the anisotropy of the undrained shear strength is important to consider, triaxial compression (and extension) tests should also be conducted. Empirical relations should always be used as supplements and for control of the reasonableness of the results obtained by the different test methods. In general, the CPTs gave more reliable test results of undrained shear strength as compared to the field vane tests and fall-cone tests. The spread of results, around the average correction value of 0,65 for field vane and fall-cone tests, was large.

For evaluation of undrained shear strength from CPTs, the highest possible accuracy class of equipment (i.e. the most sensitive probe) should be used. For field vane tests, pre-drilling of the dry crust is very important to avoid negative effects on the tests. It should be observed that, due to the varved structure of sulphide soils, the values of undrained shear strength may vary between centimetre thick layers when conducting fall-cone tests. Temperature and rate effects must be considered when conducting direct simple shear tests and triaxial tests and evaluating undrained shear strength from the test results.

In order to obtain "undisturbed" samples for testing of e.g. undrained shear strength in the laboratory, the sampling and handling procedure in the field must be conducted with great care and with suitable equipment. Due to the silt and organic content, sulphide soils are very sensitive for disturbance and sample handling.

ACKNOWLEDGEMENTS

The two research projects (one or both) were/are supported financially by Tyréns AB, Swedish Rescue Services Agency (Räddningsverket), The Swedish Road Administration (Vägverket), The Swedish Railway Administration (Banverket), The Development Fund of the Swedish Construction Industry (SBUF), Swedish Geotechnical Institute, and Luleå University of Technology.

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