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Characterisation of the human influence of near-shore soft clay layers in site investigations

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Abstract. Soft marine clay layers have been confined beneath thick gravel and rock fills as a result of extensive landfilling along the Stockholm coastline. These clays have been subjected to remoulding and subsequent reconsolidation under complex stress states involving both vertical loading and shear stresses induced by slope geometry. This paper presents a case study of such encapsulated near-shore clays based on CPT, CRS oedometer and CAU triaxial testing. The results show that interpreted overconsolidation ratios are frequently close to unity, while CPT- and fall cone-derived undrained shear strengths are lower than values obtained from consolidated triaxial testing. The findings indicate that standard empirical correlations developed for naturally deposited marine clays are not directly applicable to anthropogenically modified deposits, highlighting the need for adapted interpretation strategies in slope stability assessments.

1 Introduction

The understanding of the behaviour of natural clays is far advanced from the initial investigations exploring soil samples in the laboratory and the field ([1], [2] and [3]), to constitutive models including anisotropy and soil structure, [4] and [5]. Management of the risk of landslides in sensitive clays has consequently improved, as the scientific insight into the material has improved design practice [6], [7] and [8].

An essential part of geotechnical design for the soft and sensitive clays is the characterisation of the soil, including the description of the geological processes governing the stress history of the material. There are very helpful recommendations for the use in site investigations, e.g. [9], [10], [11]. However, the description of the clay structure and behaviour found in the scientific literature is mostly based on the detailed study of quite homogenous clay depositions, such as the deep clay valleys in along the coasts of Norway and Canada, [1], [6], [8].

Stockholm, the capital of Sweden, is located on a group of islands between the lake Mälaren and the Baltic Sea and has consequently been called the “Istanbul of the North”. The sedimentation of clays along the shoreline commenced at the end of the Weichselian ice age, and most parts of the shores were covered with soft clays when the city was founded around 1250. As the urban developed subsequently followed along the shores of the city a large part of the shores were covered by fill material, mostly gravel and sand. After dynamite was introduced in the 1860s by Alfred Nobel, large rock formations were excavated to create space for the growing city.In most cases, the remains of the rock were then placed in the water along the shores, especially as quay structures, and consequently the city expanded significantly in this period.

Many of the original clay formations were covered by rock and gravel during the period, and the original shoreline of the city current contains many areas with encapsulated clay layers. These layers have a strong impact on slope stability, and their extent and properties must be carefully considered in slope stability assessments, especially for near-shore slopes and rock-filled quays [12].

Such encapsulated layers of compressed clay are not only present in thinner seams in the soil strata, which is well known phenomena from site investigations, e.g. [13] and [14]. There are frequently quite massive layers of clay encapsulated within the soil strata which has a depth of several meters and can extend along the length of the shoreline.

Fig 1 illustrates the interface between the encapsulated clay layer and the overlying gravel and rock layer at 22 to 23 m depth. The samples were obtained during a site investigation campaign in the centre of Stockholm. The samples in Fig 1 were retrieved using a custom-made piston sampler capable of penetrating the gravel layers. Due to frequent boulders in the fill, the transition between fill and clay is normally difficult to observe in detail.

Compared to naturally sedimented clays, the encapsulated clay has a more complex stress history, including remoulding during fill placement and subsequent reconsolidation under high vertical and shear stresses, especially in slopes.

In near-shore slope stability assessments, deep encapsulated clay layers often reduce stability. Characterising their strength is challenging, both in site

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investigations and in the interpretation of in-situ and laboratory tests. This paper presents a case study from a typical near-shore slope in the Stockholm region to illustrate these challenges.

Fig. 1. The interface between the encapsulated clay layer and the gravel fill layer in sample.

2 Encapsulated clay – case study

A site investigation including characterisation of the encapsulated clay layer was carried out in the municipality of Nacka close to Stockholm, shown in Fig 2.

The area originally consisted of a peninsula and an island. In the 1870s area was developed into an industrial site due to the proximity to Stockholm. Large amounts of rock fill were deposited in the bay during the construction of a phosphate factory. Waste products from the factory, mainly consisting of pyrite cinder, were also deposited in the bay. This resulted in massive fill layers consisting of gravel, rocks and boulders as well as finer grained, highly contaminated materials with a low relative density. The peninsula and island were connected by a bridge in the 1920s, and eventually the strait between them was filled making the island Hästholmen a part of the peninsula.

During the second half of the 20th century the factory was demolished and eventually replaced by an oil terminal. During the last twenty years the area has been converted into a storage area for construction materials, whilst also being investigated as a potential site for residential development by the municipality.

Fig 3 shows the area today, where large piles of gravel and rock from nearby residential development are temporarily stored along the shoreline.

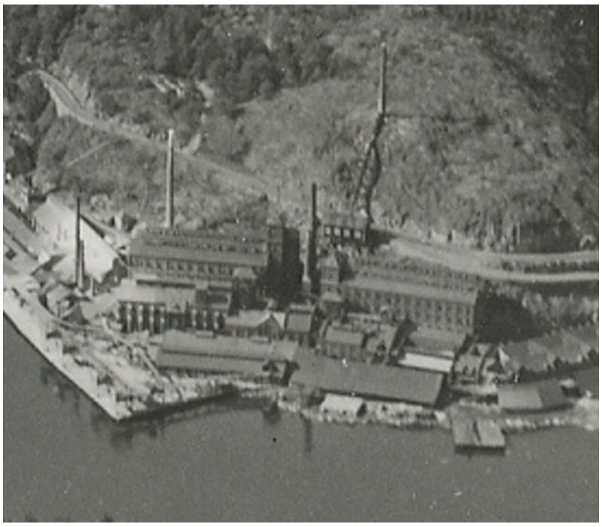

Fig. 2. The phosphate factory on the peninsula, historical photography from the beginning of the 20th century.

Fig. 3. Large piles of rock and gravel are stored in the area today.

3 Site investigations

An extensive site investigation was carried out as part of the development of the area. A succession of site investigation campaigns covered the inland and the shores, with a large number of tests carried out nearshore (shown in Fig 4).

The site investigation included soil-rock drilling to determine the soil stratigraphy, disturbed and undisturbed soil sampling, and in-situ tests including cone penetrations tests (CPT). In areas with encapsulated clay, steel casings were pre-drilled through the fill to the clay layer, after which piston sampling and CPT were carried out in the clay. The pre-drilling with the casings extended from 5 m to around 20 m at some locations. The execution of the pre-drilling and the subsequent soil sampling could last one full day.

Fig. 4. Site investigations along the shore from a barge.

4 Slope stability considerations

A large number of geological cross-sections along the shore were documented based on the interpretation of the soil strata along the shore. In most of the these, the encapsulated clay layer was estimated to around 2 to 6 m. Fig 5 shows a typical cross-section including the interpretation of the soil stratification, which is generally dominated by the landfill. In many cases the clay layer extents into the subsea slope further into the bay as part of the original clay sedimentation in the area. The geological processes and the landfill activity have therefore resulted in wide continuous layers of the encapsulated clay in the soil.

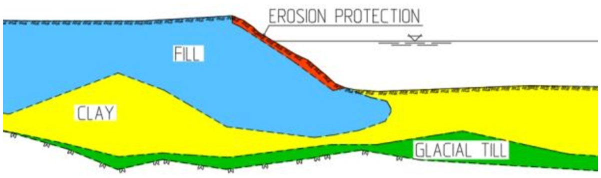

Fig. 5. A cross-section of a slope along the shore, with the gravel and rock fill in blue, erosion protection in red, the encapsulated clay layer in yellow and the glacial till in green, displaying a typical soil stratigraphy along the shore.

Slope stability analyses frequently resulted in slip surfaces extending through the fill into the clay layer, resulting in relatively low calculated factors of safety. Interpretation of the extent and properties of the encapsulated clay layer was therefore critical.

Due to the large number of tests which were carried out in the area, this paper concentrates on some of the tests to elaborate on the interpretation of the soil properties and to display some of the interesting features of the encapsulated clay layer.

5 Soil properties

To illustrate some interesting features of the encapsulated clay, a detailed examination of some of the samples is included. Fig 6 shows an overview of the peninsula, with the area of special interest displayed in a circle. In this area 3 samples are examined, A, B and C. The soil strata at these locations are shown in Table 1. Sample 1 and 2 are obtained in almost the same location with the same soil strata, and sample C somewhat further south.

The data in Table 1 shows the wide differences between the nearby samples, in which sample 1 and 2 has around 14 m overburden pressure from the rock and the gravel fill, and sample C less. The particular soil stratification is probably the result of the large displacement of the original sediment during the construction of the quay in the 19th century. During this process, the clay in some parts along the shore were encapsulate in thinner layers as the surcharge pressed the soil towards the bay, while on some other locations along the shoreline the interpreted depth of the encapsulated clay layer and the glacial till layer is larger.

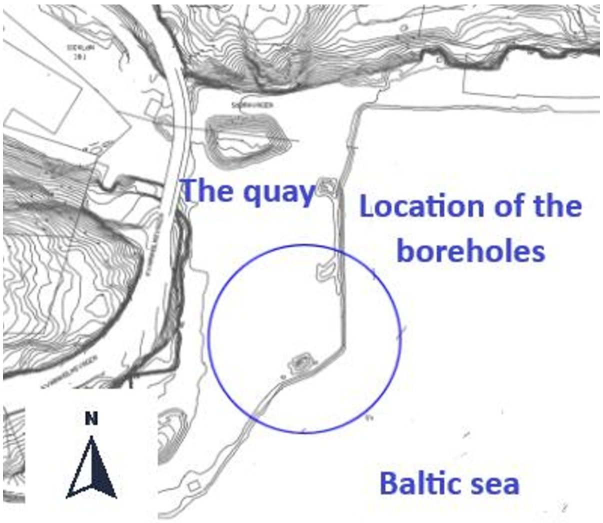

Fig. 6. The location where samples A, B and C were retrieved.

Index properties of sample A/B and C are shown in Table 2, showing a quite compact clay layer with quite low sensitivity. In sample C, the top layer has been influenced by the mixing of pyrite cinder (a by-product from the industrial process), which probably has reduced the interpreted sensitivity of the sample due to the change in water content. Considering the properties of the samples retrieved further from the shore, the density is lower (from 1,5-1,7 t/m3 compared to 1,8-1,9 t/m3 from the samples onshore), and the clay has likely experienced significant compression.

Some of the retrieved clay samples can be examined in detail to illustrate some of the features of the remoulded and subsequently reconsolidated encapsulated clay layers. Fig 7 shows a cross-section of sample A at 16 m depth. This soil layer has a 14 m surcharge load from the landfill material. The sample has embedded layers of silt and sand, and an inclination of the layers of the soil, probably resulting from deformations in the clay during the construction of the landfill.

Table 1. Soil strata at sample A, B and C.

Soil layer	Sample A, B	Sample C
Gravel/rock fill	14 m	6 m
Encapsulated clay	3 m	7 m
Glacial till	2-3 m	4 m
Bedrock	-	-

Table 2. Index properties for the encapsulated clay in sample A, B and C.

Soil layer	Symbol	A	B	C
Density	ρ (t/m^3)	1,8-1,9	1,7	1,5-1,8
Natural water content	w_n (%)	35-39	52	45-89
Liquid limit	w_L (%)	38-47	-	50-125
Senstivity	S_t (%)	11-15	-	4-17

Fig 8 and 9 show sample B from a location near sample A, at 15 m depth. Fig 8 shows the sample after it was pressed out from the sampler tube in the laboratory, displaying large inhomogeneities and cavities in the sample. Fig 9 shows in the cross-section of the sample, showing large inhomogeneities as well in the sample.

Fig 10 shows a cross-section of sample C at 12,5 m depth. This sample shows clear stratification but less inclination of the layers.

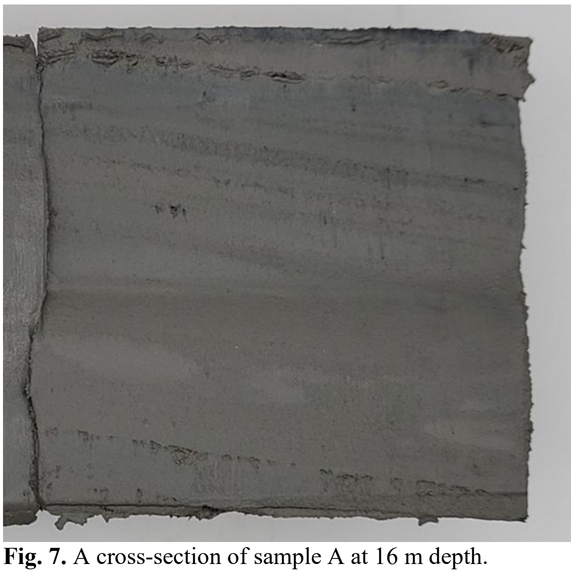

Fig. 7. A cross-section of sample A at 16 m depth.

Fig. 8. Sample B at 15 m depth after exposure of the clay from the sampler tube.

Fig. 9. A cross-section of sample B at 15 m depth.

Fig. 10. A cross-section of sample C at 12,5 m depth.

6 In-situ tests

Cone penetrations tests were carried out in the encapsulated clay layer after pre-drilling through the landfill material with a steel casing. Standard bearing capacity factors were utilized to assess the strength parameters of the clay. However, especially the development of the pore pressures during the cone penetration can be used to assess the homogeneity of the clay layers.

Fig 11 shows the pore pressure (u_2) of the CPT, the hydrostatic ground water pressures, and the excess pore pressure in sample A. Fig 12 displays the same parameters in sample B, which is located in the same area as sample A. The pore pressure development in Sample A between 14 and 18 m depth consists of a fast increase as CPT enters the clay layer, and subsequently holds a steady level throughout the layer, with some normal fluctuations.

Fig 12 shows a quite different response for Sample B: After an initial quick response in the encapsulated clay level in which the excess pore water pressure is comparable to Sample A, the pore pressure is reduced and approaches the hydrostatic groundwater pressure at the end of the clay layer. This shows the response of the CPT as a result of the inhomogeneity of the clay layer in sample B, which was shown in Fig 9.

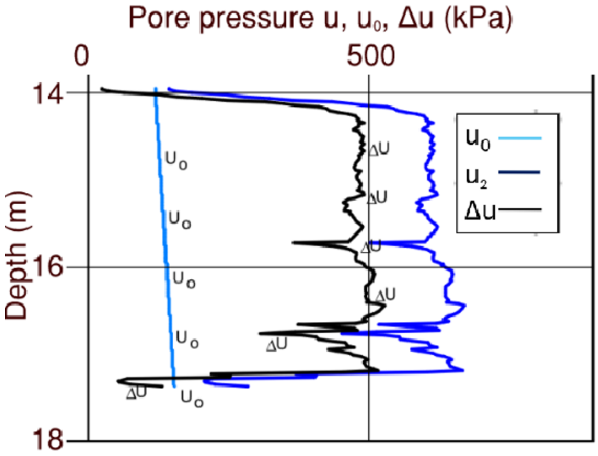

Fig. 11. Pore-water pressure reading in CPT, Sample A.

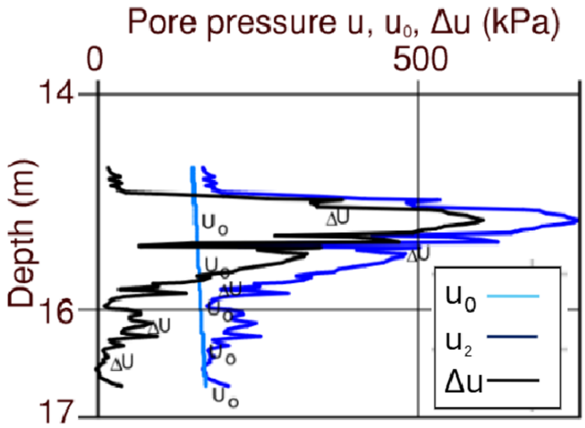

Fig. 12. Pore-water pressure reading in CPT, Sample B.

7 Laboratory tests

Constant rate of strain (CRS) oedometer tests were carried out on the samples retrieved from Sample A and C. Because of the inhomogeneity of Sample B, no tests were executed on these. For Sample A, CRS-tests were conducted on the samples from 15 m depth and 16 m depth. These are shown in Fig 13, with the dashed line showing the development of the constrained modulus of the soil. The samples are quite similar with little difference in the evaluated pre-consolidation pressures. An unloading-reloading loop was carried out which showed a similar response.

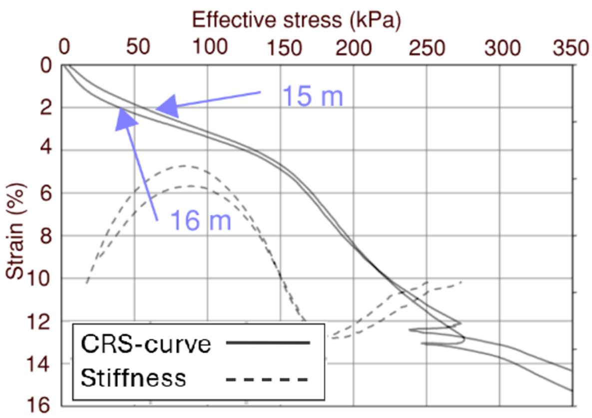

Fig. 13. CRS-tests on sample A, samples from 15 m and 16 m depth.

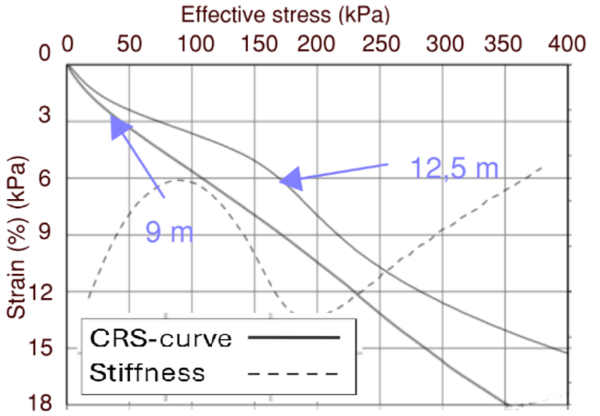

Fig. 14. CRS-tests on sample C, samples from 9 m and 12,5 m depth.

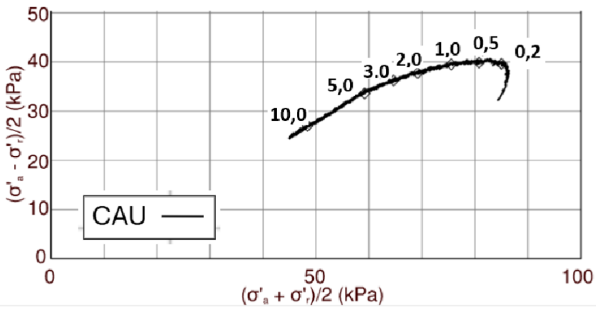

Fig. 15. CAU triaxial test on sample A, 15 m depth, s'-t diagram, with strain levels shown.

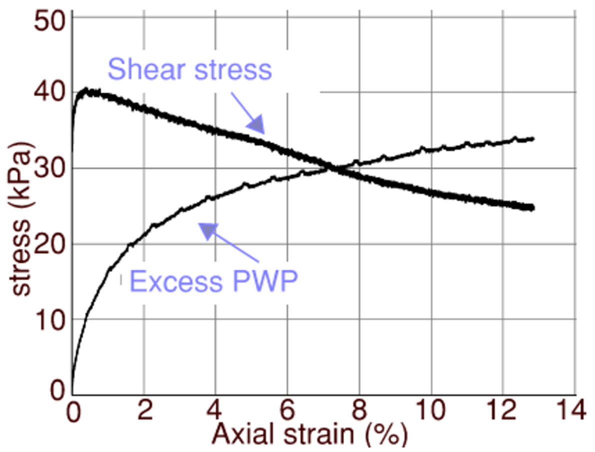

Fig. 16. CAU triaxial test on sample A, 15 m depth showing the development of shear stress and the excess pore-water pressure.

Fig 14 shows the CRS-tests on samples from 9 m depth and 12,5 m depth. The 9 m sample shows hardly any structuration, while the sample from 12,5 m depth shows a more pronounced preconsolidation pressure.

However, the interpretation of preconsolidation pressure should be treated with caution due to sample heterogeneity and possible disturbance during retrieval.

A CAU (consolidated-anisotropic-undrained) triaxial tests was possible to execute on sample A and is shown in Fig 15 in the s'-t stress space, and Fig 16 for the development of the shear stress and excess pore water pressure. The sample was inspected after the tests, and while it contained several sand layers, the compression during consolidation was comparable to standard clay samples. The development of the stress-strain behaviour and the excess pore water pressure during the test, shown in Fig 16, was similar to other normally consolidated or lightly consolidated clays.

8 Soil parameter interpretation

The samples A, B and C have been examined in some detail to illustrate the heterogeneity of the encapsulated clay layer. In the slope stability assessment, the in-situ and laboratory information is collected to provide a design soil profile. Some of this data is now considered for the encapsulated soil layer.

Fig 17 shows the preconsolidation stress at different depths in the soil layer, with the vertical effective stress. The pyrite cinder content in the fill material can also increase the density of the material, hence the estimate of the density of the fill to 2,0 t/m^3 can in some locations be considered low. The diagram shows that the overconsolidation ratio in most of the soil profile is less than unity, hence the soil is at least normally consolidated. It should be noted that the sand layers in the samples which were observed in the photographs can influence the structure of the soil by de-structuration and compression during the retrieved of the samples, hence the low overconsolidation ratios should be regarded with some scepticism.

Fig 18 shows the even greater challenge: the determination of the undrained shear strength of the encapsulated clay layer. The Fig 18 shows the collected measurements of the undrained shear strengths in the area from Fig 6, containing CPT-tests (with bearing capacity factors following [15]), fall cone (FC) tests of the retrieved samples and the triaxial test. The grey lines in the Fig 18 shows the 10 % upper and lower bands of the empirical determination of the undrained shear strength for OCR = 1, in which the undrained is calculated according to Equation 1, [15]. Hence, the evaluated undrained shear strengths of the samples are mostly lower than the empirical value for OCR = 1.

$$c_u^{DS} = (0.125 + 0.205\left(\frac{w_L}{1.17}\right)) \cdot \sigma_v' \quad (1)$$

The triaxial test which was carried out on sample A is exhibited in Fig 18 and is significantly higher than most of the other tests, including the evaluated undrained shear strength from the CPTs.

Fig 18 displays the undrained shear strength of the clay interpretated through standard correlations for the soil strength for fall cone and CPT-tests. These correlations were estimated from natural soil deposits, and consequence should be used with caution for the embedded clay layers in the current study.

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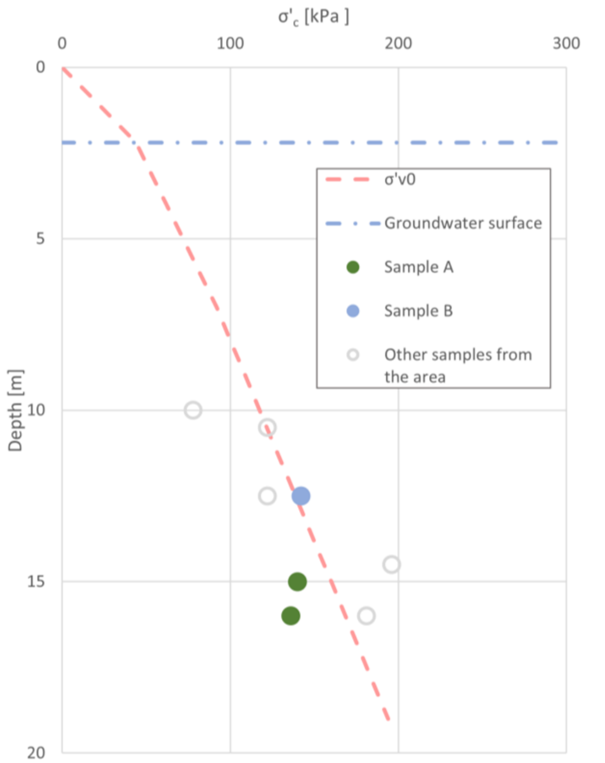

Fig. 17. The preconsolidation pressure from CRS-tests (dots) and the vertical effective stress.

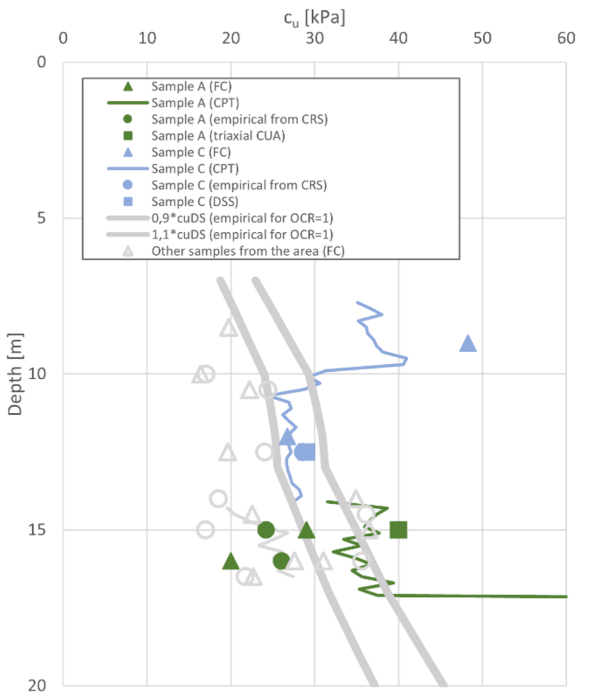

Fig. 18. Measurements of undrained shear and empirical correlations for OCR = 1 in grey with 10 % bands.

9 Discussion

Some of the features of typical samples of encapsulated clay layers in nearshore areas in Sweden were illuminated in this case study, in which in-situ and laboratory tests were included. The characterisation of the strength and deformation properties of this soil in practical engineering has been shown to be cumbersome as result of the difference in the geological history compared to natural soils on which most scientific knowledge is based. The stress history and consolidation of the encapsulated clay since the material was sedimented, remoulded and reconsolidated is complicated, making the standard empirical relations which are normally used in the field not directly reliable for these types of materials.

These stress history and the mineral content of the encapsulated clay layers also is also not uniform. These factors will probably have significant influence on the mechanical properties of the clay, and hsould be takten into account in practical design.

There are also practical challenges in the characterisation of the material in the field and in the laboratory. The pre-drilling to great depths and retrieval of the samples is very time-consuming. The presence of sand and silt layers made laboratory testing difficult for many samples and complicated the determination of design parameters. The retrieval of the samples from great depth probably influences the samples and causes de-structuration of the clay as a result of swelling of the samples after retrieval.

The evaluation of the overconsolidation ratio and undrained shear strength displayed low OCR and low undrained shear strength in comparison to standard empirical correlations. However, the results from the triaxial CAU test which was possible to execute on sample A showed higher shear strength and displayed an expected development of the excess pore water pressure in the sample. The geological reconstruction of the clay which was carried out for the triaxial test probably has a large influence on the type of samples with sand and silt bands, in comparison to more homogeneous samples where the standard correlations are obtained.

The reliability of empirical correlations of strength and stiffness parameters for the encapsulated clay layers can also be questioned. Both the mineral content as well as the stress history of the encapsulated clays are in many cases significantly different from the natural clay layers from where the empirical correlations are obtained. The silt layers in the clay could have an especially large influence on the in-situ tests.

However, in practice the limited information from the site investigations needs to be used in design. The detailed examination of the geological and the historical background of the area from historical records can provides a deeper understanding of the encapsulated clay in the interpretation of the site investigation. For the site characterisation of similar locations, it is recommended to initially obtain a suitable comprehension of the geological history and the soil stratigraphy, and that laboratory tests are carried out on carefully obtained samples for the field. This preferably includes consolidated triaxial tests, since the consolidation has a large influence on the structure of these particular samples. The laboratory tests should also be supported by in-situ tests in the encapsulated clay layer during interpretation of the soil parameters.

10 Conclusions

Encapsulated near-shore clay layers beneath historical landfill deposits exhibit mechanical behaviour that differs from naturally sedimented marine clays. The study shows that apparent OCR values near unity may not fully reflect in-situ stress history, and CPT-derived shear strengths may be significantly lower than strengths obtained from consolidated triaxial testing. Soil heterogeneity significantly influences both in-situ and laboratory interpretation, hence standard empirical correlations may not be directly applicable.

For slope stability assessments in similar environments, it is recommended to first make careful geological reconstruction and then interpret the in-situ and laboratory results together, while also critically evaluating the chosen soil parameters. Due to the large variability of the soil in the area, soil parameters for practical design should be determined for a specific area in which sufficient information is available. The challenge of the site investigation is to determine the necessary extent of field and laboratory tests in the specific site investigation campaign.

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