Degradation of clay due to cyclic loadings and deformations

La dégradation de l'argile due à des chargements et des déformations cycliques

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ABSTRACT: Cyclic loading and large deformations may significantly reduce the undrained shear strength of clay. The stability of constructions and clay slopes can be significantly affected if subjected to disturbances from large local loads and different kinds of construction works such as piling, blasting, etc. The risk for widespread failures may be particularly high when quick clay is present in the area. At the Swedish Geotechnical Institute, a study has been performed on the susceptibility to disturbance from cyclic stresses and strains of different clays. The influence of different factors on the strength degradation has been examined in series of laboratory tests on different types of sensitive clays. The laboratory tests on the soils have included basic characterisation tests, CRS oedometer tests and active static and cyclic triaxial tests. The triaxial tests have been performed at various overconsolidation ratios with varying cyclic shear stress levels and deformation levels. In the field, trials with cyclic T-bar tests in situ have also been performed. The results of the study have given an increased insight into the effect of cyclic stresses and deformations on the degradation of different types of clay.

RÉSUMÉ : Le chargement et les déformations cycliques peuvent réduire de manière significative la résistance non drainée au cisaillement de l'argile. La stabilité des constructions et des pentes d'argile peut être considérablement affectée si elles sont soumis à des perturbations causées par de grandes charges locales et différents types de travaux de construction tels que l'enfoncement de pieux, le dynamitage, etc. Le risque de rupture généralisée peut être particulièrement élevé lorsque l'argile sensible est présente dans la région. Une étude a été réalisée à l'institut suédois de géotechnique, SGI, sur la sensibilité de différentes argiles sensibles aux perturbations par des contraintes cycliques. L'influence de différents facteurs sur la dégradation de la résistance a été étudiée dans une série de tests en laboratoire. Les tests de laboratoire ont inclus entre autres des essais oedométriques CRS et des essais triaxiaux actifs statiques et cycliques réalisés à différents rapports de surconsolidation avec différents niveaux de contrainte de cisaillement cyclique et différents niveaux de déformation. Sur le terrain, des essais « T-bar » cycliques ont également été réalisés. Les résultats de l'étude ont accru notre connaissance de l'effet des contraintes et des déformations cycliques sur la dégradation de différents types d'argile.

KEYWORDS: cyclic loading, sensitive clay, shear strength,

1 INTRODUCTION

Failures in soft clay sometimes occur in connection to construction work. Occasionally, these and other local failures also develop into large scale landslides. The parameter commonly used for estimation of risks in connection with construction work and local failures is the sensitivity of the soil and quick clay areas are considered as special risks. However, the sensitivity alone does not describe how much disturbance is required to break down the soil structure and strength. Available charts and methods to estimate risks in this aspect are normally connected to earthquakes and do not include highly sensitive clays. Other parameters to describe this property in clays and methods to measure it has therefore been sought for a long time, (e.g. Söderblom 1969, Larsson and Jansson 1982, Tavenas et al. 1983). However, no generally established methods and rules have been brought forward.

An investigation has recently been performed at the Swedish Geotechnical Institute (SGI) with the aim of finding guidelines for which types of sensitive clay in Sweden can have their strengths easily broken down and thereby constitute special risks (Åhnberg and Larsson 2012). This paper presents some of the results in this project.

2 SCOPE OF THE INVESTIGATIONS

2.1 *Types of soil tested*

Twelve different test sites were involved in the investigations. Four of these are located in the eastern part of Sweden - two in the Stockholm-Mälardalen area and two in the Linköping-Norrköping area. The clays here have been deposited in alternating lake and brackish sea water. The other sites are located in the western part of Sweden, five along the Göta river valley and three further to the northwest in the middle part of the Bohuslän province. The clays at these sites are marine clays deposited in sea water. The environment with salt seawater at deposition generally resulted in heavy flocculation of the clay particles and a more open structure compared to the clays deposited in brackish water in eastern Sweden. Leaching of the salt and possibly other processes have later led to various degrees of increased sensitivities, (e.g. Rankka et al. 2004). The sites were chosen to cover clays with different conditions at deposition, with low, medium and high plasticity and with sensitivities varying from medium to quick clays. The investigations have been made on clays with the typical environments at deposition, mineral compositions and types of organic matter in this region. A special emphasis has also been made on highly sensitive and quick clays which are common and constitute special problems here.

Sampling of clay was performed at one to three different sampling levels at each test site. In all, twenty-two different types of clay were investigated in the study. The different soils are listed together with their base characteristics in Table 1.

2.2 *Investigation methods*

The investigations required large uniform samples with preserved properties also in the "elastic" small strain region. The size of the samples should allow taking out a fairly large number of "identical" test specimens.

Sampling of the clay was performed with a new sampler constructed at SGI in 2009 with the aim of obtaining large high quality samples in all types of mainly soft to medium strength fine-grained soil (Larsson et al. 2012). The sampling tube is about 1 m long with an inner diameter of 200 mm. The samples are cut into six parts, before being sealed and carefully transported to the laboratory. In the laboratory, test specimens of a diameter of 50 mm were trimmed from the part samples.

Table 1. Properties of the clays used in the investigations.

Test site	Depth *(m)*	ρ *(Mg/m³)*	w_P *(%)*	w_L 1) *(%)*	w_N *(%)*	S_t	$c_{u\text{-}rem}$ 1) *(kPa)*	Org. cont. *(%)*
Mellösa	5	1.45	35	94	101	10	1.02	3.4
	8.5	1.54	25	87	86	10	1.58	1.3
Strängnäs	6	1.55	22	55	71	49	0.20	0.8
Norrköping	5	1.54	24	73	82	19	0.81	0.8
Linköping	5	1.6	24	71	73	16	1.25	1.0
Gläborg	4.5	1.58	25	50	79	185	0.08	1.3
	6	1.6	25	46	75	180	0.10	1.0
	10	1.69	23	42	62	190	0.11	0.8
Munkedal	5	1.83	21	39	42	28	0.86	1.8
	10	1.69	25	45	61	253	0.12	1.0
Fultaga	6.5	1.63	28	64	81	94	0.21	1.1
	10	1.66	24	53	63	95	0.37	0.9
Onsjö	3.6	1.68	22	56	59	25	0.96	0.6
	7	1.59	27	57	71	219	0.14	0.8
Torpa	3.5	1.60	27	58	70	41	0.50	1.2
	5.5	1.54	27	71	79	42	0.48	1.0
	8	1.57	29	76	79	26	0.93	1.0
Fråstad	6.5	1.60	28	65	71	49	0.47	1.2
Äsperöd	2.7	1.69	24	54	54	15	1.60	1.9
	7	1.59	26	57	74	100	0.27	1.6
Kattleberg	4.5	1.46	26	69	108	151	0.08	0.8
	8	1.59	25	55	81	224	0.07	1.3

1) Determined by the fall cone method

Control of the homogeneity showed no significant differences across the diameter or along the length of the samples. Evaluation of the specimen quality (or disturbance) in accordance with the method proposed by Lunne et al. (1997), where the change in void ratio, Δe, during reconsolidation to in-situ stresses in the triaxial cell or in the oedometer is compared to the initial void ratio, e_0, showed that the specimens generally met the criteria of "very good to excellent quality". For each test site and sampling level, comparative CRS-oedometer tests and static active triaxial tests were performed on samples taken with the Swedish standard piston sampler (St II) for control and comparison of the sample quality. For most part also the latter samples met the criteria of very good to excellent quality showing that the Swedish standard piston sampler in normal cases is adequate for routine sampling of soft clays (Larsson et al., 2012). The main testing programme was performed on samples taken with the new large diameter sampler.

CPTs and static and cyclic full-flow penetration tests with a T-bar penetrometer were carried out at each test site. The CPTs were performed according to the European standard (ISO 2012) with higher demands for accuracy corresponding to the recommendations by the Swedish Geotechnical Society for soft clays (SGF 1993). The T-bar tests were performed using equipment with recommended dimensions and according to recommended practice (DeJong et al. 2010). Cyclic T-bar tests were performed at all levels where sampling had been performed and the cycling was made over the same 1 m depth interval. The static phase of the T-bar tests was normally continued one or a few metres below the deepest cycling level

The laboratory testing involved classification tests of basic geotechnical properties, CRS-oedometer tests and active static and cyclic triaxial tests. The classification tests comprised the normal Swedish routine tests of bulk density, natural water content, liquid limit and undrained and remoulded shear strength, the last three determinations being made with the Swedish fall cone test (ISO 2004). They also comprised additional tests of plasticity limit, organic content through analyses of organic carbon, clay content through sedimentation tests, pH in the soils by use of electrodes and resistivity by use of a so-called Soil-box (Camitz 1980).

The triaxial tests were performed on specimens that were first anisotropically consolidated for about 80% of the estimated preconsolidation stresses in both vertical and horizontal directions, giving an overconsolidation ratio of 1.3. An overconsolidation ratio of about 1.3 or slightly lower is typical for soft clays in Sweden. In tests with higher overconsolidation ratios, the specimens were then unloaded to the estimated stress conditions after a corresponding unloading. The consolidation process was usually completed within 24 hours. The static undrained active tests were then performed at a rate of compression of 0,01 mm/min (approximately 0,6%/h), which is the normal testing rate in undrained tests on clay used at SGI.

Cyclic triaxial tests were performed with both stress-controlled and strain-controlled cyclic loading. The stress-controlled cyclic tests were performed as undrained compression triaxial tests with an initial static shear stress state corresponding to a factor of safety of 1.3, and an additional cyclic stress oscillating around this initial stress state. The tests were performed with different sizes of the cyclic stress components. The specimens for the strain-controlled cyclic tests were consolidated in the same way as those for the stress controlled tests and started at the same initial static shear stress conditions. The strain-controlled cyclic tests were performed with two levels of strain; up to the failure strain at static loading and up to two times this strain.

The cyclic loading was for most part performed with a frequency of 1Hz, but some tests were also performed at slower rates (lower frequencies) to study the influence of frequency.

3 RESULTS

T-bar testing was tried out with the main purpose of testing the rate of shear strength degradation during cyclic tests. The results have led to new interpretation methods for Swedish clays similar to those used for CPT-tests. New correlations for interpretation of remoulded shear strength and sensitivity have also been brought forward. However, the measuring accuracy of the equipment was found to be insufficient for accurate determinations in the soft sensitive Swedish clays where the remoulded shear strength often is very low (Åhnberg and Larsson 2012).

The laboratory investigations together with tests in the field directly after the samples had been taken showed that the parameters liquid limit, remoulded shear strength and sensitivity change with time of storage in the laboratory. This is in agreement with earlier experience (e.g. Larsson 2011). Since only a small increase in the remoulded shear strength has a large effect on the sensitivity in quick clays, it is important that these properties be determined as soon as possible. However, further control tests showed that a storage time of up to three months had little influence on other properties or the behaviour during static and cyclic strength and deformation testing.

The classification tests in the laboratory largely verified earlier established correlations between properties found for

Swedish clays and similar soils. In Swedish practice, the plastic limit of the soil is seldom determined and empirical relations are usually linked to the liquid limit instead of plasticity index. Correspondingly, the liquidity index of the soil is usually replaced by a quasi liquidity index w_N/w_L. For the Swedish soils in this investigation, which all had water contents higher or equal to the liquid limit, a relation between the indices of

$$I_L = 2\,{}^{w_N}/_{w_L} - 1 \qquad (1)$$

showed a high correlation, Fig.1.

The remoulded shear strength was found to be directly related to the liquidity indicies. The sensitivity is the relation between undrained and remoulded shear strength and for a good correlation with a liquidity index, the value of the undrained shear strength should also be considered.

The triaxial tests showed that cyclic loads or imposed deformations that do not cause strains larger than the failure strains at static loading do not cause any significant reduction in undrained shear strength, Fig. 2. This is in agreement with earlier observations by e.g. Andersen (2009). The failure strain at static loading, and thereby the “safe” limit, is related to the soil plasticity and the organic content and increases with these parameters.

Rate effects entail that a limited number of cyclic loads can bring shear stresses higher than the static failure load without leading to failure. The size of the rate effects depends on the frequency (or duration) of the cyclic load and the soil properties. The frequency of wave and wind-loads is normally assumed to be about 0.1 Hz, which brings fairly long durations of the loads and moderate rate effects. Traffic and other cyclic

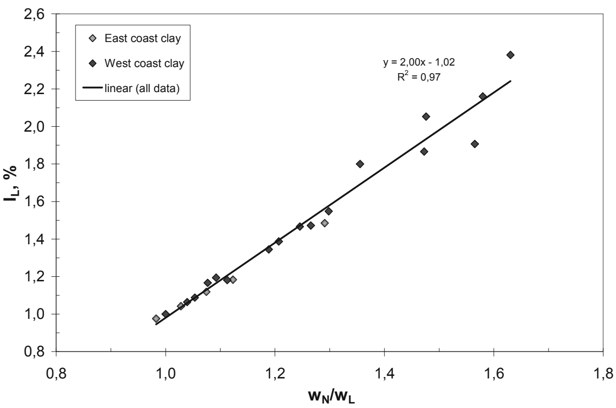

Figure 1. Correlation between liquidity index and quasi liquidity index.

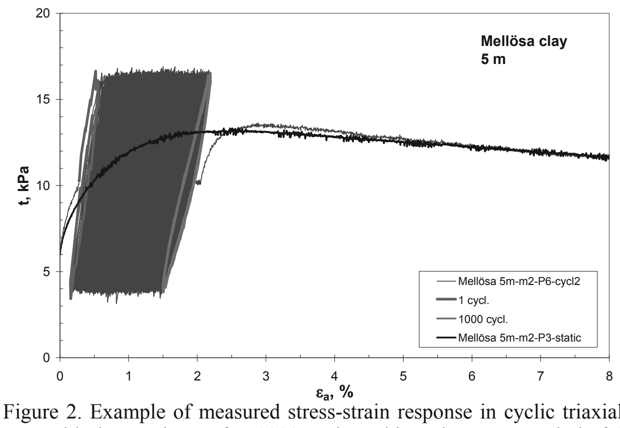

Figure 2. Example of measured stress-strain response in cyclic triaxial tests with the specimen after 1000 cycles subjected to a rest period of 1 hour followed by static shearing as compared to that measured in an ordinary static test.

construction loads are normally assumed to have frequencies of about 1 Hz, which gives higher rate effects, and blasting normally gives vibrations with even higher frequencies, Fig.3. The size of the rate effects is also influenced by the same parameters that affect creep rates, which are linked to the void ratio of the soil, (e.g. Larsson 1986). The rate effects thus increase with increasing void ratio. Since the void ratio in soft clays is more or less linked to the liquid limit, this generally means that the rate effects increase with increasing plasticity, but the relation is complex and depends on more factors.

At continued stress-controlled cyclic loading after passing the static failure strain, the build- up of strains and pore pressure accelerates and failure occurs after roughly about twice the static failure strain. There is a certain scatter in the results, but the real failure strain and the margin between passing the static failure strain and actual failure at cyclic loading generally increase with mainly plasticity and organic content.

The cyclic stress level leading to failure at a certain number of load cycles and the number of cycles leading to failure at a certain cyclic stress level both increased with decreasing sensitivity and increasing organic content. For a given clay, the relation between cyclic stress level and log number of cycles to failure is fairly linear, Fig. 4.

The strain-controlled tests showed that both the total decrease in maximum shear stress in the cycles passing the static failure strain, Figure 5, and the rate for this degradation, Figure 6, generally increased with sensitivity and the corresponding liquidity indices. Both types of tests also showed that clays with embedded loose silt layers can rapidly lose their strength. The same can be assumed for clays with embedded loose sand layers. The tests showed that both static and cyclic strains are larger in organic soils, but on the other hand they can withstand cyclic loads and large deformations better than clays. This is in agreement with earlier findings by e.g Vucetic (1994).

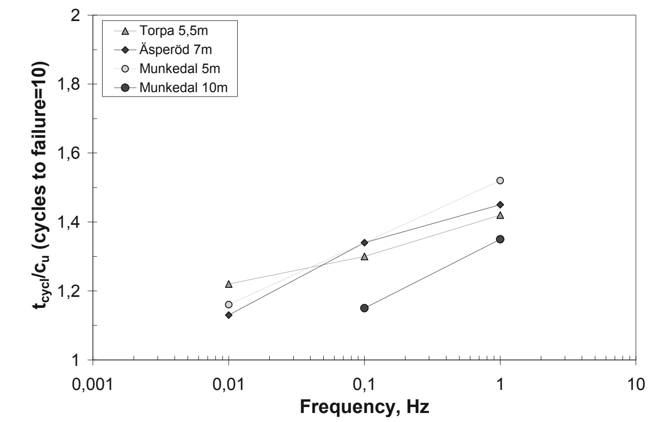

Figure 3. Influence of frequency on stress level leading to failure after 10 cycles at stress-controlled loading

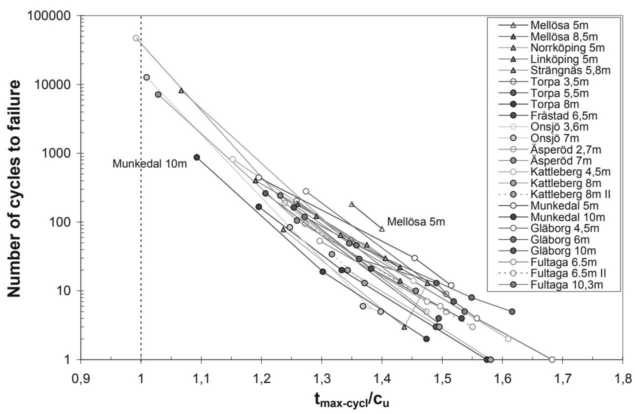

Figure 4. Relation between cyclic stress level and number of cycles to failure in stress-controlled tests.

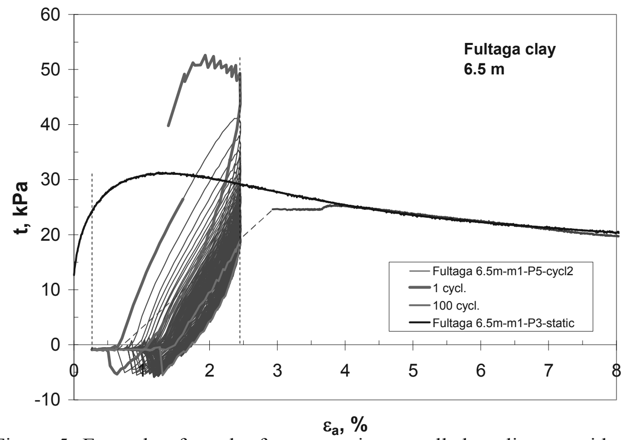

Figure 5. Example of results from a strain-controlled cyclic test with cyclic strains of two times the static failure strain with the specimen after 1000 cycles subjected to a rest period of 1 hour followed by static shearing as compared to that measured in an ordinary static test.

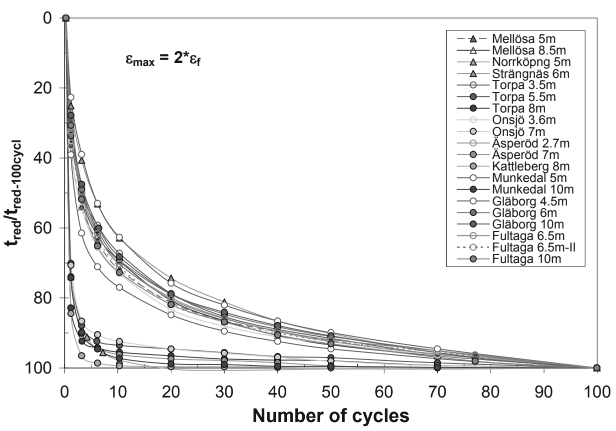

Figure 6. Illustration of how fast different types of clay are broken down with number of strain-controlled cycles expressed as shear stress reduction in relation to the total reduction after 100 cycles.

4 CONCLUSIONS

The investigation tried to simulate a case where a considerable part of the available shear strength in clay is already mobilized by static forces and cyclic loads or enforced deformations are applied in addition. This is a common situation in natural slopes and during the building phase of many constructions. Other cases, such as earthquakes, wind- and wave loads and other combinations of static and cyclic stresses as well as other types of enforced deformations can give very different results concerning the sizes of the stresses, strains and deterioration of the shear strength (e.g. Andersen 2009). Nevertheless, the general pattern for what soil properties affect the behaviour and susceptibility for strength degradation can be expected to be about the same.

The results generally confirm earlier indicative findings in Sweden and Canada by Larsson and Jansson (1982) and Tavenas et al. (1983) regarding influence of plasticity and sensitivity, but the behaviour in different phases is here investigated in more detail.

The general influence of different soil properties that could be outlined from the results is by necessity simplified. To discern the effect of the various parameters in greater detail, more tests would be required and possibly also tests on artificial soils enabling a more systematic study of the influence of various parameters separately.

Tentative calculations made in connection with this project show that high traffic loads, dumping of large boulders, rockfall etc. in certain cases can result in large deformations and significant strength reductions in the underground. Enforced deformations that exceed the static failure strain always bring a strength reduction.

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