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THE EFFECT OF SAMPLE DISTURBANCE ON THE GEOTECHNICAL PROPERTIES OF SOFT CLAYS

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CONTENTS

SYMBOLS

c_v = coefficient of consolidation
f = frequency of disturbance
m_v = coefficient of volume change
q_u = compressive strength from unconfined compression test on undisturbed samples
q_u' = compressive strength from unconfined compression test on disturbed samples
S_t = sensitivity
t = duration of disturbance
w_L = liquid limit (determined by fall-cone test)
w_n = natural water content
γ = density
ε = relative compression
σ' = consolidated pressure
σ_c' = preconsolidation pressure
τ_{fu} = undrained shear strength of undisturbed sample
τ_{fu}' = undrained shear strength of disturbed sample
τ_R = undrained shear strength of fully remoulded sample

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Linköping, December 1981
Bui Dinh Nhuan

1. INTRODUCTION

It is widely known that the geotechnical properties of soil determined from laboratory tests are generally affected by sample disturbance. This problem has become important in the geotechnical research and practice. Since the first studies on soil sampling introduced by Hvorslev et al (1949), numerous studies have followed.

Sources of sample disturbance have been extensively studied by many authors such as Hvorslev et al (1949), Kallstenius (1958), International Group of Soil Sampling (1971), The Sub-Committee on Soil Sampling (1981). All the authors have found that the sample disturbances occur during sampling, handling, shipping, storage, extrusion, specimen preparation and laboratory test processes.

The recognition of sources of sample disturbance is important and necessary for technicians and engineers in civil engineering. However, it is more important to know the effect of such disturbances on the geotechnical properties of soil. The effect of sample disturbance on the geotechnical properties of soils especially of soft cohesive soils have been studied by T. Kallstenius (1958, 1971), S.B. Bromham, T. Okumura, D.M. Milovic (1971), B. Broms (1978), H. Kramer (1979), Adachi, Alonso, Atkinson (1981) and many others.

The effect of sample disturbance can be determined either at the site or in the laboratory. The results obtained from these studies have been presented in proceedings, reports of many international conferences on soil mechanics and foundation engineering, symposia, committees and sub-committes on soil sampling etc.

Almost all these studies have concerned sample disturbance in soft cohesive soils very sensitive to disturbance. The sample disturbance affects the geotechnical properties especially the strength, deformation and permability of soft soils. The determination of the effect of sample disturbance has been introduced in order to make the laboratory test results more reliable and correspondent to in situ conditions of soils. The influence of sample disturbance on geotechnical properties of soils depends mainly on the degree of disturbance. The degree of disturbance in term is dependent on the technique of sampling and on condition of transportation, storage and testing.

In Vietnam the technique of sampling, the condition of transportation and storage of soil samples are limited, the sample disturbance and effect of such disturbance therefore should be especially considered. At present in Vietnam, some different types of samplers are used. The writer is convinced that it is important and necessary to compare the sample disturbance occured by different samplers and determine the effects of such disturbance on the geotechnical properties in Vietnam conditions.

This investigation was carried out on suggestions and orientation by the Swedish Geotechnical Institute (SGI). The purpose of the investigation is to determine some effects of sample disturbance after sampling on the geotechnical properties of soft clays by means of laboratory tests. Some calculation examples are presented in order to see the effect of sample disturbance on the design parameters concerned with economic index. The clays to be examined were taken from Tornby and Bäckebol in Sweden. However, these investigation results will be a basis of the writer's further investigations in Vietnam.

2. TEST METHODS

2.1 Shear strength

In the investigations the following laboratory test methods were performed

- routine tests for determination of density, water content and liquid limit
- the shear strength was determined by the Swedish fall-cone test.

For shear strength as well as for liquid limit and density the fall-cone tests were performed in the standard laboratory fall-cone apparatus (Fig. 1). A millimetre-graded scale of the apparatus makes the accuracy in determining the cone penetration approximately 0.2 mm. The determination of the cone penetration was carried out on 6-8 sample surfaces and the shear strength was taken as an average value.

The shear strength was also measured in unconfined compression tests (Fig. 2).

2.2 Compressibility

Oedometer tests were performed to determine the compressibility of clays in a fixed ring oedometer. (Fig. 3)

The height and diameter of the ring is 20 and 40 mm respectively. The ring was lubricated on the inside by silicone grease to reduce friction between the soil and the ring. The samples were trimmed and mounted by a special cutting device (Fig. 3). The oedometer tests were performed by the incremental loading method with 24 hours duration. In the tests the standard procedure was used with increments 10, 20, 40, 80, 160 and 320 kPa. The time required for every test was 6 days.

During the test the sample was drained from both ends. Based on data from oedometer tests the stress-strain curve for every sample and the time-settlement curve for each increment were established. From these curves the preconsolidation pressure and the coefficient of consolidation was evaluated by Casagrande's and Taylor's methods respectively.

2.3 Method for disturbance of sample

In order to determine the effect of sample disturbance on the properties of soil, the samples were disturbed in a rotating apparatus or in a laboratory vibrator with different frequencies or different durations of disturbance. By this method disturbed samples with different degrees of disturbance were manufactured. (Figs. 4 and 5)

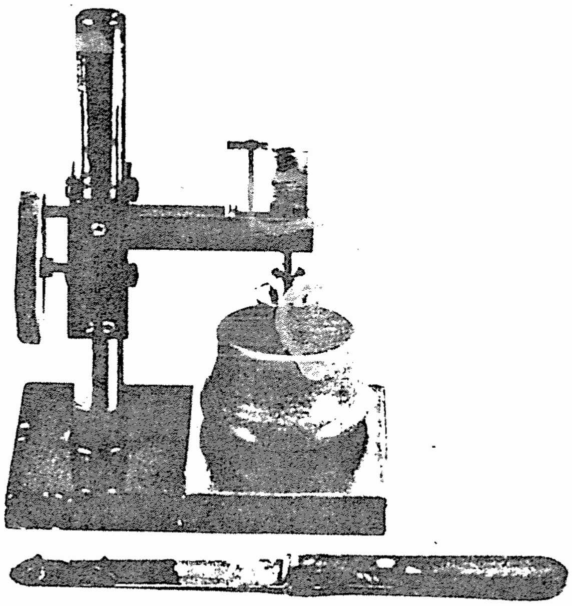


Fig. 1. Laboratory fall-cone apparatus.

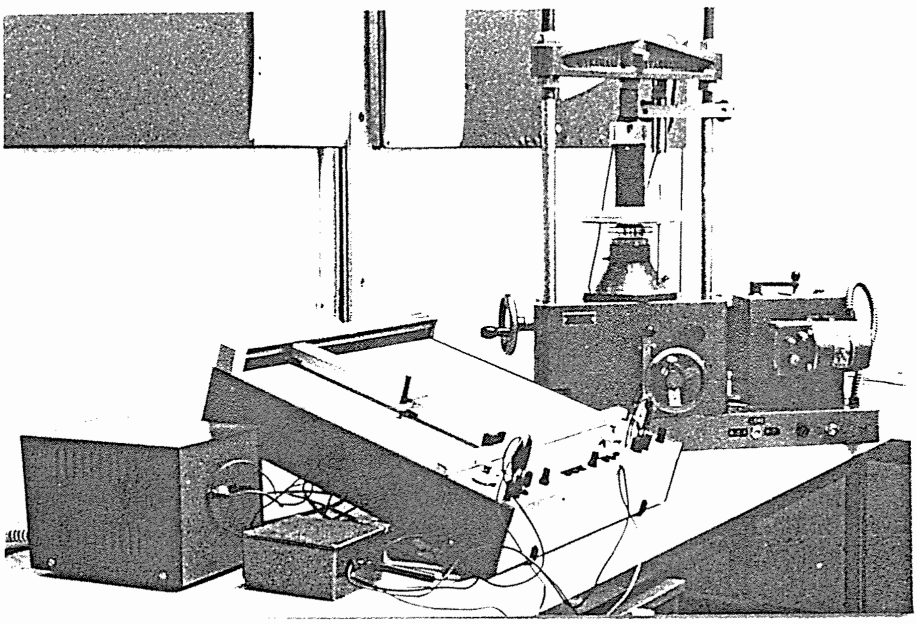
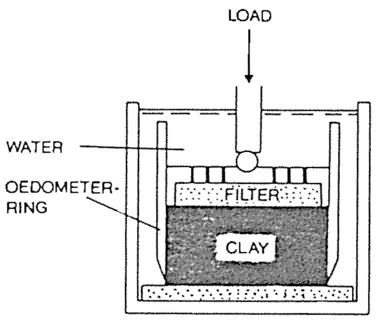
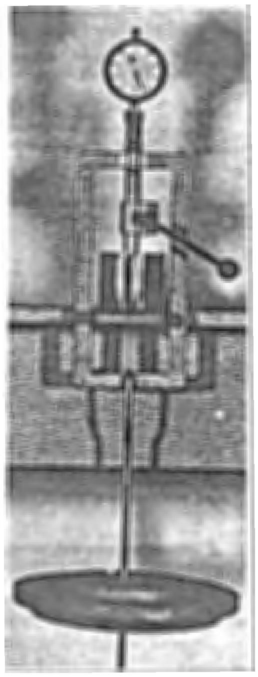


Fig. 2. Apparatus for unconfined compression tests.





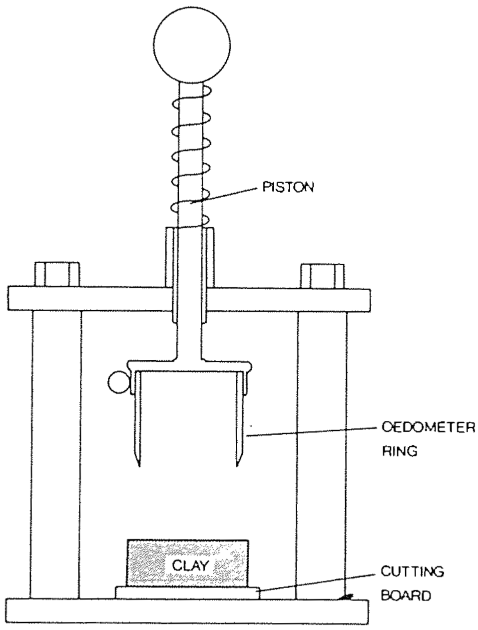


Fig. 3. Apparatus in incremental oedometer tests (a) and cutting device used for mounting clay sample (b).

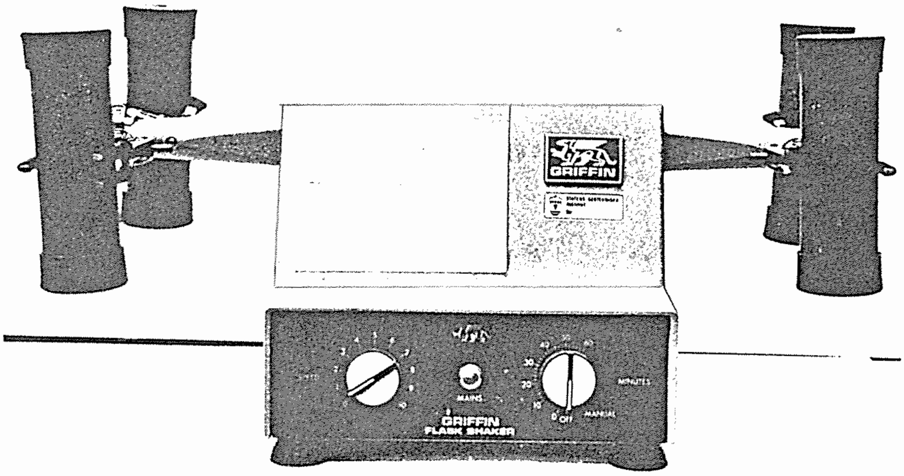


Fig. 4. Laboratory vibrator.

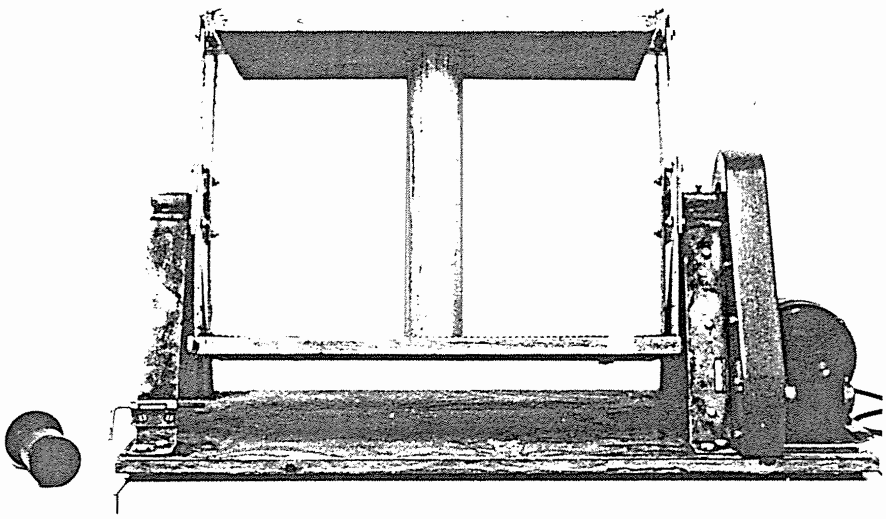


Fig. 5. Rotating apparatus.

3. CHARACTERISTICS OF SOILS

The study was made on two types of soil: Tornby clay and Bäckebol clay. For Tornby clay, the sampling was carried out with the Swedish Piston Sampler (std I) and samples were taken from every metre of depth below the dry crust down to 8 metres below the ground surface. For Bäckebol clay big cylindrical samples (diameter = length = 20 cm) were taken by a Canadian sampler at a depth of 7.0 metres. The tested samples were taken from this big cylindrical samples into the standard sample tubes of the Swedish Piston Sampler.

For both clays, routine tests have been carried out for every sample. The liquid limit, undrained shear strength and sensitivity have been determined by fall-cone tests and unconfined compression tests. Oedometer tests have been performed by the incremental loading method with a duration of 24 hours for the determination of the compression characteristics of clays. Results from these tests are listed in Tab. 1 and shown in Fig. 6.

Tab. 1. Characteristics of studied soils.

Soil	Depth (m)	Density (t/m^3)	Natural water content (%)	Liquid limit (%)	Undrained shear strength (kPa)		Sensitivity	Existing effective overburden pressure (kPa)	Preconsolidation pressure (kPa)
					undisturbed	remoulded			
		γ	w_n	w_L	τ_K	τ_R	S_t	σ'_o	σ'_c
Tornby Clay	2	1.65	58.5	49.5	13.4	0.64	21.0	34	42
	3	1.51	91.0	81.6	12.8	0.82	16.0	39	48
	4	1.52	86.0	74.0	12.8	0.93	14.0	44	56
	5	1.52	84.0	76.6	12.5	1.03	12.0	49	58
	6	1.53	77.5	73.6	13.4	1.11	12.0	54	70
	8	1.61	70.0	62.0	13.4	1.17	11.5	66	79
Bäckebol Clay	7	1.50	95	70	10.4	0.45	23	45	51

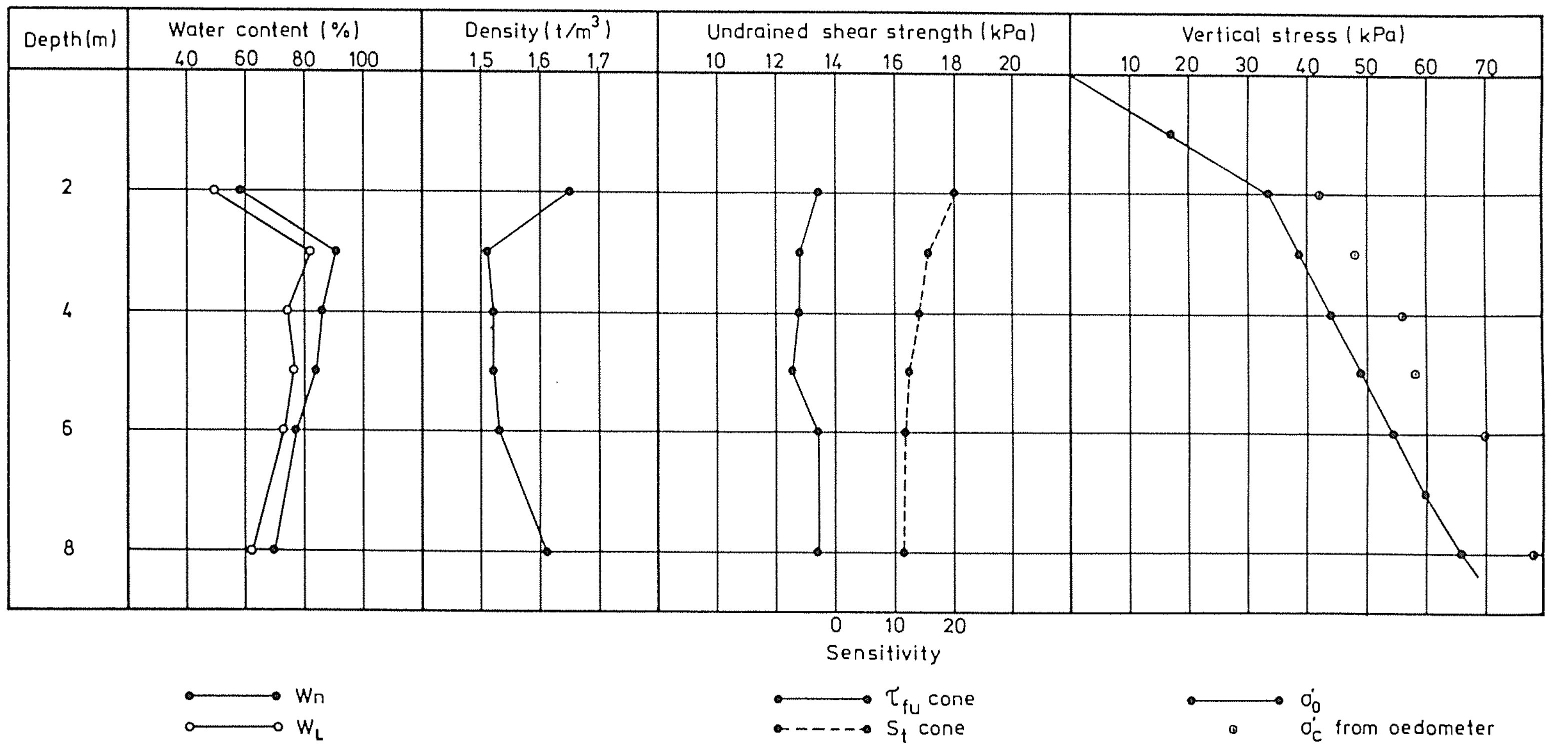


Fig. 6. Characteristics of Tornby clay.

The results show that both clays have a natural water content, w_n, higher than the liquid limit, w_L. Both clays are medium sensitive with the sensitivity S_t = 12-20. The liquid limit of the clays is of the range w_L = 61-81%. Therefore, according to the classification, the investigated clays are high-plastic. The clays are soft and normally or slightly overconsolidated.

4. EFFECTS OF SAMPLE DISTURBANCE

In the laboratory, the geotechnical properties especially the strength and the deformation properties of soil should be determined on undisturbed samples. The samples in fact can only be considered as "undisturbed" samples in which the material has been subjected to such little disturbance that it is suitable for all laboratory tests, especially for determination of strength, deformation and permeability characteristics and other physical properties of soil in situ. However, the samples taken from the ground and transported to the laboratory are seldom undisturbed. The sample disturbances affect the sample quality and thus affect directly the geotechnical properties of soils, especially of soft clays.

The sample disturbance may be due to mechanical, physical, chemical or other reasons. If speaking about disturbance stage we have two types of disturbance: the primary and secondary disturbance. The primary disturbance is caused by the sampler during the sampling and the secondary disturbance occurs after sampling due to incorrect shipment and storage etc. of samples. In the primary disturbance the following influences are considered:

- the type of sampler
- the sample size (length and diameter of sample)
- the sampler shape
- the punching operation (friction, piston travel, inside clearance, edge sharpness, edge angle etc.)

The secondary disturbance depends on many different factors. However, the following factors are considered the most important.

- Time factors: time of disturbance and time between sampling and testing.

- Mechanical factors: shocks, vibration during transportation of samples to the laboratory.
- Changes in some characteristics (e.g. temperature, water content) due to incorrect storage of samples.

In this paper some factors of sample disturbance such as time factors, mechanical factors, changes of some characteristics in clay have been investigated. The disturbance caused by the sampler has also been investigated by determining the effect of disturbance within the sample tubes.

4.1 Disturbance in sample tubes

Every sample taken by the Swedish Piston Sampler is collected by three sample tubes called the upper, the middle and the lower tube. Many researchers have found that, due to disturbance, the properties of a soil will vary not only between the samples and the partent material (Hvorslev et al (1949), Sone, Tsuchiya and Saito (1971), Kallstenius (1972)). The degree of disturbance have shown that the soil is disturbed most in the upper part of the upper tube and less disturbed in the middle tube. That is why the middle tube is usually taken for determination of the geotechnical properties, especially strength and deformation properties of the soil.

In order to determine the sample quality in the tubes, routine tests have been carried out parallelly (at the same time) on the upper tube and the middle tube for all samples. These tests have been performed only for Tornby clay. The test results are shown in Fig. 7.

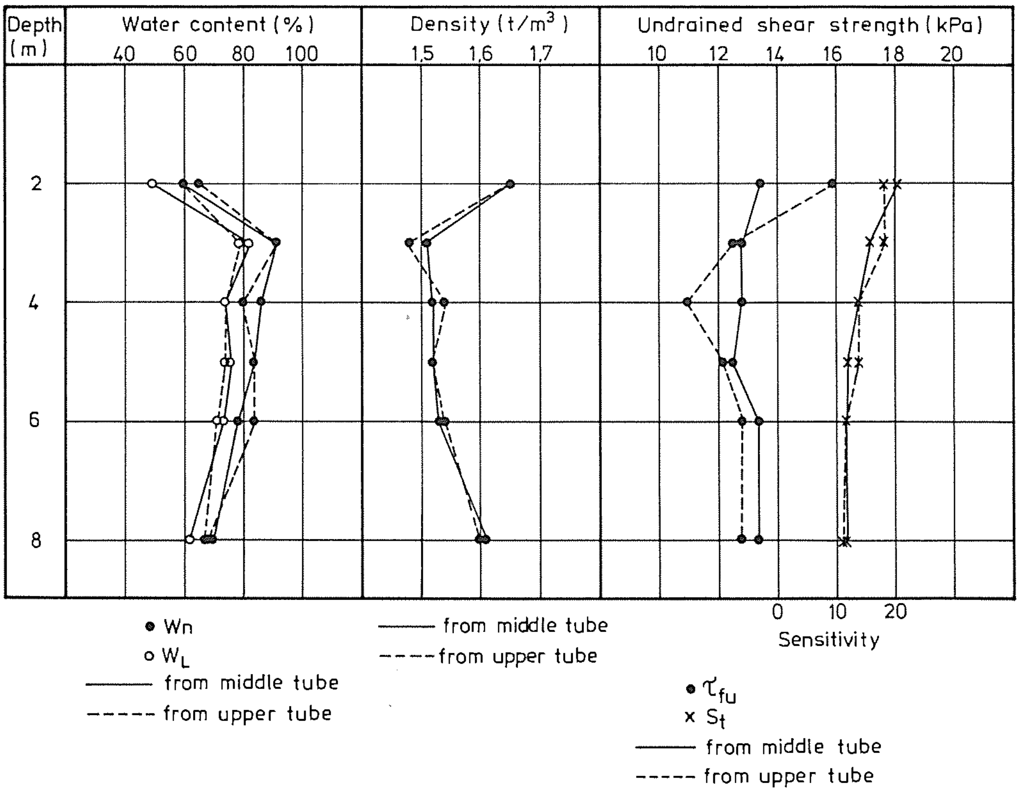


Fig. 7. Comparison of soil properties measured in the middle tube and the upper tube of sample for Tornby clay.

As seen in Fig. 7 the water content, density and liquid limit of the clay in both tubes have nearly the same values. The very small difference in these values can be due to accuracy in the tests. However, the undrained shear strength determined by fall-cone test of clay in the upper tubes is lower than that in the middle tubes except at 2 metres of depth. This shows that due to disturbance the clay in the upper tube loses a part of its strength. However, the decrease of strength is very small (2-4%), except for 14% at 3 metres of depth.

4.2 Disturbance by shocks and vibrations

This investigation was performed in order to determine the effects of sample disturbance caused by shocks and vibrations during transportation of samples to the laboratory. With this purpose the disturbance of the samples was carried out either in a rotating apparatus (for Tornby clay), see Fig. 4, or in a laboratory vibrator (for Bäckebol clay), see Fig. 5.

As we know the sample disturbance will lead to a change of the geotechnical properties of the soil. This change depends mainly on the degree of disturbance and the type of soil. In this investigation different degrees of disturbance were made by rotation or vibration with different durations or different frequencies. For Tornby clay, the tested samples were disturbed in a rotating apparatus at the same rotation speed but during different times (duration of disturbance). The duration of disturbance was chosen to 10 minutes, 100 minutes and 1000 minutes. For Bäckebol clay, two groups of samples were tested. The disturbance of the samples was made by a laboratory vibrator. The samples in the first group were disturbed during the same duration (t = 60 minutes) but at different frequencies (f_1 = 50 cycles/sec, f_2 = 100 cycles/sec and f_3 = 200 cycles/sec). In the second group, the tested samples were disturbed at the same frequency (f = 100 cycles/sec) but during different durations (t_1 = 60 minutes, t_2 = 120 minutes and t_3 = 180 minutes). By this way of disturbance we shall have three different degrees of sample disturbance. The routine tests and the oedometer tests were performed parallelly for both undisturbed and disturbed samples.

4.2.1 Change in physical properties

For both undisturbed and disturbed samples the physical properties such as water content (w_n), liquid limit (w_L) and density (γ) were determined. Results from the tests indicate no change in these parameters due to sample disturbance for both Tornby and Bäckebol clay.

4.2.2 Change in undrained shear strength

The results from fall-cone tests indicate that due to disturbance the samples lose their strength. The comparative results of undrained shear strength obtained from fall-cone tests between undisturbed and disturbed samples are listed in Tab. 3 and 4.

Tab. 3. Decrease in undrained shear strength of Tornby clay due to disturbance.

Type of tested sample		Average shear strength τ_{fu} (kPa)	Decrease in undrained shear strength
undisturbed sample		12.8	
disturbed sample s = constant	t_1 = 10 min	11.9	7
	t_2 = 100 min	11.3	12
	t_3 = 1000 min	10.8	14

Tab. 4. Decrease in undrained shear strength of Bäckebol clay due to disturbance.

Type of tested sample		Average shear strength τ_{fu} (kPa)	Decrease in shear strength (%)
undisturbed sample		10.4	0
disturbed sample t=60 min=const	f_1 = 50 c/sec	8.8	15
	f_2 = 100 c/sec	8.0	24
	f_3 = 200 c/sec	7.6	27
disturbed sample f=100 c/sec=const	t_1 = 60 min	8.0	24
	t_2 = 120 min	7.6	27
	t_3 = 180 min	7.3	30

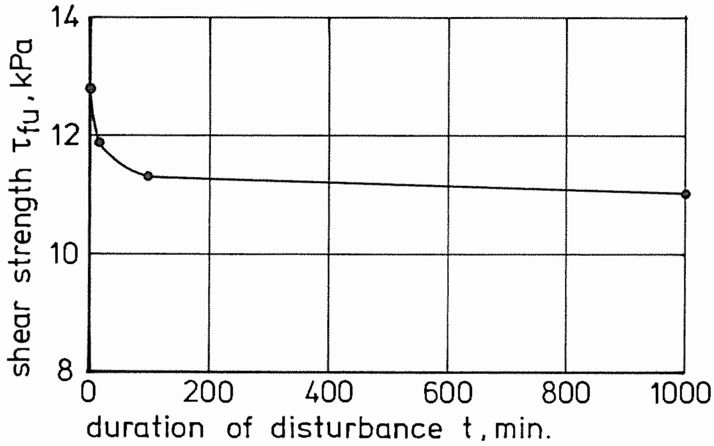


Fig. 8. Effect of sample disturbance on shear strength for Tornby clay (according to duration of disturbance).

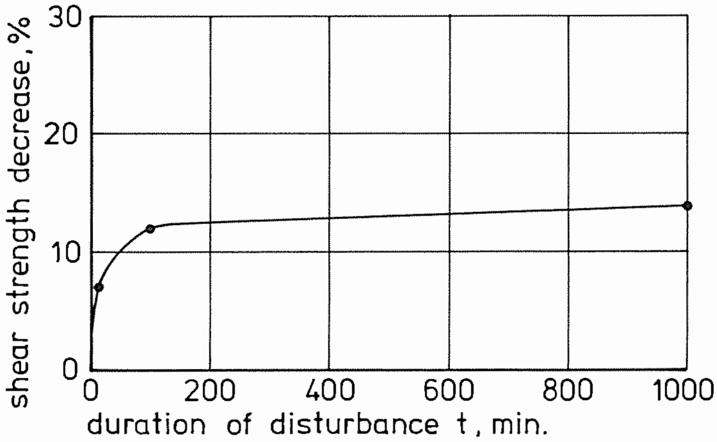


Fig. 9. The rate of decrease in shear strength for Tornby clay (according to duration of disturbance).

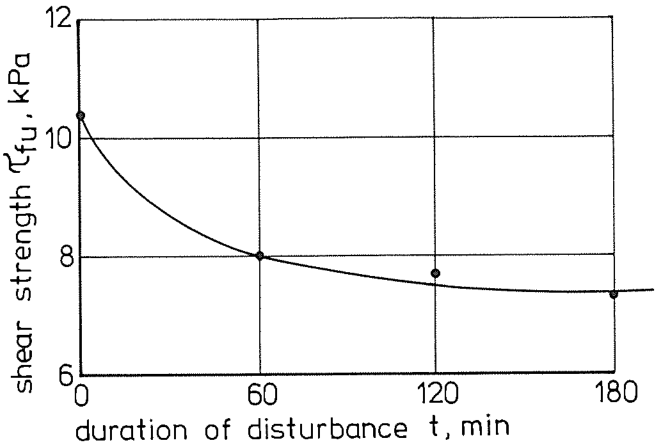


Fig. 10. Effect of sample disturbance on shear strength for Bäckebol clay (according to duration of disturbance).

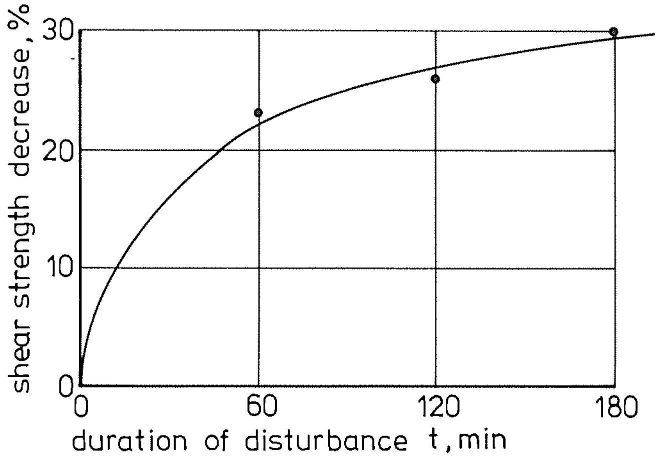


Fig. 11. The rate of decrease in shear strength for Bäckebol clay (according to duration of disturbance).

The result shows that due to disturbance, the samples lose a part of their strength. The average values of undrained shear strength from fall-cone tests on undisturbed and disturbed samples are shown in Fig. 8 and 9 for Tornby clay and Fig. 10-13 for Bäckebol clay. As seen in these figures the decrease of shear strength depends on the degree of disturbance: the more the sample is disturbed, the greater is the decrease in shear strength. For Tornby clay, after disturbance with different durations, the samples lose 0.9-1.8 kPa of their shear strength, while the samples from Bäckebol clay lose 1.6-3.1 kPa of their shear strength after disturbance (by vibration) with different durations and different frequencies.

The decrease in shear strength is well seen in Fig. 11, 12 and 13. The decrease in shear strength has the range of 7-14% for Tornby clay and 15-30% for Bäckebol clay.

This results indicates an agreement with a lot of previous research (Kallstenius, Okumura, Nelson (1971), Begemann and Leeun (1979), and others).

In 1971 Kallstenius found that for soft clay the decrease in strength due to shocks and vibrations is in the order of 30% and 22% respectively.

The results from fall-cone tests can be confident because the obtained variation in shear strength between undisturbed and disturbed samples as well as between disturbed samples with a different degree of disturbance is greater than the accuracy of the method.

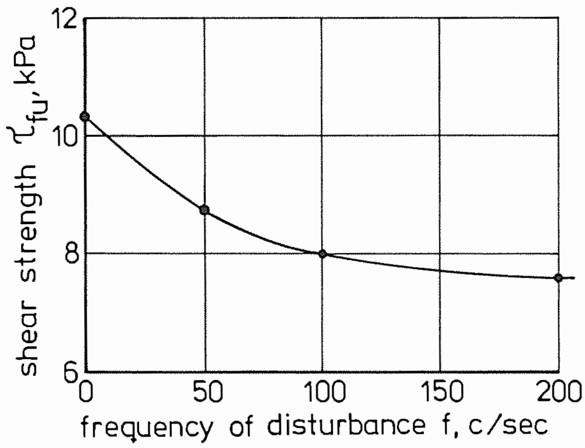


Fig. 12. Effect of sample disturbance on shear strength for Bäckebol clay (according to frequency of disturbance).

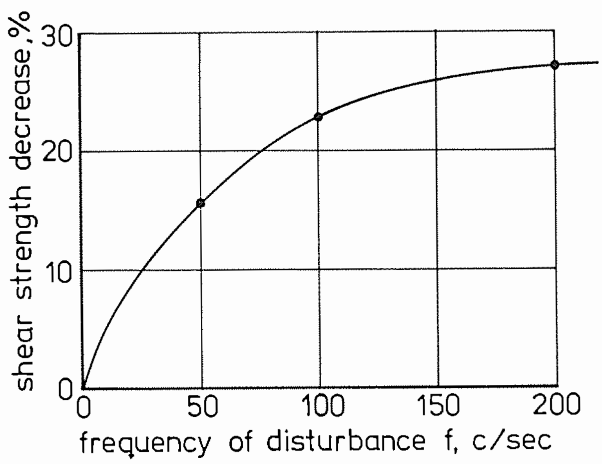


Fig. 13. The rate of decrease in shear strength for Bäckebol clay (according to frequency of disturbance).

In order to see the influence of sample disturbance on the shape of the stress-strain curve, unconfined compression tests were carried out. The test result is shown in Fig. 14 for Tornby clay.

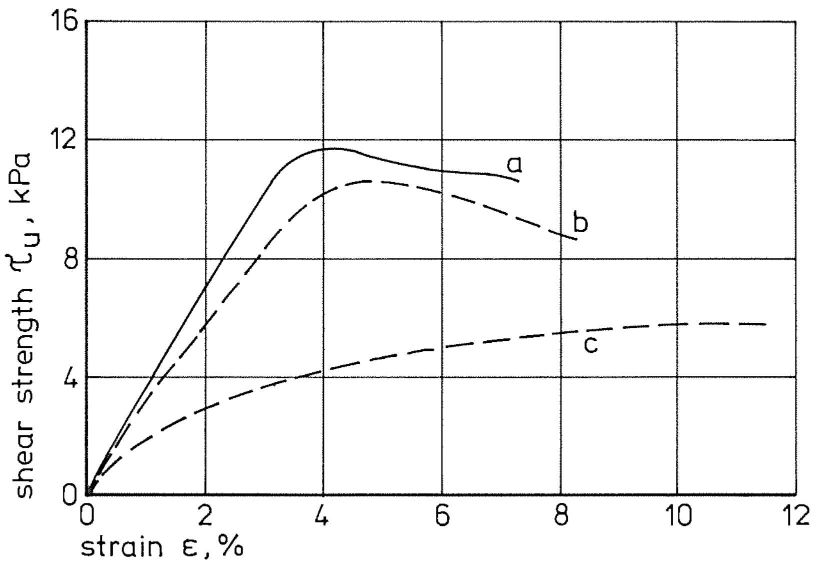


Fig. 14. Stress-strain curves from unconfined compression tests for Tornby clay.
curve a for undisturbed sample
curve b for disturbed sample with t = 30 min
curve c for disturbed sample with t = 60 min

As seen in Fig. 14, the shape of the stress-strain curves of unconfined compression tests is influenced by sample disturbance. The unconfined compressive strength q_u of an undisturbed sample is greater than that of all disturbed samples. The tests gave the unconfined compressive strength values of 11.4, 10.4 and 5.9 kPa for undisturbed sample and samples disturbed by vibration with the same frequency f = 200 c/s during t = 30 minutes and t = 60 minutes respectively. This is in agreement with other authors, e.g. Rutledge et al (1949), Adachi (1981) and many others.

The results from the unconfined compression tests show a change not only in the strength but also in the strain at failure. The strain at failure ε_f' for a disturbed sample is generally greater than that for an undisturbed sample.

As seen from the above the decrease in shear strength increases with increasing degree of disturbance. However, the relationship between the rate of this decrease and degree of disturbance is non-linear. The rate of this decrease is largest in the first degree of disturbance. This was found for both Tornby clay and Bäckebol clay.

The obtained result allows the conclusion that the measurement of shear strength is a good way to evaluate the effect of sample disturbance. In some cases, for soft homogeneous clay fall-cone tests can be employed for evaluation of the sample disturbance. However, shear strength from unconfined compression tests seems to be a better parameter for this purpose. The compressive strength as well as the strain at failure may be mainly affected by the shape and the position of the failure surface. Therefore in this method it is necessary to observe the failure surface of the tested sample during the test.

4.2.3 Change in sensitivity

It should be noted that sample disturbance influences the sensitivity of soil. The sensitivity of soft clay is usually determined in the laboratory from fall-cone tests. Sensitivity is then calculated by the relationship:

$$S_t = \frac{\tau_K}{\tau_R}$$

where

S_t = sensitivity

τ_K = shear strength of "undisturbed" sample

τ_R = shear strength of remoulded sample

τ_K- and τ_R-values are considered as maximum and minimum shear strength of clay. As indicated above, due to sample disturbance the maximum shear strength decreases while the minimum shear strength remains. In this case, sensitivity of disturbed sample depends only on the maximum shear strength: the decrease of the maximum shear strength will lead to a decrease in sensitivity. If relationships between the degree of sample disturbance and the decrease of sensitivity are expressed by figures, the shape of the curves will look similar to that of relationships between the degree of sample disturbance and the degree in undrained shear strength (Fig. 10-13) for Bäckebol clay.

4.2.4 Change in the shape of the oedometer curve and in the preconsolidation pressure

Oedometer tests on clays were performed by the incremental loading method with a duration of 24 hours to determine the compression characteristics. The test results indicate changes in the compression characteristics for both Tornby clay and Bäckebol clay. All disturbed samples show greater deformation up to the preconsolidation pressure than the undisturbed sample.

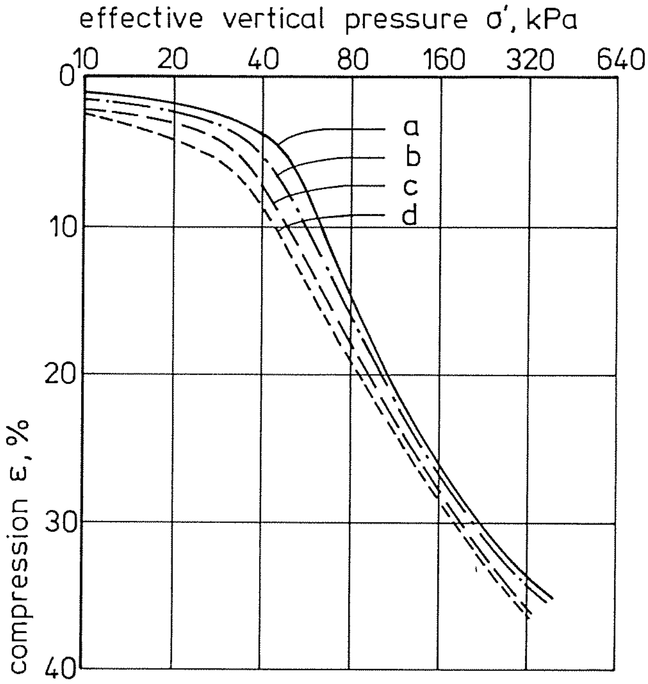


Fig. 15. Effect of sample disturbance on oedometer curves for Bäckebol clay (according to duration of disturbance).

Fig. 15 shows typical compression-log pressure curves obtained from oedometer tests. In this figure, curve (a) is for undisturbed sample, curve (b), (c) and (d) for disturbed samples with duration of disturbance of 60, 120 and 180 minutes respectively. As seen in the figure the sample disturbance affects the shape of the curve. The compression-log pressure curves of disturbed samples are displaced further and further from the curve of the undisturbed sample as the degree of disturbance increases. The obtained results are correspondent to observations by Schmertmann (1956), Davis and Poulos (1966), Bromham (1971). The values of the preconsolidation pressure determined by Casagrande's method are presented in Tab. 5 and 6.

As seen in Tab. 5 and 6, due to sample disturbance the preconsolidation pressures of disturbed samples are generally less than that of an undisturbed sample. This is in agreement with observations by Okumura (1971), Schmertmann (1956) and others. The decrease in the preconsolidation pressure for both clays was 15-30% increasing with increasing degree of disturbance.

Tab. 5. Decrease in the preconsolidation pressure σ_c' of Tornby clay due to sample disturbance.

Depth (m)	Preconsolidation pressure σ_c' (kPa) of samples				Decrease in preconsolidation pressure (%)
	Undisturbed sample	Disturbed sample			
		t_1 = 10 min	t_2 = 100 min	t_3 = 1000 min	
3	48	40	-	-	17
4	56	-	46	-	18
5	58	-	-	44	24

Tab. 6. Decrease in the preconsolidation pressure σ_c' of Bäckebol clay due to sample disturbance.

Type of tested sample		preconsolidation pressure σ_c' (kPa)	decrease in presonsolidation pressure (%)
Undisturbed sample		51	0
Disturbed sample f=100 c/sec=const	t_1 = 60 min	43	16
	t_2 = 120 min	39	24
	t_3 = 180 min	36	29

From the above results it can be said that the oedometer curve is a good indicator for the sample quality of soft clay. If the influence of sample disturbance on the shape and position of the oedometer curve is obvious the preconsolidation pressure can be well used for this purpose. However, when the effect of sample disturbance on the oedometer curve is not obvious, the determination of sample quality on the basis of the preconsolidation pressure should be used with caution. In this case, due to test error and method of evaluation, there could be a great scatter in the value of the preconsolidation pressure.

4.2.5 Change in the coefficient of consolidation

Results from oedometer tests also show the change due to disturbance in the coefficient of consolidation. The values of the coefficient of consolidation determined by Taylor's method are listed in Tab. 7, 8 and 9.

Tab. 7. Coefficient of consolidation c_v from undisturbed and disturbed samples of Tornby clay.

Range of pressure (kPa)	Coefficient of consolidation $c_v \cdot 10^{-8}$ m^2/sec					
	undisturbed	t_1=10 min	undisturbed	t_2=100 min	undisturbed	t_3=1000 min
10-20	36.6	36.0	48.6	46.1	96.1	80.0
20-40	35.9	35.3	40.5	36.0	79.0	64.2
40-80	1.3	1.5	1.3	1.4	1.1	1.1
80-160	0.7	0.6	2.8	1.2	1.0	1.0
160-320	1.2	0.8	6.2	2.2	2.4	2.2

Tab. 8. Coefficient of consolidation c_v from undisturbed and disturbed samples with different frequencies of Bäckebol clay.

Range of pressure (kPa)	Coefficient of consolidation $c_v \cdot 10^{-8}$ m^2/sec			
	Undisturbed sample	Disturbed sample t = 60 min = constant		
		f_1 = 50 c/sec	f_2 = 100 c/sec	f_3 = 200 c/sec
10-20	44.8	42.1	42.4	42.4
20-40	35.1	31.2	22.5	22.4
40-80	8.1	3.6	3.0	1.9
80-160	5.8	5.0	4.8	4.2
160-320	12.3	6.8	6.2	5.9

Tab. 9. Coefficient of consolidation from undisturbed samples and disturbed samples during different duration of Bäckebol clay.

Range of pressure (kPa)	Coefficient of consolidation $c_v \cdot 10^{-8}$ m^2/sec			
	Undisturbed sample	Disturbed sample f = 100 c/sec = constant		
		t_1 = 60 min	t_2 = 120 min	t_3 = 180 min
10-20	44.8	42.4	42.0	42.0
20-40	35.1	20.5	14.1	12.8
40-80	8.1	3.2	2.9	2.2
80-160	5.8	4.8	3.8	3.6
160-320	12.3	6.2	5.7	5.3

As seen in Tab. 6, 7, 8 and 9 it is obvious that almost all samples due to disturbance lose a part of their coefficient of consolidation. It is necessary to note that for Tornby clay only three values from 30 calculated values give the opposite result. This can be due to errors of tests. Many investigations have shown that the decrease in the coefficient of consolidation increases with increaseing degree of disturbance (Davis and Poulos (1966), and Bromham (1971). This was not found for Tornby clay. However, for Bäckebol clay this was shown very clearly. Results from Bäckebol clay allow to conclude that the more the sample is disturbed the greater is the decrease in the coefficient of consolidation. This is illustrated in Fig. 16 and 17. In these figures the c_v-values are plotted against the pressure σ (in log-log scale) in order to at the same time see the relationship between the coefficient of consolidation and the consolidation pressure. As seen in Fig. 16 and 17 the coefficient of consolidation of an undisturbed sample has higher values at lower consolidation pressure and decreases rapidly around the preconsolidation pressure and after that slowly increases.

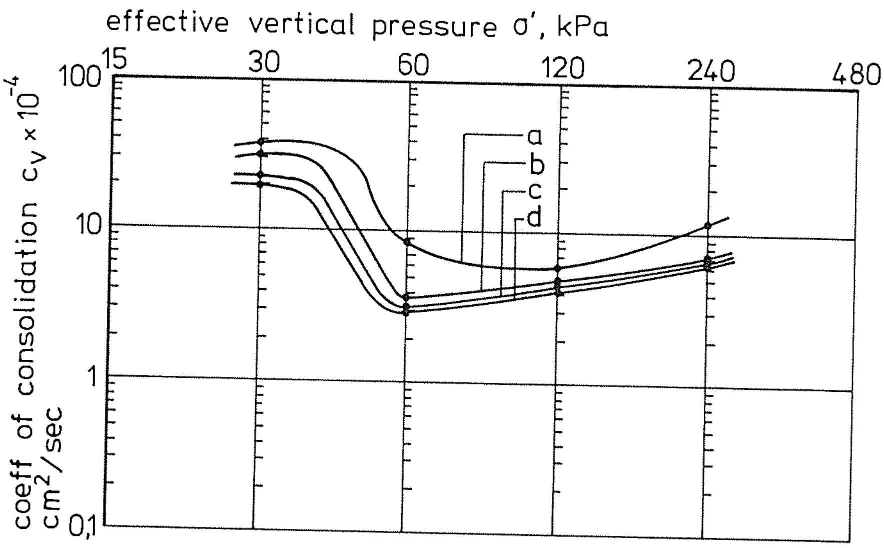


Fig. 16. Effect of sample disturbance on coefficient of consolidation.
a = curve for undisturbed sample
b = curve for f = 100 c/sec, t = 60 min
c = curve for f = 100 c/sec, t = 120 min
d = curve for f = 100 c/sec, t = 180 min

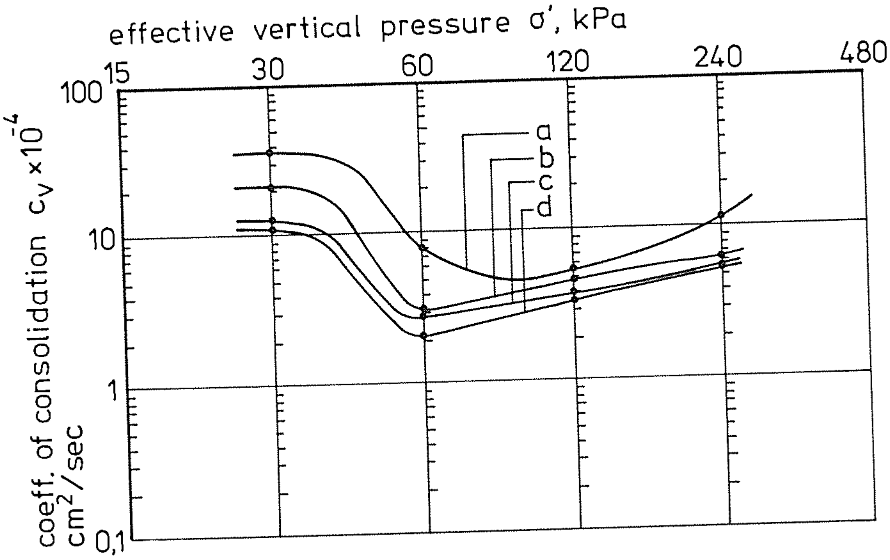


Fig. 17. Effect of sample disturbance on coefficient of consolidation.
a = curve for undisturbed sample
b = curve for t = 60 min, f = 50 c/sec
c = curve for t = 60 min, f = 100 c/sec
d = curve for t = 60 min, f = 200 c/sec

For disturbed samples the relationship between the coefficient of consolidation and the consolidation pressure is almost the same as for undisturbed samples but with a difference as follows. After the preconsolidation pressure the c_v of disturbed samples decreases rapidly to a minimum value and then increases linearly with consolidation pressure. Whereas for undisturbed samples after the preconsolidation pressure c_v also decreases rapidly but the minimum value of c_v seems to be at a stress somewhat higher than that for the disturbed samples. The figures also show that the coefficient of consolidation of disturbed samples at any stress is lower than that of the undisturbed samples. The coefficient of consolidation decreases with increasing degree of disturbance. The c_v-log $\bar{\sigma}$-curves of disturbed samples therefore are displaced further and further away from the curve of an undisturbed sample as the disturbance increases (see Fig. 16 and 17). This result indicates an agreement with results obtained by other authors, e.g. Davis and Poulos (1966), Bromham (1971).

From the above results it has been found that the coefficient of consolidation obtained from oedometer tests can be a valuable parameter for determination of the effect of sample disturbance.

4.2.6 Change in coefficient of volume change m_v

The coefficient of volume change m_v is calculated by the formula:

$$m_v = \frac{\Delta H}{H} \left(\frac{1}{\Delta\sigma}\right)$$

where

ΔH = decrease in height of sample, mm

H = initial height of sample, mm

$\Delta\sigma$ = loading increment, kPa

In Tab. 10 (for Tornby clay) and Tab. 11 and 12 (for Bäckebol clay) are shown values of the coefficient of volume change m_v calculated for both undisturbed and disturbed samples.

Tab. 10. Coefficient m_v for Tornby clay.

Range of pressure (kPa)	Coefficient of volume change $m_v \cdot 10^{-3}$ m^2/kN for samples					
	undisturbed	t_1=10 min	undisturbed	t_2=100 min	undisturbed	t_3=1000 min
0-10	0.94	0.80	0.77	0.42	1.22	1.06
10-20	0.58	0.79	0.86	0.57	1.03	1.61
20-40	0.42	0.79	0.81	0.63	0.57	0.70
40-80	2.98	3.98	2.27	3.00	2.21	2.96
80-160	2.2	1.83	2.36	2.2	2.22	1.82
160-320	0.57	0.70	0.56	0.69	0.60	0.62

Tab. 11. Coefficient of volume change m_v for Bäckebol clay (undisturbed sample and disturbed samples with different frequency).

Range of pressure (kPa)	Coefficient of volume change $m_v \cdot 10^{-3}$ m^2/kN for samples			
	Undisturbed sample	Disturbed samples t = 60 min = constant		
		f_1 = 50 c/sec	f_2 = 100 c/sec	f_3 = 200 c/sec
0-10	1.70	1.36	1.04	1.00
10-20	1.84	1.52	1.08	1.29
20-40	1.93	2.02	1.79	2.05
40-80	3.35	3.46	3.02	4.19
80-160	1.72	1.42	1.50	1.44
160-320	0.61	0.57	0.59	0.59

Tab. 12. Coefficient of volume change m_v for Bäckebol clay (undisturbed sample and disturbed samples during different duration).

Range of pressure (kPa)	Coefficient of volume change $m_v \cdot 10^{-3}$ m^2/kN for samples			
	Undisturbed sample	Disturbed sample f = 100 c/sec = constant		
		t_1 = 60 min	t_2 = 120 min	t_3 = 180 min
0-10	1.70	1.04	1.55	1.10
10-20	1.84	1.08	1.65	1.66
20-40	1.93	1.79	2.11	2.13
40-80	3.36	3.02	3.21	3.44
80-160	1.71	1.50	1.62	1.61
160-320	0.61	0.59	0.61	0.62

The values in Tab. 10, 11 and 12 show changes in the coefficient of volume change m_v due to sample disturbance. For Tornby clay it is difficult to say whether the coefficient of volume change decreases or increases due to disturbance. However, for Bäckebol clay the result indicates a tendency of decrease in the coefficient of volume change. This can be confident because about 85% of the m_v-values from disturbed samples are less than that from the undisturbed sample. This conclusion agrees with the results obtained by Okumura and Bromham (1971) and others.

From the obtained results and compared with the results of other authors it can be said that the main effect of sample disturbance is to produce a decrease in the coefficient of volume change. However, the decrease in the coefficient of volume change with the degree of disturbance was not found. Due to inaccuracy of the tests and the calculation method, in some cases m_v-values have a great scatter. For example, for Tornby clay it has been found that about 50% of the m_v-values indicate a decrease in m_v and 50% an increase in m_v. The coefficient of volume change is not a good indicator for sample quality evaluation. It may be used to distinguish (discover) sample disturbance on the basis of the change in the coefficient of volume change. It should not be used for evaluation of sample quality.

4.2.7 The rate of decrease in the mechanical properties

From the above it has been found that, the main effect of sample disturbance is to produce a decrease in the mechanical properties of clays. The decrease in shear strength, preconsolidation pressure and coefficient of consolidation is depending on the disturbance. The relationships between the rate of decrease in these parameters and the degree of disturbance for Bäckebol clay are shown in Fig. 18.

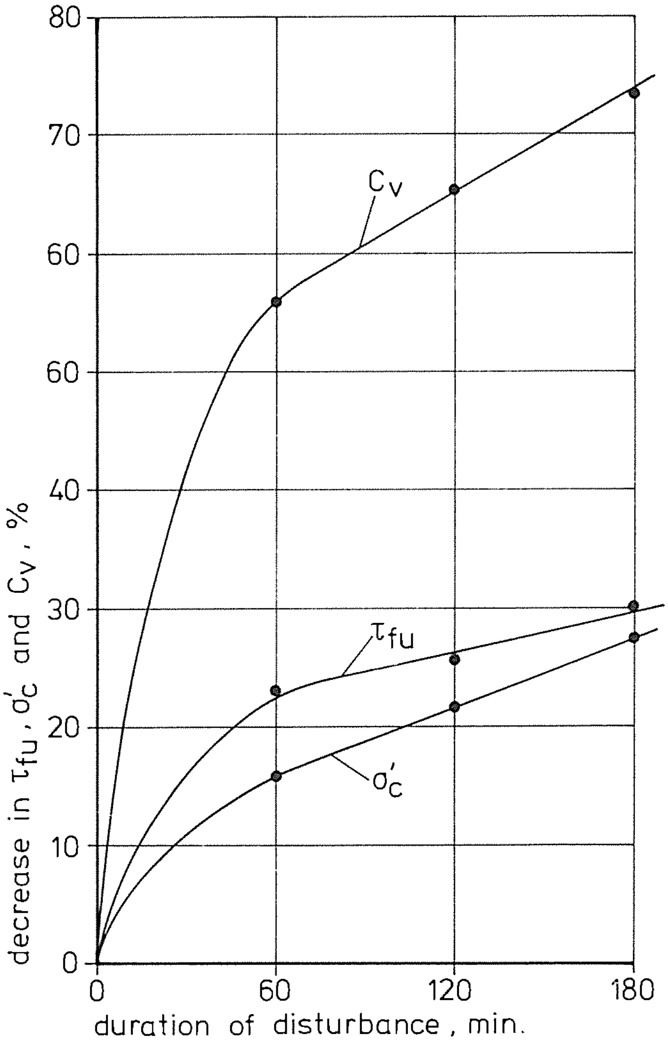


Fig. 18. The rate of decrease in τ_{fu}, σ_c' and c_v according to duration of disturbance.

It is interesting to note that the soft clay has a special characteristic. The special characteristic is that the rate of decrease in σ'_c, c_v and τ_{fu} is largest at the first degree of disturbance and then changes and becomes lower. In other words, due to disturbance σ'_c, c_v and τ_{fu} of clay decrease rapidly at the beginning and during a certain duration, after that these parameters decrease slowly as seen in Fig. 18. In this figure it is seen that all curves σ'_c, c_v and τ_{fu} have a very big inclination at the beginning. Then the curves bend and change into smaller inclination.

The rate of decrease in σ'_c, c_v and τ_{fu} allows to conclude that the examined Bäckebol clay is sensitive to deformations and vibrations. For this clay only a little work is required to break it down. This is characteristic for a clay with a water content higher than the liquid limit ($w_n > w_L$). According to Söderblom et al (1974) the examined clay (Bäckebol clay) may belong to a highly sensitive clay with a high rapidity.

The author suggests that every soft clay has its defined duration (or frequency) of disturbance during which the strength and deformation properties decrease rapidly. This duration depends on the type of soil and what parameters that are studied. Knowing this duration that can be called the "critical" duration may be useful in practice.

The "critical" duration of disturbance can be approximately evaluated as follows:

For the examined parameter (for example shear strength, τ_{fu}) of a particular soil (for example Bäckebol clay), the typical shear strength-disturbance duration curve (or shear strength decrease-disturbance curve) is plotted as seen in Fig. 19.

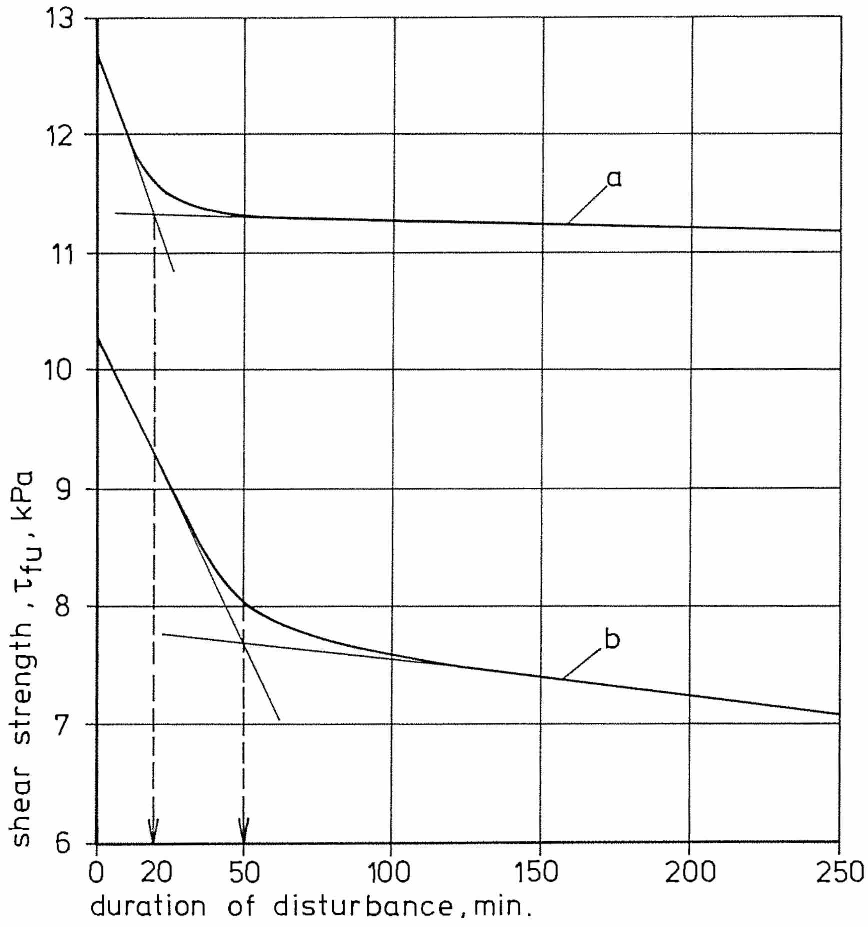


Fig. 19. Graphical method for evaluating the "critical" duration of disturbance.

Two portions of the curve are drawn and extended. The point of intersection between the two portions corresponds to the "critical" duration that should be evaluated (see Fig. 19).

By this method the duration of disturbance during which the shear strength rapidly decreases is 20 and 50 minutes for Tornby clay and Bäckebol clay respectively. For Bäckebol clay the critical duration is 30 and 45 minutes for the preconsolidation pressure and coefficient of consolidation respectively.

It can be said that for particularly soft clays (e.g. Bäckebol clay) due to disturbance the majority decrease in τ_{fu}, σ'_c and c_v is produced during the first 30 to 50 minutes of disturbance. After that the decrease in these parameters can be considerably smaller. This makes us to take extreme care when transporting samples of soft clays.

5. METHOD FOR CHECKING DISTURBANCE OF SAMPLE

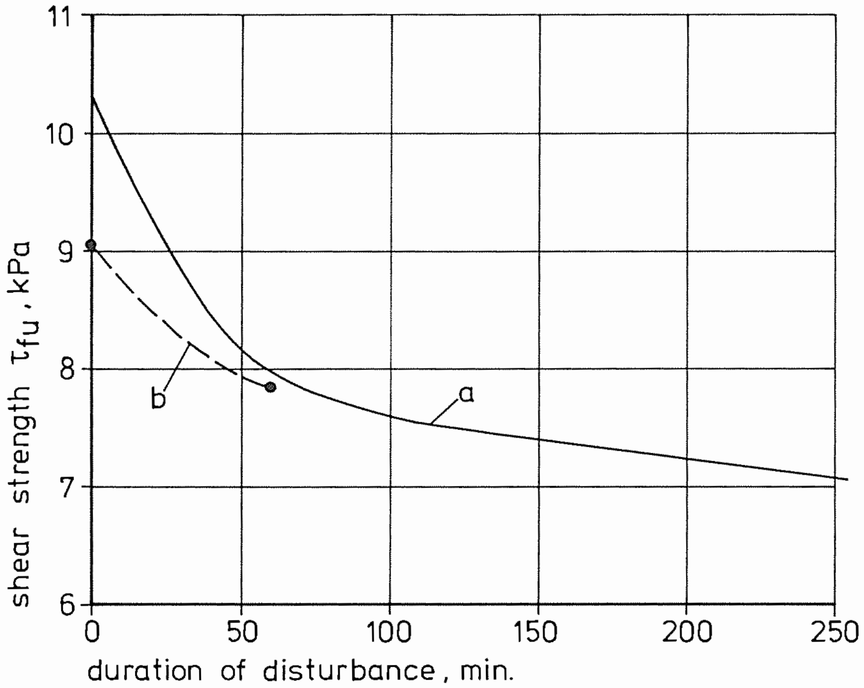
The sample transported from the field to the laboratory may already have been disturbed before testing. To check the disturbance of the sample laboratory tests can be performed on shear strength or compressibility. In all these tests, the Swedish fall-cone test for determination of the shear strength is the simplest and the most quick method. Therefore, it is proposed to be used for checking the disturbance of sample of soft homogenous clay. This method is only applicable when the typical relation between the shear strength and duration of disturbance (curve a in (1), Fig. 20) and the relation between the rate of decrease in shear strength and duration of disturbance ((2) in Fig. 20) are known. Due to test error ($\pm$3%) the disturbance area is evaluated as shown in Fig. 20 (2). To be able to know if the samples transported to the laboratory are disturbed or not, the following procedures can be carried out.

- Determine the shear strength by fall-cone tests on an undisturbed sample and on disturbed samples with certain duration of disturbance (for instance by vibrations).

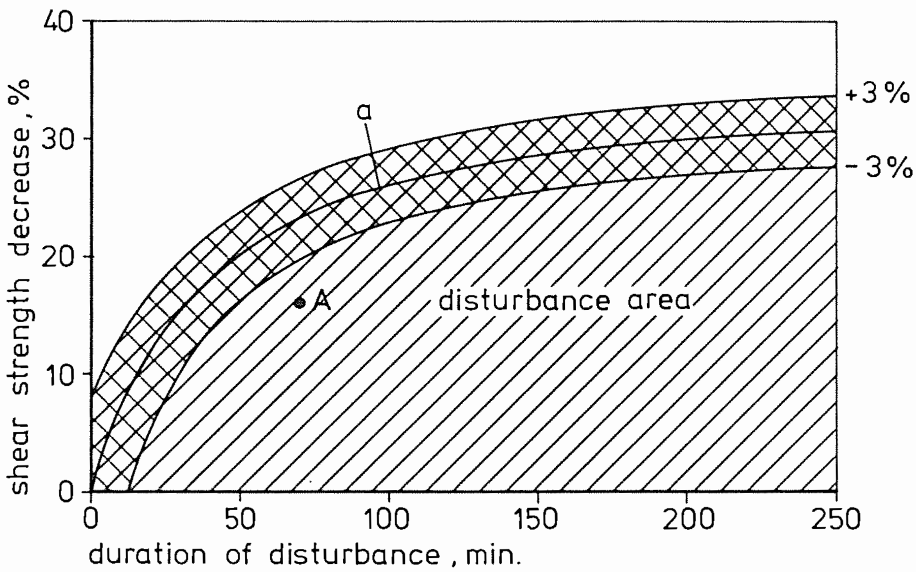
- Curve b as shown in Fig. 20 (1) based on the results from the fall-cone tests is plotted.

- Compare curve a and curve b. If the inclination of curve b is lower than that of curve a, it can be said that the samples may be disturbed.

- If the difference between the inclination of the two curves is not obvious, the percentage of decrease in τ_{fu} is calculated. The samples are considered to be disturbed when the percentage of decrease in τ_{fu} lies in the disturbance area (as point A in Fig. 20 (2)).



(1)



(2)

Fig. 20. Method for checking disturbance of sample.

6. INFLUENCE OF SAMPLE DISTURBANCE ON DESIGN

Results obtained by numerous other authors as well as by the author indicate firmly the influence of sample disturbance on the design parameters. In order to see the effect of sample disturbance on the design a simple calculation example is presented below. In this example the economic indices based on the design parameters of undisturbed and disturbed samples are compared.

In Bäckebol clay a strip footing with load P = 55 kN/m is to be founded at a depth z = 1.0 m below the ground surface. Laboratory tests give undrained shear strength τ = 10.4 kPa and τ = 7.3 kPa for undisturbed and disturbed samples respectively. The bulk density is 1.5 t/m^3. This sample disturbance affects the width of the strip footing under the same condition (P = 55 kN/m, z = 1.0 m).

The ultimate bearing capacity is calculated by the formula:

$$q_u = C \cdot N_c + \gamma z \, N_q$$

where

q_u = ultimate bearing capacity

$C = \tau$ = undrained shear strength

γ = bulk density

z = depth at which footing is to be founded

N_c, N_q = bearing capacity factors

According to Terzaghi, when $\phi = 0$ we have:

$$N_c = 5.7; \quad N_q = 1.$$

The allowable bearing capacity q_a is calculated by the formula:

$$q_a = q_u / F_c$$

where

q_a = allowable bearing capacity

q = ultimate bearing capacity

F_c = factor of safety

Tab. 13 shows calculated results based on the values of undisturbed and disturbed samples with a factor of safety F_c = 2.0 for a light structure.

Tab. 13. Comparison of calculated values based on undisturbed and disturbed soil samples for strip footing P = 55 kN/m, z = 1.0 m.

Sample	Undrained shear strength τ (kPa)	Ultimate bearing capacity q (kPa)	Allowable bearing capacity q_a (kPa)	Width of footing B (m)
Undisturbed	10.4	74.28	37.0	1.48
Disturbed	7.3	56.60	28.3	1.94

As seen in Tab. 13 the sample disturbance affects directly the design parameters (shear strength) and that also affects calculated values (bearing capacity and width of footing). Under the same construction conditions, the width of a strip footing calculated on the results obtained from disturbed samples is 14-31% larger than that from undisturbed samples.

As the width of the footing increases the foundation cost increases.

In the case where the width of the footing could not be increased a reduction of the weight of the structure has to be carried out. The weight reduction is generally made by using light materials that are much more expensive than traditional materials and finally the construction cost is increased.

From this simple calculation example it can be said that the sample disturbance affects the design parameters and therefore directly affects the economic index of a construction. The unnecessary additional concrete foundation cost or the additional cost for light materials will lead to an increasing total construction cost. If the sample disturbance is not taken into account, the engineer may underestimate the soil conditions. If the design parameters are based on the underestimated values, the construction cost will be increased and the project will therefore be un-economic.

Finally it can lead to the conclusion that if a quantitative determination method of effect of sample disturbance is established, an economical exploration and rationalistic design could be performed.

7. CONCLUSIONS

7.1 Conclusions

The investigation allows to make the following conclusions:

1. There are different effects of sample disturbance. The main effect of sample disturbance is to produce changes in the geotechnical properties of soft clays.

2. The Swedish Standard Piston Sampler is valuable for soft clays. Compared with the middle tube, the sample quality in the upper tube is more affected by sample disturbance. However, this effect is negligable.

3. The main effect of sample disturbance is to produce the decrease in shear strength and compressibility. Due to disturbance the disturbed samples lose a part of their shear strength, preconsolidation pressure, coefficient of consolidation, coefficient of volume change. The decrease in shear strength, preconsolidation pressure and coefficient of consolidation depends on the degree of disturbance; the more the sample is disturbed the greater is the decrease in these parameters. It is found that the rate of decrease in these parameters is largest at the first degree of disturbance.

4. The sample disturbance affects the stress-strain relationships of soft clays. The shape of the stress-strain curves of unconfined compression tests and of oedometer tests is influenced by sample disturbance. Due to disturbance the oedometer curves of disturbed samples are displaced further and further away from the curve of an undisturbed sample. In the unconfined compression tests the strain at failure for disturbed samples is generally greater than that for an undisturbed sample.

5. There are no changes in the physical properties such as water content, liquid limit and density due to sample disturbance.

6. The effect of sample disturbance can be determined by means of different laboratory tests. For soft clay the oedometer tests, the unconfined compression test and the Swedish fall-cone test can be used for this purpose. The effect of sample disturbance can be determined on the basis of the following parameters:
   - stress-strain curve of oedometer tests on unconfined compression tests
   - preconsolidation pressure σ_c'
   - coefficient of consolidation c_v
   - undrained shear strength τ_{fu}

7. The undrained shear strength determined from fall-cone tests can be used as a parameter for determination of the effect of sample disturbance. However, due to test errors (especially for non-homogeneous clay) this parameter is only suitable for soft homogeneous clay and it may be applicable for determination of the effect of sample disturbance. For this purpose the unconfined compression test or the triaxial test are preferable methods. The unconfined compression test is simple and reliable, but the shape and position of the failure surface of the sample can affect the test results.

8. The effect of sample disturbance influences directly the design parameters which in turn greatly affect the construction cost of the project. If a quantitative determination method of the effect of sample disturbance was established, an economical exploration and rationalistic design could be performed.

7.2 Recommendations

1. For homogeneous soft clay it is possible to use the undrained shear strength measured by fall-cone tests as a parameter for determination of the effect of sample disturbance.

2. In order to determine the influence of transportation or other sample disturbances after sampling fall-cone tests should be carried out right after sampling in the field and in the laboratory for comparison.

3. Soil samples may get some disturbances during extrusion from the sample tubes before the laboratory tests. It is possible to determine the influence of the sample extrusion on the sample quality of soil especially of soft soil.

4. The laboratory data are generally affected by sample disturbance. Suitable methods for correcting these data should be established in order to get true values of the soil in situ. This may be performed on the basis of laboratory testing combined with field testing.

7.3 Further investigations

This study has only been a preliminary investigation to determine some effects of sample disturbance of Swedish soft clays (Tornby clay and Bäckebol clay). Only some laboratory tests were carried out and a simple calculation example was performed. In the further investigations the following work should be performed in order.

1. To determine the effect of sample disturbance of different types of soils.

2. To compare the effects of sample disturbance between sample sizes and sampling methods (samplers) to establish the best sampling methods.

3. To determine the effect of sample disturbance in the laboratory as well as in the field by different tests in order to reduce the disturbance to a minimum and to get correct geotechnical properties corresponding to the in situ state.

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