Settlement estimation by using continuous oedometer tests

Emploi des essais oedométriques (essai CRS) pour le calcul des tassements

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ABSTRACT: On soft clay areas, where settlements are expected to cause problems, one has to find the best possible parameters in order to calculate the settlements and consolidation time. Traditional oedometer tests with incremental loading are recommended. However, in many cases the testing time is limited, and that is why continuous loading oedometer tests are carried out.The best equipment is available but there is still doubt whether the quickly and easily measured parameters are correct. Pre-consolidation pressures seem to have increased and in some cases they are unrealistically high compared to the geostatic pressures. A comparison between 24-hour tests and continuous tests has been done.

1 INTRODUCTION

This article deals with the choice of the parameters for settlement analysis. During the last 20 years the tangent modulus method (Janbu 1963) (or exactly the parameters of the tangent modulus) has been used in one-dimensional settlement calculations in Finland. The method is suitable for cohesive soils but is has been used also for analysing non-cohesive soils. The stress-strain relationship is described with a power function (Eq. 1).

$$\epsilon_l = (1/m\beta)\,(\sigma/\sigma_v)^\beta + C \qquad (1)$$

where m, β and C are parameters and σ_v = 100kPa

In the calculations only two parameters of the equation (1) are needed:

- m modulus number
- β stress exponent.

The parameters have different values when the soil is normally consolidated (m, β, m_1, β_1) or overconsolidated (m_2, β_2). Of course the pre-consolidation pressure (σ_p) is needed in the calculations. Modulus number, stress exponent and pre-consolidation pressure are normally determined from the results of oedometer tests.

1.1 *Standard oedometer test (STD)*

The traditional testing method is 24 hours incrementally loaded oedometer test. The results of the incremental loading test (in this article called the standard test STD) can be used for settlement analysis without any modifications or reduction of the parameters. In practice the parameters are often calculated by using t=24h values instead of U=100% values. The problems in the interpretation of the test results are mostly concentrated to the evaluation of the pre-consolidation pressure. Several graphical and analytical methods are developed for determining σ_p but it is not possible to find an exact value. Several load increments (>3) on the normal compression line is necessary for reliable determination of the parameters. STD test is also suitable for determining the coefficient of primary consolidation of soil.The reliable determination of the secondary consolidation coefficient often needs longer load duration than 24 hours.

1.2 *Constant Rate of Strain oedometer test (CRS)*

In many labortories continuous loading oedometer tests are carried out instead of incremental loading tests. The Constant Rate of Strain (CRS) test and the Constant Porepressure Ratio (CPR) test are normally lasting only 1...2 days. In most cases the tests and the processing of the test data are fully automatized, and that is why the test results are quickly available. CRS and CPR testing has several advantages, but the preliminary problem of these tests is still unsolved: the results must be reduced before using in the settlement calculations.

1.3 *Reducing of the CRS-test results*

In this article three different reducing methods are compared:

- SS, Swedish Standard method (Svensk Standard 1991),
- TL, empirical method (Tim Länsivaara, 1996) and
- LS, large strains method.

The Swedish Standard method proposed by Sällfors (1975) is a practical graphical method for finding the smallest effective stress value (σ_p) for elastoplastic strains. This method is suitable when the tangent modulus is used for calculating settlements. The effective stress - tangent modulus -curve is moved along the effective stress axis.The value of the reduction factor is the same as the value of reduction factor of the pre-consolidation pressure. This method is not very good for the calculations which uses the parameters m and β instead of the tangent modulus M, because these parameters are not at all reduced. This problem is obvious when $\beta < -0.5$.

The empirical reduction method of Länsivaara (1996) is based on the test results from Canada (Leroueil et al 1985) and from Finland (Länsivaara 1996). The reduction of the parameters σ_p and m is dependent on the rate of strain in CRS-test and the rate of strain approximated in the calculations (Equation 2). The reference rate for calculations used in this article is 10^{-7} 1/s. When the rate of strain in CRS -test is 0.0025mm/min for 15 mm sample, the reduction factor for pre-consolidation pressure is k=1.27. This reduction method is dependent on the empirical relationship between the rate of the strain and normalized pre-consolidation pressure. After the experience of some years it is possible to check if the used relationship is correct for Finnish clays.

Table 1. Taimisto, Helsinki. Oedometer test results, and the reduction of CRS test results.

Test results									Reduced test results								
N:o of test	Depth m	w %	σ'_{vo} kPa	σ_p kPa	m_1	β_1	C_1	Note $\dot{\varepsilon}_1$, %/h	σ_p SS	k TL	σ_p TL	m TL	σ_p LS	m LS	β LS	C LS	Limit kPa
CRS 5205A4	4.0	59.0	61	94	3.4	-0.985		0.8	82	1.25	75	4.2	95	3.9	-0.79		135
STD 1921	4.02	87.4	61	69	4.2	-0.767	0.435	t=1d									
				79	3.8	-0.856	0.416	U=100%									
CRS 1023	4.05	90.4	61	79	3.8	-0.927	0.432	1	65	1.27	62	4.7	63	4.9	-0.58	0.51	115
STD 1935	4.07	91.0	61	49	5.9	-0.426	0.572	t=1d									
				54	6.1	-0.388	0.591	U=100%									
CRS 5205A5	5.4	85.7	68	85	3.4	-1.606		0.8	75	1.25	68	4.9	63	5.7	-0.53		120
STD 1922	5.42	100	68	63	4.4	-0.599	0.532	t=1d									
				64	4.8	-0.403	0.652	U=100%									
CRS 1018	5.47	97.7	68	85	2.8	-1.333	0.392	1	76	1.27	67	3.9	66	4.6	-0.66	0.48	115
CRS 1033	5.37	82.0	68	56	6.2	-0.635	0.427	0.33	45	1.18	47	6.9	44	7.3	-0.38	0.54	100
CRS 5205A6	6.8	73.6	75	86	5.3	-0.563		0.8	74	1.25	69	6.0	85	5.4	-0.56		85
STD 1923	6.82	80.4	75	69	6.1	-0.407	0.521	t=1d									
CRS 1024	6.85	84.0	75	86	5.3	-0.550	0.436	1	77	1.27	68	6.0	71	6.4	-0.35	0.55	150
CRS 1034	6.87	84.6	75	95	4.5	-0.682	0.418	4	77	1.41	67	5.7	65	6.6	-0.34	0.57	150
CRS 5205B5	5.5	88.7	68	81	3.3	-1.482		0.8	70	1.25	65	4.6	62	5.2	-0.58		115
STD 1924	5.52	102	68	63	4.2	-0.830	0.461	t=1d									
STD 1936	5.56	100	68	68	3.5	-1.184	0.410	t=1d									
CRS 1019	5.57	99.9	68	77	3.1	-1.279	0.389	1	70	1.27	61	4.2	66	4.3	-0.79	0.45	100
CRS 5205B6	6.2	92.1	72	101	1.8	-2.184		0.8	88	1.25	81	2.9	78	4.0	-0.75		125
STD 1925	6.22	106	72	76	2.9	-1.122	0.452	t=1d									
CRS 1020	6.25	83.3	72	95	2.8	-1.260	0.363	1	80	1.27	75	3.8	66	5.4	-0.54	0.48	150

Test methods
STD Standard test, incremental loading (t=24h)
CRS Constant Rate of Strain

Reduction methods
TL Tim Länsivaara (Länsivaara 1996)
SS Swedish Standard (Svensk Standard SS 02 71 26, 1991)
LS Large Strain

Limit means minimum effective pressure for fitting the parameters of LS - method.

$$k = (\dot{\epsilon}_{test} / \dot{\epsilon}_{calc})^B \tag{2a}$$

$$\sigma_{pcalc} = \sigma_{ptest} / k \tag{2b}$$

$$\beta_{calc} = \beta_{test} \tag{2c}$$

$$m_{calc} = m_{test}\, k^{\beta} \tag{2d}$$

Parameter B is dependent on the shape of the rate of strain - pre-consolidation pressure -curve. In this article the value of B=0.073 (Länsivaara 1996).

The large strains method is based on the stress-strain observations in the CRS-test when the compression ϵ_l>15...20% which often occurs when $\sigma \approx 1.5\ \sigma_p$. The large strain method is explained in Chapter 3.

2. GEOTECHNICAL CONDITIONS

Several standard oedometer tests and CRS tests were carried out on undisturbed clay samples which were taken from Taimisto, Helsinki. The soft clay layer is 10....15m thick. The clay is normally consolidated or lightly overconsolidated. The soil profile is situated in the area where the regional stability is critical ($F \approx 1$).

Oedometer test results are presented on table 1. Standard oedometer tests (STD) were carried out at Helsinki University of Technology. The testing procedure were traditional with 24 hours double load increments. Constant Rate of Strain tests (CRS) were carried out both at Helsinki University of Technology and at Helsinki City.

The calculation of the overburden pressure (σ'_{vo}) is based on the bulk density values and the measured ground water level (3,5m below the ground surface) on the neighbouring area. No information of the excess pore water pressure was available. This is a typical situation in geotechnical design: reliable data from the changes of water table and pore water pressure is lacking.

The values of the pre-consolidation pressure (σ_p) of STD tests are simple to evaluate because of the steep slope of normal compression line. All the values are near to the maximum value of van Zelst (1948) method. The values of the pre-consolidation pressure (σ_p) of CRS tests represent the maximum value of pre-consolidation pressure which is determined by fitting the Equation (1) to the test results. This value of (σ_p) is not suitable for settlement analysis.

3 REDUCTION OF CRS-TESTS BY METHOD OF LARGE STRAINS

One way to avoid problems dealing with pore pressures and the rate of strain in CRS-tests is to study large measured values of strains and stresses. The most suitable method of calculating consolidation settlements is probably a power-function (Eq 1). It contains a simplyfied linear Hooke's law with β = 1. Critical state model is achieved with the value of β = 0.

Usually the parametres are determined by the means of the least squares method to obtain the best overall response. However this method does not test whether the power-function is valid througout the whole range of stress - strain relationship.

The parametres of a general power function (Eq 1) are easily determined by Equation (3).

$$\log(M) = \log(m) + (1-\beta) * \log(\sigma/\sigma_v) \tag{3}$$

where $M = \delta\ \sigma / \delta\ \epsilon$.

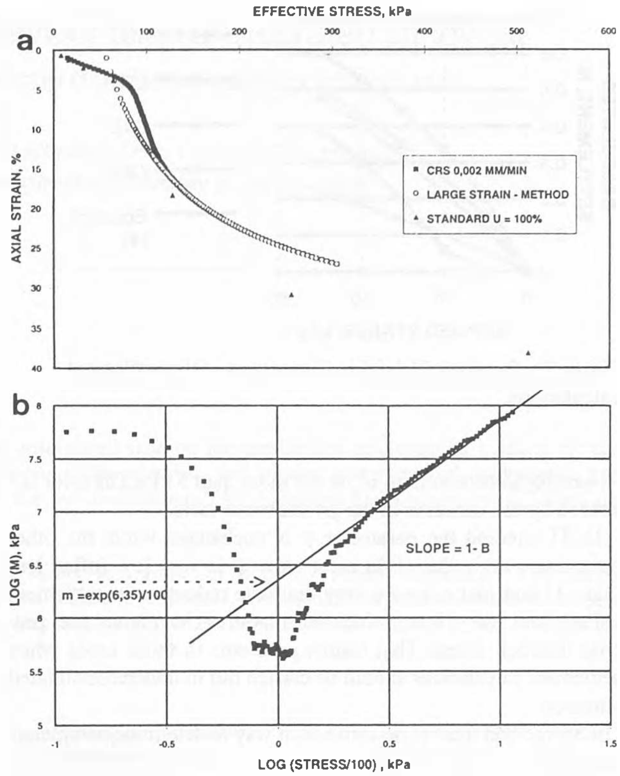

Figure 1. Taimisto, Helsinki. CRS5205A5. STD1922. a) data and reduced curve (LS) b) determination of parameters (LS)

At the same time the suitability of the power-function (1) for settlement calculations can be tested. The relationship of measured values plotted in scale log (M) - log (σ/σ_v) is linear in that range where relationship (1) is valid. Usually a good response is found with large and small values of strains and stresses. In the neighbourhood of pre-consolidation stress the power function is not always valid because of the rate of strain and the irregularities in pore pressures. By this method the influence of irregular measured values can be neglected. In the range of large strains and stresses the influence of pore pressure is relatively smallest. This is illustrated in Figure 1 where an example of determining the parametres by method of large strains is shown. Also in Figure 1 the measured and the calculated values are compared. Also results of standard 24-hour oedometer (STD) test of similar sample are shown.

The irregulaties of the relationship of modulus - stress - curve above pre-consolidation stress are reduced by large strain method. The method is similar to the method developed by Sällfors.

The difference between the reduced and measured values is mainly depending on the ratio of the consolidation "coefficient" c_v and the rate of strain in CRS-tests. The reduced parametres show to be near to those determined by standard oedometer test or by Sällfors as illustrated in Table 1.

One priviledge over the other reduction methods in LS method is that the measured values are not changed at all - only part of them is neglected so that the equation (1) is forced to suit for settlement calculation purposes.

4 CONCLUSIONS

The most important parameter used in settlement calculations is the pre-consolidation stress. As shown in Table 1 the parameters of CRS-test should be reduced, because almost in every case σ_p in CRS-test is unrealistically high compared to σ'_{vo} or to σ_p in STD-test. In these cases there is no reason in the site why the clay should be overconsolidated.

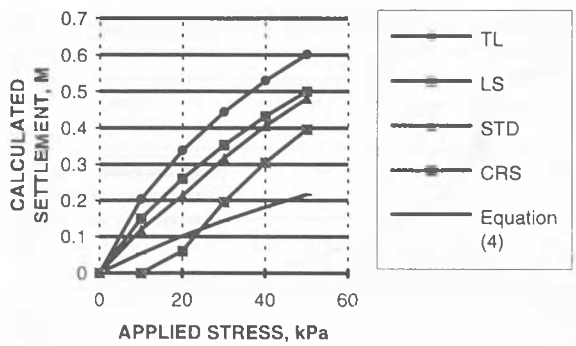

Figure 2. Taimisto, Helsinki. The results of the settlement calculations.

The error in determining σ'_{vo} is not more than 5 kPa.The error is - caused by the variation in the groundwater table.

In TL-method the parameter β is unchanged while the other parameters are reduced. In most cases β is very low (often less than -1) and that causes a very dramatic reduction in settlement values and very low values of modulus M above the pre-consolidation stress. That causes problems in those cases when settlement calculations should be carried out in underconsolidated situation.

In SS-method there is no convenient way to determine parameters m and β.

In LS-method the measured test results are not changed. Only the suitability of equation (1) is tested graphically. In cases when β is larger than ~ - 0,5 there will be no significant reduction of parameterss in CRS-test.

The surveyed clay area, which is representated by parametres shown in Table 1 (laboratory tests 1921, CRS 1023, 1922, CRS 1018, 1923 and CRS 1024) is assumed to be loaded with 10 - 50 kPa applied pressure. The consolidation state in all cases is assumed as determined in Table 1. The results of settlement calculations are plotted in Figure 2. The settlement calculations have also been carried out by the means of equation (4).

$$\epsilon = 0,85 * \mathrm{sqrt}(w) * \log^{10}((\sigma'_{vo} + \Delta\sigma)/\sigma'_{vo}) /(2,65 + 1/w) \qquad (4)$$

where w is water content, $\Delta\sigma$ = applied stress and 2,65 is the specific gravity of soil.

This example shows that calculations made by the help of STD-test, CRS-test reduced by LS-method or by TL-method do match quite well. On the other hand CRS-test without any reduction according to this data will result to wrong values of settlements. The reason for this is mainly the high values of pre-consolidation stresses of unreduced CRS-tests. The high values of pre-consolidation stress are mainly caused by unreliable pore pressure measurements. The weakest point in CRS-test is pore pressure measurement; that is why you have to reduce the parameters.

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