Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1007

Settlement calculation with stress-dependent parameters

Calcul de tassement avec parametrès dépendants de la pression

A. Aalto, P. Vepsäläinen & O. Ravaska
Dept. of Civil and Environmental Engineering, Helsinki University of Technology, Finland

ABSTRACT
Inaccurate and scattering results of the international competition for calculating settlement of the Haarajoki test embankment in Finland initiated a project in which stress-dependence of the calculation parameters was studied. These parameters are permeability *k*, coefficient of consolidation c_v and the Ohde-Janbu parametrs *m* and β. The effect of *k* and c_v is discussed elsewhere and this paper deals with the effect of the parameters *m* and β. Based on a large amount of settlement data a stress-dependence model for *m* and β was created, and settlement calculations were carried out and compared with measured data to clarify the effect of stress-dependence.

RÉSUMÉ
Dispersion des résultats même inexacts de la compétition internationale pour calculer le tassement de remblai d`essai de Haarajoki en Finlande. Cela a entrepris un projet dans lequel on étudiait dépendance des contraintes des paramètres de calcul. Ces paramètres sont perméabilité *k*, coefficient de consolidation *c*, et le Ohde Janbu paramètres *m* et $\beta$. L`effet de k et c_v est discuté d`ailleurs quand ce document ci se trait de l`effet des paramètres *m* et β. On a crée un modèle de dépendance des contraintes pour m et β qui se base sur un matériel de tassement nombreux. Ainsi les calculs de tassement étaient réalisés et comparés avec matériel mesuré pour clarifier les effets de dépendance des contraintes.

1 INTRODUCTION

In 1997 the Finnish Road Administration organized an international competition for calculating settlement of a test embankment at Haarajoki clay area in Finland (http://www.hut... , 2004). The results were very surprising. Even though all the competitors had the same information, the scattering of the results was enormous. The measured settlements after two years in two calculation points were 320 and 500 mm while the calculated ones varied in the range of 120…1800 mm. The results were discouraging and proved that there is much to do in improving the accuracy of the settlement calculations. Later on a project aiming for that was built up with the financial aid of the Academy of Finland. The paper presents some of the results obtained.

In the Nordic countries the calculation of settlement is normally carried out using the Ohde-Janbu stress-strain model the parameters of which, modulus number *m* and stress exponent β, are obtained by fitting the model function to a set of oedometer data. Settlement is then calculated using these parameters instead of the parameter C_c which is more commonly used in the world but too rough to represent the settlement properties of Nordic clays in a large stress scale. The present settlement calculation methods are based on the wrong assumption that the four parameters needed are constants in each soil layer independent of stress (depth). The tentative calculations carried out at the Laboratory of Soil Mechanics and Foundation Engineering of the Helsinki University of Technology showed that if the stress-dependence of one particular parameter, the coefficient of consolidation c_v, is taken into account, the calculation time for the total settlement will become two of three times longer (Ravaska and Vepsäläinen, 2001). The obvious fact that permeability decreases during consolidation was taken into account using a strain-permeability model discussed in detail by Ravaska and Aalto (2003).

After that an intensive study to declare the stress-dependence of the Ohde-Janbu model parameters *m* and β was started. Continuous samples were taken from deep and homogeneous clay formations. The depths and preconsolidation pressures were compared with the corresponding *m* and β values in order to build up a mathematical model which presents their relationship and which was to be incorporated into the settlement calculation program. Preliminary considerations about this relationship were discussed by Aalto et al. (2004). The present paper will discuss them in more detail and observed settlements will be compared with the ones calculated by a program which takes into account the stress-dependence of permeability *k*, coefficient of consolidation c_v, modulus number *m* and stress exponenent β.

2 OHDE-JANBU TANGENT MODULUS CONCEPT

The Ohde-Janbu tangent modulus model, (Ohde, 1969) and (Janbu, 1967), is presented by Eq. (1).

$$M_t = \frac{d\sigma}{d\varepsilon} = m\sigma_r\left(\frac{\sigma}{\sigma_r}\right)^{1-\beta} \tag{1}$$

where σ is vertical stress, σ_r reference stress of 100 kPa and the model parameters *m* and β are named as modulus number and stress exponent respectively. The strain is presented by Eqs. (2) and (3).

$$\varepsilon = \frac{1}{m\beta}\left[\left(\frac{\sigma}{\sigma_r}\right)^{\beta} - \left(\frac{\sigma_0}{\sigma_r}\right)^{\beta}\right], \quad \beta \neq 0 \tag{2}$$

$$\varepsilon = \frac{1}{m}\ln\left(\frac{\sigma}{\sigma_0}\right), \quad \beta = 0 \tag{3}$$

where σ_0 is the initial stress. The parameter *m* represents the compressibility of the soil and β the form of the stress-strain curve. If $\beta < 0$ (normally consolidated clay), the curve is concave on a semi-logarithmic scale while if $\beta > 0$ (sand, overconsolidated clay), it is convex. In the special case of $\beta = 0$ (silt), Eq. (3) must be used as Eq. (2) is not valid. Eq. (3) corresponds to the C_c model with a linear relationship between the logarithm of stress and the void ratio. The relationship between m and C_c can be written as Eq. (4).

$$m = \frac{(1+e_0)}{C_c}\ln 10 \qquad (4)$$

where e_0 is the initial void ratio.

The numeric values of the parameters m and β can generally be characterized as the coarser material the higher are both values and therefore a certain correlation must exist between them, see e.g. Fig. 1.

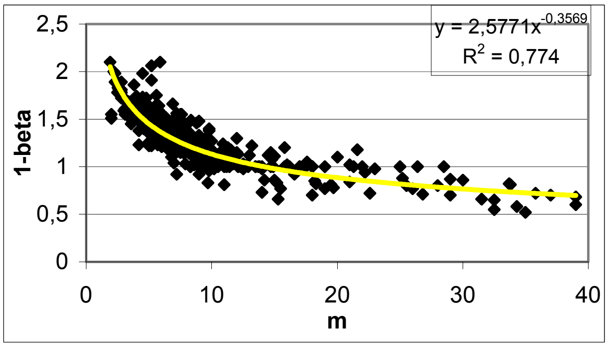

Figure 1. Correlation between m and 1-β for a number of Finnish clays

3 STRESS-DEPENDENCE OF THE MODULUS NUMBER ④ AND STRESS EXPONENT β

The stress-dependence of the modulus number m was investigated by performing a large number of oedometer tests. Continuous samples were taken from deep and homogeneous clay formations in ten test sites of the coastal part of Southern and Western Finland (Fig. 2). The clay formations in the test sites consist of soil material with a clay content of 26-90 % and an organic content of 0-9 %. Preconsolidation pressures were compared with the corresponding m. The test data are based on 1-day settlement results (the loading time of one step is 24 hours).

Figure 2. Test sites in Southern and Western Finland.

At first glance the stress-dependence of the modulus number m was not evident, but further data processing revealed the importance of water content of the samples in the case of stress-dependence. The dependence of modulus number m and preconsolidation pressure, σ_c can be seen in Fig. 3 in which water content values (55%, 75%, 100% and >112%) form parallel limiting values of particular two-dimensional areas, Eq. (5).

$$m = k_1 \times \sigma_c + B \qquad (5)$$

The slopes of the water content lines are constant as k_1 = -0.08 and the constant B varies between 8.8 and 14.5.

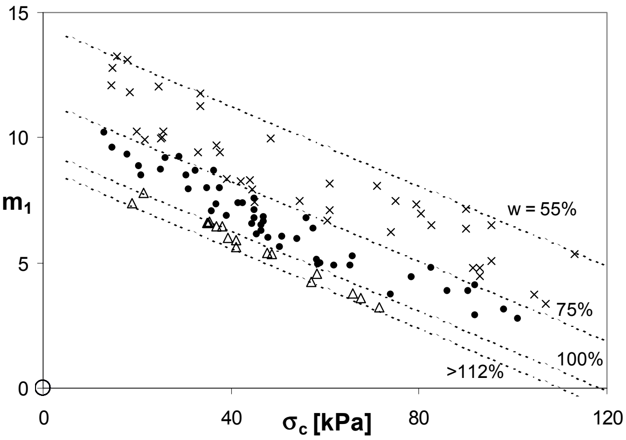

Figure 3. Modulus number m vs. preconsolidation pressure σ_c in different water content areas.

The function of constant B is parabolic between the water contents of 55 – 112 %. For water contents more than 112 %, the function is assumed to be constant (Fig. 4). Now the modulus number m gets the form of Eq. (6) where the water content w is a dimensionless number.

$$m = -0.08\times\sigma_c + \frac{7,94}{w} \quad \Rightarrow w \le 55\% \qquad (6a)$$

$$m = -0.08\times\sigma_c + 10.6w^2 - 27.6w + 26.4 \qquad (6b)$$

$$\Rightarrow 55\% < w < 112\%$$

$$m = -0.08\times\sigma_c \quad \Rightarrow w \ge 112\% \qquad (6c)$$

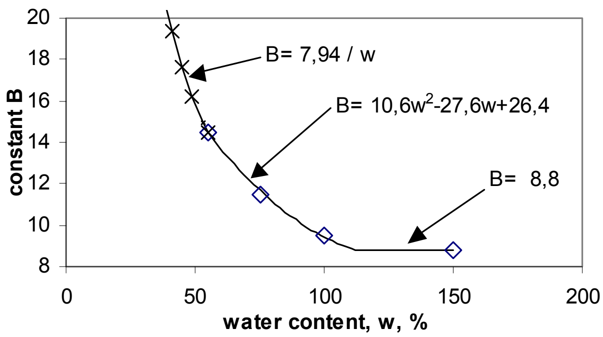

Figure 4. Water content w vs. constant B.

The correlation between the modulus number m and the stress exponent β was investigated using the same oedometer test data as above. The correlation was quite moderate (Fig. 5) and Eq. (7).

$$\beta = 0.63\ln(m) - 1,59 \tag{7}$$

The scattering of test data from the western coast test sites (Vaasa, Murro, Perno and Turku) was evidently lower than the total scattering. The research work is now concentrated on different geological properties of sedimentary deposits in different parts of Finland.

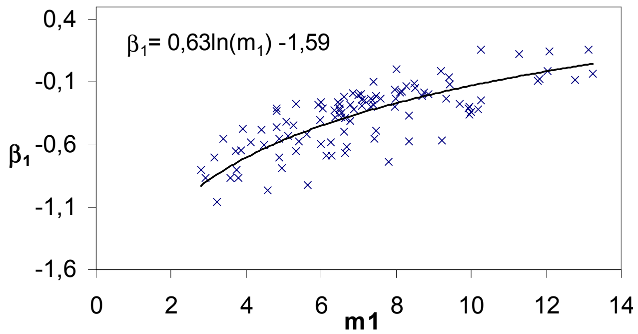

Figure 5. Modulus number m vs. stress exponent β.

4 CONSOLIDATION TIME PARAMETERS

In the settlement calculations presented in the next chapter, the same models for the coefficients of permeability and consolidation, i.e. k and c_v, were used as discussed in the papers Ravaska and Vepsäläinen (2001), Ravaska and Aalto (2003) and Ravaska et al. (2003). Permeability and its dependence on the strain was modelled by Eq. (8).

$$k = k_0(1-\varepsilon)^{\alpha} \tag{8}$$

where k_0 is permeability at zero strain, ε is strain and α constant. Eq. (8) combined with Terzaghi's equation for c_v and Janbu's Eq (1) gives a stress-dependent model for c_v, Eq. (9), in which also the decrease of permeability during consolidation is taken into account.

$$c_v = \frac{k_0(1-\varepsilon)^{\alpha} m\sigma_r}{\gamma_w}\left(\frac{\sigma}{\sigma_r}\right)^{1-\beta} \tag{9}$$

5 CALCULATION EXAMPLE

5.1 *Soil layers and parameters*

As a calculation example the settlement of the Murro test embankment was analyzed with the stress-strain model presented above. The test embankment was set up in 1993 by the Finnish Road Administration near the town of Seinäjoki in the western part of Finland. The embankment was well instrumented and observations of settlements, horizontal displacements and pore pressures have been collected for more than ten years. Site investigations, sampling and laboratory tests were made before the construction of the test embankment and also in 2001 under the embankment in order to study the changes that have taken place in the soil. A summary of the test results was published by Koskinen et al. (2002), and it was used as a basis for new calculations, see Table 1.

The models of the modulus number and the stress exponent, Eqs. (6) and (7), are valid for normally consolidated parts only. As the layer number 1 is overconsolidated, information is needed also of the overconsolidated part. In the layer no. 1 the preconsolidation pressure is 80 kPa and the modulus number m_{OC} = 100 and the stress exponent β_{OC} = 1 so that the modulus of compressibility M is independent of the effective vertical stress and is M = 10 000 kPa according to Eq. (1).

The ground water level is at the depth of 1.6 metres. The effective unit weight below the ground water level is calculated by subtracting the unit weight of water (10 kN/m^3) from the total unit weight γ_t in Table 1. In normally consolidated layers the preconsolidation pressure in Eq. (6) is the same as the initial effective vertical pressure calculated using the effective unit weights and depths of layers.

The permeability parameters k_0 and α in Eq. (8) were measured by CRS tests (Constant Rate of Strain) and by compression permeameter tests in an oedometer cell using the falling head method. The coefficients of permeability at zero strain k_0 are presented in Table 1. According to the permeability tests the model parameter α = 9.

Table 1. The soil layers and settlement parameters used in calculations.

Layer number	Soil type	Depth z, m	γ_t kN/m^3	w, %	k_0 m/a
1	Clay (OC)	0.0 - 1.6	16.2	50	0.22
2	Clay (NC)	- 3.0	15.6	70	0.21
3	Clay (NC)	- 4.7	14.5	90	0.19
4	Clay (NC)	- 6.7	14.5	90	0.13
5	Clay (NC)	- 8.3	15.1	80	0.095
6	Clay (NC)	- 10.0	15.1	70	0.095
7	Clay (NC)	- 11.5	15.5	70	0.095
8	Clay (NC)	- 13.2	15.5	65	0.095
9	Clay (NC)	- 15.0	15.5	65	0.095
10	Clay (NC)	- 17.0	16.0	55	0.095
11	Clay (NC)	- 19.0	16.0	55	0.095
12	Clay (NC)	- 21.0	16.0	55	0.095
13	Clay (NC)	- 23.0	16.0	50	0.095

5.2 *Loads and boundary conditions*

The width of the upper part of the test embankment is 10 metres, the length 30 metres and the height is 2.0 metres with the slopes 1:2 (height/length). The unit weight of the embankment material is 20 kN/m^3. The embankment load is given for calculations as a uniform vertical surface loading on a rectangular area. The construction time of the embankment is supposed to be 18 days. After that the vertical load is constant with time.

The consolidation boundary conditions are such that the upper surface of the layer number 1 and the lower surface of the layer number 13 are permeable.

5.3 *Calculation method and results*

The model presented by Eqs. (6)…(9) was programmed to the program SETTLE at the Laboratory of Soil Mechanics and Foundation Engineering, Helsinki University of Technology. The vertical stress distribution in the ground induced by the embankment loading is calculated by the elastic Boussinesq stress theory. The modelling of the primary consolidation stage is based on the one-dimensional Terzaghi consolidation theory with few modifications: Handling of several layers with both over and normally consolidated parts, the load history dependence and the solution by FEM with numerical time integration with the implicit method.

The calculated and observed settlements of the centre of the embankment are presented in Fig. 6. Settlements are in millimeters and time in years in linear time scale. Despite a very simple and easily measured settlement parameter, water content *w*, and a rough one-dimensional calculation method, the calculated and observed settlements are almost identical.

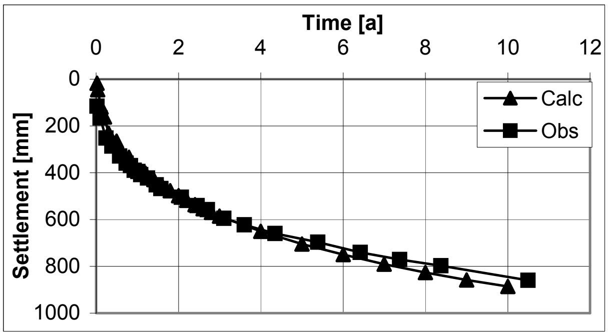

Figure 6. Calculated and observed settlements of the centre line of the Murro test embankment.

6 CONCLUSIONS

A settlement calculation with stress-dependent parameters was presented. Stress-dependence was taken into account partly with the Ohde-Janbu tangent modulus concept and partly with a strain-dependent permeability model. Numerous oedometer test results proved that the modulus number *m* in the Ohde-Janbu model has a correlation with the stress exponent β and therefore it was possible to replace β with a model function. It was also found that the modulus number *m* also correlates with the preconsolidation pressure and water content and thus also *m* could be replaced.

Finally, the only soil parameters needed as input parameters for the calculations were the unit weight, water content and permeability at the beginning of consolidation. The calculation method was tested with the settlement data obtained from the Murro test embankment. Despite a very simple and easily measured settlement parameter *w* (water content) and a rough one-dimensional calculation method, the calculated and observed settlements are almost identical.

ACKNOWLEDGEMENT

This paper was made with the aid of a research project "Comprehensive time-settlement model" financed by the Academy of Finland.

REFERENCES

Aalto, A., Lojander, M., Ravaska, O. 2004. On the stress-dependence of settlement parameters of Finnish clays. *NGM-2004, XIV Nordic Geotechnical Meeting, Proceedings.* Swedish Geotechnical Society, Report 3:2004, Vol. 2: I-27…I-38.

Janbu, N. 1967. Settlement calculation based on the tangent modulus concept. *Soil Mechanics and Foundation Engineering,* The Technical University of Norway.,Trondheim.

Koskinen, M., Lojander, M., Vepsäläinen, P., Modelling of Anisotropic Behaviour of Clays, Test Embankment in Murro, Seinäjoki, Finland. *Finnish Road Administration. Finnra reports,* Helsinki 2002. 62 p.

Ohde, J. 1969. Zur Theorie der Druckverteilung im Baugrund. *Bauingenieur* 14(1939):33/34:451-468.

Ravaska, O., Aalto, A. 2003. Modelling permeability in consolidation. *Proc. of the XIII Eur. Conf. of Soil Mech. and Geotech. Eng., Prague.* The Czech Geotechnical Society CICE, Czech Republic, Vol. 1: 205-210.

Ravaska, O., Aalto, A., Lojander, M. 2003. Consolidation properties of natural and disturbed clay. *Int. Workshop on Geotechnics of Soft Soils-Theory and Practice.* Vermeer, Schweiger, Karstunen & Cudny (eds.), Noordwijkerhout, The Netherlands. Verlag Glückauf GmbH, pp. 485-490.

Ravaska, O., Vepsäläinen, P. 2001. On the stress-dependence of consolidation parameters. *Proc. of the XV Int. Conf. of Soil Mechanics and Geotechnical Engineering, Istanbul.* A.A. Balkema Publishers. Vol. 1: 205-254.

http://www.hut.fi/Units/Civil/FoundationSoil/Tiedostot1/Painuma/pailase.htm 15.11.2004.