Behaviour of transdanubian clay under unloading and reloading

Comportement des transdanubiennes sols argileuses pendant chargement et déchargement

E. Koch
Széchenyi István University, Győr, Hungary

ABSTRACT

In recent years, in the field of geotechnical design, software based on FEM has come to the front. Advanced computer programs make it possible to use more developed soil models besides the most current elastic-plastic Mohr-Coulomb model. By using these computer programs, nonlinear behaviour of the soil can be followed better, even in the case of more complicated load events. Among the constitutive models incorporated in the commercial software the Hardening Soil Model (HS) and Soft Soil Model (SS) are the most promising ones. Observations and experience gained in tunnel construction, deep open excavation or preloaded embankment prove that with these soil models reality can be followed more accurately, especially in cases where unloading and reloading are present.

In order to produce the software input parameters, in case of more complicated soil model, more demanding laboratory tests are needed. In case of HS model one of the basic demands is to determine the power for stress-level dependency of stiffness (m), tangent stiffness for primary oedometer loading (E_{oed}^{ref}) and unloading/reloading stiffness (E_{ur}^{ref}).

The paper focuses on the behaviour of transdanubian clay common in Hungary. Sampling, laboratory investigations and evaluation aimed to determine the input parameters for the HS are described. Results based on a number of oedometric tests accomplished with unloading and reloading proved to be adequate for the computational purposes.

RÉSUMÉ

Dans ces derniéres années, des logiciels monté sur la methode des elements finis se mettre en avant dans le domain du projet de géotechnique. Ces nouvelles logiciels permettent d'utiliser diverses modéles avancées á coté de la modéle plastique-elastique (Mohr-Coulomb) qui est la plus courante. En utilisent ces nouvelles modéles, on peut suivre mieux la comportement de la sol en cas des chargement compliqués. Celles la modéle durcissemente (Hardening Soil Model-HS) et la modéle sol spongieux (Soft Soil Model-SS) qui sont les plus prometteuses. En juger par l'experience des mesures, il est possible de suivre la réalité plus précisement, particulierement dans les cas de déchargement et/ou réchargement, par example des tunnels, des fouilles de travaux ou des remblais prechargés.

Pour identifier les paramétres d'inputs d'une modéle de la sol plus compliquée, on a besoin des test de laboratoire plus détaillé. Definir du changement d'indice d'une puissance de la coefficient de compression tipique de la premiere chargement et la definition des coefficient relatifs pendant déchargement et rechargement - ces sont des exigences essentielles (m, E_{oed}^{ref} , E_{ur}^{ref})

On a fait des recherches sur le comportement des sols argileuses hongroises, utilisent les échantillons effectué sur le Sud de la Transdanubia. L'objectif de cette investigation scientifique a été la determination des paramétres d' inputs de la modéle HS dans le cas de la sol argileuse transdanubienne. Les resultats se basent sur les nombreuses test oedometrique, accomplissent réchargement/déchargement.

Keywords : nonlinear constitutive model, Plaxis, Hardening Soil Model, clay

1 INTRODUCTION

In civil engineering lately we have several projects where unloading and reloading are present. The typical case is creating a deep excavation in an urban area or applying preload to an embankment. Movements induced by consecutive excavations demand more accurate calculation and analysis of soil-structure interaction especially in urban areas. In such cases the strains and displacements cannot be descried accurately by the conventional constitutive model: the elasto-plastic model with Mohr-Coulomb failure criteria. Excavation and reloading can be analyzed only by a constitutive model capable of describing nonlinear behavior and hardening process. Advanced programs like PLAXIS now make it possible to use more complex soil models. The two most promising new models are: the Hardening Soil Model (HS); and the Soft Soil Model (SS). Observations and experience gained in tunnel construction, deep excavations, and preloaded embankments show that these soil models more accurately describe field behavior. This is especially true where there are complex loading and unloading sequences in construction.

Geotechnicans using these computational facilities often face the problem of having inadequate or inaccurate data for preliminary geotechnical estimations or suggestions for structural design. To overcome this difficulty the laboratory at Széchenyi István University has performed approximately two hundred oedometer tests using unloading and reloading during the last few years. We have analyzed the test results and established correlations with the computational model parameters. The aim of this research was to determine reliable relationships to substitute or estimate missing data and serve as a design aid during the preliminary phase of a project.

2 INVESTIGATED SOIL PROPERTIES

Table 1. shows the main parameters of the tests. The plasticity index ranges between 9 % and 60 % with an average value of 21 %. The consistency index is between 0,5 and 1,6, the average value is 1.0. The average value of the oedometer modulus due to primary compression is 12 MPa, and the average elastic unloading/reloading modulus is 47 MPa. Note that the unloading/reloading is about four times the primary

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-463

compression. This is in line with recommendations in the Plaxis manual which states that the quotient should be between three and five. The collected data have been evaluated statistically and correlations have been evaluated, and these results are presented below.

The samples originated from the southern part of Hungary. The points are above the A-line and diverge from the A-line with increasing liquid limit values (Figure 1). The equation of the best-fit line is $I_p=0{,}85\cdot(w_L-18{,}2)$ with a correlation coefficient r = 0,95. The tested samples plot are above the A-line, so they are mainly medium and high plasticity clay but with some silt too.

Figure 2. shows the relationship between water content and consistency index. The linear correlation is descried by the equation $I_c=1{,}9-0{,}04\cdot w$, with a correlation coefficient r=0,7.

3 PARAMETERS OF HARDENING SOIL MODEL

The Hardening Soil model (HS) is an advanced model for simulating the behavior of different types of soil, both soft and hard. A basic feature of the present HS model is the stress dependency of soil stiffness. The HS model uses moduli both from oedometer tests and from triaxial tests. Oedometer test results demonstrate the dependence of stiffness on confining stress. The increase of the oedometric modulus depends on the mean hardening stress. This is described by the equation

$$E_{oed} = E_{oed}^{ref} \cdot \left(\frac{c \cdot ctg\varphi - \sigma_1'}{c \cdot ctg\varphi + p^{ref}} \right)^m \tag{1}$$

where the E_{oed}^{ref} is the reference oedometer modulus, and the strength and stress parameters are raised to the power m. The reference pressure, p^{ref} is typically 100 kPa. Under triaxial conditions, the parameter E_{50} is the confining stress dependent stiffness modulus for primary loading and is given by the equation

$$E_{50} = E_{50}^{ref} \cdot \left(\frac{c \cdot ctg\varphi - \sigma_3'}{c \cdot ctg\varphi + p^{ref}} \right)^m \tag{2}$$

where E_{50}^{ref} is a reference stiffness modulus corresponding to the reference confining pressure p^{ref}. For unloading and reloading stress paths, another stress-dependent stiffness modulus is used (figure 3) :

$$E_{ur} = E_{ur}^{ref} \cdot \left(\frac{c \cdot ctg\varphi - \sigma_3'}{c \cdot ctg\varphi + p^{ref}} \right)^m \tag{3}$$

where E_{ur}^{ref} is the reference Young's modulus for unloading and reloading, corresponding to the reference pressure p^{ref}.

Table 1. Properties of the investigated soil

parameter		minimum value	maximum value	average value
w	%	10,0	35,0	22,5
I_p	%	9,0	59,9	20,9
I_c	-	0,5	1,6	1,0
E_{oed}	MPa	3,7	40,4	12,3
E_{ur}	MPa	8,6	125,6	46,6
A	-	0,007	0,118	0,032
B	-	0,22	0,92	0,57
m	-	0,08	0,78	0,43

Application of the HS model requires the user to have known m, E_{oed}^{ref} modulus and E_{ur}^{ref} modulus.

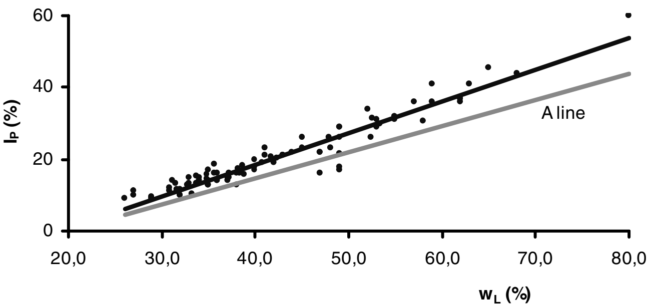

Figure 1. Correlation of Ip - w_L

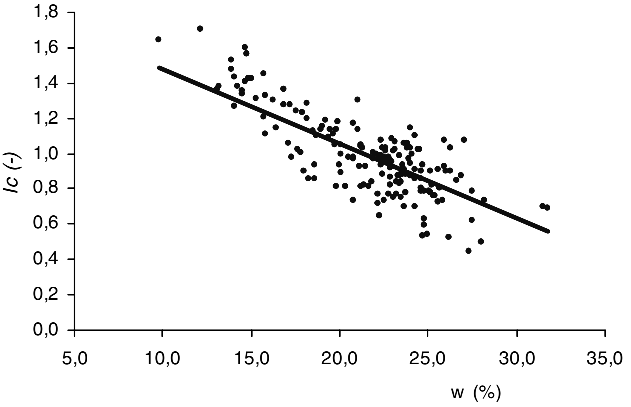

Figure 2. Best-fit linear regression between consistency index, I_c and water content, w

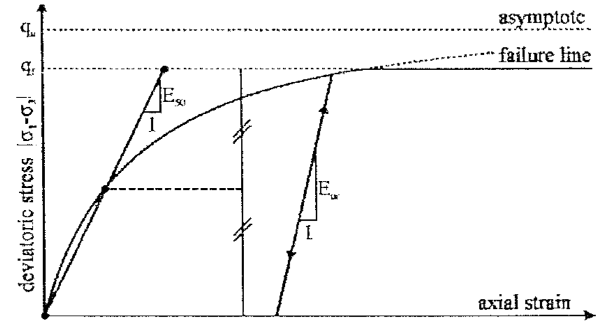

Figure 3. Deviatoric stress vs. axial strain showing E_{50} and E_{ur}

In order to determine the modulus input parameter, we model the stress-strain behavior as a power curve (as suggested by Janbu) :

$$\varepsilon_z = A\left(\frac{\sigma_z}{p}\right)^B \tag{4}$$

where ε_z – the vertical specific strain, σ_z - the vertical stress, A – scale factor relating stress and strain, B – power factor relating stress and strain, p=100 kPa. With this formula we get the same shape as it is in the HS model. By taking the derivative of the

$$E_s = \frac{p}{A \cdot B} \cdot \left(\frac{\sigma_z}{p}\right)^{1-B} \tag{5}$$

equation, we can formulate the oedometric tangent modulus as a function of σ_z:

Figure 4. shows the relation between A and B. The correlation can be descried by the equation:

$$B = \frac{0,125}{A^{0,41}} \tag{6}$$

The correlation coefficient is r = 0,86, implying good correlation The compression curve can now be descried exactly by these A and B parameters.

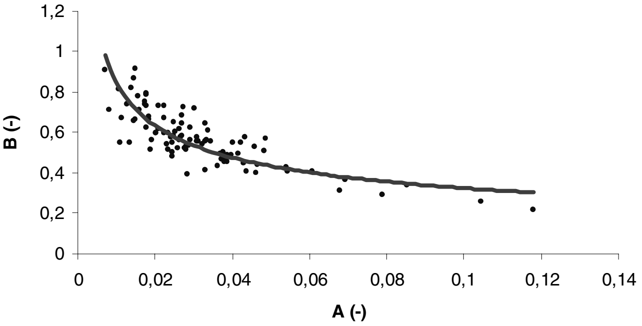

Figure 4. A and B parameters from oedometer test results

Further investigations were performed to establish correlations for other parameters. The relationship between parameter A and water content gives the best result (figure 5). The correlation coefficient is only r=0,64, which means moderately close relationship. The equation of the line is

$$A = \frac{3 \cdot w - 35}{1000} \tag{7}$$

The relation of the oedometer modulus due to primary compression and the modulus due to unloading/reloading is shown on figure 6. The second modulus is 3,6 times bigger than the first modulus with a correlation coefficient r = 0,7.

Figure 7. shows the correlation between the stress dependent stiffness according to a power law (m = 1-B) and the consistency index. It can be seen that the average m parameter hardly changes with the consistency index. The average value is m = 0,45 in case of plastic and hard clay.

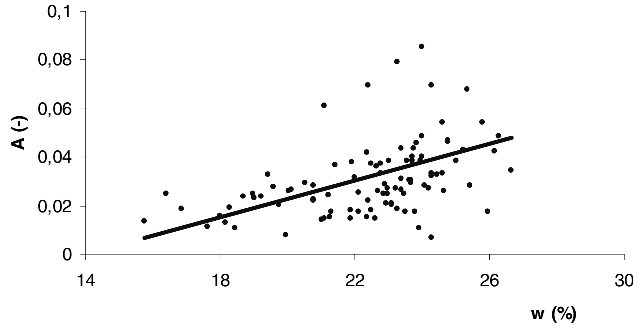

Figure 5. Relation between parameter A and water content

4 SUMMARY

In order to produce the software input parameters, for more complicated soil models, more demanding laboratory tests are needed. The basic demands are to determine the power for stress-level dependency of stiffness (m), tangent stiffness for primary oedometer loading (E_{oed}^{ref}) and unloading/reloading stiffness (E_{ur}^{ref}) when using the Hardening Model.

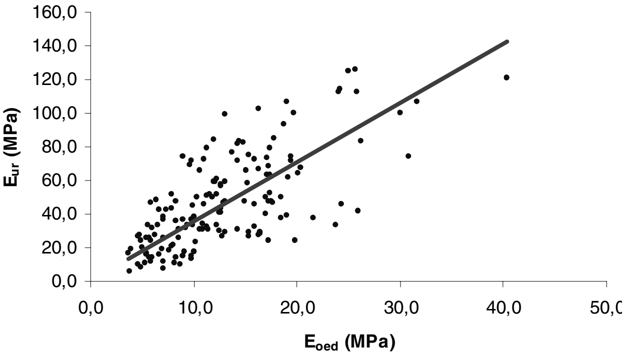

Figure 6. Relation between E_{oed} and E_u

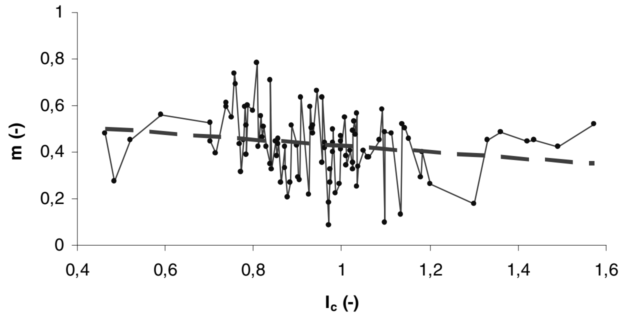

Figure 7. Relation between m and consitency index, Ic

The correlations determined from over 200 oedometer and index tests are: A = (3·w-35)/1000, B = $0,125/A^{0,41}$, $E_{ur} = E_{oed} \cdot 3,6$, m = 0,45.

These parameters are in agreement with the recommended value in the Plaxis manual. They can be applied by geotechnical engineers in cases where only index properties are available or when they are performing preliminary evaluations. These correlations also add confidence to the analyst when performing computations using Plaxis or other sophisticated programs.

ACKNOWLEDGEMENTS

This project has been undertaken by the Department of Structural Engineering, Széchenyi István University, Hungary.

REFERENCES

Atkinson, J. : The mechanics of soils and foundation, Taylor & Francis Group, London, 2007, pp. 161–201.

Brinkgreve, R. B. J., Vermeer, P. A.: *Plaxis*, Balkema (1998)

Hans-Georg Kempfert, Berhane Gebreselassie : Excavations and Foundations In Soft Soils. Springer, Berlin, 2006, pp. 57-111.

Szepesházi Róbert.: Dispalcements around deep excavations (*manuscript, in Hungarian*), Miskolc, Hungary, 2007

Szymansky, A. : The use of constitutive soil models in consolidation analysis of organic subsoil under embankment. Proceeding of the Workshop on Advances in Understanding and modelling the mechanical behaviour of peat, Balkema, Rotterdam:231-240, 1994