

Profiling and analysis of the overconsolidation ratio and strength parameters in hungarian soils of the metro 4 stations in Budapest, Hungary

Profiliranje in analiza prekonsolidacijskega količnika in trdnostnih parametrov v kiscellijski glini za postaje proge 4 metroja v Budimpešti na Madžarskem

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Abstract

The study is about the determination of the overconsolidation ratio and the strength parameter analysis related to Metro 4 stations in Budapest. The overconsolidation ratio was determined from oedometer tests using the Casagrande method, and from cone resistance of Cone Penetration Tests (CPTu) in the upper soil strata. For the metro stations a great number of boreholes were made with core samples carried out from depths of 10 m to 40 m. Unloading-reloading modulus (E_{ur}) and secant modulus at 50 % strength (E_{50}) were derived from triaxial tests carried out with the mentioned layer called Kiscell clay in the Buda side. In this clay, the strength and consolidation parameters dominantly depend on depth. In this paper the correlation between the different parameters were determined.

Key words: overconsolidation ratio, CPTu, oedometer test, triaxial test, Kiscell clay

Izvleček

Predmet študije sta bila določanje prekonsolidacijskega količnika in analiza trdnostnih parametrov pri gradnji postajališč proge 4 podzemne železnice v Budimpešti. Prekonsolidacijski količnik so določali z edometrijskimi preizkusi po Casagrandejevi metodi in odpornostjo stožcev pri preizkusu s statičnim konusnim penetrometrom (CPTu) v zgornjih plasteh zemljine. Na lokacijah postaj metroja so zvrtili večje število vrtin, ki so jih jedrovali v globinah med 10 m in 40 m. Modul razbremenitve-ponovne obremenitve (E_{ur}) in sekantni modul pri 50-odstotni trdnosti (E_{50}) so izpeljali iz rezultatov triosnih preizkusov, ki so jih izvedli v hribini s kiscellijsko glino na območju Bude. V preiskovani glini so trdnost in konsolidacijski parametri izrazito odvisni od globine. V članku je opisano ugotavljanje povezave med različnimi parametri.

Ključne besede: prekonsolidacijski količnik, CPTu, edometrijski preizkus, triosni preizkus, kiscellijska glina

Introduction

For the construction of Metro Line 4 in Budapest, a large number of soil explorations in high quality was required, and through the processing of these samples, further information have been gathered about the clay soils situated in great depths, and on the changes of the relevant soil-physical parameters in the function of depth. Triaxial and oedometer tests were carried out by using continuous core output samples.^[1] For the soil models of advanced computer softwares using finite-element models (e.g. the hardening soil model), a knowledge of the soil parameters is rather important in order to ensure that the modeling should approximate reality as much as possible. In this paper the analysis and profiling of the strength and overconsolidation parameters of soil strata, and the relationship among these parameters are presented.

Stress history and overconsolidation ratio

Oedometer test

One-dimensional oedometer tests are suitable for determining the overconsolidation ratio (*OCR*) and the consolidation parameters.

The yield point denotes the preconsolidation stress (σ'_p). Determination of σ'_p from void ratio $e - \lg \sigma$ relationship is presented in Figure 1, where σ is the loading stress in kPa.^[2]

In normalized form, the degree of preconsolidation is called the overconsolidation ratio (Equation 1).

$$OCR = \frac{\sigma'_p}{\sigma'_{v0}} \quad (1)$$

where σ'_{v0} is the effective vertical geostatic stress. If *OCR* is less than 1, under-consolidated, if equal to 1, normally consolidated, and if greater than 1, then we are talking about overconsolidated soil. *OCR* is defined as the highest stress experienced divided by the current stress.

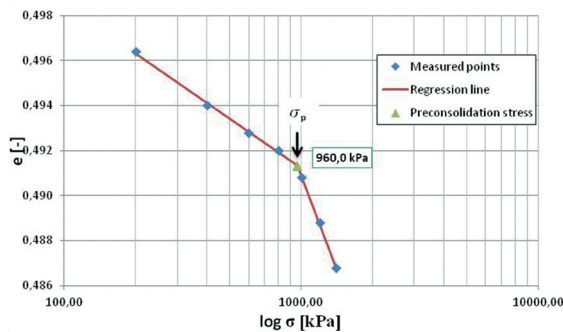


Figure 1: Determination of preconsolidation stress.

Cone Penetration Test (CPTu)

CPTu test results were compared with the results obtained from further in-situ Self boring pressuremeter (SBP) tests analysed by E. Kalman (2012) and laboratory tests. CPTu is one of the most frequently used in-situ tests in Hungary. These test methods are suitable for soil classification and derive soil-mechanical properties. The test method can be used easily and efficiently.

Triaxial tests

Reloading modulus (E_{ur}) and secant modulus at 50 % strength (E_{50}) were determined from triaxial tests using large diameter (10 cm) specimens from depths of 10 m to 40 m.^[1] The correlation between these parameters and depth was analysed.

Measurement results

On the basis of the tests, a good approximation can be achieved in determining the *OCR* value (that changes in the function of depth) by using power functions. The oedometer tests were carried out by using samples taken in depths between 5 m and 45 m, and then the determined *OCR* values were depicted in the function of depth values (see Figure 2). The results of 142 samples from 11 sites were used for the function.

The extent of approximation shows that it is not possible to handle all the stations together, however it reflects the *OCR* values properly: while depth grows, the *OCR* values get lower and move within a given range. This justifies the necessity of explorations to be taken, as well as analyses of the concomitant circumstances. For

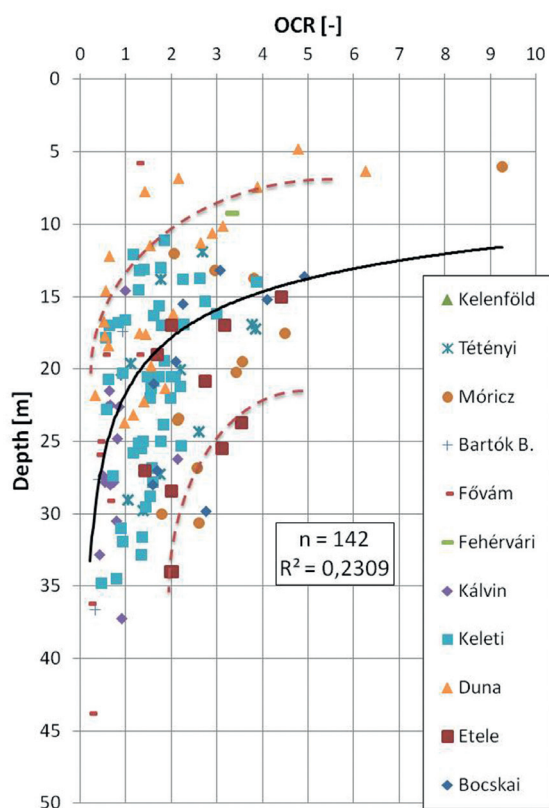


Figure 2: OCR value versus depth value.

the values belonging to some of the stations, a matching of functions took place, which is summarized in Table 4. The broken lines mark interpretation domains (see Figure 2). The Clay is from normal to heavily overconsolidated, its overconsolidation ratio varies between 0.2 and 9.3 depending on depth. Where the OCR value is less than 1, the soil is underconsolidated. In this case it could be caused by the fact that the given level was measured at loading stress in the test, and the effective stress was higher, therefore the yield point showed a local point and not the global location in the $e - \lg s$ curve. Lower value of loading stress of oedometer test than it is necessary (for example only 800 kPa) can be resulted lower preconsolidation stress.^[3] A lower than 1 value is not likely, so it can be established that laboratory tests are sensitive to the preparation of samples, the time lapsing between the test and the sampling event, as well as the level of the loading stress during the test. Higher loading stress could be resulted more accurate yield point to define preconsolidation stress. For increasing the accuracy of the approximative functions, several in-situ and

laboratory measurements are needed, in addition to the fact that the inhomogeneity of soils is pointed out by the standard deviation of the values.

Harder soil strata cannot be penetrated for using a CPTu test, therefore this method is sufficient only to reach the upper, weathered layers of the Clay. In the event of Fővám tér, Bocskai út and Kelenföld stations, CPTu test results, while in the event of Fővám tér and Bocskai út stations, oedometer test results have been compared with the results of SBP tests that had been performed earlier in this soil layer.^[4] OCR can be expressed by the Equation 2 using CPTu Test, Powell et al. (1988):

$$OCR = k \cdot \left(\frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \right) \quad (2)$$

where k is the overconsolidation factor and q_t is the corrected cone resistance.^[5] For the upper soil strata $k = 0.2$ was used.

The OCR values based on CPTu, laboratory and SBP tests are presented in Figure 3.

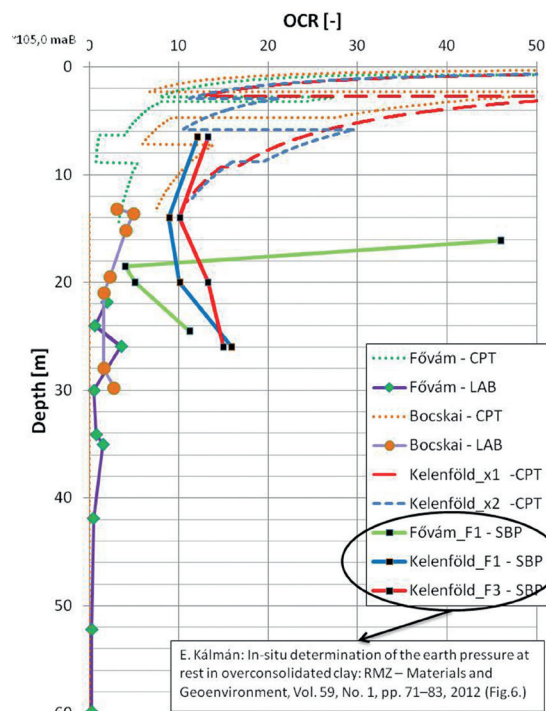


Figure 3: OCR values based on laboratory, CPTu and SBP tests.

Further on, a statistical analysis of the stiffness parameters comes. The available Rock Quality Designation index (RQD) values determined on the basis of the borings belonging to Kálvin tér,

Móricz and Etele stations have been compared with the E_{ur} and E_{50} values of the oedometer modulus (E_{oed}). There is a high standard deviation between the values, but it can be seen that the modulus values grow parallel with the improvement of the RQD value, as shown by Figure 4.

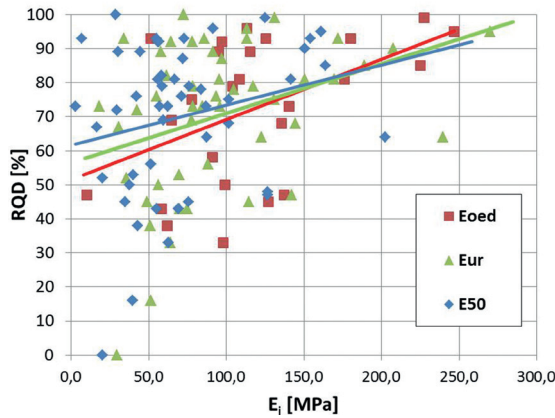


Figure 4: RQD vs. E_{oed} , E_{ur} and E_{50} .

In the Hardening Soil model (Plaxis) the relationship is hyperbolic between the vertical strain, ϵ_1 , and the deviatoric stress, q , in the primary triaxial loading (see Figure 5).

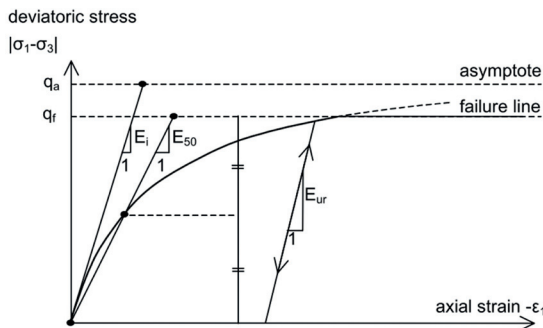


Figure 5: Hyperbolic stress-strain relation in primary loading for a standard drained triaxial test [Plaxis Manual].

As the Plaxis software recommends, E_{ur} should take the value of $3 \times E_{50}$, but the measurements show that they rather approximate the value 1. The relationships among the three moduli are shown by Figure 6.

Figures 7, 8 and 9 depict the changes of the E_{oed} , E_{ur} and E_{50} values in the function of depth, and their approximation to the straight line, where

the results of the stations of Buda side involved in the research are shown.

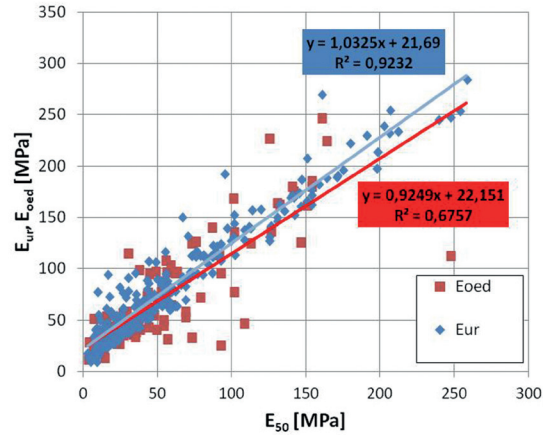


Figure 6: Correlation between E_{50} and E_{oed} , E_{ur} .

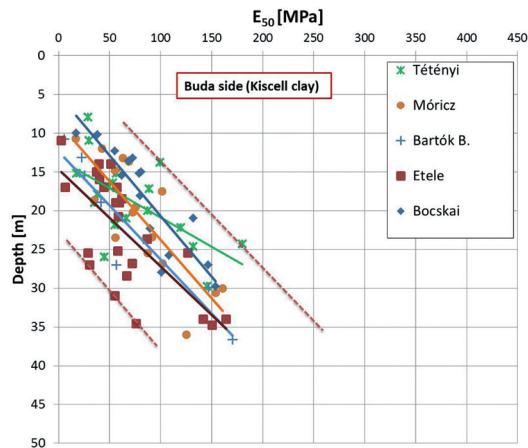


Figure 7: E_{50} value versus depth.

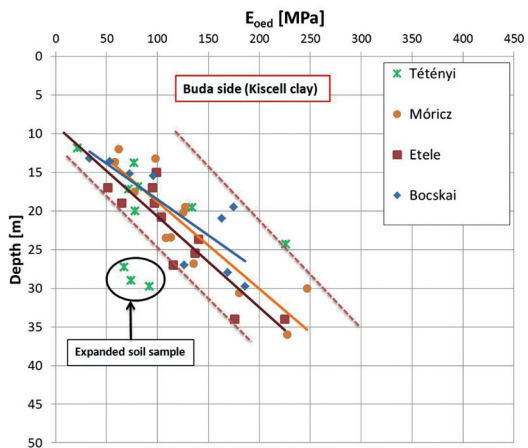


Figure 8: E_{oed} value versus depth.

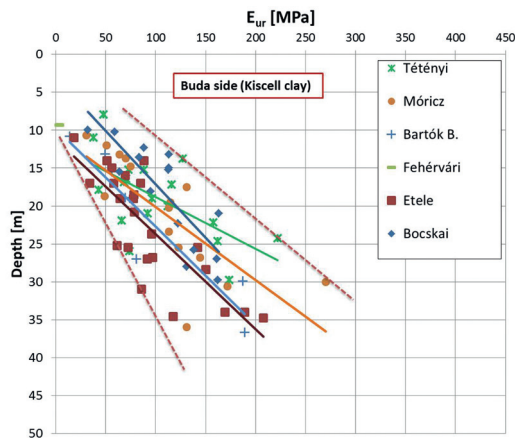


Figure 9: E_{ur} value versus depth.

By handling the various stations separately, the moduli and the changes of OCR versus depth have been determined by using the following correlations (Equation 3, 4);^[6] then Tables 1–4 give a summary of the values of the variable factors (a , b , A , α), the approximation ratio of the approximative function (R^2) and the number of data points (n).

$$E_i = a \cdot (z) + b \quad (3)$$

$$OCR = A \cdot (z)^\alpha \quad (4)$$

where z is the depth and it should be interpreted by using the meter dimension.

Table 1: $E_{50} - z$

Location	a	b	R^2	n
Tétényi	13.28	-177.36	0.40	18
Móricz	6.68	-58.50	0.66	16
Bartók B.	7.18	-88.74	0.88	7
Etele	7.96	-116.55	0.51	24
Bocskai	8.63	-44.04	0.78	15

Table 2: $E_{ur} - z$

Location	a	b	R^2	n
Tétényi	14.60	-174.34	0.40	18
Móricz	10.37	-108.66	0.57	16
Bartók B.	7.72	-75.23	0.86	7
Etele	7.97	-88.86	0.65	24
Bocskai	7.10	-21.84	0.69	15

Table 3: $E_{oed} - z$

Location	a	b	R^2	n
Móricz	8.87	-66.72	0.80	14
Etele	8.49	-75.81	0.78	11
Bocskai	10.78	-99.45	0.67	9

Table 4: $OCR - z$

Location	A	α	R^2	n
Tétényi	3683.33	-2.39	0.40	3
Fővám	31.89	-1.33	0.65	8
Duna	773.95	-2.42	0.44	22
Etele	550.75	-1.68	0.58	7
Bocskai	389.69	-1.74	0.70	7

The negative values of parameter b indicate that there was no measurement in the upper 10 m zone, as it belongs to a different soil type, therefore the approximative straight line determined by the statistical analysis is valid from cca. the 10 m depth on, and this is true also for the OCR -depth correlation and approximative function.

Conclusions

Taking into consideration first the unloading then the reloading of soils in the event of deep excavations, a good approximation can be achieved for such behaviours of soils by using the Hardening Soil Model offered by the finite-element softwares widely spread in practice. For the description of the behaviour of the Kiscell Clay occurring frequently in Buda side and of Tardi Clay typical of Pest side, the solution would be the construction of a new soil model, but the designers of the Metro construction project had decided in favour of the Hardening Soil Model mentioned above. For this application, "special" input soil parameters were needed such as E_{50} , E_{ur} , E_{oed} , and OCR . These parameters have been depicted in the function of the changes of depth so that a picture should be drawn up on the nature of changes. Occasionally, the high standard deviation and low correlation values of the approximative functions were determined by the inhomogeneity of soils or (just in the course of testing) by the measure-

ability range of deformations, or by the condition and preparation (and preparation-ability) of soil samples. In specifying the preconsolidation stress values of soils, the preparation and carving of samples, the maximum loading stress selected, and waiting out while consolidation takes place have especially high effects, as well as the time lapsing between the taking and the testing of samples, and further important but not yet examined or less examined factors, such as temperature, are also conceivable. In filtering the data, the taking into consideration of the categories of RQD did not yield better approximative functions, but as regards layers, efforts have been taken for testing soils of the same classes.

In general, the calculated Overconsolidation ratio decreased due to depth, depended on the determination method. The determination of *OCR* can be based on laboratory, CPTu or SBP tests, as well. The upper 3–5 m thick layer can result in high values of *OCR* by using the CPTu method, because the effective vertical stress is low in the upper soil strata and the cone tip resistance can be high.^[3, 6] Therefore, these high values in the upper layers should not be used in soil models of finite element modeling methods.

Lower value of loading stress of oedometer test can be resulted lower preconsolidation stress than the derived values from in-situ test. Therefore, higher loading stress (1 400–2 000 kPa) could be used to more accurate preconsolidation stress.^[3] It is recommended that the loading stress should be used up to a 2–3 × value of the total stress in order to ensure a clear outlining of the yield point by using the Casagrande method. Where the purpose is to determine the overconsolidation ratio of soils by using oedometer tests, more accurate values can be received by using loading stresses higher than the stress level belonging to them, beside the assumed overconsolidation ratio.

OCR values based on oedometer, CPTu and SBP test results were compared using previous research results.^[4] It is recommended to perform the in-situ tests parallel with the laboratory tests, because a more accurate approximation can be given on the stiffness and pre-loading

behaviour of soils by using higher amounts of data.

The determined strength parameters, as well as their correlation with depth and with one another open the way for the future for performing back-analyses, and permit the design and dimensioning of construction projects in large depths, similar to the Metro 4 project in Budapest to be carried out in an economic manner.

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