MŰEGYETEM 1782

INVESTIGATION OF SATURATED, SOFT CLAYS UNDER EMBANKMENTS

PhD thesis

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Budapest
December, 2012

1. IMPORTANCE OF THE RESEARCH PROJECT

It is one of the most important goals of Hungary to develop high quality transportation links between different parts of the country, and (with special respect to the goals the European Union) between the surrounding countries.
A very important tool in transportation development is a modern highway and road system. In case of highway constructions the general requirements are: short construction time, safe operation and low operating costs.
Modern transportation geotechnical requirements are getting more and more strict, because the used embankment material and the underground conditions highly influence the pavement's future performance. So appropriate embankment quality (e.g. density, bearing capacity) and adequate subsoil conditions are prerequisites for the usability of roads and highways.

As early as the design phase the subsoil conditions must be taken into consideration (in some cases soil improvement techniques may be necessary), because proper embankment base is required to find a durable, safe, high quality, economical and environmentally friendly solution for highway embankment construction.
It must also be taken into account that in more and more cases embankments have to be built in bad-lying areas on highly compressible and low bearing capacity soils (e.g. highway M7 near "Nagyberek" and "Véménd", highway M43), because of economical or environmental reasons. This makes the work of geotechnical engineers more challenging.
The two main requirements of highway embankments are: stability and "immobility". The reason of embankment movements (e.g. waving road) is often caused by the compression of the underlying soil. This compression depends on the weight and geometry of the embankment (i.e. on the load) and on the deformation properties of the soil. After loading, a certain deformation develops and a new state of equilibrium evolves.

The problem in general is that deformations (the settlements of embankments) develop very slowly, consolidation can take years. In most of the cases the completed road pavement cannot tolerate settlements of several decimetres without damages, so we need to have a prior knowledge about the expected settlements and consolidation time.
Thus geotechnical design of high embankments requires two basic tasks: stability and settlement analysis. These tasks require on one hand detailed information about soil behaviour (i.e. deformation characteristics) and on the other hand a geotechnical computational model which approximates the reality as accurately as possible.

2. AIMS

Considering the background and Hungarian and international results in this field, the investigation of the following topics are addressed:

1. Strength parameter determination of saturated, soft cohesive soils based on modern in situ test results (e.g. cone penetration test). Investigation of recently used methods' reliability; proposal of new empirical relationship for soft clays in Hungary.
2. Calculation possibilities of embankment settlements (i.e. the compression of the underlying soft clay layer) using analytical and finite element methods.
    a. Theoretical background of limiting depth, recommendation for limiting depth in case of soft cohesive soils under high embankments.
    b. Determination of deformation characteristics based on CPT results for analytical and finite element settlement calculation.

The geotechnical data and test results of last decade's Hungarian highway projects have been collected and evaluated in this PhD thesis.

3. THESES

Summary of thesis No. 1.

The undrained shear strength of 40 soil samples and the CPT resistance measured near the sampling location were compared and evaluated. The undrained shear strength of each sample was determined by means of (unconsolidated, undrained) triaxial test and unconfined compression test. International practice uses cone factors to describe the correlation of CPT resistance and undrained shear strength. There are several types of cone factors using different CPT resistance values. A summary of the calculated cone factor values is given and the range of the values for soft Hungarian clays is defined. This data provides a useful guideline for reliability assessment. The cone factors obtained using measured undrained shear strength and recorded CPT resistance are summarized in Table 1. This table also contains some basic statistical properties of the correlations.

Table 1. Cone factors

	$N_k = \frac{q_c - \sigma_{v0}}{c_u}$	$N_{kt} = \frac{q_t - \sigma_{v0}}{c_u}$	$N_{ke} = \frac{q_t - u_2}{c_u}$	$N_{\Delta u} = \frac{u_2 - u_0}{c_u}$
Mean value	18,4	23,0	18,5	6,3
Minimum value	10,5	11,9	10,9	1,8
Maximum value	27,6	32,1	28,6	13,1
Standard deviation	4,4	5,0	4,9	2,8
Coefficient of variation	23,7%	21,7%	26,4%	43,7%
Range of 80% confidence interval	12,8-23,9	16,6-29,4	12,2-24,8	2,8-9,8
	±30%	±28%	±34%	±56%

It has been stated that cone factors using CPT tip resistance (N_k N_{kt} and N_{ke}) can be used with about the same reliability to estimate undrained shear strength. The ranges of 80% confidence intervals vary approximately ±30% in both cases.

These values point out that obtaining undrained shear strength based on CPT results can be used as a rough estimate. However it must also be noted that undrained shear strength itself has high coefficient of variation. With the help of laboratory tests and site specific correlations this prediction accuracy can be increased. In case of the analysed data the use of N_{kt} resulted in slightly better predictions compared to that of correlations using N_k values. Using effective CPT resistance (q_t-u_2) does not improve the reliability of undrained shear strength prediction. The experienced $N_{\Delta u}$ cone factors vary over a significantly wider range.

Publications in connection with Thesis No. 1.

Farkas J., Rémai Zs. (2009) Determination of shear strength properties (in Hungarian). Mélyépítő Tükörkép VIII:(8) pp. 24-27.

Rémai Zs. (2012) Estimation of Hungarian Holocene clays' undrained shear strength using CPT results (in Hungarian). Szlávik L (ed.) Magyar Hidrológiai társaság XXX. Vándorgyűlése. Kaposvár, Magyarország, 2012.07.04-2012.07.06. (ISBN: 978-963-8172-29-7)

Rémai Zs. (2013) Correlation of undrained shear strength and CPT resistance. Periodica Polytechnica – Civil Engineering (accepted publication)

Summary of thesis No. 2.

The reliability of undrained shear strength can be improved by using more reliable cone factors. In order to obtain more reliable cone factors, analyses have been performed to find correlation between the cone factors and other soil parameters (e.g. plasticity index, OCR, etc.).

It has been found that a good correlation exists between pore pressure ratio (B_q) and $N_{\Delta u}$ cone factor (Figure 1.). The correlation between them can be described by the following formula:

$$N_{\Delta u} = (24.3 \cdot B_q) \pm 2$$

In case of low B_q values the cone factors (and consequently the calculated undrained shear strength) still vary over a relatively wide range. As pore pressure ratio increases the effect of "± 2" component decreases, therefore in this case the undrained shear strength can be estimated in a more reliable way. In case of soft clays, the B_q values are generally high, so the following formula is proposed to calculate undrained shear strength based on CPT results:

$$c_u = \frac{u_2 - u_0}{24{,}3 \cdot B_q}$$

The estimated undrained shear strengths of all samples have been calculated using the formula $N_{\Delta u} = 24.3 \cdot B_q$ and the mean values of cone factors N_k, N_{kt} and N_{ke} (see Table 1.), and the ratio of estimated values and measured values (i.e. laboratory test results) have been calculated. This ratio is plotted against pore pressure ratio in Figure 2.

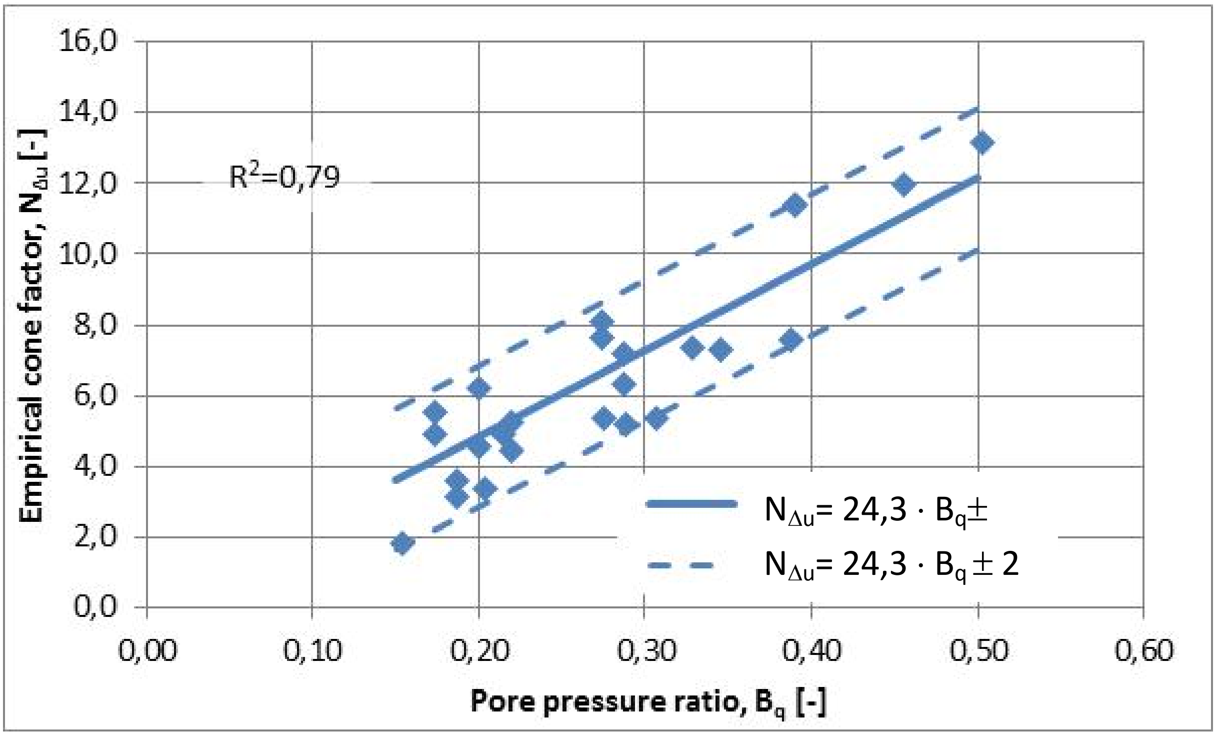

Figure 1. $N_{\Delta u}$ cone factor vs. Pore pressure ratio

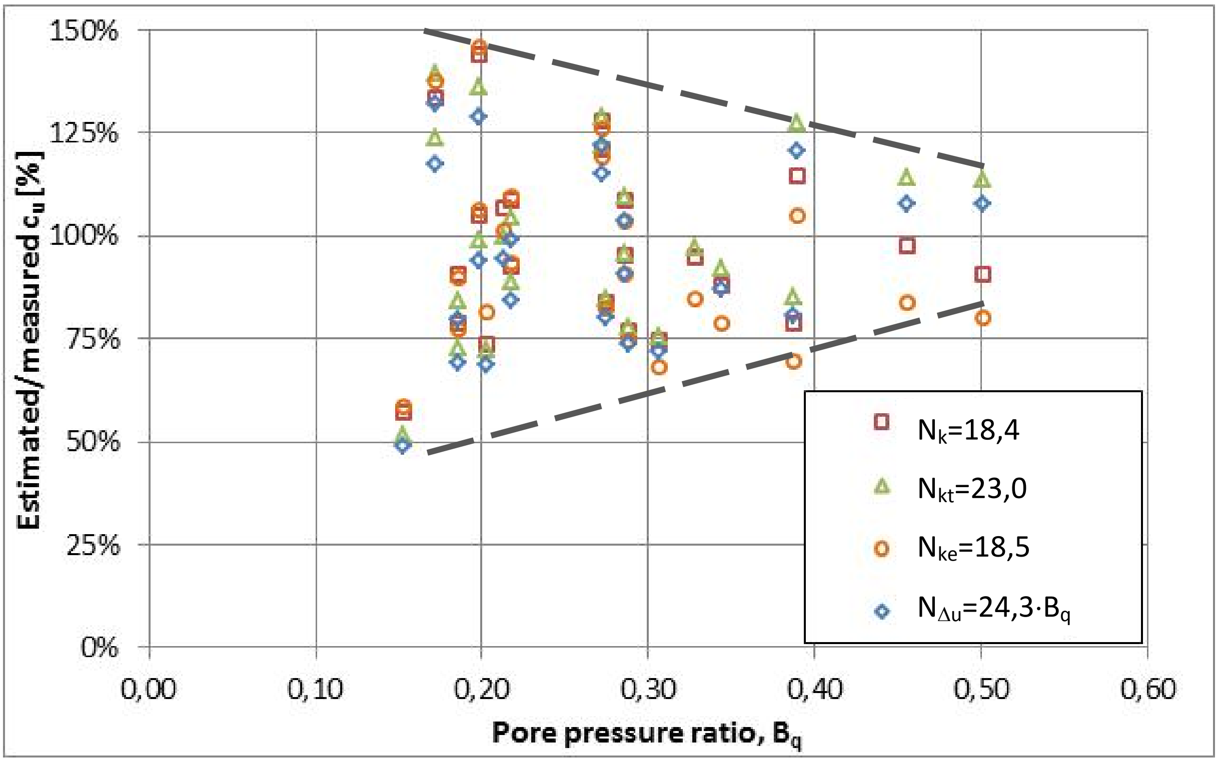

Figure 2. The ratio of estimated and measured undrained shear strength against pore pressure ratio

It has been stated that the undrained shear strength of soft clays can be estimated more reliably based on CPT results, when the pore pressure ratio is high. In cases when pore water pressure ratio was higher than 0.25 the calculated undrained shear strength values deviate by less than 30% from the measured values.

Publications in connection with Thesis No. 2.

Rémai Zs. (2012) Estimation of Hungarian Holocene clays' undrained shear strength using CPT results (in Hungarian). Szlávik L (ed.) Magyar Hidrológiai társaság XXX. Vándorgyűlése. Kaposvár, Magyarország, 2012.07.04-2012.07.06. (ISBN: 978-963-8172-29-7)

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Summary of thesis No. 3.

The reliable estimation of embankment settlement requires on one hand the proper knowledge of soil's deformation characteristics; on the other hand we must be aware of the thickness of compressing soil layer (i.e. limiting depth). Recent advances in geotechnical research have pointed out that in the range of very small strain ($\varepsilon<10^{-3}$) the stiffness of soils increases significantly (Figure 3.). This phenomenon plays an important role in embankment settlement prediction.

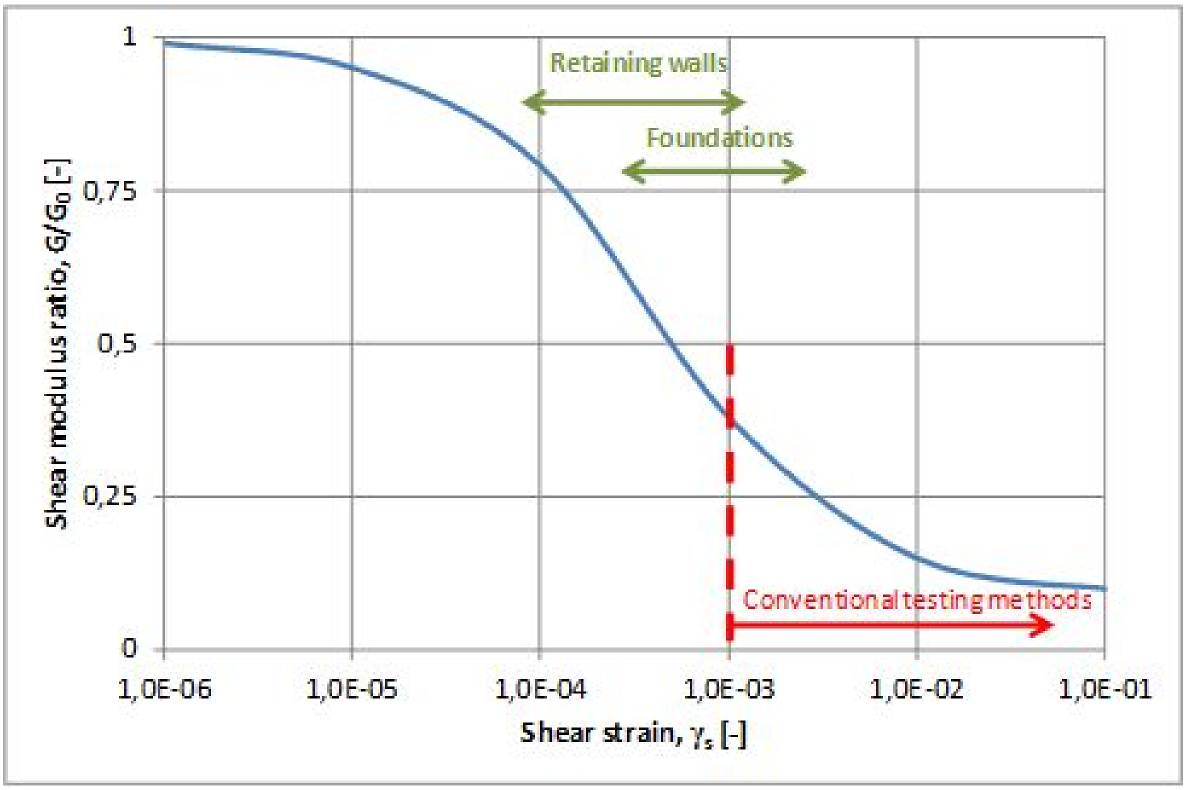

Figure 3. Degradation curve od shear modulus

Earlier experiences have shown that in case of finite element analyses the model depth (which is chosen by the user) has a great influence on the calculated settlements. Thus even in case of up to date soil models (e.g. hardening soil, modified cam-clay etc.) the traditional limiting depth theories must be used to estimate the proper model size.

The aforementioned soil models are capable of taking into account the facts that relative stress decreases with depth (as the stresses diffuse), and the stiffness of the soil increases (as the compression curve becomes flatter). On the other hand the diminishing deformation is also caused by the increased stiffness in the small strain range. With the help of a soil model that takes into consideration this fact the limiting depth can be calculated by finite element analysis.

A series of FE analyses has been performed to investigate this possibility. The FE models consisted of a 10 m high, 80 m wide embankment placed on a soft clay layer of different thickness (i.e. different model depths). The clay behaviour has been described by different soil models including the "HSsmall" model which can take into account the increased small strain stiffness. The settlements at the axis of the embankment are plotted against the chosen model depths in Figure 4. In contrary to the other models using "HSsmall" the model depth does not influence significantly the calculated settlements; consequently the expected settlements can be calculated independently on the model depth.

It has been stated that "limiting depth" is not an exact depth, but a depth range, and the diminishing deformation is primarily caused by the soils' significantly increasing stiffness in small strain range. Thus the limiting depth is not governed by stresses but strains. I propose to use soil models that can take into account the increased soil stiffness in small strain range to calculate the settlement of embankments on soft clays.

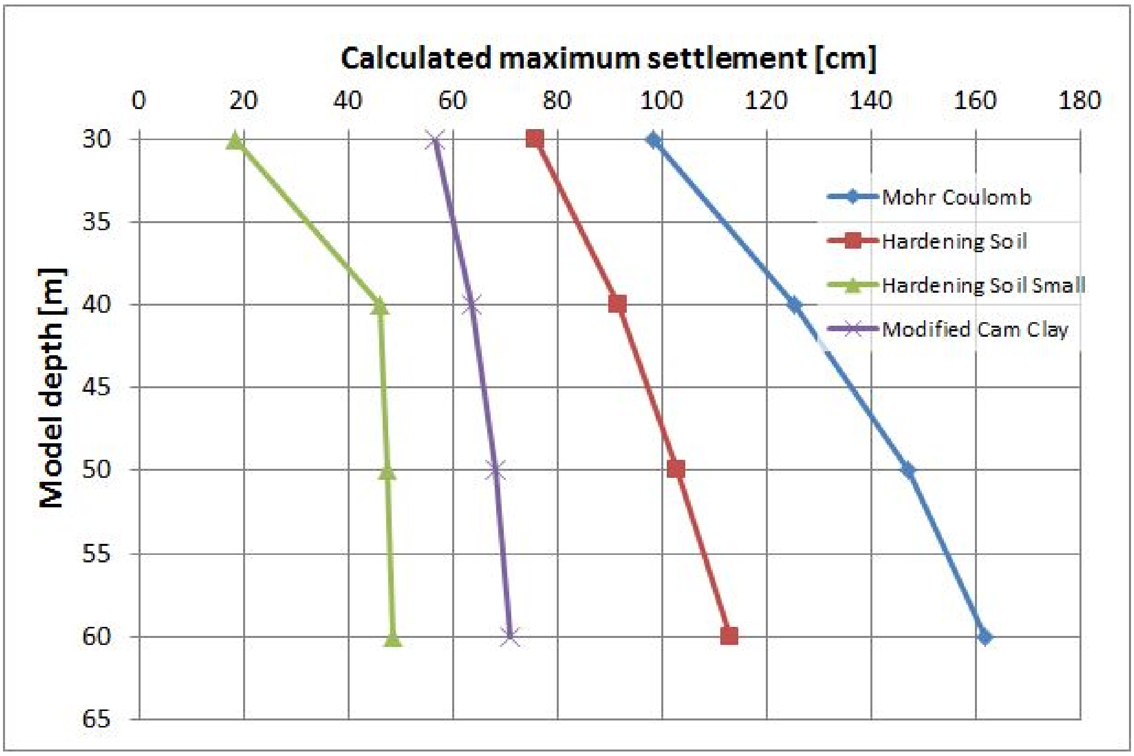

Figure 4. Calculated embankment settlement assuming different model depths and soil models

Publications in connection with Thesis No. 3.

Rémai Zs. (2012) Possibilities of limiting depth determination (in Hungarian) in Török Ákos, Vásárhelyi Balázs (eds.) Mérnökgeológia-Kőzetmechanika 2011. Budapest, Magyarország, 2012.01.26. Hantken Kiadó,Budapest pp. 117-124.(Mérnökgeológia-kőzetmechanika kiskönyvtár; 12.)(ISBN: 978-615-5086-04-5))

Rémai Zs. (2012) On limiting depth. Central European Geology

Summary of thesis No. 4.

Everyday (analytical) settlement calculation still requires an exact limiting depth. With reference to the previous thesis I propose the following: the limiting depth shall be chosen at the depth where the calculated strain is approximately in the middle of the limiting depth range, so the neglected and overestimated deformations balance each other. The calculations have shown that the use $\varepsilon=3\cdot10^{-3}$ is a good criterion for this.

A series of finite element analyses has been performed to compare the calculated limiting depths with the ones used in everyday practice. The calculations were done assuming 80 m embankment base width and the following parameters:

- embankment heights: 5 m – 7,5 m – 10 m
- groundwater level: ground surface – infinite depth
- sub-soil: soft clay ($E_{oed}=E_{50}^{ref}$=5 000 kPa), stiff clay ($E_{oed}=E_{50}^{ref}$=12 000 kPa)

For each calculation the limiting depth has been obtained by FE analysis, and I calculated how many percent of the initial effective vertical stress is the stress increment (caused by the embankment). Summarizing the results it has been concluded that this percentage is 10-15% in case of soft soils, and 25-35% in case of stiff soils. Thus the limiting depth is larger in case of soft soils.

Additional FE analyses have been carried out, in order to obtain which percentage could be proposed for soft clays under high embankments. The input parameters are summarized in Table 2. The results are illustrated by Figure 5.

Table 2. Input parameters for FE analyses

Embankment heights, H [m]	5 – 7,5 – 10
Embankment widths, B [m]	50 – 60 – 70 – 80
Deformation properties, $E_{oed}^{ref}=E_{50}^{ref}$ [kPa]	5000
Small strain parameters, $G_0/\gamma_{0,7}$ [MPa/-]	$45/2\cdot10^{-4}$ – $60/3\cdot10^{-4}$
Groundwater level	ground surface – infinite depth

and

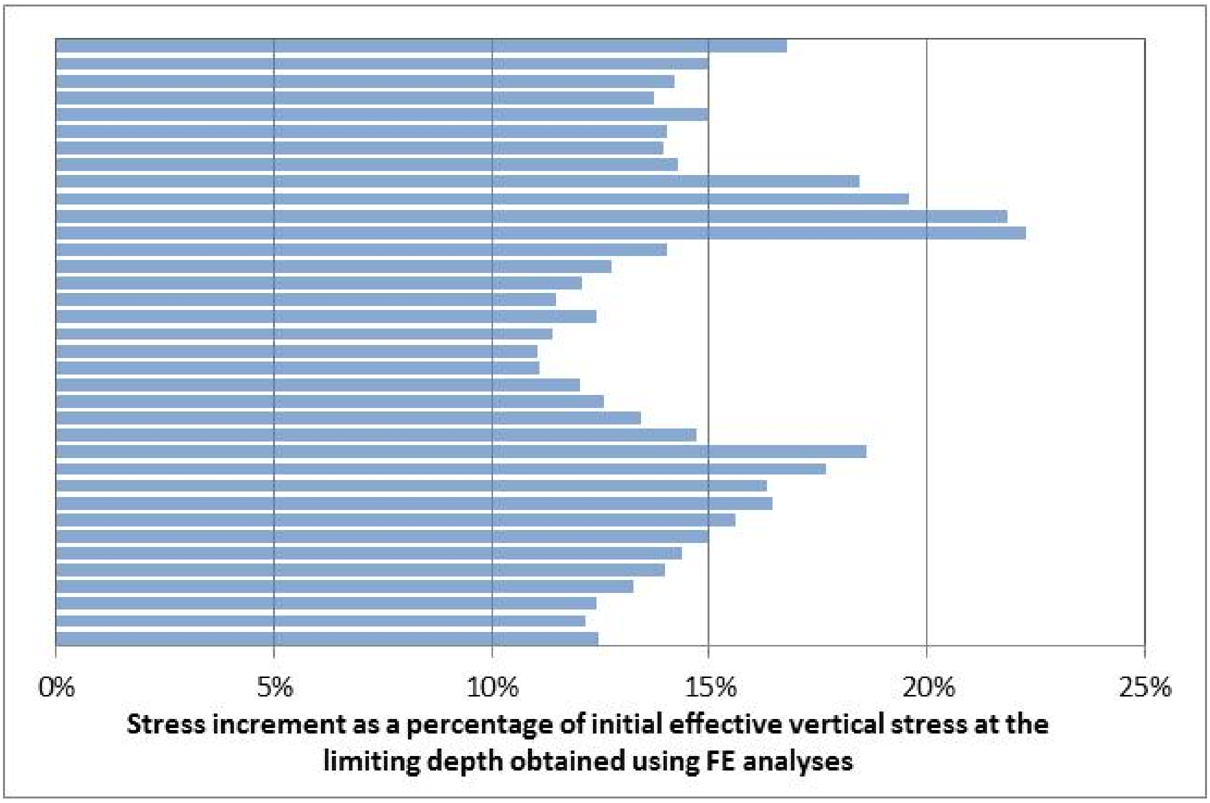

Figure 5. Stress increment at limiting depth (obtained using HSsmall soil model)

It has been stated that the limiting depth is influenced by the soil's deformation properties (primarily by the parameters of the degradation curve) as well – in case of soft soils the limiting depth is larger, in case of stiff soils, smaller. Based on the analyses results I propose to define the limiting depth at the level at which the stress increment decreases to 15% of the initial effective vertical stress.

Publications in connection with Thesis No. 4.
Rémai Zs. (2012) Possibilities of limiting depth determination (in Hungarian) in Török Ákos, Vásárhelyi Balázs (eds.) Mérnökgeológia-Kőzetmechanika 2011. Budapest, Magyarország, 2012.01.26. Hantken Kiadó,Budapest pp. 117-124.(Mérnökgeológia-kőzetmechanika kiskönyvtár; 12.)(ISBN: 978-615-5086-04-5))
Rémai Zs. (2012) On limiting depth. Central European Geology

Summary of thesis No. 5.

The correlation between modulus of compressibility (oedometer modulus) and CPT tip resistance can be expressed by the following formula :

$$E_{oed} = \alpha \cdot q_c,$$

where α is an empirical coefficient depending on soil type. Based on available literature data, its value varies between 2 and 8 in case of soft soils.

Embankment settlement measurements results of 12 sites at highways M43 and M6 have been chosen for back analysis. The sites adopted for the current investigation share a common feature: the majority of the soil deformations, about 70-90% of the total settlement, develop in the first, upper clay layer. Thus the deformation of the underlying layers has only slight influence on the measured settlements.

The deformation properties (E_{oed}, E_{50}) of the soft clay have been back calculated and the α values have been obtained. In case the investigated Hungarian soft clays the experienced of values varied between 3.5 and 5. It has been also found that the value of α decreases as CPT friction ratio increases (Figure 6.). Larger friction ratio generally implies clays of higher plasticity, so this finding is in good agreement with the tendency of the Kopácsy (1953) expression.

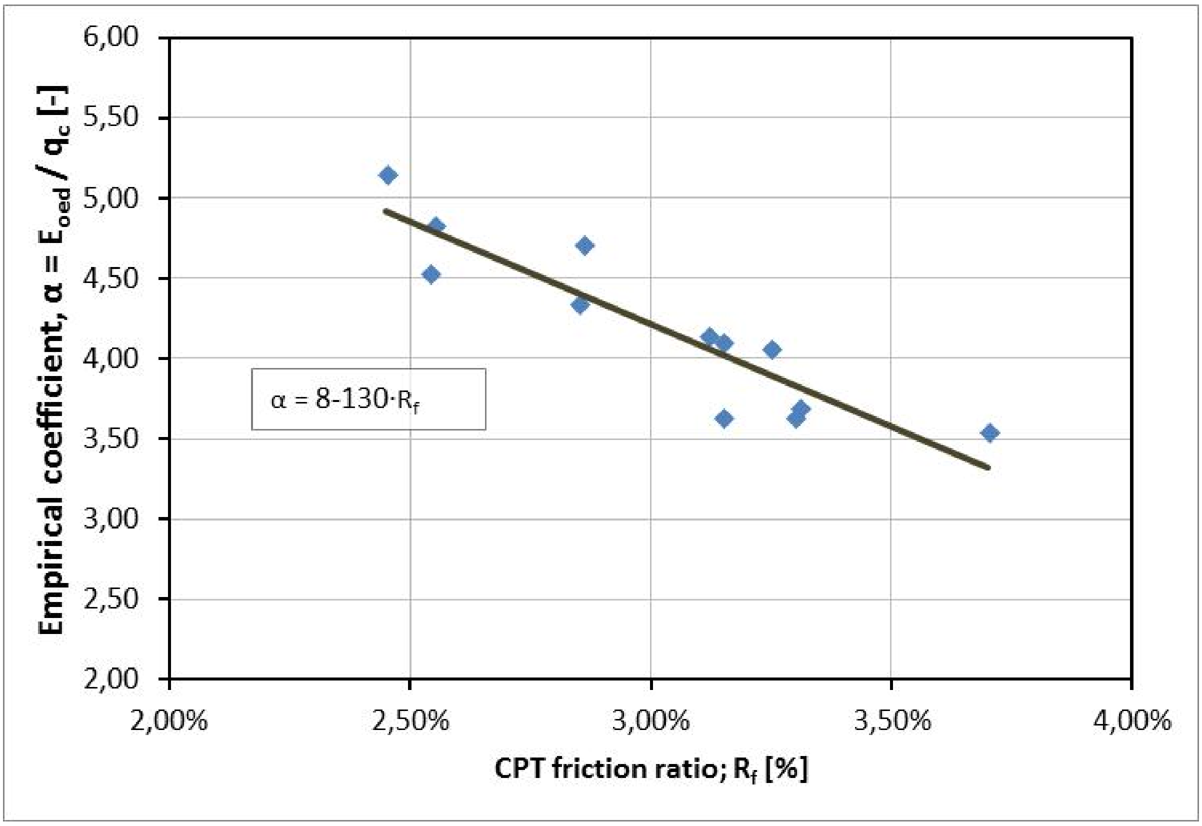

Figure 6. The experienced $\alpha=E_{oed}/q_c$ ratio vs. CPT friction ratio

Based on the analyses results, the following expression is proposed to estimate the modulus of compressibility in case of soft, cohesive soils:

$$E_{oed}=(8-130\cdot R_f)\cdot q_c.$$

Publications in connection with Thesis No. 5.

Farkas J., Rémai Zs. (2009)Determination of deformation properties: Testing of soft, organic and cohesive soils (in Hungarian) Mélyépítő Tükörkép VIII:(5) pp. 4-6.

Rémai Zs. (2012) Back analysis of soft clay behaviour under highway embankments. Asian Journal of Civil Engineering – Building and Housing (accepted publication)

Summary of thesis No. 5.

The back analyses of the aforementioned 12 sites have been performed considering an analytical settlement calculation method (proposed by MSZ 15004-1989) as well. The back calculated moduli of compressibility values are significantly lower. The reason for this tendency is that this method assumes K_0 stress state in the soil mass, but in the analysed cases significant lateral movements were observed (Figure 7.).

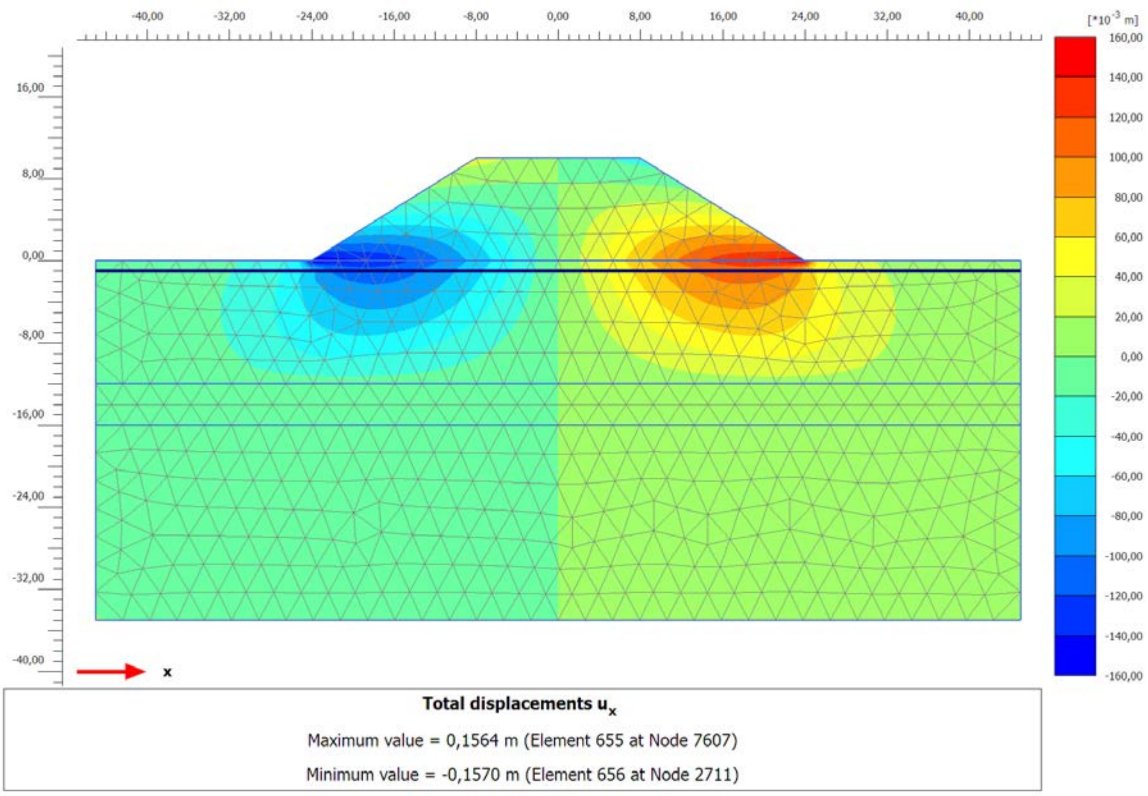

Figure 7. Lateral movements under the embankment

Therefore in case of embankments on soft clays I propose to use a reduced modulus of compressibility for the calculation of MSZ 15004-1989. The reduction rate depends on the safety factor, in general a reduction by 20-30% is proposed.

Similarly to the previous thesis the E_{oed} values have been back calculated, and the following formula is proposed to calculate the reduced modulus of compressibility:

$$E_{oed}^{(red)}=(6-110 \cdot R_f) \cdot q_c.$$

Publications in connection with Thesis No. 5.

Farkas J., Rémai Zs. (2009)Determination of deformation properties: Testing of soft, organic and cohesive soils (in Hungarian). Mélyépítő Tükörkép VIII:(5) pp. 4-6.

Rémai Zs. (2012) Back analysis of soft clay behaviour under highway embankments. Asian Journal of Civil Engineering – Building and Housing (accepted publication)

4. FURTHER INVESTIGATIONS

The PhD thesis summarizes the last decade's geotechnical experiences of embankment construction on soft clays. The research results highlighted numerous new research topics. For example it is still not definite what can be considered as limiting depth; the increased stiffness in small strain range does not give the answer to all related questions. Presumably there is real threshold strain (or stress) under which there is no deformation, but its theoretical background is not yet clarified.

The thesis deals with the behaviour of soft, saturated, cohesive soils. However it has been shown that the problem of obtaining the limiting depth arises for all soil types. The analysis methods described in the thesis can be used gain more information about limiting depth in stiff soils as well. Such analyses can lead to a more general formulation of the recent limiting depth theory.

I also propose to perform settlement measurements at larger depth too, in order to validate the theoretical statements related to limiting depth. Measuring displacement at larger depths too, could provide more detailed picture of soil deformation, therefore it would enable better back analyses.

With the advance of measurement techniques, smaller and smaller deformations can be measured reliably. It is recommended to perform static and dynamic tests and compare their results.
There are many empirical correlations available in the international literature to estimate the shear modulus and degradation curve of soils. It would be useful to collect and summarize Hungarian experiences in this field, and to investigate the reliability of the empirical methods.

The recommended tests and analyses would provide useful and important information for better embankment settlement prediction in case of soft cohesive and stiff or granular soils as well.

PUBLICATION LIST

Journal papers

1. Rémai Zs., 2013. Correlation of undrained shear strength and CPT resistance. Periodica Polytechnica – Civil Engineering (accepted)
2. Rémai Zs., 2012. On limiting depth. Central European Geology
3. Rémai Zs., 2012. Monitoring and observational method in geotechnics (in Hungarian). Műszaki Ellenőr I:(9) pp. 36-38.
4. Rémai Zs., 2012. Back analysis of soft clay behavior under highway embankments. Asian Journal of Civil Engineering – Building and Housing (accepted)
5. Pusztai J, Rémai Zs, Thomázy Cs., 2009. Applying observational method in geotechnical design (in Hungarian). Mélyépítő Tükörkép VIII:(4) pp. 22-25.
6. Farkas J., Rémai Zs., 2009. Determination of shear strength properties (in Hungarian). Mélyépítő Tükörkép VIII:(8) pp. 24-27.
7. Farkas J., Rémai Zs., 2009.) Determination of deformation properties: Testing of soft, organic and cohesive soils (in Hungarian). Mélyépítő Tükörkép VIII:(5) pp. 4-6.
8. Thomázy Cs., Rémai Zs., 2008. Little damage – large bother: Unapproved activity is hard to control (in Hungarian). Mélyépítő Tükörkép VII:(1) pp. 8-10.

Conference papers

9. Rémai Zs. (2012) Estimation of Hungarian Holocene clays' undrained shear strength using CPT results (in Hungarian). Szlávik L (ed.) Magyar Hidrológiai társaság XXX. Vándorgyűlése. Kaposvár, Magyarország, 2012.07.04-2012.07.06. (ISBN: 978-963-8172-29-7)
10. Rémai Zs. (2012) Possibilities of limiting depth determination (in Hungarian) in Török Ákos, Vásárhelyi Balázs (eds.) Mérnökgeológia-Kőzetmechanika 2011. Budapest, Magyarország, 2012.01.26. Hantken Kiadó,Budapest pp. 117-124.(Mérnökgeológia-kőzetmechanika kiskönyvtár; 12.)(ISBN: 978-615-5086-04-5))