ROCZNIKI INŻYNIERII BUDOWLANEJ – ZESZYT 11/2011
Komisja Inżynierii Budowlanej Oddział Polskiej Akademii Nauk w Katowicach

THE METHOD OF EXPRESSION OF THE DEFORMATION PARAMETERS OF SOILS FOR THE PROGNOSIS OF SETTLEMENT OF HIGH-RISE BUILDINGS FOUNDED IN DEEP EXCAVATION PITS

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1. Introduction

Recently, the construction of high-rise buildings is worldwide conditioned by the effort to achieve to most effective increasing of the value of land, but it also becomes the subject of dominance and economic prestige of the company. The same trend can be observed also in the construction activity in Slovakia, mainly in Bratislava.

The subsoil of Bratislava can be split, from the geological point of view, into the following formations:

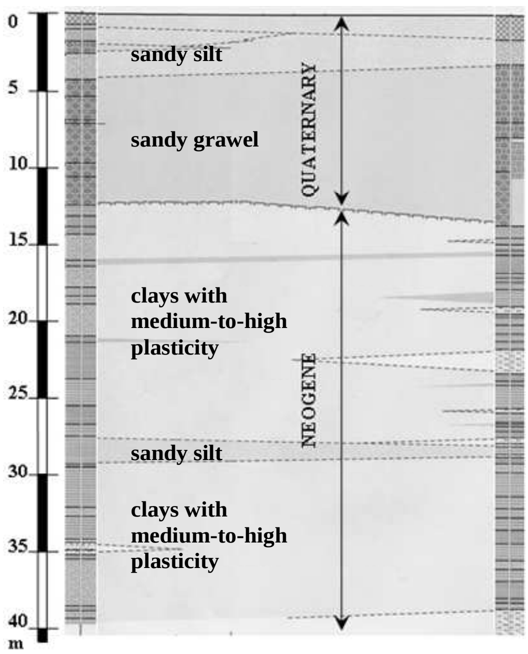


Fig.1 Subsoil composition in the central part of Bratislava

- Quaternary – formed in the upper minority part by alluvial sediments (sandy silt and sandy clay), in the main part formed by proluvial and fluvial sediments (silty gravels or clayey gravels and sandy gravel sediments);
- Neogene – limnic sediments forming the subsoil of the Quaternary sediments, represented by clays with medium-to-high plasticity with sporadic locations of sands.

The boundary between two different geological formations (Quaternary–Neogene) is, in the conditions of Bratislava, usually situated between 8–18m under the terrain surface. Fig. 1 depicts the geological profile from the central part of Bratislava [3].

The realization of the high-rise buildings in the conditions of Bratislava requires, among others, to cope with the problem of considerable number of parking spaces. Parking is usually resolved in basement areas of the high-rise objects and so there is a number of basement floors under the high-rise object (usually 2–4 basement floors). Thereby the position of the footing bottom shifts to the boundary of Quaternary–Neogene or, possibly, directly into Neogene. The strata of Quaternary with higher bearing capacity and the less compressible ones, formed by gravelly soils, are removed by the excavation of the excavation pits, and the foundational constructions lay on Neogene clay soils with less bearing capacity and the more compressible ones. For the reason of elimination of deformations of the Neogene clay subsoil due to more substantial load, the foundations of the high-rise buildings in Bratislava are mainly laid on rafts foundation.

2. Modifications of the condition of the state of stress of the subsoil in course of building the construction

In course of realization of the construction of a high-rise building, the state of stress in the subsoil changes significantly. By excavation of a deep excavation pit (at 2–4 basement floors, the depth of the excavation is 7–15m under the level of the original terrain), the load onto footing bottom is significantly reduced and the subsoil rises (deconsolidates). If we consider the unit weight of the soil γ_n = 20kN.m^{-3}, the reduction of load in the footing bottom at the excavation depth of 7–15m represents the stress of 140–300kPa. After the excavation works are done, the foundational construction and gradually the upper construction are built. Through the foundational construction, the load is transferred to the subsoil and, subsequently, its deformation occurs.

The simplest and, for expression of the changes of the state of stress in the subsoil being an acceptable idealization, is the theory of linearly elastic semispace [1], introduced by the French scientist Boussinesq in the year 1885. The equation for statement of vertical stress σ_z in arbitrary depth z under the corner of the foundational construction with dimensions *bxl*, loaded with uniform load with the value *f* and situated on the surface of a homogenous, isotropic, linearly elastic semispace, has the following form:

$$\sigma_z = \frac{f}{2\pi}\left[arctg\frac{l.b}{z\sqrt{l^2+b^2+z^2}}+\frac{l.b.z}{\sqrt{l^2+b^2+z^2}}\left(\frac{1}{l^2+z^2}+\frac{1}{b^2+z^2}\right)\right] \qquad (1)$$

Using the equation (1) allows to express the course of change of stress in subsoil not only in dependence on additional load by the building construction, but also the course of change of state of stress induced by unloading – by excavation of the excavation pit. In the case of a uniformly loaded raft foundation, which will behave as a ductile foundational construction (small thickness in relation to the length and width of the raft), extreme vertical stresses in the subsoil at the vertical passing through the centre of the raft can be awaited. As the computing model (1) is created for the corner of the foundational construction, the value of vertical stress σ_z under the centre has to be specified by superposition, by the method of corner points. The raft foundation with the dimensions of *b x l* is divided into quarters, and the resulting effect of the vertical stress under the centre of the base is the sum of effects of the vertical stress of the four raft foundations with the dimensions of *b/2 x l/2* under their corners.

A high-rise building usually constitutes a dominant of a whole complex of objects, the foundation of which is usually resolved at a common depth level, on raft foundations divided by dilatation. Load of the raft foundation of a high-rise building is a multiple of the load of the foundation construction of other low-rise parts. Significant unloading occurs along the whole area of the footing bottom of the complex of objects; however, significant additional load is in the footing bottom only on the area delimited by the foundational construction of the high-rise building. Fig. 2 shows an example of the change of the condition of the state of stress in the subsoil of a high-rise building founded in a deep foundation pit. This is a high-rise building based on a raft foundation with the dimensions of 15 x 45m, in an excavation pit with the dimensions of 62,8 x 174,6m.

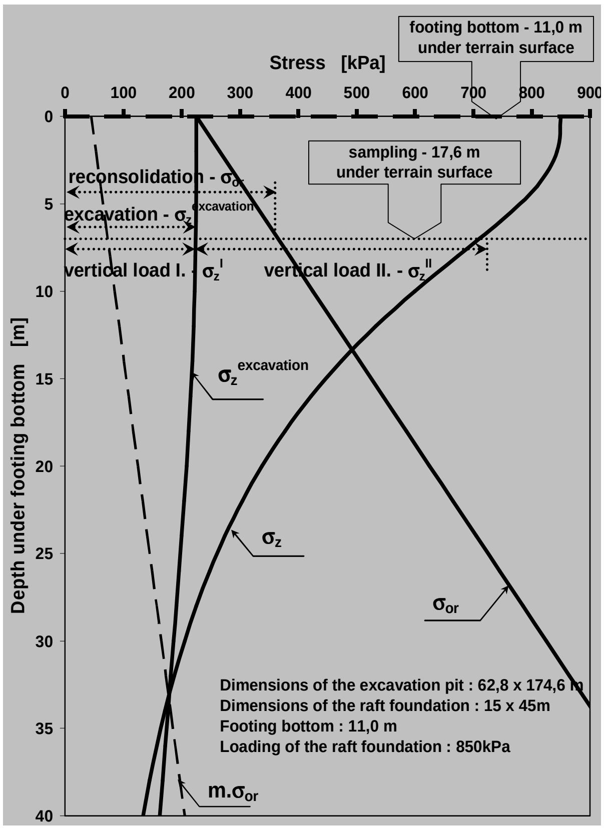


Fig.2 Changes of the state of stress under the footing bottom

The footing bottom is situated in the depth of 11m under the terrain surface and its load in the location of the high-rise building was specified to 850kPa. Fig. 2 depicts the original state of stress (the behaviour of geostatic stress σ_{or}), influence of the unloading of the footing bottom (excavation of the excavation pit $\sigma_z^{excavation}$), and influence of vertical load of the footing bottom in the location of the high-rise building (vertical load σ_z^{I} and σ_z^{II}). Besides that, the behaviour of structural strength of soil $m.\sigma_{or}$ is drawn here (considered to be approx. $0{,}2.\sigma_{or}$). The place of intersection of the course of structural strength ($m.\sigma_{or}$) and vertical load (σ_z) provides a picture showing the extent of the deformation zone [4] (33m under the footing bottom – 44m under the surface of the original terrain). Further, in Fig. 2 the stresses are marked which should be respected by the oedometric compressibility test.

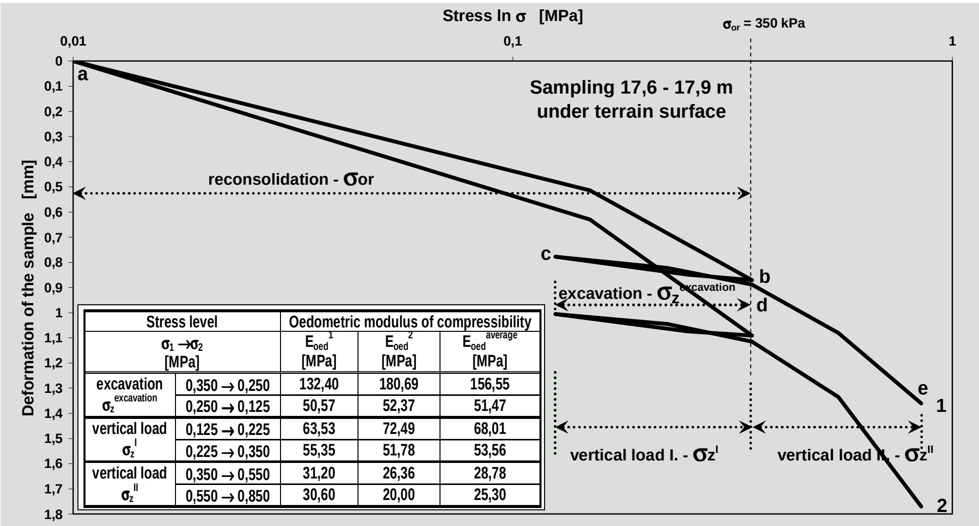
In Fig. 2, those stresses are marked which were used in the odeometric test for the sample of soil taken from the depth of 17,6–17,9m under the terrain surface (i.e. 6,6–6,9m under the footing bottom). This method allows, for any depth level of taking samples, to specify the stresses at which the odeometric test will be performed.

3. Experimental measurements of deformation parameters of soils

Experimental verification of the deformation properties of soils is performed in the laboratory conditions by an odeometric test. This is a model test of a so-called one-dimensional consolidation. In order that the odeometric method takes into account the changes of the state of stress in the subsoil of the object, it is necessary to perform the experimental measurement in the following steps:

1) sample reconsolidation by the original geostatic stress σ_{or} – the soil gets into such state of stress in which it was before taking the sample from the subsoil;
2) sample unloading by the stress $\sigma_z^{excavation}$, which represents the excavation of the excavation pit – it is necessary to take into account the influence of unloading in the respective depth of taking of the sample;
3) vertical load of the sample σ_z^{I} – load up to the level of the reconsolidation stress σ_{or};
4) vertical load of the sample σ_z^{II} – load above the level of the reconsolidation stress σ_{or}.

The method of quantitative specification of the individual load or unload stages is graphically depicted in Fig. 2 and, subsequently, in Fig. 3 it is projected into the behaviour of the oedometric test of compressibility.



Stress level		Oedometric modulus of compressibility		
$\sigma_1 \rightarrow \sigma_2$ [MPa]		E_{oed}^{1} [MPa]	E_{oed}^{2} [MPa]	$E_{oed}^{average}$ [MPa]
excavation $\sigma_z^{excavation}$	0,350 → 0,250	132,40	180,69	156,55
	0,250 → 0,125	50,57	52,37	51,47
vertical load σ_z^{I}	0,125 → 0,225	63,53	72,49	68,01
	0,225 → 0,350	55,35	51,78	53,56
vertical load σ_z^{II}	0,350 → 0,550	31,20	26,36	28,78
	0,550 → 0,850	30,60	20,00	25,30

Fig. 3 The method of loading/unloading of the sample of soil in the oedometric test

The results of the test of compressibility are interpreted by the line of compressibility, as the dependence of the magnitude of sample compression on the acting normal stress in a semi-logarithmic scale $ln\sigma$ – Fig. 3. After unloading of the soil sample loaded by reconsolidation stress σ_{or} by the stress representing the influence of excavation $\sigma_z^{excavation}$, the branch of unloading of the line of compressibility (section b-c) remains under the branch of primary vertical load (section a-b). From this part of the oedometric test, the elastic oedometric modules can be expressed, on the basis of which the elevation of the bottom of the excavation pit can be prognosticated (for the presented sample of soil, they are in the range of E_{oed} = 51,47–156,55MPa). After repeated loading up to the level of reconsolidation stress σ_{or} by the stress σ_z^{I} representing vertical load by the object (section c-d), the line of compressibility creates a hysteresis loop; after exceeding the reconsolidation stress σ_{or} by the stress σ_z^{II} (section d-e) the line changes back to the original line of compressibility. The soil once compressed acquires by consolidation, after unloading and repeated vertical load in the extent of preconsolidation stress, more favourable physical and mechanical properties. It has smaller porosity, higher strength and, most important of all, it is less compressible. This can be documented also by the values of the oedometric modules of deformation. For the first branch of vertical load, those values are in the range of E_{oed} = 53,56–68,01MPa; for the second branch of vertical load E_{oed} = 25,30–28,78MPa.

4. Presentation of the results of the experimental measurements

At founding of the high-rise buildings in deep excavation pits, the radius of the deformation zone under the original terrain surface is signficant. The depth of the deformation zone often reaches 30–40m under the level of the footing bottom (depending on the intensity of the load of the raft foundation), at the excavation depth of 10–15m this represents 40–55m under the original terrain level. The soils in major depths are exposed to considerable geostatic stress; this is proven also at the deformation characteristics of the soils. It is reasonable to expect that increasing depth under the original terrain level and the increase of the geostatic stress resulting thereof will be positively reflected in the properties of soils. Firstly, the compressibility of soils will gradually decrease with increasing depth (and the values of the deformation characteristics will increase). Therefore it is inevitable to monitor the way how the values of the deformation characteristics are influenced not only by the change of the state of stress under the foundations of the high-rise buildings realized in deep excavation pits, but also by the depth under the original terrain level.

An example of evaluation of experimental verification of the deformation properties of Neogene soils in dependence on the depth of sampling under the original terrain level, taking at the same time into account the change of the state of stress in the respective depth, is shown in Figs. 4a, b, c [2].

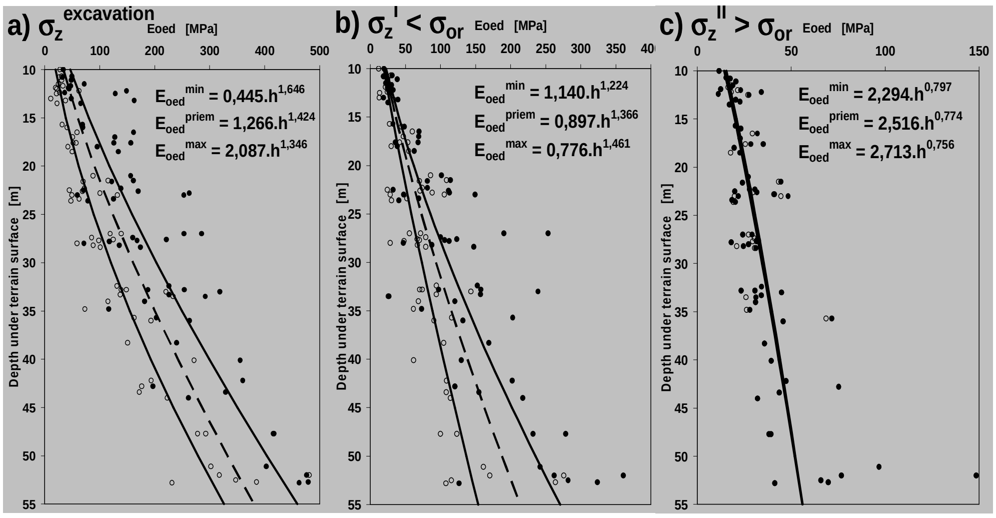


Fig.4 An example of evaluation of deformation characteristics in dependence on the depth under the original terrain level : ○ – minimum E_{oed} values; ● – maximum E_{oed} values; a) – oedometric moduli of elasticity (unloading by excavation $\sigma_z^{excavation}$), b) – oedometric moduli of deformation $E_{oed}^{\sigma z<\sigma or}$ (vertical load I. σ_z^I – up to the level of the original geostatic stress σ_{or}), c) – oedometric moduli of deformation $E_{oed}^{\sigma z>\sigma or}$ (vertical load II. σ_z^{II} – above the level of the original geostatic stress σ_{or})

Within the geological exploration [2] realized at the locality Bratislava – Račianska street, 66 intact Neogene samples were taken, mainly those of the claylу soils. The change of the state of stress was considered according to the behaviour of the stresses in Fig. 2, and the procedure of loading/unloading of the samples in the oedometric test was identical with the technique presented in Fig. 3.

Figs. 4a, b, c also show the regression functions describing the dependence of the change of the deformation characteristics with depth, for the minimum, average and maximum measured values. From the comparison of the deformation moduli in Figs. 4b and 4c, an evident influence of the repeated vertical load in the extent of the preconsolidation stress can be seen. The values of the deformation moduli $E_{oed}^{\sigma z<\sigma or}$ for vertical loads $\sigma_z<\sigma_{or}$ are noticeably higher than the values $E_{oed}^{\sigma z>\sigma or}$ of the moduli for vertical loads $\sigma_z>\sigma_{or}$. It is possible to utilize this fact at the prognosis of deformations of the subsoil under the foundational constructions of the deeply founded buildings. In the case of extremely high loads of the foundational constructions, where even after unloading by excavation, the vertical loads in the range of the entire deformation zone exceeds the original (geostatic) stresses, it is necessary to consider, for the prognosis of the deformations, lower values of the deformation moduli $E_{oed}^{\sigma z>\sigma or}$. However, if unloading by excavation and repeated vertical load by the object will not be noticeably different, or if unloading by excavation will be the same as vertical load caused by the object, then it is possible to use, for certain parts or for the entire deformation zone, for the prognosis of the deformations, the more favourable values of the deformation moduli $E_{oed}^{\sigma z<\sigma or}$.

5. Conclusion

The actual prognosis of subsoil deformations under the foundations of the high-rise buildings realized in deep excavation pits is possible only on the basis of the results of experimental verifications of the deformation properties of soils. It is necessary to project the changes of stress resulting from the technique of building the construction into the procedure of experimental measurement. The mentioned method provides a real conception concerning the deformation properties of the subsoil of high-rise buildings.

References

[1] Jesenák, J., 1994 : Mechanika zemín, STU Bratislava
[2] Šujan, M., Blažo E., Menzelová, O., Masarovičová, M., Slávik, I., Kovács, T.: Polyfunkčný dom Slovany, Podrobný IG prieskum, EQUIS spol. s.r.o., Bratislava, 2008.
[3] Šujan, M., Blažo E., Masarovičová, M., Slávik, I.: Bratislava – Nová Mýtna, Podrobný IG prieskum, EQUIS spol. s.r.o., Bratislava, 2005.
[4] STN 73 1001 Základová pôda pod plošnými základmi.

SPÔSOB VYJADRENIA DEFORMAČNÝCH PARAMETROV ZEMÍN PRE PROGNÓZU SADANIA VYSOKÝCH BUDOV ZALOŽENÝCH V HLBOKÝCH STAVEBNÝCH JAMÁCH

Anotácia

Spoľahlivá prognóza deformácií podložia pod hlboko založenými základovými konštrukciami výškových budov je možná iba na základe experimentálneho overenia deformačných parametrov zemín. Aby boli deformačné parametre reálnym obrazom stavu podložia je potrebné, experimentálnymi meraniami rešpektovať zmenu napätosti podložia vyvolanú výstavbou výškovej budovy. Uvedený spôsob meraní deformačných vlastností zemín dáva reálnu predstavu o deformačných vlastnostiach podložia výškových budov.