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Design of a foundation of a high-rise building in Bratislava

Proposition de mise en place de fondations d'immeuble de grande hauteur à Bratislava

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ABSTRACT: High-rise buildings have been placed in the downtown of the Bratislava city and give to the city new look. A multifunctional complex is now being built in an area of the old bus station. The complex is consists of administrative and commercial premises and a new bus station in the basement. The whole space has a ground plan dimension of almost 350 x 175 m. The foundation base of the lower level is located at a depth of 12.6 m below the original surface. The geological conditions of the site are consists of quaternary gravels up to a depth of 13.8 m and neogene sediments below them. The groundwater level is in a depth of 6 m below the surface. Vertical stress from the upper structure is estimated at the value of 700 kPa. The design of the foundation included 3 alternatives: spread footing - slab, spread footing on improved subsoil and pile foundation. The calculations showed that the requirements of the serviceability limit state are the most critical for the design. The tasks were solved using analytical models as well as numerical models. The analysis showed that the most optimal foundation is the spread footing on the improved subsoil. The subsoil will be improved using jet grouting columns reaching a depth of 18 m below the foundation bottom. The geotechnical monitoring includes settlement of the construction and allows verification of the design during it's construction.

RÉSUMÉ: Dans la région de la capitale de Slovaquie, Bratislava, près du fleuve de Danube, des immeubles de grande hauteur, qui donnent à la ville un nouveau visage, sont construits depuis plusiers années. Le niveau des eaux souterraines est situé dans une couche de graviers quaternaires dans une profondeur moyenne de 5.5 m sous le terrain. Une tension verticale d'environ 700 kPa se produira dans l'assise de fondation d'immeuble de grande hauteur. Avant de proposer la méthode de la construction, il était nécessaire d'analyser en profondeur les caractéristiques de déformation des sols. Il a été proposé de fonder un immeuble de grande hauteur sur la dalle de fondation avec des propriétés du sol améliorées. Le facteur décisif pour la conception de la manière de mise en place de fondations a été la détermination du tassement estimé. Cette tâche a été résolue par le calcul analytique classique et également par la méthode FEM. Les meilleurs résultats ont été obtenus avec le modèle de dalle de fondation de 2.1 m d'épaisseur avec le sol amélioré par des colonnes de jet grouting s'étendant jusqu'à 9 m, respectivement 18 m de profondeur sous l'assise de fondation. Une surveillance permanente du tassement de la construction est assurée afin de comparer le tassement réel et prévu de la structure selon les principes de la 3ème catégorie géotechnique. Les premières mesures ont déjà montré que la méthode de montage proposée était correcte.

Keywords: serviceability limit state; settlement; consolidation of soil

1 INTRODUCTION

A complex, which include a new bus station, business and administrative centres, has begun be built at a place of the old bus station in the Bratislava city. A floor plan dimension of the complex is 350 x 175 m. The terrain is about 137.0 m above the main sea level. The new bus station, which will be situated at a basement, requires a clearance height of 7.2 m. The supporting structure is a composite reinforced concrete frame. Manoeuvring areas for buses at the basement require large spans between bearing columns. The vertical loads in columns from the upper structure are in range of 5000 to 32000 kN. A part of the areal will be an atrium. The bearing columns at this place will be stressed by uplift forces of groundwater at the value of about 8000 kN. The major part of the complex is a high-rise building which has 32 floors and a height of 122 m above the terrain. At present, the construction has 12 floors. The building under construction is shown in Figure 1.

Figure 1. Photo of the current state

2 GEOLOGICAL CONDITIONS OF THE BUILDING SITE

The subsoil consists of fine-grained fluvial sediments to a depth of about 2.3 m below the surface. The second layer is consists of quaternary coarse gravels of a thickness of 10 - 14 m. A neogene subsoil, which begin at a depth of about 12 - 16 m below the surface, is consists of clay sandy and clay with medium plasticity (Vlasko, 2014). The bottom of the foundation is at a depth of 13.68 m below the surface, which correspond to an altitude 122.8 m above the main sea level (AMSL). The geological profile in the area of the high-rise building is shown in Figure 2. Based on the depth of the foundation and the geological conditions, there is only thin layer of gravels located below the bottom of the foundation. The distance of the building site from the Danube river is only about 700 m. The flowing groundwater has caused, that some levels of the gravel layer are at the loose state with following properties: I_D = 0.21 to 0.34 (*the density index*) and E_{def} = 22 to 49 MPa (*the deformation modulus*). The laboratory tests showed that the neogene subsoil has stiff consistency and the consistency index is in range of 1.04 to 1.31. The average mechanical properties of the neogene subsoil determined by laboratory testing are follows: the effective angle of shear strength φ' = 27 °; the effective cohesion c' = 19 kPa and the oedometer modulus E_{oed} = 37 MPa. More precise laboratory testing of neogene clays allowed determining the properties for different loading situations. The values of oedometer modulus are summarized in Table 1. A very important point is an impact of repeat loading to the value which equals to the original geostatic stress. The shear strength properties and the unit weights were determined using laboratory tests for each class of the soil, see Table 2.

Table 1. Oedometer modulus of neogene clays

Depth (m)		E_{oed} (MPa)		
Below the terrain		13.5 - 18.0	18.0 - 26.0	26.0 - 35.0
About the main sea level (AMSL)		123.5 - 119.0	119.0 - 111.0	111.0 - 102.0
Charactieristics	E_{oed}^0	63.5	125.5	142.4
	E_{oed}^1	53.5	79.8	100.2
	E_{oed}^2	21.1	33.2	40.1
Notes	E_{oed}^0 - unloading of the original geostatic stress = excavation of the pit,			
	E_{oed}^1 - loading to a stress equal to the original geostatic stress			
	E_{oed}^2 - loading to a stress equal to the stress from upper structure			

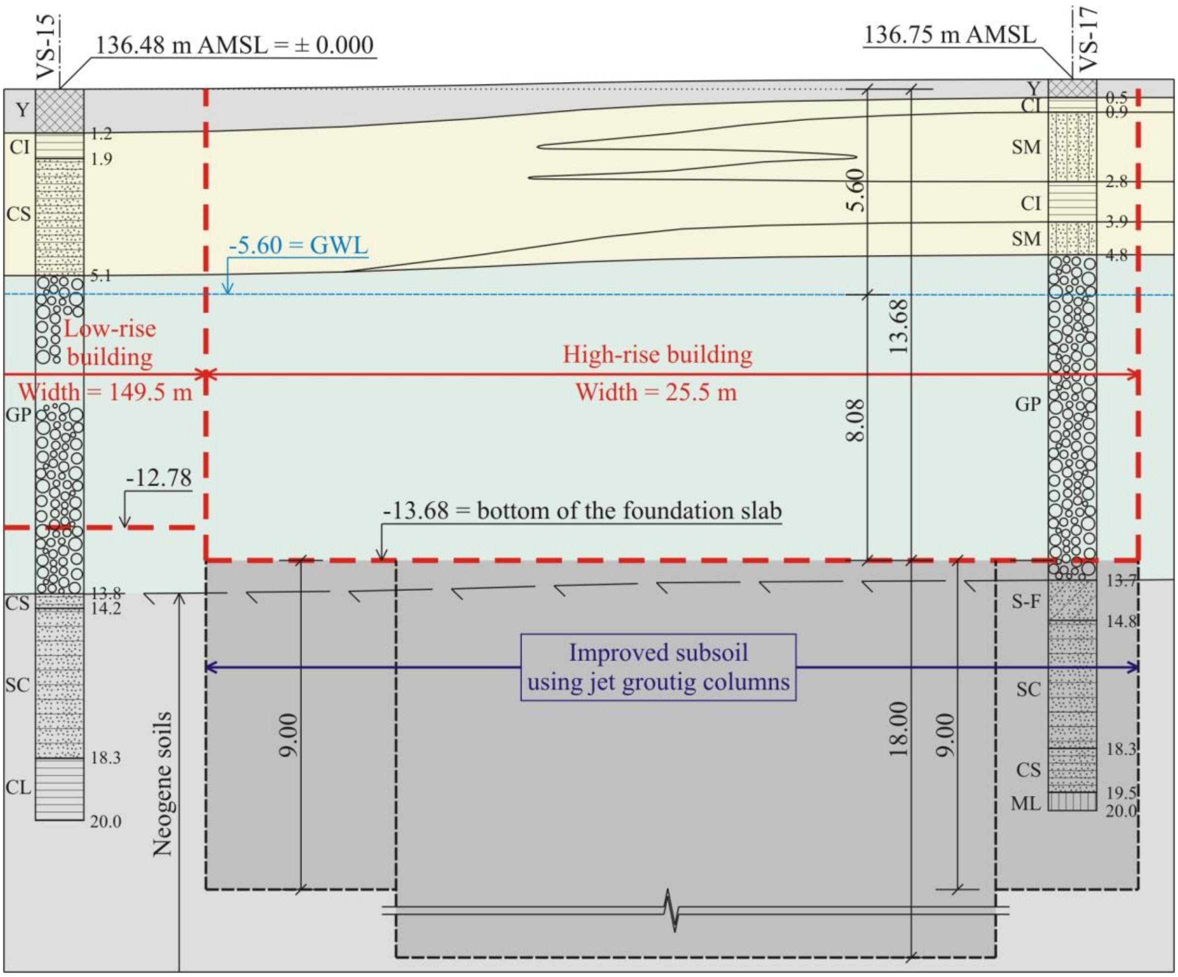

Figure 2. Geological profile with a scheme of the borders of the excavation pit and the soil improved area

Table 2. Shear strength and index properties of neogene soils

Soil name	Soil class	Parameter		
		γ (kN.m^{-3})	φ' (°)	c' (kPa)
Clay with high plasticity	F8 - CH	20.3	19.8	21
Clay with medium plasticity	F6 - CI	20.7	24.7	16
Silt with medium plasticity	F5 - MI	20.2	28.6	16
Clay sandy	F4 - CS	20.2	29.9	10

The design included also analysis of foundations of already constructed buildings in adjacent areas, presented by Hulla and Mazor (1998), and Slavik and Gallikova (2009). They presented results of laboratory tests of neogene fine-grained soils, which were determined for the CBC1 building. The results of their study were very similar to the results of laboratory tests made for presented construction.

Due to the excessive final settlement, the Keller Company designed support of the foundation slab by the jet grouting columns. A diameter of the single column was 2 m. The columns were designed in a square mesh of 3.56 x 2.61 m. The column have a length of 9 m under a less loaded part of the high-rise building (peripheral part) and a length of 18 m under a more loaded one (central part). The columns made of the jet grouting significantly increased stiffness of the original subsoil below the foundation bottom of the high-rise building. The deformation modulus of the jet grouting columns was assumed at the value of 2000 MPa, which was determined on tested jet grouting columns in similar geological conditions.

The cross section area of the single jet grouting column is follows: $A_{p1} = \pi r^2 = \pi .1^2 = 3.14$ m^2. There were installed 150 jet grouting columns on the ground plan area of dimensions 25.75 x 52.27 m (the area equal to 1346 m^2).

The total area of the jet grouting columns is 471 m^2. The area of the original subsoil between the stone columns was determined as follows: $A_z = A - A_p = 1346 - 471 = 875$ m^2. A modified oedometer modulus of deformation in the area of subsoil improved using jet grouting columns was computed as follows:

$$E = \frac{E_z A_z + E_p A_p}{A} = \frac{21.1\,.875 + 2000\,.471}{1346} = 714\ MPa$$

The oedometer modulus equal to 40.1 MPa was assumed for the original neogene subsoil below the jet grouting columns, which corresponded to the modulus determined for the stress equal to the stress from the upper structure.

3 DETERMINATION OF THE SETTLEMENT OF THE FOUNDATION SLAB

The dimensions of the foundation slab are 25.75 x 52.25 m and a thickness is 2.3 m. Due to an asymmetric construction and loading, the foundation slab was split to 3 parts with equivalent uniform loading, see Figure 3. An eccentricity in the shorter direction of the foundation slab was equal to 3.58 m and an eccentricity in the longer direction was equal to 0.06 m.

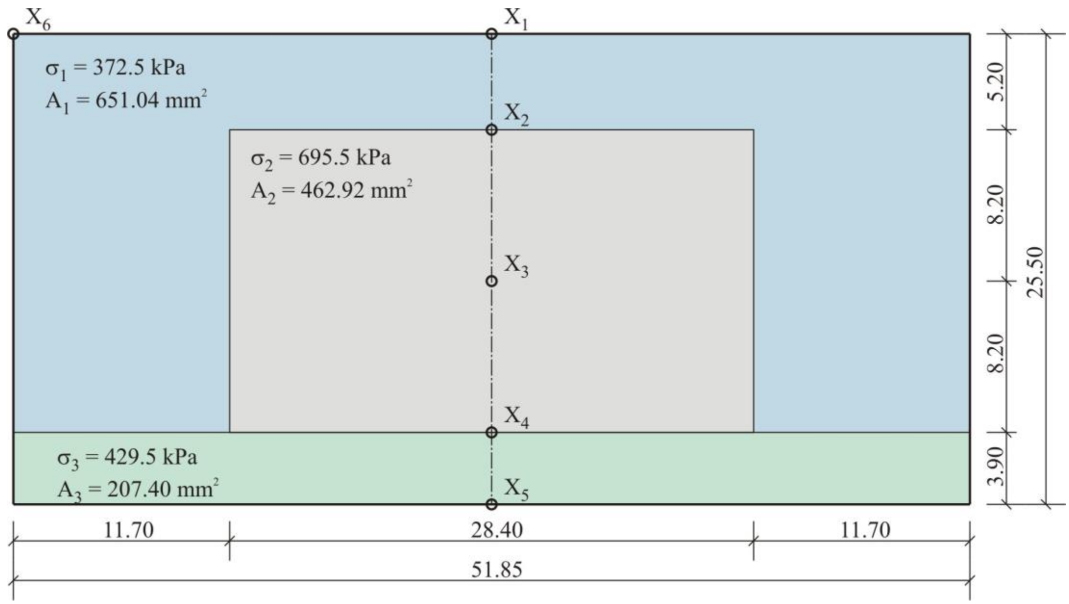

Figure 3. Scheme of ground plan split to loading areas

Due to the difficultness of the task, the settlement of the foundation slab was calculated by three independent projects teams: the Department of geotechnics of STU in Bratislava, structural engineers of the structure and the Keller Company. Geotechnician from the Department of geotechnics of STU in Bratislava determined settlement in selected typical points X_1 - X_6 (marked in Figure 3) using the analytical solution presented by (STN EN1997-1/NA: Eurocode 7: Geotechnical design. Part 1: General rules / National annexe) taking into account a principle of the superposition (Turcek, Sulovska, 2017). The final settlements at selected points were equal to: X_1 = 24.831 mm; X_2 = 34.256 mm; X_3 = 51.373 mm; X_4 = 32.851 mm; X_5 = 30.856 mm; X_6 = 0.3 mm.

The results of the settlement at following typical points were determined using the FINE Geo5 geotechnical software (module Slab) taking into account the Winkler - Pasternak model of the subsoil as follows: X_3 = 58.64 mm; X_5 = 50.15 mm and X_6 = 35.0 mm. The settlement of 55.6 mm in the X_3 point was determined using the same software in the Settlement module.

Structural engineers computed settlement of the foundation slab using the SCIA Engineering software with the Soilin module. The deformations calculated corresponded to the results determined using the analytical solution as well as the results determined using the FINE Geo5 software. Their computational model has more precise taken into account an eccentricity in lateral direction. They computed following settlements for selected typical points: X_1 = 41.1 mm; X_3 = 50.5 mm and X_6 = 18.3 mm. The settlement of the foundation slab calculated using different ways is presented in Figure 4 for main cross sections. The top view of the foundation slab deformations computed using the SCIA Engineering software is shown in Figure 5.

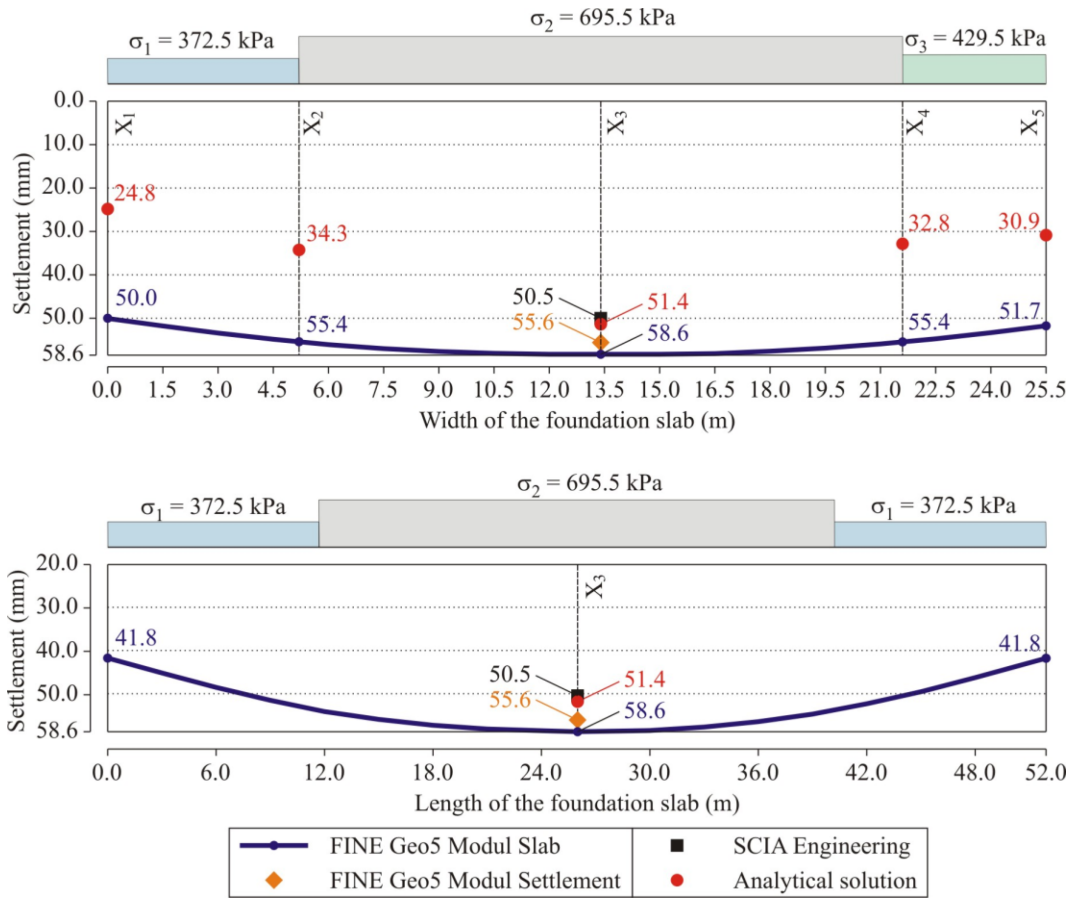

Figure 4. The settlement of the foundation slab - cross sections in main directions

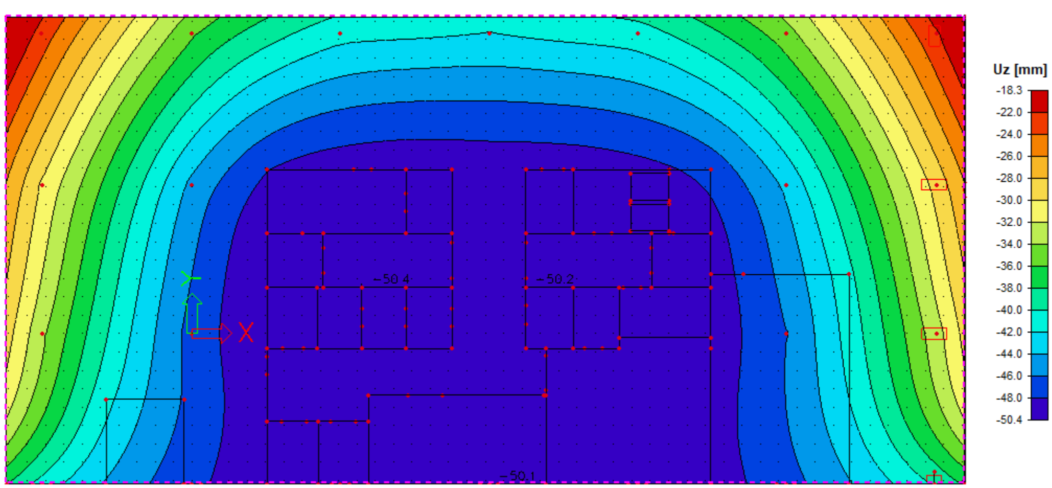

Figure 5. The settlement of the foundation slab taking into account maximal uplift of groundwater

The Keller Company determined the settlement of the foundation slab using the GGU-Footing and GGU-Settle software, and also using the KID (Keller Improvement Designer) software. The first computational model didn't take into account the soil improvement using the jet grouting columns. The results of the settlement at the X_3 point were as follows: 63.6 mm without taking into account the uplift of groundwater and 58.1 mm taking into account the uplift of groundwater.

The second computational model takes into account soil improvement of the subsoil using the method of homogenisation of the improvement subsoil. The value of the oedometer modulus of the improvement subsoil was equal to 2000 MPa. The settlement was about 42.2 mm at the X_3 point and about 9.6 to 12.1 mm at the X_6 point when the uplift of groundwater was taken into account. In the case when the uplift of groundwater was not taken into account, the settlement was about 58.5 mm at the X_3 point and about 23.9 to 25.4 mm at the X_6 point.

The third computational model estimated the value of the oedometer modulus in the improved subsoil at the value of 6000 MPa. The settlements computed were smaller at all the points. The value of the settlement was about 37.5 mm at the X_3 point and about 9.5 to 11.7 mm at the X_6 point when the uplift of groundwater was taken into account. In the case when the uplift of groundwater was not taken into account, the settlement was about 45.2 mm at the X_3 point and about 23.4 to 24.3 mm at the X_6 point. The results of the settlements in presented ranges were evaluated as acceptable because of the difficulty of the construction.

4 CONSOLIDATION OF THE SUBSOIL

The first step of the calculation was determination of the deformation of the bottom of the excavation pit after removing (excavating) the soil. It was assumed that construction works will be very fast. The value of the oedometer modulus of 710 MPa was used for unloaded neogene subsoil in the area of the soil improvement when the excavation pit reached a depth of 12.78 - 13.68 m (Figure 2) below the surface. The uplift of the bottom of the excavation pit was about 7 mm. The calculation assumed that construction of a one floor level will takes about 7 - 10 days. This assumption has correlated with process of construction. The calculation of the consolidation process showed that about 95 % of the total settlement will be reached at 900 days.

5 IMPACT OF SURROUNDING CONSTRUCTIONS

The high-rise building is under construction and a part of the high-rise building is already constructed. The surrounding low-rise buildings are just beginning to build (Figure 1). The stress below the low-rise parts will be about 160 - 180 kPa. It will caused that the settlement of the high-rise building will be affected. Two main situations are estimated in the design:

- there will be almost the complete consolidation of the subsoil from the high-rise building;
- low-rise buildings will be built before the end of the consolidation of the subsoil below the high-rise building.

The second situation is considered as more likely. The calculations showed that additional settlement of the X_1 point will increased for about 3 mm.

6 CONCLUSION

The design of a complex of constructions consisting of a high-rise and a low-rise buildings is one of the most difficult geotechnical tasks. The article is focused on the settlement of the foundation slab of the high-rise building. The building is part of a large complex of the structures which is under construction near the downtown of the Bratislava city. The settlement of the foundation slab was determined by 3 different engineers groups. The results of their calculations showed, that the final settlement of the middle point of the foundation slab was in range of 51.4 to 58.64 mm. A high degree of accuracy of calculations was considered as very positive. The building is still under construction.

The measured settlement of the foundation slab was in range 2.7 to 17.45 mm. These settlements were recorded for the construction with 12 above-ground floors and 3 underground floors. Based on the comparison of measured and calculated settlements it can be stated that the calculated settlements will be reached at the end of construction and the values will not be exceeded.

7 ACKNOWLEDGEMENTS

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