# Geotechnical aspects of «Moscow-City» International Business Center design

## Geotechniques aspects de projection de centre d'affaire international «Moscow-City»

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ABSTRACT: The paper presents some of scientific support studies that were performed during the geotechnical design and construction of «Moscow-City» International Business Center. Underground part of the complex covers the square of more than 50000 $m^2$ with depth of excavation by 25 m. The main aspects of geotechnical design are discussed. The results of numerical modeling and monitoring at the site are presented..

RÉSUMÉ: Cet article presente les resultats d'une surveillance scientifique des travaux reabiser pendant du elaboration getechnique des projects et construction de centre d'affair unternational «Moscow-City». Le souterrain ensemble recouvrit la surface de 50000 $m^2$ avec la profondeur de l'excavation environ de 25 m. Les principal aspects de project geotechnique sont discoutés. Les résultats du simulation numérique et de monitoring en place sont presentés.

## 1 INTRODUCTION

The International Business Center «Moscow-City» is situated at the district of Krasnopresnenskaya embankment at the left bank of the Moskva river. Prospective sight of the Center is shown in Fig.1. The Central Mall of the complex is designed as a multifunctional eight-storeyed building covering 125m x 470m square. Six underground levels of the Central Mall contain large transportation joint with two subway metro stations and a mini railway station. The designed complex is one of the largest in the world among buildings of the same type.

Figure 1. Prospective sight of the Center.

Underground part of the complex is surrounded with diaphragm curtain. This reinforced-concrete wall is 90 cm thick, 20-25 m deep and it was constructed by means of slurry-trench and secant piles methods. Total length of the diaphragm wall is 1761 m. Excavation is terraced and deepens towards the center. Maximum excavation depth is about 25 m. The volume of excavation is over 1 million $m^3$.

The main picularity of «Moscow-City» Center construction is the unprecedented for Moscow interference in natural geological conditions connected with excavation of enormous soil masses and following application of loads from designed high-rise buildings.

The designed Central Mall of the Business Center is very compound building site unique in its technical solution. Soil and groundwater conditions are characterized as complicated. The borders of the construction site situate comparatively close to existing buildings and engineering communications. Deformations of the soil massif caused by the construction may affect on the surrounding structures.

Construction of the Complex leads to changes in stress-strain conditions of the soil massif. The intensity of these changes depends greatly on the design solutions, technological methods at the site and sequence of construction stages.

In order to solve complicated engineering problems that rose in process of design and construction the program of geotechnical scientific support was elaborated. This program included :

- Complex analysis of soil and groundwater conditions at the site;
- Numerical modeling of stress-strain behavior of designed structures of the Central Mall interacting with soil;
- FE modeling of groundwater flow and analysis of changes in regional groundwater conditions;
- FE analysis of changes in stress-strain conditions of the soil massif and prediction of influence on adjacent buildings;
- Monitoring at the site including measurements of groundwater levels inside and outside excavation, measurements of displacements of diaphragm wall, monitoring of deformations of the buildings near-by.

## 2 SOIL AND GROUNDWATER CONDITIONS

The construction site is situated near-by the embankment of the Moskva river. According to the investigations geological profile is complicated. The upper soil leyers consist of quarternary deposits - fill, alluvial sands and silt. The total depth of quarternary soils is up to 8 m. Qarternary deposits are underlaid by carbonian limestones, dolomites and clays. Rock layers are from heavily slightly weathered. Typical geological profile as well as generalized soil parameters are shown in Fig. 2.

Three aquifers are met at the depth up to 30 m, as it is shown in Fig.2. The upper one saturates fill, alluvial sands and demolished limestone, the second the third aquifers saturate limestone layers. The first aquifer is unconfined, the other two are confined with the head 6-20 m. Permeabilities of aquifers are very high. Coefficients of permeability vary from 7 to 73 m/day.

## 3 GENERAL DESIGN SOLUTIONS

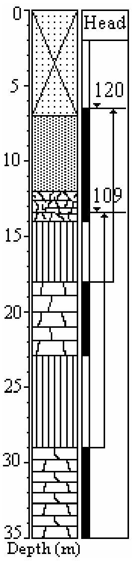
Two competitive decisions for protection of excavation from groundwater were considered. One of the preposals was to use dewatering of open excavation by surface pumps. This means that 11000 $m^3$ of grounwater should be discharged per day.

Another proposal put by NIIOSP was to construct a curtain deepened into waterproof clay layer and preventing the excavation from groundwater flow. The comparison of proposals gave an advantage to the last one.

It was designed to construct the curtain belting not only the Central Mall site but also the adjacent lots for prospective construction to the south. Schematic plan of the site with indication of curtain position is shown in Fig. 3.

The curtain was constructed partly with the help of diaphragm wall technology at its linear sections, and partly with the help of cutting piles at the rounded section. Thickness of the diaphragm wall is 90 cm. The diameter of cutting piles is 80 cm. Depth of the curtain varies from 20 to 25 m. General length of the curtain is 1762 m. Diaphragm wall was intended not only for protection of excavation from groundwater flow. Its upper part was designed to bear lateral soil and groundwater pressure and was reinforced up to the depth of 15 m. According to initial design the upper part of the curtain should work as cantilever retaining wall.

The excavation by itself was terraced and deepened towards center of the site. Soil berms contoured the excavation and provided stability of retaining wall. The volume of excavation at the Central Mall site reached 1 million $m^3$. Cross section of the Central Mall is presented in Fig. 4.




| Soil type | | Soil parameters | | | |
|---|---|---|---|---|---|
| | | γ | φ | c | $R_c$ |
| | | kN/m3 | deg. | kPa | MPa |
| $kQ_{IV}$ | fill | 18.5 | 21 | 8 | |
| $aQ_{IV}$ | sand | 19.3 | 25 | 0 | |
| $eC_{3pr}$ | very poor limestone | 20.0 | 29 | 40 | 7 |
| $C_{3nv}$ | stiff clay | 21.6 | 19 | 50 | |
| $C_{3rt}$ | weathered limestone | 22.0 | 38 | 150 | 20 |
| $C_{3vs}$ | hard clay | 22.3 | 21 | 50 | |
| $C_{3sv}$ | limestone | 22.1 | 40 | 200 | 25 |

Figure 2. Typical soil profile.

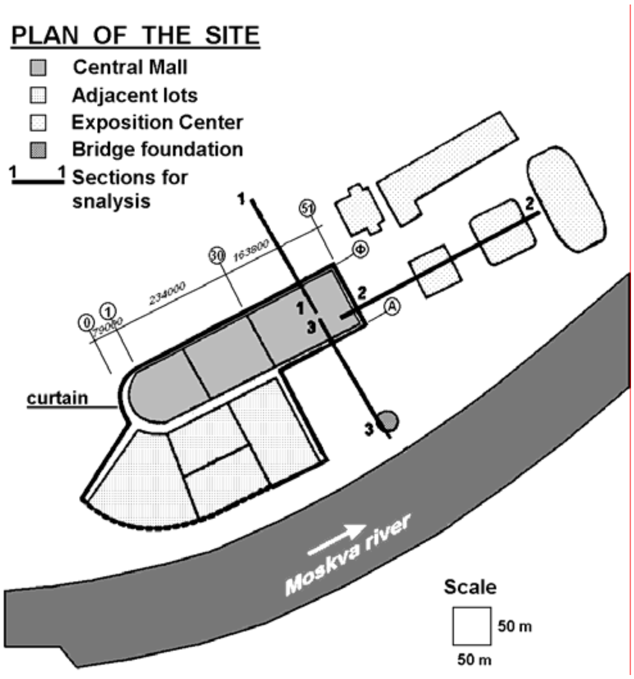



Figure 3. Plan of the site.

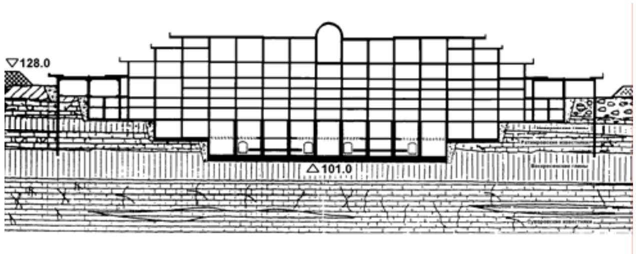



Figure 4. Cross section of the Central Mall.

## 4 ANALYSIS OF STRESS-STRAIN BEHAVIOUR OF SOIL MASSIF

The prognosis of changes in stress-strain conditions of soil massif due to construction of the Central Mall was done with the help of finite element modeling. Initial stage of modeling was undertaken to predict dimension of "influence zone" around excavation and differential settlements of adjacent buildings and structures. This stage included two-dimensional FE analysis for three sections which were chosen as the most critical concerning influence on near-by buildings. The position of sections for analysis is shown in Fig. 3.

In order to rise reliability of prediction analysis for each section was done by different companies ( NIIOSP, MGSU, MIGG ) with the help of various software codes. Analysis of stress-strain behavior used the results of 3-D modeling of transient groundwater flow that was done by GEOCENTRE-MOSCOW.

The studies of changes in stress-strain conditions of soil massif caused by construction of the Central Mall included:

- determination of adequate dimension of FE mesh;
- elaboration of geotechnical model for soil behavior;
- detailed elastic-plastic FE analysis following sequence of construction stages at the site;
- analysis and comparison of results;

- inference on influence degree and safety of adjacent buildings and structures.

The results of prediction that was done by three independent companies show good correspondence. Comparison of main results of FE analysis is shown in Fig. 5.

The first stage of FE analysis showed that construction of the Central Mall "Moscow- City" doesn't cause the formation of developed plastic domains in soil massif. The zone of influence of construction spreads horizontally for approximately three depths of excavation i.e. up to 75 m. This means that all of the existing buildings and structures are situated at the border of influence zone or out of it.

Maximum predicted settlements of the Exposition Center pavilions (section 2) caused by construction of the Central Mall does not exceed 2 mm. The additional settlement of the bridge foundation (section 3) was calculated to have maximum about 5 mm. According to numerical modeling the construction wouldn't affect on the dwelling houses situated to the north of the site (section 1). Thus safety of adjacent buildings was confirmed. Additional differential settlements for all buildings were much less then their permissible values.

The considerable changes in architectural design plans were undertaken when the retaining wall was completed and soil excavation works were already in progress. This caused necessity of elongation of lower underground storeys and correspondingly reduction of perimetral soil berms at eastern side of excavation (section 2). The lower part of the berm was going to be shortened for approximately 40 m. It was necessary to design some measures in order to provide the stability of diaphragm wall and the slope as only upper 15 m of the wall were reinforced according to initial design.

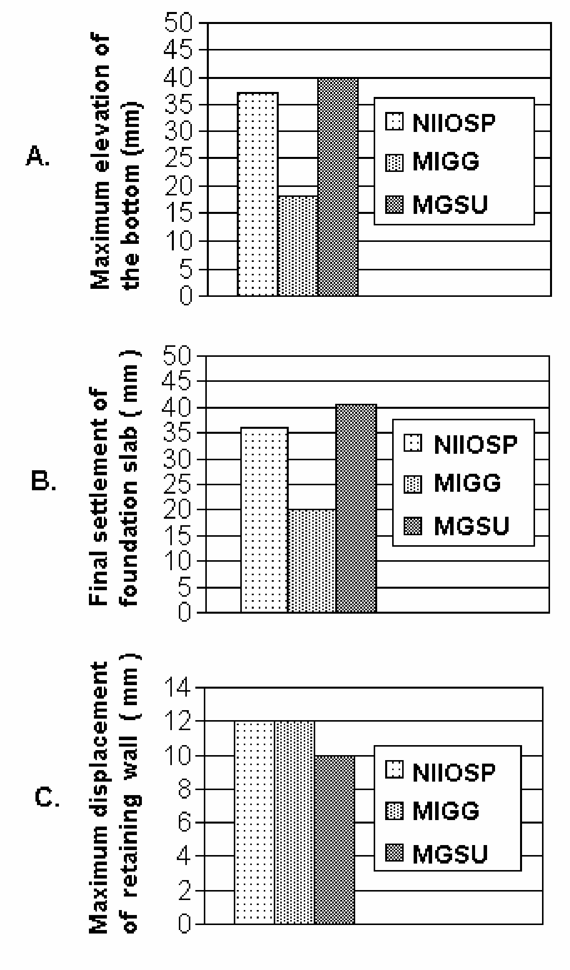



Figure 5. Comparison of main results of FE analysis.

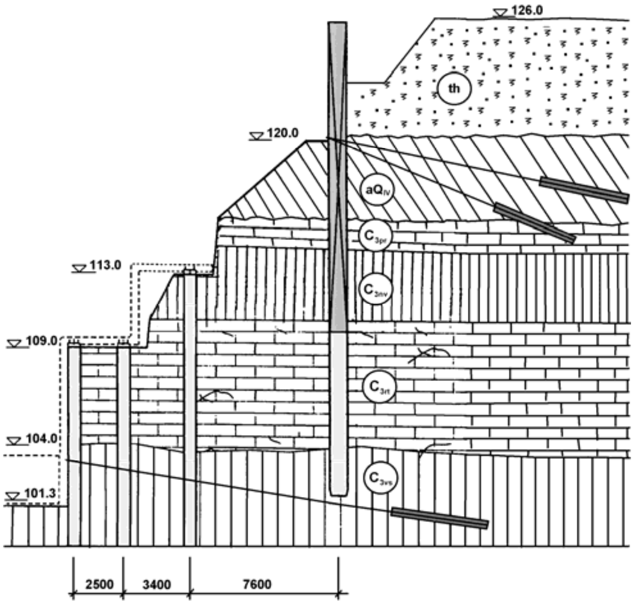



Figure 6. The final profile of retaining wall at the eastern side.

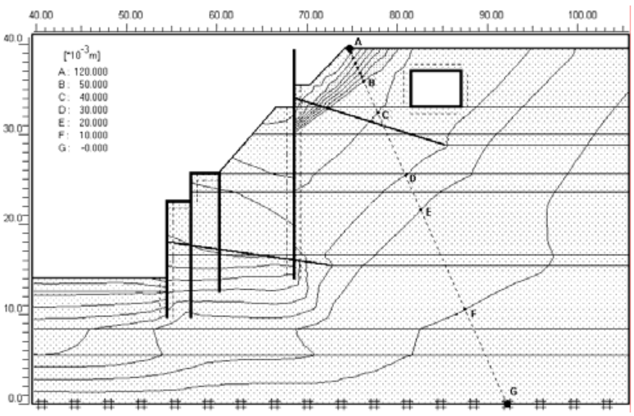



Figure 7. Contour lines of total displacements in soil massif.

The efficiency of different protective measures was analyzed by means of FE modeling. The general safety factor should be achieved not less than 1.2 and bending moment in the reinforced part of diaphragm wall should not exceed 900 kN*m/m. The lateral displacements of retaining structure were not actually limited as far as buildings of Exposition Center lay out of influence zone.

The decision that was chosen proposed bracing of the wall and slope with two rows of prestressed anchors. Since the demanded bearing capacity of upper row anchors was not provided an additional unloading trench was excavated outside the retaining wall. The depth of unloading trench was about 4 m. The final profile of retaining wall at the eastern side of excavation is presented in Fig. 6. Some results of FE modeling of protective measures are shown in Fig. 7.

The predicted lateral displacement of the top of diaphragm wall was equal to 129 mm. This value has a good agreement with monitoring data. The measured lateral displacements of this part of diaphragm wall varied between 92 and 142 mm. The safety of retaining structure was provided.

## 5 EXCAVATION PROTECTION FROM GROWNDWATER FLOW

As it is seen in Fig. 3 the excavation is deepened in impermeable hard clay with thikness of layer 6-9 m. The clay is underlaid by saturated suvorov limestone with the head up to 20 m. Taking into consideration that the completion of excavation decreases the thickness of waterproof clay up to 4 m, it was necessary to decrease heads in underlying suvorov limestone in order to prevent bottom uplift. The residual value of the head sufficient to provide safety was calculated to be equal to 8 m.

According to the initial design it was assumed that the curtain should completely exclude lateral inflow. Thus the main problem considered to be a decrease of the heads in suvorov limestone.

The design solution of this problem intended construction of 12 self discharging wells. The diameter of these wells was 425 mm. The walls were positioned into two lines along northern and southern sides of the excavation. Considering the sequence of excavation works that were started from eastern side (axis 51 in Fig. 3), the wells were put into operation successively. Calculations of their inflow volume were done for transient groundwater flow problem. Average total inflow was predicted to be about 10 m3 per hour.

In spite of the initial design the completion of the curtain was delayed and ran behind the schedule of excavation works. In order to keep time-limits of construction it was decided to begin excavation of saturated perhurov limestone (C3pr) layer while the curtain was not completed at its southern part.

Special series of 3D finite element analysis of transient groundwater flow with changing in time contour of the curtain was fulfilled by GEOCENTRE-MOSCOW company. Provided numerical modelling proved principal possibility of excavation dewatering in conditions of unclosed curtain and showed that changes in groundwater levels outside the curtain would be not dramatic for safety of the adjacent buildings.

Two longitudinal open pumping trenches were organised in the excavation. These trenches were deepened while excavation works proceeded. The groundwater inflow volume consisted from 1000 to 1200 m3 per day. The monitoring of the groundwater levels decrease outside the excavation was performed with the help of 16 observational wells. The maximum monitored decrease of upper groundwater level outside the curtain consisted 1.0-1.2 m. These values showed a good agreement with the predicted values of 1.0-1.5 m.

After completion of the curtain and excavation up to the final level two linear drains were organised at the bottom and two drainage layers were put. The drainage was designed in order to accept rainwater, inflow through the curtain and inflow through the bottom.

The exploitation of drainage layer and discharging wells is going to be ceased when the weight of constructions of the Central Mall will equalise the uplift force corresponding to the natural head level in suvorov limestone.

The numerical FE modelling gave a prediction for prospective changes in groundwater conditions caused by the construction of "Moscow-City" complex. The predicted long-term rise of groundwater level outside the constructed curtain is equal to 1.0-1.2 m. This value is permissible from ecological point of view as well as acceptable for safety of existing buildings and structures. In order to prevent unforeseen changes in water levels the horizontal tube drainage was designed outside the curtain.

## 6 CONCLUSION

The example of the Central Mall "Moscow-City" construction evidently demonstrated the importance of geotechnical scientific support. Co-operation between different companies involved in the program of geotechnical support contributed greatly to solution of problems faced during the construction. The following outcomes should be mentioned:
- numerical modelling anticipated design showed principal possibility of construction and predicted permissible influences on the adjacent buildings;
- the design solution to construct a waterproof curtain contouring the site proved to be efficient;
- changes in initial design solutions caused by various reasons resulted in additional efforts to keep construction as safe as it should be;
- the monitoring at the site showed a good correspondence of actual data with the predicted values;
- the construction did not effect on changes in natural groundwater conditions.

The construction of underground part of the Central Mall "Moscow-City" complex is nearly finished now. Construction at the adjacent lots is going to be started.


## 7 ACNOWLEDGMENTS

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