Deep excavation design to carry out construction of national and university library by Jože Plečnik (NUK II) in Ljubljana, Republic of Slovenia

Dessin de Protection de Fouille Pour Satisfaire aux Besoins de Construction de la Bibliotheque Nationale et Universitaire de Jože Plečnik (NUK II), a Ljubljana, Slovenie

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ABSTRACT

In the Ljubljana city center the Ministry of Higher Education, Science and Technology has plans for a construction of a new National University Library by Jože Plečnik (NUK II). The structure is designed in such a way that a central part of the library a high shelving storage is located over four cellar floors. The structure arrangement affects the foundation soil up to a depth of 17.0m. Geologically the region of construction is one of the most demanding in Slovenia. The structure site is located on the passing through high compressible sediments of the Ljubljana Moors (in a thickness of up to 32m) at a southern part and somewhat better gravel and clayey alluvium of the Ljubljana field at a northern part. There are two groundwater levels at the site. The geological soil structure gave rise to a choice of technology for protection of the deep excavation by braced thick diaphragm wall and technology of top-down structure construction.

RÉSUMÉ

Au centre ville de Ljubljana, le Ministere de l'Enseignement Superieur, de la Science et de la Technologie envisage la construction d'une nouvelle Bibliotheque Nationale et Universitaire de Jože Plečnik (NUK II). La partie centrale de la bibliotheque, un haut rayonnage de stockage, est dessinee de facon qu'il s'etale par quatre etages de cave. La conception de l'ouvrage implique l'intervention au sol de fondation jusqu'a la profondeur de 17.0m. Geologiquement, la region de construction est une des regions les plus exigeantes de la Slovenie. L'ouvrage est situe au passage des sediments de haute compressibilite de Marais de Ljubljana (d'une epaisseur jusqu'au 32m) a la partie du sud et des alluvions un peu meilleures de gravier et d'argile de Ljubljansko polje a la partie du nord. Au site deux niveaux de la nappe phreatique sont trouves. La composition geoloqique du sol a dicte le choix de la technologie de protection de fouille par le diaphragme ouvert d'un mur epais et par la technologie de la construction de l'ouvrage du haut en bas.

Keywords: urban environment, geotechnical engineering, deep excavation, diaphragm wall, groundwater lowering, hydro geological modeling

1 INTRODUCTION

The Government of the Republic of Slovenia and the city of Ljubljana envisage construction of, for a long time indispensable, new library premises, providing users of the two central Slovene libraries, the Central Technical Library (CTK) and the National University Library (NUK), with substantially better conditions, as well as major and quicker access to the library material itself. According to the Ljubljana town planning the region of the foreseen construction is found in the city centre itself, within Roman remains of the ancient Emona, between Zoisova street in the south, Rimska street in the north, Slovenska street in the west and Emonska street in the east. In the past years at the construction site itself the archeological works were carried out, presenting surprising archeological findings and discoveries, conveying information on the stage of development of the then Roman civilization. In addition to the archeological findings, in the structure design major importance was attributed also to the Ljubljana town planning. Consequently, the structure was conceived by setting the central part of the library, a high shelving storage, over the four cellar floors. This means that the building construction will affect the foundation soil, within urban environment up to a depth of 17.0 m. Construction location particularities also apply to geological – geotechnical conditions. The area of construction lies at a passage of high compressible sediments of the Ljubljana moor and slightly better gravel and clayey alluvium of the Ljubljana field. This area represents one of the most demanding geological regions in the Republic of Slovenia.

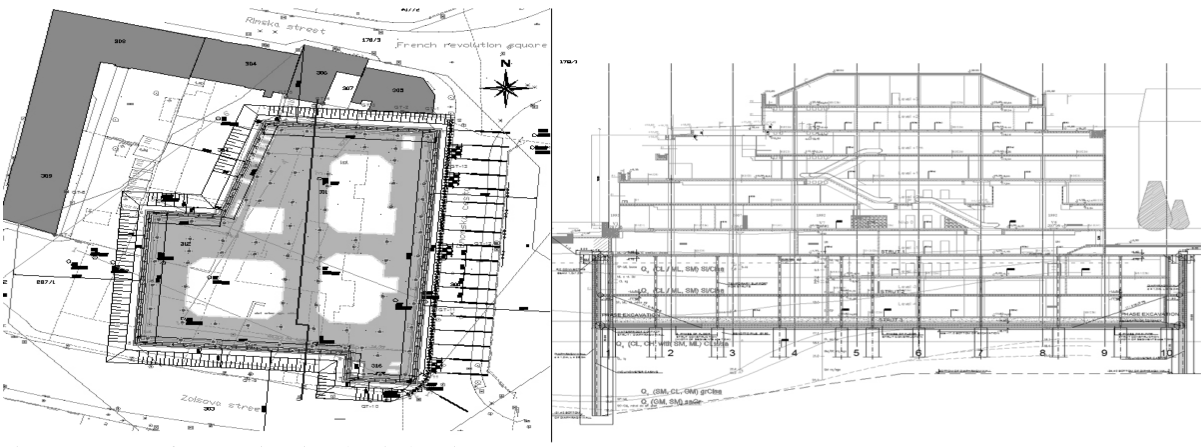

Figure 1: Layout of construction pit and typical section

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2 INVESTIGATIONS, GEOLOGICAL AND HYDRO-GEOLOGICAL CONDITIONS

In the area of the construction site several geological-geotechnical investigations were conducted in the previous years (1992, 1997 and 2007). In total, 19 exploratory borings were performed, of which two were equipped for inclinometer measurements and two for measurement of the piezometer groundwater level. Simultaneously, numerous field and laboratory examinations were also carried out.

Generally, the geological structure of the ground at the location was very heterogeneous and extremely demanding for construction of deep excavation. The building is situated at the border of two elements, various in sedimentation, the Ljubljana moor in the south and the Ljubljana field in the north. In the southern part of the construction site the marshy and overflow dam sedimentation prevailed in the geological past, resulting in the clayey-silty soils, while in the northern part mainly alluvial sediments are deposited with typical deposits of gravel and sand.

Based on the investigations and the basic geological map of Slovenia a geological and geomechanical model of the construction site was established (Fifer et al., 2008). There were 5 separate layers in the model (Fig. 2). In the upper parts prevail heterogeneous, clayey - silty, in some places sandy soils with a layer of highly plastic and compressible clay at a depth of 9.0m up to 12.0 m below the surface. The clayey layers appear up to a depth of around 29 m in the southern and eastern parts, while in the northern part they can be found up to a depth of around 16 m. Under a stratum of clayey - silty layers medium dense to dense clayey and silty gravels are found. Hydro geological conditions of the region studied were established on the basis of the field investigations. Two groundwater levels were found, namely the upper (perched) groundwater table and the lower, the proper groundwater table of the Ljubljana aquifer. The upper water table occurs at a relative elevation around 6.0 m and lower at 15.0 m under The lower groundwater table is free in some areas, but mostly subartesian, at areas where the clayey-silty layers descend below the relative water table elevation of 15.0m under the surface. In planning, due to an exceptional heterogeneity of the upper clayey - silty and in places sandy layers, groundwater table of 5.8m under ground was taken into account as the initial level of the groundwater. Between both groundwater levels it has been adopted that the soil is entirely saturated. Hydraulic properties of aquifers were evaluated as:

- $k = 10^{-7}$ to 10^{-9} m/sec for upper clayey – silty layers
- and $k = 5 \times 10^{-4}$ m/sec and $T = 1.5 \times 10^{-2}$ m^2/sec for gravel-sandy fill, where T is aquifers transmissivity.

A depth of the lower Ljubljana aquifer is about 35m in this part.

3 PROBLEMS AT DESIGN OF DEEP EXCAVATION

Initially, by its architectural design the building NUK II envisaged construction of a high shelving storage of an area of 1.220 m^2 and a height of 10 m. The storage of library material was located over four cellar floors, namely from the bottom of the fourth (-IV.) cellar to the top of the first (-I.), uniform in volume. When geotechnical engineers joined the project, the users, client, the architects also, required the initial design of the cellar premises should be respected.

Already within the phase of the ground investigations, it was clear that the use of the permanent geotechnical prestressed anchors for the protection of excavation would be impossible. Due to a favorable ground plan form of the structure in the form of a letter "L" and ceiling slabs of the cellar floors, a solution of supporting the diaphragm walls by ceiling slabs of the structure, using the top-down technology of construction. By the initial design an 80 cm thick diaphragm wall was foreseen along a circumference of the deep excavation, which should be braced by four (4) ceiling slabs of the cellar floors. However, such a design was in conflict with the requirement of a uniform high shelving storage. As a compromise, it was decided to use a 100 cm thick diaphragm wall, braced by two ceiling slabs of the cellar floors (a ceiling slab of the first cellar and a ceiling slab of the fourth cellar), and a floor slab of the fourth cellar floor. In this way the high shelving storage was divided into two independent sets.

Due to poor ground properties, and in order to reduce the diaphragm loading, we were compelled to include the floor slab itself in the function of taking over a part of the horizontal loading. It was foreseen to execute the core of the floor slab first, followed by the excavation and a simultaneous installation and bracing by a floor slab. The individual segments would be in a width of up to about 7m. The expected technology of deep excavation construction foresees the use of the structural elements of the building itself to support the diaphragm wall. Concrete piles were used to carry out the structure founding as addition for protection of excavation. Because of a great distance between parallel walls of the excavation (also more than 40.0m), the Benotto piles were used for vertical support of both bracing slabs. At piles installation it was projected that steel columns are to be built above a concrete part of the pile, thus providing an adequate support to the braced slabs.

Owing to groundwater presence, in digging up below level of the second braced slab, which is at an elevation -11.36m, lowering groundwater level within the building pit was foreseen. Groundwater lowering will be achieved by a large number of wells. In order to lower groundwater table to the bottom of excavation, it would be necessary to pump up to about 500 l/s. The construction pit in study is special also in a sense of construction of the excavation itself. Due to a limited space and unfavorable ratio between a width and final depth of the excavation, in order to remove the excavated material from the excavation, it was planned to use the continuous conveyor belts, enabling the removal of the material to the surface through the slits in the ceiling slabs.

4 MODELLING

All geotechnical and hydro geological data acquired in the previous years was used to assess appropriate calculation models that were analyzed by adequate software tools in order to simulate the actual conditions at the construction site. A great attention was given to the assessment of stiffness parameters of the soil, and to the model of hydro geological conditions in the soil.

4.1 *Geostatical analysis*

For a geostatical analysis of the excavation a computer program PLAXIS 2D, 8.6 was used. Non-linear analyses were carried out by finite element method for six (6) characteristic calculation examples.

The ground behavior was modeled by "the Hardening soil" material model. The shear strength parameters were obtained from direct and triaxial shear tests. Stiffness parameters were assessed from a large number of edometer tests. For each soil layer loading and unloading indices (C_C in C_r) were evaluated, and the average values were used in the model. The initial pore pressure distribution in the model was based on the observations that there were two groundwater levels and between these levels fully saturated clayey silt. The assumption of a single groundwater table at the elevation of 5.80m below ground surface represents rather unfavorable but realistic calculation example and was used in design.

The 100 cm thick reinforced-concrete diaphragm wall was modeled with plate elements of reduced stiffness (by a factor of 10^{-6}) and by volume elements having the actual thickness of the diaphragm wall with linear elastic material properties for concrete.

Elastic material properties of the braced slabs were assessed in such a way that the development of calculation shrinkage of the slabs was taken into account and consequently the development of larger horizontal displacements of the retaining wall. Calculation steps were modeled in accordance with the construction technology. By modeling groundwater pumping within the excavation groundwater inflow through the bottom of the pit was modeled.

Modeling of the excavation under the elevation of the second braced slab was very important. In order to reduce the displacements of the wall and area behind the wall, it has been planned to execute the last excavation stage in phases of the excavation and concreting the floor slab by segments. Such type of construction was successfully modeled by means of "Mstage" calculation parameter, built in the program. From figure 2 a calculation model can be seen.

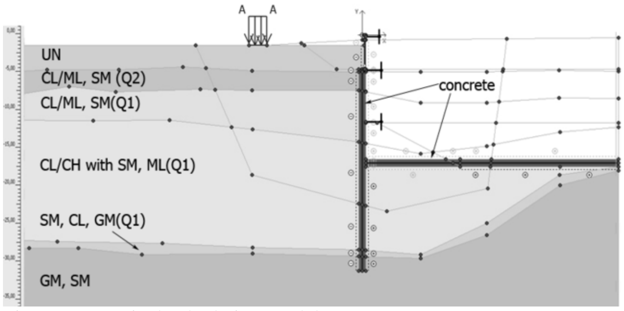

Figure 2: Typical calculation model

Table 1 gives the values of the material parameters considered.

Table 1: Material parameters

material	γ [kN/m^3]	c' [MPa]	φ' [°]	E_{oed}^{ref} [MPa]	E_{ur}^{ref} [MPa]	k [m/day]
UN	21,0	2,0	40,0	40000	1,2E5	1,0
CL/ML, SM	20,9	1,0	30,0	4212,0	34960,0	6,65E-6
CL/ML, SM	20,9	1,0	30,0	4201,0	34868,0	6,65E-6
CL, CH, with SM, ML	20,0	3,0	28,0	2936,3	18640,0	7,43E-5
SM, CL, GM	20,4	1,0	28,0	10000,0	30000,0	1,0E-4
GM, SM	23,0	1,0	35,0	62000	1,86E5	0,01

4.2 *Hydro geological analysis*

A great deal of attention was paid to lowering of a groundwater level inside the excavation, since it is of an extraordinary importance for safe construction. For that purpose a 3D model of the region treated was prepared and numerical calculation of the groundwater inflows into the construction pit was calculated. The simulations of the steady-state groundwater flow were performed by Groundwater Modeling System (GMS) software, based on finite difference method, applying a modulus MODFLOW-2000 (McDonald & Harbaugh, 1992).

The initial state of groundwater table was considered at a relative elevation of 5.8m below the ground surface. It was also assumed that the entire region below this elevation is fully saturated. According to the design the bottom of the excavation is at the altitude of 281.5 m, that is why the altitude of 281.0 m was considered as the maximum allowable altitude of the groundwater for safe construction of the building. Three variant calculations of water lowering were carried out:

- VARIANT 1: simulation, at which lowering of the groundwater level was considered only in the area of a partial excavation – foundation slab core. For this simulation a calculation model was used, where groundwater table was pre-assigned and the result of calculation was the quantity of water that needed to be pumped out (Dirichlet boundary condition).
- VARIANT 2: simulation where flow rate in wells, needed to lower water table to an elevation of 281m, was pre-assigned (Neumann boundary condition).
- VARIANT 3: simulation where flow rate from wells was pre-assigned, in order to reach a groundwater level about 281m, within the region of the entire construction pit (within the diaphragm wall).

5 RESULTS

5.1 *Results of geostatic analyses*

The geostatic calculations were carried out as regulated by Eurocodes (EC0, EC1, EC2, and EC7). Each individual construction phase was suitably modeled and analyzed by individual calculation steps (loading cases). By means of a great number of analyses we tested the susceptibility of each individual calculation model to modifications of more or less important material and geometric characteristics of the calculation elements.

The most critical loading case has proven to be the final stage after the excavation and installation of the entire floor slab.

From Figure 3, where contour lines of total displacements are shown, the region of major calculation settlements behind the wall can be seen. The calculated maximum displacements of this area of up to 3.3 cm are estimated as still acceptable.

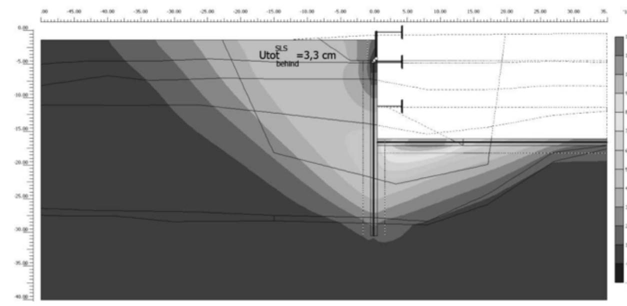

Figure 3: Contour lines of total displacements – final excavation stage

The envelope of the internal forces within the diaphragm wall and calculated displacements of the diaphragm wall for the serviceability limit state (at F=1.0) are shown in the figure 4.

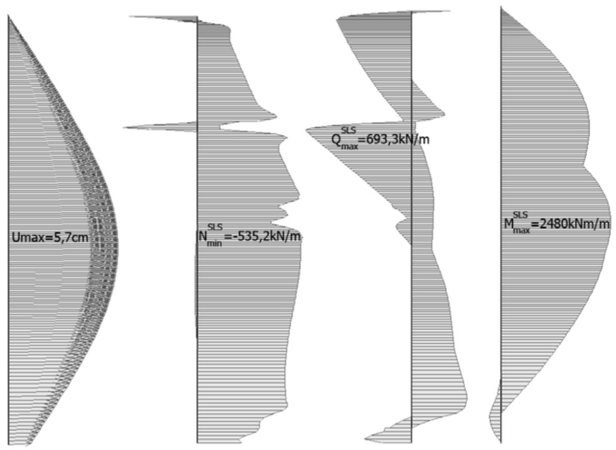

Figure 4: Deformations and internal forces of the diaphragm wall

The magnitude of calculated loadings of braced slabs at the serviceability limit state was from 290kN/m for the slab at the first level up to 1010kN/m for the slab at the second level. The maximum calculated axial force in the floor slab was 365kN/m.

During the analysis of the global safety of the retaining structure, it has been found out by means of a parametric study that the global safety depends mainly on the reliability and integrity of the braced slabs. If braced slabs are properly installed and details and joints of the various structural elements suitably executed, the actual safety of the structure will significantly exceed the required minimum values. Supervision during construction process will be given a great importance, in order to attain sufficient degree of safety and to minimize the influences on the nearby structures.

5.2 *Results of hydro geological analyses*

The results of the VARIANT 1 have shown that for a required water lowering (water level in the area of a partial excavation at an elevation 281.0m of altitude) it is necessary to pump about 313l/s of water. Namely 301l/s from the lower layer of the Ljubljana aquifer and 12l/s from the upper silty layers.

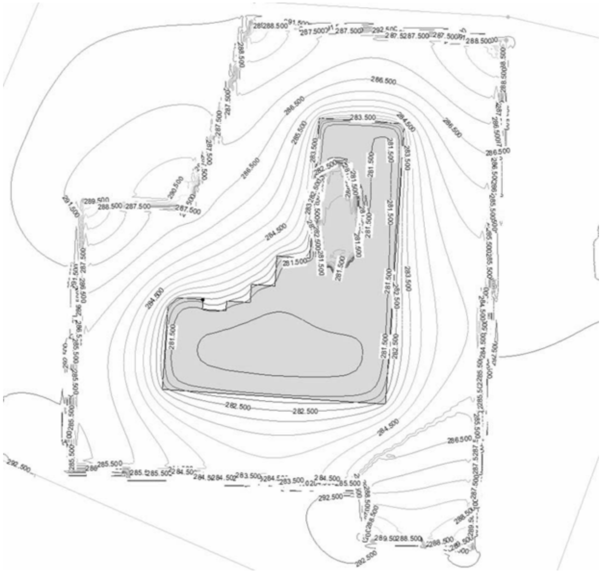

Figure 5: Ground water levels in the central part at variant 1

The result of the calculation for the VARIANT 2 has shown that for a desired lowering of the groundwater level it is necessary to carry out pumping from 12 wells with an average pumping from an individual well of about 30 l/s. Pumping screen should be installed between the depths of 270 m and 278 m of altitude. The total quantity amounts to 372 l/s by calculation.

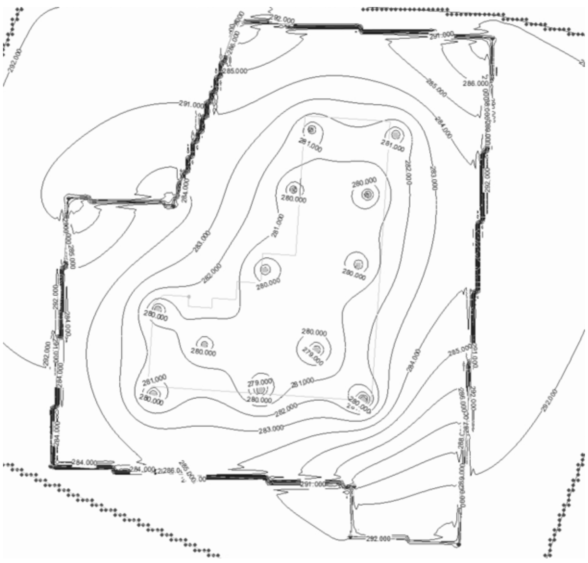

Figure 6: Water lowering in the central part by pumping from the wells

The calculation for the VARIANT 3, at which simulation of lowering the groundwater level was carried out for the entire region of the excavation with a system of wells, has shown that pumping 480 l/s is required to attain the desired groundwater lowering. A major quantity of water would be pumped from the lower layer of the Ljubljana aquifer. An average quantity of pumping from an individual well is about 26 l/s, and the screens are to be installed in depth of 278 to 270 m of altitude.

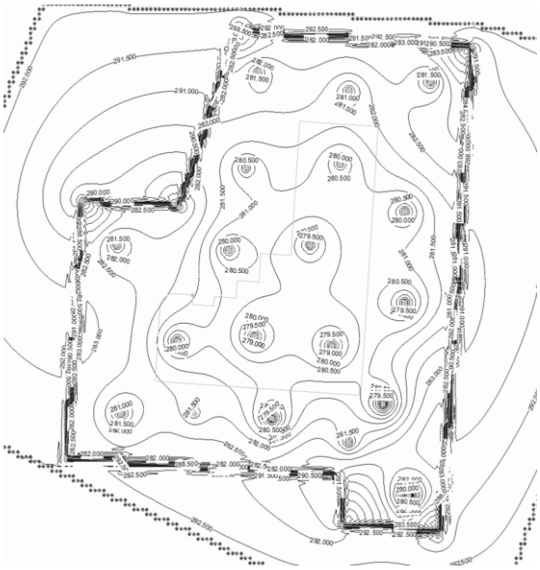

Figure 7: Groundwater level as a consequence of pumping from wells at the entire area of the excavation.

6 CONCLUSION

During the design of deep excavation for the construction of the cellar premises of the national university library II, we had a very difficult task to adjust the needs of the users of the building to the very demanding geotechnical conditions. The compromise for the deep excavation design by means of a braced retaining wall, made from reinforced – concrete diaphragm wall in a thickness of 100 cm, with panel lengths up to 27,0m, braced at three levels by the structure slabs, has proved appropriate during design phase. During construction of the building, a great attention should be paid to deformations of the area behind the construction pit and the diaphragm wall itself. During constructing it will be of prime importance to set up a monitoring system, already foreseen by the design.

In the final stage of the excavation groundwater level will have to be lowered to the depth under the bottom of excavation. The actual pumping quantity will be large regarding relatively high permeability of the lower aquifer. Due to heterogeneous soil in the upper part, a deviation from the calculated value is to be expected, but will be of minor importance.

By elaboration of the design documents to obtain a building permit, suitable guidelines were given for preparation of the executive design and at the same time contractors attention was drawn to a very demanding work at construction site.

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