Aspects on designing and monitoring a deep excavation for a highly important structure

Aspects de conception et de suivi d'une excavation profonde d'une très importante structure

Popa H., Manea S., Batali L., Olteanu A.
Technical University of Civil Engineering of Bucharest, Geotechnical and Foundations Department, Romania

ABSTRACT: Building large and deep excavations in urban areas is always a complex problem. The geotechnical investigation should be very detailed and the design rigorous. As well, the monitoring of such a work is mandatory. The paper presents a retaining structure from Bucharest, Romania for a deep excavation of 66 x 127 m size in plan and a maximum depth of over 16 m. This open pit was required for building the infrastructure of the largest Cathedral in Romania, the National Redemption Cathedral. The paper presents aspects regarding the geotechnical investigations and interpretation, soil parameters, calculation of the diaphragm wall, anchors and dewatering system, as well as displacement monitoring.

RÉSUMÉ : Les excavations profondes et de grandes dimensions réalisées en milieu urbain représentent toujours un problème complexe. L'investigation géotechnique doit être très détaillée et la conception rigoureuse. De même, le suivi d'un tel ouvrage est obligatoire. L'article présente une structure de soutènement de Bucarest, Roumanie pour une fouille de plus de 16 m de profondeur et ayant 66 x 127 m dimension en plan. Cette excavation a été nécessaire pour construire l'infrastructure de la plus grande Cathédrale de Roumanie, la Cathédrale de la Rédemption du Peuple. L'article présente des aspects concernant l'investigation géotechnique et son interprétation, les paramètres du sol, le calcul de la paroi de soutènement, des ancrages et du système de rabattement de nappe, ainsi que le suivi des déplacements.

KEYWORDS: retaining structure, diaphragm wall, deep excavation.

1 INTRODUCTION

At the present, in Bucharest is under construction the larger orthodox cathedral in Romania, the National Redemption Cathedral. The location of the Cathedral is in the city centre, next to another very large building, the People's House, on a high area called the Arsenal Hill.

The size of the future Cathedral is: length and height of more than 120 m and a width of over 60 m. The Cathedral basement has 2 stories and the total surface of the future cathedral plus the adjacent buildings is of about 11 000 sqm. Figure 1 presents the photo of the concept design of the future cathedral.

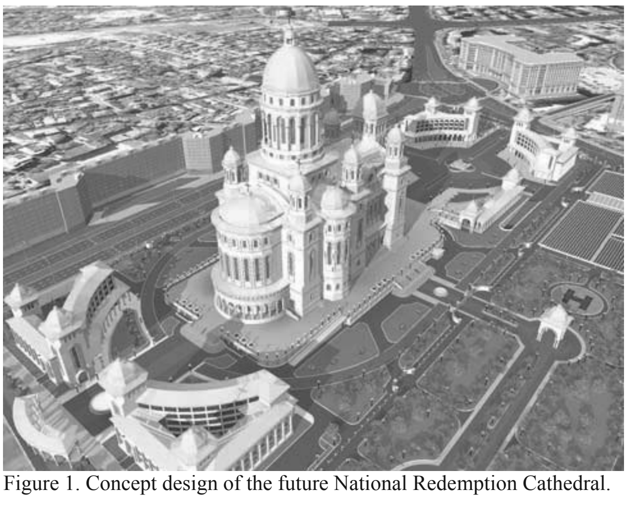

Figure 1. Concept design of the future National Redemption Cathedral.

Based on previous analyses of various foundation solutions it was chosen as final solution a cellular raft (basement walls as part of mat) of 4 – 6 m thickness. The raft thickness plus the basement height let to the necessity of excavating a pit of up to 16 m depth. Taking into account the pit depth, as well as its large size (~ 127 m x 66 m) it was chosen as retaining structure a diaphragm wall supported by anchors.

The Cathedral project, including also the deep excavation retaining structure has been submitted to a national contest for choosing the best option.

Paper presents aspects regarding the geotechnical investigation of the site, the design of the diaphragm walls, construction and monitoring the deep excavation.

2 SITE INVESTIGATION

Geotechnical investigation was performed in two stages:
- a preliminary geotechnical study (2008) based on which several preliminary projects were draw in order to participate to the national contest;
- after selecting the best project, a new detailed geotechnical study was performed by the Technical University of Civil Engineering of Bucharest for the final design of the Cathedral foundations and open pit diaphragm walls.

This geotechnical study comprised the following site investigations: 8 boreholes 25 – 70 m deep, SPT tests, hydro-geological measurements (permeability, analysis of the groundwater flow regime).

Laboratory tests comprised static and cyclic triaxial tests, for determining both shear strength and dynamic parameters of soils. As well, were carried out tests with various stress paths, with unloading – reloading cycles for determining the calculation parameters for the retaining wall. Table 1 presents the main soil parameters obtained from the site and laboratory investigations.

Table 1. Geotehnical parameters

	layer	thickness, m	E_{oed}, MPa	E_d, / G_d MPa	k_o	ϕ` °	c`, kPa	N_{SPT}
1	man-made fill	0.6–2.8	-	-	-	-	-	-
2	silty clay	11.4-16.2	7-16	56.5 / 19.5	0.6-0.7	16-23	51-92	10-34
3	sand, gra-vel	0.9-6.9	30*	-	0.4	35*	-	16-33
4	clay	10.5-16	8.3-11.7	54.5 / 18.9	0.7	9-20	61-113	11-39
5	sand	6.7-7	40*	57.8 / 20.2	0.5	30*	-	23-59
6	clay	21.7-27.8	-	71.2 / -	-	14	141	-

* - values estimated from SPT tests.

where:

- E_{oed} – oedometric modulus, corresponding to 0.2-0.3 MPa stress interval;
- E_d, G_d – linear deformation modulus and shear modulus for 300 kPa stress;
- k_o – at rest earth coefficient;
- ϕ`, c` - drained shear strength parameters;
- N_{SPT} – number of blows from SPT test.

Hydro-geological study emphasized two aquifers: a free level aquifer (layer 3) and a second confined aquifer (layer 5). The excavation will be 2 – 3 m below the groundwater level.

3 RETAINING STRUCTURE

3.1 *Geometrical and technological characteristics*

The deep excavation was retained using diaphragm walls 80 cm thick, with variable length, from 20 m to 24 m. The lower level of the wall remained constant (+60.50 m), while the upper level varied according to the architectural details of the basement and adjacent buildings (+84.50 m along the long sides and +80.50 m along the short sides of the pit).

Figure 2 presents a layout of the diaphragm wall enclosure and the final excavation levels.

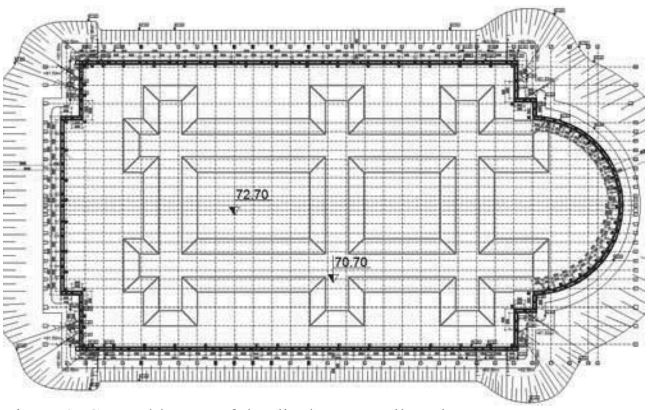

Figure 2. General layout of the diaphragm wall enclosure

The natural ground level varies on the site around +87.0 m, so for the working platforms required for the diaphragm walls execution, a sloped excavation was realized. The final excavation levels are +72.7 m and +70.7 m (for the 6 m thick raft area), respectively, which led to a maximum excavation level of approx. 16.3 m below the ground level.

It can be seen that the foundation level of the raft is in the sand and gravel layer (layer 2).

The temporary support of the diaphragm wall was ensured using 2 or 3 levels of anchors. The total length of the anchors was comprised between 20 m and 25 m. In the corners were used metallic struts and wale beams.

Figure 3 presents a cross section through the diaphragm wall for the sides with 3 anchor levels.

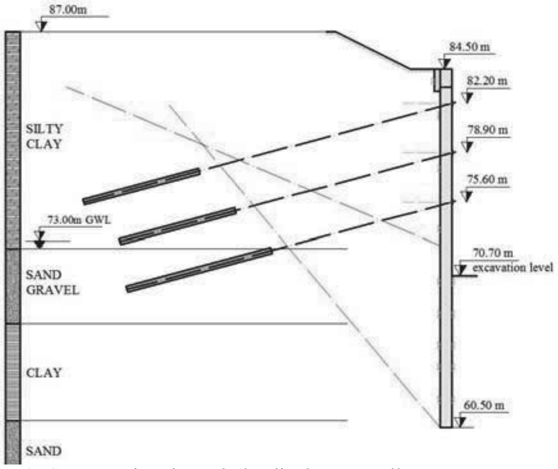

Figure 3. Cross section through the diaphragm wall

For the anchors on 3 levels the characteristics are the following:

- Anchors level 1: +82.20 m
  - inter-axis distance: ~ 1.75 m
  - number of strands in each anchor: 4
  - maximum pull-put force / anchor estimated by calculation (ULS) = 200 kN
- Anchors level 2: +78.90 m
  - inter-axis distance: ~ 1.75 m
  - number of strands in each anchor: 4
  - maximum pull-put force / anchor estimated by calculation (ULS) = 250 kN
- Anchors level 3: +75.60 m
  - inter-axis distance: ~ 1.20 m
  - number of strands in each anchor: 6
  - maximum pull-put force / anchor estimated by calculation (ULS) = 320 kN.

As it can be seen on figure 3, the lowest level of the pit base is 3.0 m below the groundwater level. The soil permeability and the ground level differences led to a water flux in the enclosure of about 90 l/s, unevenly distributed, being higher on the Southern side. Considering these conditions, a dewatering system was designed, comprising 12 wells disposed along the enclosure sides.

3.2 *Diaphragm wall calculation*

Diaphragm wall calculation was done based on Eurocode 7 (SR EN 1997-1:2004 and the Romanian National Annex SR EN 1997-1/NB). According to the National Annex in Romania, the calculations were performed for design approaches 1 and 3, approach 2 not being recommended by this document.

As well, according to the Romanian technical norm for retaining structures (NP 124-2010), the seismic action was considered on the wall. The seismic coefficient was decreased considering the temporary character of the retaining structure, according to the same technical norm.

Figure 4 shows some of the results obtained for the stresses in the diaphragm wall, corresponding to the side with 3 levels of anchors, for ULS calculation. Calculations were performed according to technological stages (excavation and installation, anchors pretension) up to the final excavation level.

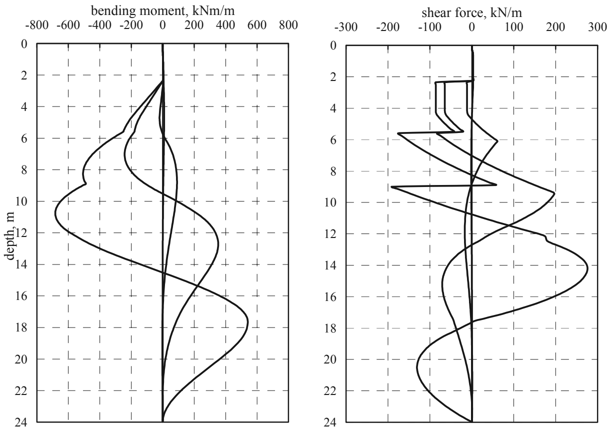

Figure 4. Bending moment and shear force in the diaphragm wall

Figure 5 shows the horizontal displacements of the wall corresponding to the same calculation stages (SLS calculation). It can be seen that the maximum displacements are less than 10 mm, which was confirmed by the inclinometer measurements, presented figure 11.

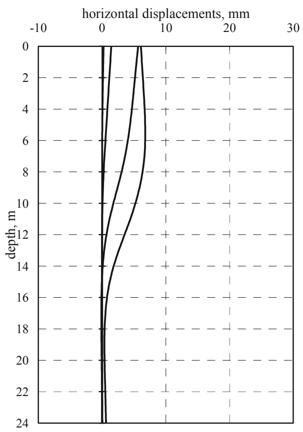

Figure 5. Horizontal displacements of the diaphragm wall

3.3 *Aspects during the diaphragm wall execution*

Figures 6...9 present some photos taken during the execution of the deep excavation.

Figure 6. Installing the reinforcement cage of the diaphragm wall

Figure 7. Installation of the first level of anchors

Figure 8. Final stage of excavation

Figure 9. Lead waterproofing

As it can be seen in photo figure 9, prior to build the raft a waterproofing layer has been laid on the excavation base. Considering the life time of the cathedral of minimum 500 years, the waterproofing was done with lead, being the only solution guaranteed on such long time. From this point of view, this solution is new for Romanian civil engineering.

3.4 *Monitoring the diaphragm wall*

The enclosure monitoring was performed by measuring:

- vertical displacements of the wall - measured at the linking beam level using geodetic methods;
- horizontal displacements of the wall - measured at the linking beam level and along the wall depth using inclinometer measurements;
- outflow from the dewatering wells;
- groundwater level inside and outside the enclosure.

Regarding the inclinometer measurements, these were carried out using 6 tubes located in various areas and along different sides of the diaphragm wall (4 on the sides with 3 anchors level and 2 along the sides with 2 anchor levels). A cross section showing the position of the inclinometer tube inside the wall is presented figure 10.

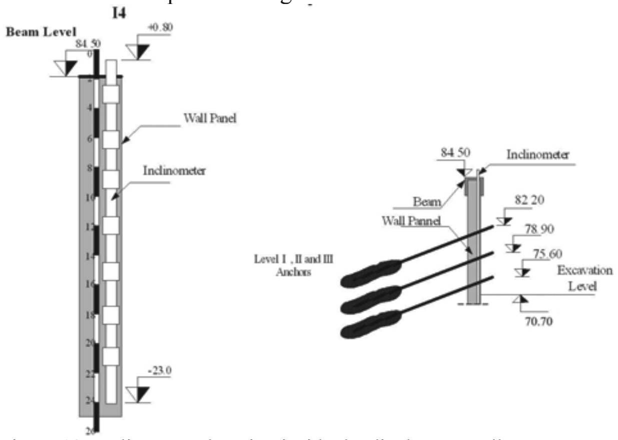

Figure 10. Inclinometer location inside the diaphragm wall

The monitoring of the anchored structure was carried out from April 15 2011 until January 12 2012. The activity during the 9 months of monitoring was according to the technological stages of the excavation works and retaining structure.

The frequency of monitoring activity was established according to preliminary stages of infrastructure works. Due to the construction progress, changes in construction technology flow on site (adjacent traffic infrastructure, frequency and tensioning of anchors system, etc.), weather changes (temperatures on 2012 winter) the frequency of the measurements was increased.

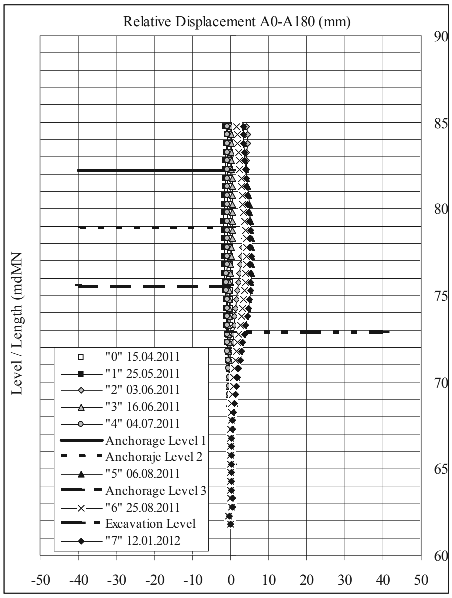

Figure 11. Inclinometer measurements for the diaphragm wall

The main purpose of monitoring activity was to verify design assumptions regarding the deformations of the structure, but also to provide detailed information on the effect induced by the anchors on the retaining wall.

Figure 11 presents a graph of the measured lateral displacement of the wall for the side with 3 anchor levels.

According to measurements, the maximum horizontal displacement of the diaphragm wall didn't exceed, on all sides, 10 mm, confirming the estimation by calculation.

4 CONCLUSIONS

Designing and building a retaining structure for a deep excavation in urban area is always a challenge, taking into account the associated risks. The characteristic parameters of interaction are numerous and their control difficult. For this reason the approach of such works should be done carefully during all stages: geotechnical investigation, design, execution and service.

Paper presents a case study for a deep excavation in centre Bucharest required for the construction of the Redemption Cathedral, which was approached according to Eurocode 7. Considering its size and the supporting system using anchors, this excavation is among the largest in Romania. The anchor supporting system allowed a space-free enclosure and the infrastructure works took place very rapidly.

The work was classified as in geotechnical category no. 3, which imposed a complex approach also from geotechnical investigation, as from design point of view. The execution was permanently monitored and the measurements were compared with the calculations, allowing a rapid intervention if the real behavior would be different from the estimated one.

5 ACKNOWLEDGEMENTS

Authors acknowledge The Romanian Patriarchy and to SC Altfel Construct SRL (general designer) for allowing this paper to be published and for providing some of the data used in this paper.

6 REFERENCES

SR EN 1997-1:2004 Eurocod 7: Proiectarea geotehnică. Partea 1: Reguli generale.
SR EN 1997-2:2007 Eurocod 7: Proiectarea geotehnică. Partea 2: Investigarea și încercarea terenului.
SR EN 1997-1:2004/NB:2007 Eurocod 7: Proiectarea geotehnică. Partea 1: Reguli generale. Anexa națională.
NP 124-2010 Normativ privind proiectarea geotehnică a lucrărilor de susținere.