Comparative study of different deep excavation retaining systems

Etude comparative de différents systèmes de soutènement de fouilles profondes

Josifovski J., Gjorgjevski S.
Department for Geotechnics, Faculty of Civil Engineering-Skopje, University Ss. Cyril and Methodius - R. Macedonia

ABSTRACT: In the past period a building expansion and rapid construction in highly urbanized city centre of Skopje (capital of the R. Macedonia) has been witnessed. In most cases the structures are small administrative buildings which do not exceed $800m^2$ with underground often used for offices or parking. This has been an inspiration to investigate the comparative advantages of different deep excavation retaining systems. In fact three designer tasks, very similar by many parameters, had been used to draw the general conclusions. The selected construction sites are located closely to each other, thus share similar ground conditions. The following retaining systems were considered: (1) system of solder H piles with lagging, (2) reinforced concrete diaphragm wall, (3) secant pile wall with primary (reinforced concrete) and secondary (concrete) piles. Although systems are different in general they can still be compared, especially from the economic point of view. All retaining systems had been calculated numerically and controlled according to the Eurocode provisions. The concluding remarks offer a preferred solution for underground construction on narrow and build-up sites.

RÉSUMÉ: Le centre-ville très urbanisée de Skopje (capitale de la république de Macédoine) a été témoin ces derniers temps de nombreuses constructions de bâtiments neufs. Dans la plupart des cas, ce sont de petits bâtiments administratifs qui ne dépassent pas $800m^2$ avec des sous-sols souvent utilisé pour des bureaux ou le parking. Cela a été l'occasion d'enquêter sur les avantages comparatifs des différents systèmes de soutènement de fouilles profondes. En fait, trois principes de soutènement, très semblables par de nombreux paramètres, ont été utilisés pour tirer des conclusions générales. Les chantiers de construction sélectionnés sont très proches les uns des autres avec des conditions de sol similaires. Les systèmes de soutènement suivants ont été considérés: (1) Système de poutres en H soudée après-coup, (2) paroi moulée en béton armé, (3) pieux sécants avec pieux primaire (béton armé) et secondaire (béton). Bien que les systèmes soient différents, en général, ils peuvent encore être comparés, en particulier du point de vue économique. Tous les systèmes de soutènement ont été calculés numériquement et contrôlés selon les dispositions Eurocode. Les conclusions offrent une solution pratique pour la construction souterraine en zone densément construite.

KEYWORDS: deep excavation, retaining system, supporting elements, finite element analysis.

1 INTRODUCTION

The problem of deep excavation in highly urbanized area such as the city centre of Skopje has proved to be quite formidable engineering task. In particular the greater depth and the built-up surrounding make it especially difficult. The ever growing prize of a square meter has led to extensive utilization of the underground. Such an idea has been very attractive for the investors which always look for the most economic solution of the underground works, generally constrained by the excavation depth and retaining system.

The tendency to optimize the structures has been an inspiration for the authors to investigate the comparative advantages of different deep excavation retaining systems and their supporting elements. The objective has been to offer a qualitative study which considers all relevant aspects of the underground construction in urban areas.

The paper presents case studies of three different retaining systems used to secure the excavation pits which do not exceed $800m^2$ in base. All of them are located in the area of around 2km, thus share similar ground conditions. There are different limitations and/or specifics on every site, as to the surrounding e.g. existing structures or very frequent streets. The depth of the excavation pit varies from 6.5 to 18m. All retaining systems had been calculated numerically and controlled according to the Eurocode provisions.

1.1 *System of solder H piles with lagging*

In the first case example a 7m deep pit should be excavated for the construction of the new National theatre. Larger part of the structure has been already finished, only the part adjacent to the street is left to be erected. The excavation pit is rather narrow only 3.05m in width (enlarging to 6.1m) and 36.65m long, see Figure 1.

Figure 1. Site location No.1 in front of the new National theatre.

The task has been to secure the pit from only one side (namely from the frequent street which connects the main city square) allowing undisturbed traffic and pedestrian communication.
As solution a temporary structure of solder H piles with lagging has been proposed. The supporting system uses rikers and struts (positioned on -2.0m and -4.65m from the top) acting upon the foundation of the existing structure. There were several arguments in favour of this solution, foremost it is light and suitable for a temporary structure, does not take a lot of space and last but not least it is relatively cheap.

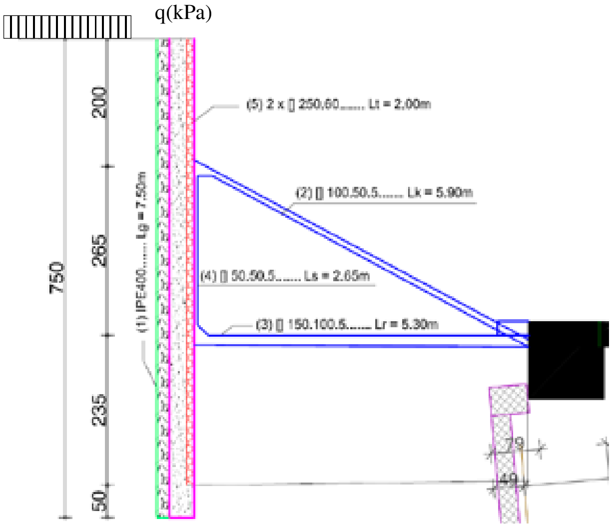

Figure 2. Site location No.1 with RW as solders H piles with lagging.

The structure is modular consisted of eighteen solder H piles placed on every 2m with total length of 7.5m. The piles are embedded with depth 0.5m. A steel IPE 40 profile has been chosen according to DIN 1025 B1.5 and DIN 17100 specifications.
The ground profile from 0 to 3m is defined by a layer of fill with pieces of construction material such as bricks and mortar. From 3 to 7.5m there is claly silt with smaller pieces of construction debris with the following material properties: unit density as γ=19kN/m^3, cohesion as c=5kPa, angle of internal friction as ϕ=28^0 and Compressibility modulus as M_v=8000kPa.
A standard traffic load with q=16.67kPa acting on the far away and p=5kPa on the nearby strip has been assumed.
The problem is calculated using the finite element method using plane and beam element. The structural elements of the wall are assumed to be linear with smeared stiffness as in equivalent plane-strain model. The soil is discretized by Mohr-Coulomb material behaviour. A plot of the total displacements is shown in the Figure 3.

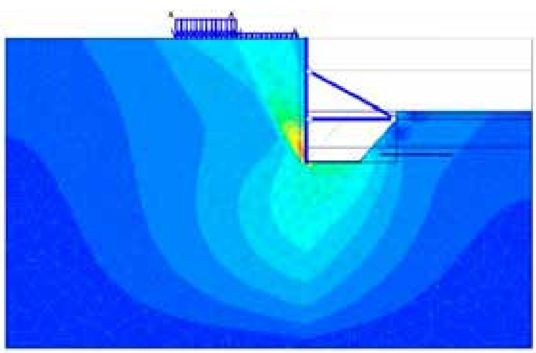

Figure 3. Shading plot of the total displacements.

The maximal total displacement is 64mm registered in the toe of the wall while on the top(-surface) it is around 10 times smaller.

The results of the analysis of solder H pile wall are presented in the Figure 4.

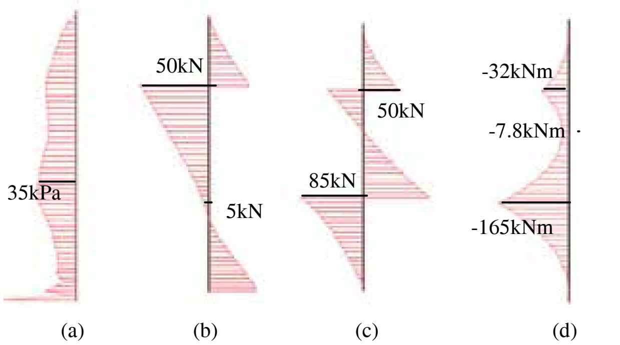

Figure 4. Diagram of (a) Active earth pressure, (b) Axial force, (c) Shear force and (d) Bending moment.

The steel cross sections are calculated according to the provisions in EC3 with γ_S=1.15. A steel type „Fe235“ with allowable stress of 204MPa has been used.
The rickers prop the wall at -2.0m and are positioned at angle of 23.5 degrees with length of L_k=6.65m. They are designed as a rectangular hollow section []100.50.5. The struts prop the wall at -4.65m with length of L_r=6.1m. They are designed to accept compression force using rectangular hallow section []150.100.5. Last but not least, the wooden lagging (b=25cm, l=182cm and t=12cm) are positioned over the height of 7m between the soldier piles.
Finally, the global stability is controlled using the so-called *phi-c* reduction procedure. A global factor of safety F_s=1.37 has been obtained which is larger than 1.1 as recommended value for temporary structure.

1.2 *Top to down construction of system with diaphragm wall*

Following the site conditions (see Figure 5) a building with five underground floors with depth of -15.86m should be constructed. From two sides there are existing buildings, one of which is adjacent on six floors and one basement while the other one is 3m away with only two floors and shallow basement. From the third side there is very frequent boulevard which leads to the centre and main city square.

Figure 5. Site location No.2 on M.T. Gologanov boulevard.

The base dimension of the excavated pit are 27.65x11.55mn not very large around 320m^2, but due to the difficult surrounding conditions and the great depth it has been decided to use the top to down approach of construction. The diaphragm wall is considered to be a permanent structural element, which in the first phase carries the horizontal (earth) pressure loads while in exploitation it will be responsible also for the loads form the superstructure. Following the top-down procedure the diaphragm will be supported by the previously constructed RC slabs, thus enabling the further excavation of the pit. The excavation process and slab support construction is described in Table 1 with respect to the depth *h*.

Table 1. Excavation phases

Phase	1	2	3	4	5	6	7
h (m)	0.0	-3.5	-6.11	-8.5	-10.9	-13.9	-15.8

The diaphragm RC segments are 2.5m long and 0.4m width organized as primary and secondary. The base plan with depth and sequence of construction is presented in Figure 6.

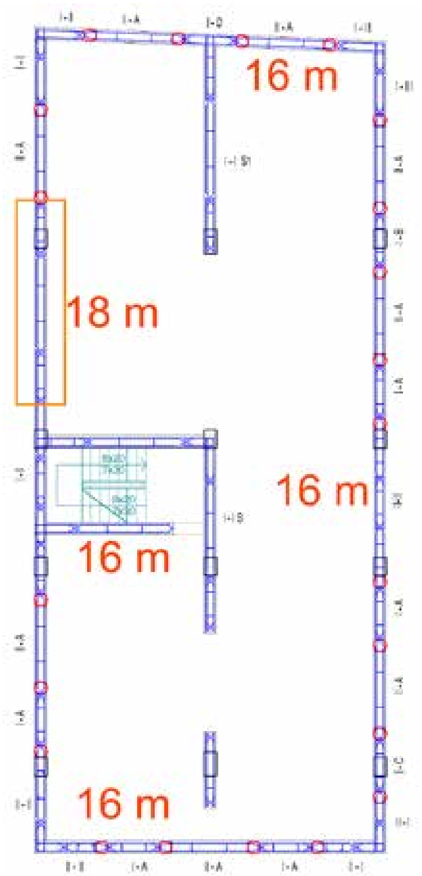

Figure 6. Base plan of primary and secondary diaphragm segments.

The depth is 16m only in one section its 18m due to the requirement necessary for elevator equipment. The soil profile is established through set of field and laboratory investigations which were used to define the material properties given Table 2.

Table 2. Soil properties

Type	h(m)	γ(kN/m^3)	ν (/)	M_v(MPa)	c (kPa)	ϕ (^{0})
N	-1.0	17.0	0.30	3	5	18
GW	-3.5	19.0	0.32	30	0	32
M	-4.0	22.0	0.27	35	100	30
M	-10.0	24.0	0.26	45	150	32
M	-20.0	24.0	0.26	55	200	34

where γ is a unit weight, ν is a Poisson's ratio, M_v is Compression modulus, c is cohesion and ϕ is angle of internal friction. They are given for every lithological unit: top layer (N) is a man-made embankment brownish silty clay containing pieces of bricks and roots with a thickness of 1m, followed by layer (GW) is sandy gravel with thickness of 2.5m to 3.7m; continuing as a layers (M) which are Neogene's deposits composed by claylike Marls to highly weathered alveoli. The underground water is detected at -3.2m below ground surface in layers (GW) while the bottom layers are with low permeability and relatively dry.

In order to obtain more realistic behaviour of the deep excavation process secured by diaphragm wall, the problem has been analyzed using the finite element method. The ground stress-strain state during excavation is determined through a plane-strain finite element model. The soil is discretized as elasto-plastic material using a Mohr-Coulomb definition vis-a-vis the reinforced concrete wall as a linear material. The spatial discretization had been varied depending on the situation and detailing level but in general triangular plane elements with 15 nodes had been used. Two cross sections both in X-X and Y-Y direction had been discretized and calculated. The structural elements were modelled using three node beam elements, see Figure 7.

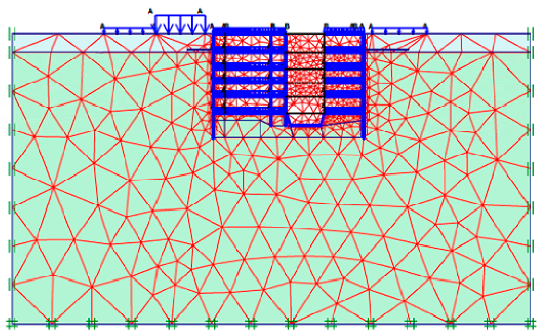

Figure 7. Finite element model of X1-X1 section.

The underground structure has been calculated for two loading combinations, namely the construction loading situation with pit excavation (in 6 phases = 1-diaphragm wall + 5-floor slabs) and exploitation situation (with permanent + temporary + seismic loads). In Figure 8 the total displacements of underground structure is presented for the second loading combination.

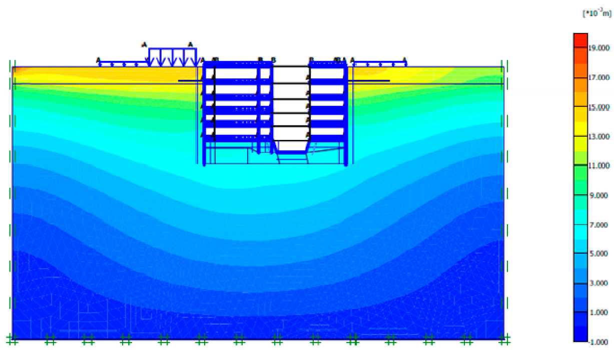

Figure 8. Total displacement of the soil-structure system in X1-X1 section.

The maximal registered displacement is 14mm with predominantly horizontal component (stiff rocking response) due to the seismic loading. According to the stress-strain distribution the internal quantities of the structural elements had been determined. They were used for structural design of elements such as, diaphragm wall, floor slabs and foundation plate. The reinforcement is determined according the EC2 for C35/45 and S500 (with γ_C=1.5 and γ_S=1.15). The reinforcement of the diaphragm wall is around 0.8%A_c (area of concrete section). The 47% of the total reinforcement will be used for the diaphragm wall, 18% for the foundation plate and 35% for the floor slabs.

1.3 *System of secant pile wall*

For the same site (see Figure 5) an alternative solution has been analysed with secant pile retaining wall to secure the excavation pit (27.65x11.55m) but this time with depth of 6.5m. In this scenario only two floors are planned to be constructed using a temporary retaining structure. In the first phase the primary, (reinforced concrete) piles with diameter of 0.6m and length of 7.5m spaced exactly 1.2m should be executed. In the next phase the secondary (concrete) piles with the same diameter but shorter depth of 5.5m are constructed. On the top they are connected by a beam with dimensions 0.6x0.4m as shown in Figure 9.

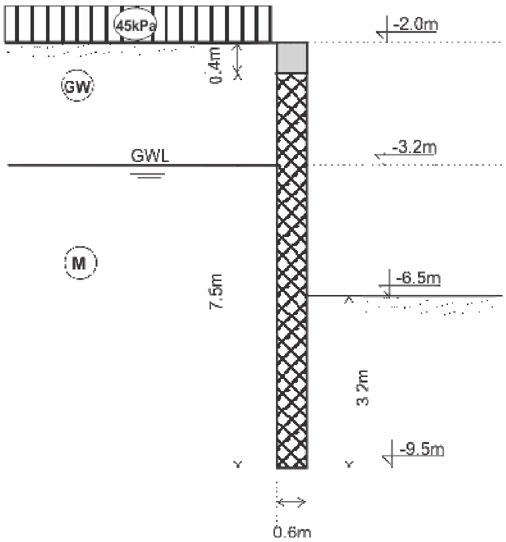

Figure 9. A plan of the secant pile wall in X1-X1 section.

The problem is discretized using three-dimensional finite element model where the soil profile is identical to the one described in Table 2. For the spatial discretization volume elements are used in combination with nonlinear-plastic material definition for the soil and linear-elastic for the concrete. The calculation is used to determine the stress-strain behaviour of the soil-structure interaction system, hence presented through the total displacement in Figure 10.

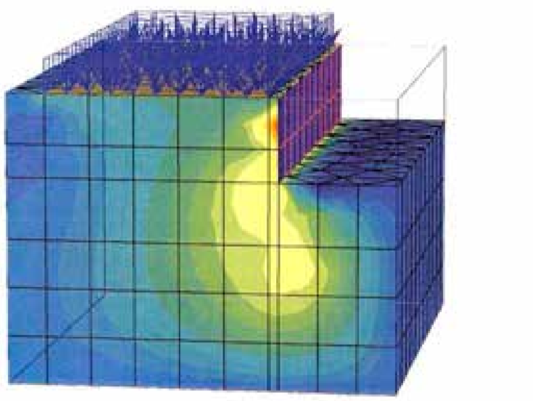

Figure 10. Total displacement of the soil-structure system in X1-X1 section.

A maximal earth pressure of 33.7kN/m^2 causes horizontal displacement of 9.8mm, which have been considered as acceptable. Furthermore, the diagrams of internal pile quantities are presented in Figure 11.

(a) (b) (c)

Figure 11. Diagram of (a) Axial force, (b) Shear force and (c) Bending moments in the pile.

The values of the maximal internal quantities: bending moment M=56.81kNm, shear force Q=-43.64kN and axial force is N=-114.8kN. The pile design has been made using interaction (M-N) diagrams for C30/37 providing the following reinforcement: longitudinal 14ϕ16 (28.2cm^2) and stirrups ϕ8/20cm. Finally, the global stability is controlled where a safety factor F_s=1.55 is obtained.

2 CONCLUSION

The solder H pile wall with lagging is rarely used in our practice, although it is highly efficient and cost effective for situations where there is no ground water. Also a greater depth can be reached when combined with adequate supporting system e.g. tieback. Nevertheless, in Skopje there are few locations with low GWL. Although very formidable the systems with diaphragm wall are seldom used, partially because there is almost no experience nor there has been clear cost-benefit analysis. For a long period of time it has been thought that the costs are very height, which with the present study had proven not to be the case. Combined with the top-down method of construction where the wall is permanent structure according to our analyses remains very cost effective solution. The secant pile wall technique, in contrast, is very often used in our practice, sometimes in combination with anchors when greater depth is needed. It represents formidable solution but usually takes a lot of the available space and construction time, also brings high expenses since it is often a temporary structure.

Finally, when comparing all retaining structures we had come to conclusion that the diaphragm wall represents a preferred solution for underground construction in highly urbanized (build-up) areas and situations with high ground water level as it is usually the case in Skopje.

3 REFERENCES

German Society for Geotechnics (Deutsche Gesellschaft fur Geotechnike.V.) 2003. Recommendations on Excavations, Ernst & SohnVerlag fur Architektur und technische Wissenschaften GmbH & Co. KG, Berlin, ISBN 3-433-01712-3.

Kempfert, H.G. and Gebreselassie, B. 2006. Excavations and Foundations in Soft Soils, Springer-Verlag Berlin Heidelberg, ISBN 540-32894-7.

Potts, D.M. and Zdravkovic, L. 2001. Finite element analysis in geotechnical engineering: application. Imperial College of Science, Technology and Medicine, Thomas Telford Publishing, Thomas Telford Ltd, ISBN 0-7277 2753-2.

Moeller G. 2012. Geotechnik. Grunbau, Bauingenieur-Praxis, 2 Ed. Erst & Sons, A Wiley Company ISBN: 978-3-433-02976-3.

EN 1997-1:1994 Eurocode 7: Geotechnical design - General rules

EN 1538:2000 Execution of special geotechnical works – Diaphragm walls