ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ
СОФИЯ

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CASE STUDY OF MULTI-STAGE BRACED EXCAVATION IN SOFIA REGION

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ABSTRACT

The paper examines a retaining wall used for excavation in Sofia region, Bulgaria. The excavation has an average depth of about 8 m and dimensions in plan 29/32 m. Due to the narrow conditions and the impossibility of placing materials outside the property, the execution of the excavation and the construction of the building was carried out in two stages, which also represents a challenge in the calculation. Different calculation methods are proposed, as well as monitoring results.

1. Introduction

It is becoming increasingly necessary to design buildings with one or more basement levels. There are many reasons for this – the decreasing free land for construction, the lack of parking spaces, as well as the increase in the cost of residential areas. Along with strict legal regulations, it is not always possible to use the areas around the construction site for the placement of construction machinery, staff offices, and storage of materials. The paper examines a construction site measuring 29/32 m. The two basement levels and the slight elevation of the terrain create the need to perform a construction excavation with a depth of 6,90 to 8,60 m. The retaining wall is located entirely along the contour of the property line, which is located in a densely populated urban environment. Since there is no space in which to place the machinery and store materials, a technological sequence has been adopted in which half of the excavation is performed, together with the structure up to the level -1. Then the remaining half of the

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building is executed. In this case, the retaining wall must be designed for a lot of construction stages. Geodetic monitoring and back analysis have also been performed.

2. Soil profile

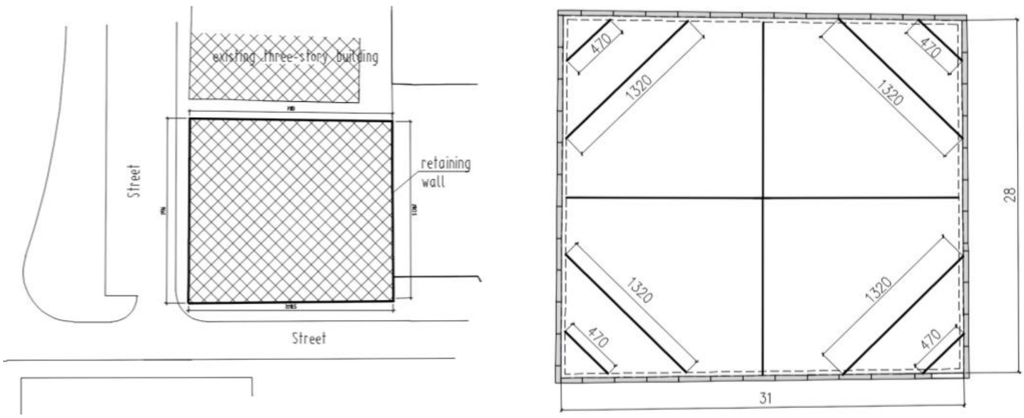
Unfortunately, the full set of soil parameters necessary for a reliable analysis of the reinforcement structure is not always available. Here a geological survey based on archival data was presented, since saving funds for the preparation of a real one is a widespread practice. Fortunately, the contractor company realized this shortcoming and ordered several laboratory tests, which gave a more real data for the soil properties. Having in mind the official geological survey and the additional test of soil during the excavation, the soil properties are summarized in Table 1.

Table. 1. Some soil properties

№	Layer	Depth, m	Volume density γ_n, kN/m^3	Internal friction angle φ, °	Cohesion c, kPa	E_{oed}, kPa
1	Man-made fills	0,8 – 1,0		–	–	
2	Plio-pleistocene pebbly deposits	2,3 – 2,5	20,8 – 20,1	34	3	30 – 32
3	Pliocene Medium and Coarse Sands	> 10,0	17,5	29	3	25 – 28

3. The construction challenges

The site is located in the eastern part of the city of Sofia. On the southern and western property lines there are secondary streets that lead the car traffic to the main city arteries. On the northern side, immediately next to the property, there are two low-rise buildings, three and five floors, the foundation level of which is about 4 m above the level of the building being built.



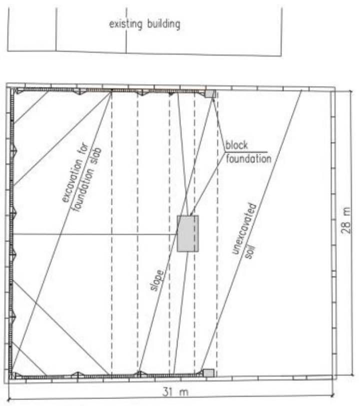
a) *b)*

Figure 1. Layout of the site
a) the excavation pit; b) idealized braces

The retaining wall is planned to be built as slurry wall. The braces shown in Fig. 1*a* are steel profiles from a company system being implemented at one level. The section is circular and it is calculated for min1200 kN, at length of 12 m. The details are designed to allow their repeated use, regardless of distances and angles of each future excavation project to be built.

In such projects, technology and available mechanization for building and retaining wall construction are leading. An ideal case is shown in Fig. 1*b*, in which the structure is self-balancing without considering special design situations. There are available design methods, which can be used [1]. Unfortunately, the technological impossibility gives rise to a relatively complex sequence:

- About half of the excavation is excavated to a level of one meter below the braces;
- Half of the undercuts are performed;
- Half of the excavation is performed to the foundation level;
- The foundation is executed;
- Half of the slab is executed at level -1;
- The braces are removed and installed on the right side;
- The second half of the soil is excavated;
- The second half of the slab is performed at level -1;
- All braces are removed and construction continues on the site.



a) *b)*

Figure 2. Excavation plan during stage 1

a) plan; b) section

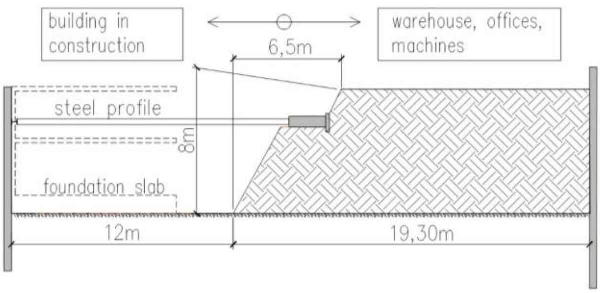
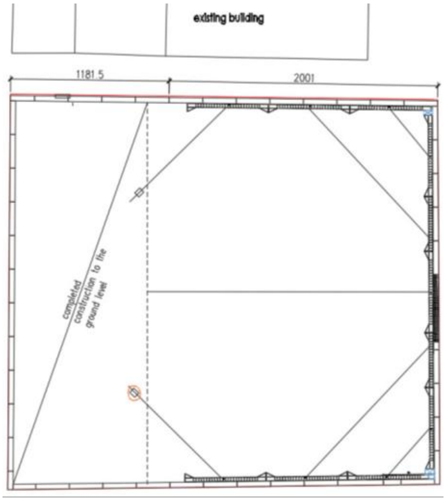


Figure 3. Excavation plan during stage section



a) *b)*

Figure 4. Excavation plan during second stage
a) design; b) execution

4. Design challenges

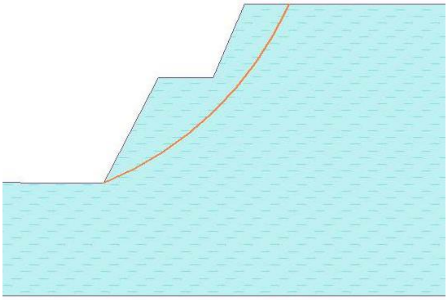
In this retaining wall shown in Fig. 2 and Fig. 4 no classical solution is possible. Here, the phasing plays a significant role in the calculation of the structure. Since the dimensions are relatively small, a planar solution would not be possible due to the spatial nature of the earth pressure. Another particular problem is in the upper right corner where the neighboring building exerts additional earth pressure and it is not known in which direction the section will tilt.

4.1. Geological report

For a reliable and accurate analysis of internal forces and deformations of retaining wall it is correct to use the finite element analysis with a suitable soil model – HSM or HSM small. However, the designer does not always have the comfort to obtain all 10 – 15 soil parameters required by these models. Sometimes the stiffness of the soil under small deformations [7, 9] has a significant impact on the behavior of the diaphragm wall. For this reason, some of the most important ones are obtained based on experience from neighboring sites, as well as inverse analysis.

To evaluate the parameter that has the greatest priority in the analysis, a sensitivity analysis must be performed. This shows which soil parameter plays the most important role for the displacement of a given point on the wall. [2, 3] reports that for correct determination of the displacement of a given point of the retaining wall the angle of internal friction plays the greatest role followed by cohesion. Deformation modules have less weight. For this reason, it is necessary to determine with greater accuracy precisely these parameters.

Of particular importance is the presence of underground infrastructure in the vicinity and its impact on the site [8].



a) *b)*

Figure 5. Excavation plan during stage section
a) excavation; b) back analysis

For this reason, seeing the stable slope (Fig. 3), a back analysis was performed in which the angle of internal friction and the corresponding cohesion were sought. Since the angle of the slope is about 65 degrees, it is expected that either the angle of internal friction will be 65 degrees with *c* = 0 kPa or that cohesion will be available. With an assumed angle of 33 degrees, the cohesion at which the safety factor is about 100 % is gradually sought. Thus, using various methods, it was proven that the soil has cohesion of about 9 – 10 kPa, shown in Table 2.

Table. 2. Results of back analysis for slope stability

Method	internal friction angle φ, °	Cohesion *c*, kPa	F_s, %
Bishop Bishop	33	***9***	100,8
Fellenius/Petterson	33	***10***	99,4
Spenser	33	***9***	101,0
Janbu	33	***9***	100,2
Morgenstern-Price	33	***9***	100,3

As the result of back analysis of slope stability has stated, the sand/gravel layer owns non-negligible cohesion *c* = 9 – 10 kPa. This was not taken in the design, just left aside as an additional security.

4.2. Lack of time to execute slurry wall cage

During the site construction, it turned out that the time for the implementation of the known reinforcement cage of a diaphragm wall (Fig. 4*a*) was too long. Therefore, different options were sought to optimize this time. As a first iteration, it was proposed to place a circular reinforcement cage (Fig. 4*b*) as for piles. As a second option, in this cage the reinforcement is concentrated near the tension edges of diaphragm wall (Fig. 4*c*). After economical evaluation it was decided to replace them with rectangular cages, in which the reinforcement is concentrated at the ends of the wall, as shown in Fig. 4*d*. The adopted configuration of the reinforcement cage is not typical, but having the temporary nature of the structure, this challenge was taken. The installation was individual, each cage was lowered individually. A variant with three joined cages was also tested, but it turned out that this creates risks of excessive deformations of the reinforcement in the assembled state, and was abandoned.

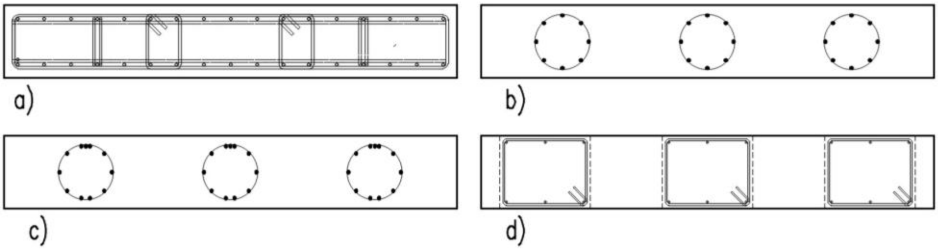


Figure 6. Different types of a diaphragm wall reinforcement cage
a) classic solution; b) pile reinforcement; c) pile reinforcement with concentration at the ends; d) selected reinforcement with rectangular stirrups

4.3. Accurate determination of earth pressure

It is known that the magnitude of the earth pressure depends on the displacement of the structure, as well as on its stiffness [4]. The German Geotechnical Society [1] offers to use increased active earth pressure and decreased passive earth pressure.

Determining the earth pressure creates its own difficulties because there are no prerequisites for a linear problem. At the ends of a closed structure, the displacements are smaller. In the middle, they already grow, which also affects the change in earth pressure.

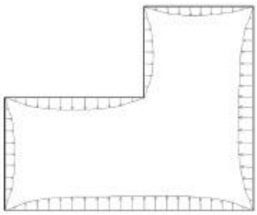
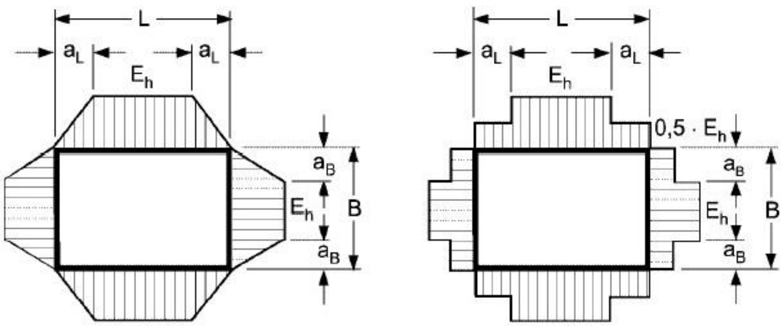


Figure 7. The corner effect shown in plan view of the horizontal displacement of a retaining wall (after Bakker) [5]



a) *b)*

Figure 8. Simplified approach for earth pressure reduction at excavation corners
a) earth pressure with chamfering; b) earth pressure with steps, after [1]

Two angles are defined – convex and concave, where spatial effects are observed. Various authors propose a methodology for calculating spatial earth pressure, all of which agree on the fact that at the corners with a concave angle it is smaller than a linear solution. The German Geotechnical Institute proposes to determine it according to one of the schemes in Fig. 8.

4.4. Sensitivity analysis of influencing factors

When analyzing a model using the FE method, over 15 parameters are used, and in the case of this geological report, only 3 – 4 are determined, and with a high degree of probability. For this reason, it is mandatory to perform a sensitivity analysis to see which parameter has the greatest influence on the assessment of deformations and internal forces. [2, 6] show the priority of the influencing factors in terms of subgrade properties was determined as follows: internal friction angle > unit weight > elastic modulus > adhesion. The effects of surcharge load and initial ground level, which can be categorized as external influencing factors, were found to be smaller compared to those of the ground material. The relationship between variation of different parameters and maximum displacement is shown in Fig. 7. [2] shows almost the same result – the most important parameter is the internal friction angle.

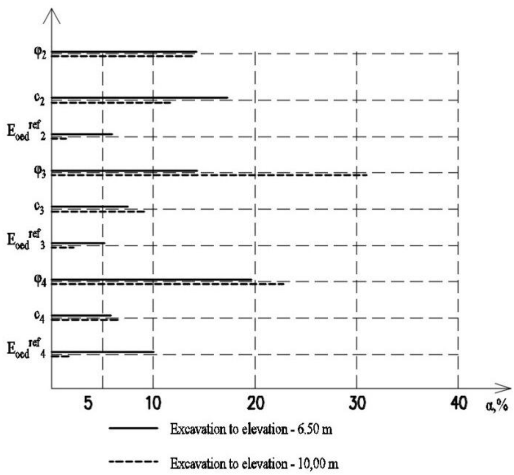


Figure 9. Diagram of relative sensitivity (after [2])

Having in mind the insufficient number of samples to perform statistical processing, for the sake of safety, the angle of internal friction was taken a few degrees less than the laboratory results.

5. Monitoring and results from 3D FEM model

5.1. Monitoring

Considering all the mentioned uncertainties in determining the soil parameters, choosing the right calculation model and correctly interpreting the results, the degree of uncertainty increases enormously. For this reason, it is extremely important to carry out accurate monitoring that adequately shows the behavior of the structure.

During the construction, one point in each camp was moved. At the first stage, the horizontal deformations across the structure were 3 – 6 mm. Considering that the device has an error of 1 – 2 mm, it can be considered that the displacement is almost zero. In the second stage, the displacement is already larger, in the order of 15 mm. But this may be partly due to time effects, i.e. the structure was excavated over a longer period of time.

This shows that all risks taken are well measured, and the adopted approach to phasing, design and implementation is correct.

5.2. FEM analysis

In order to optimize the use of inventory braces, but with sufficient certainty for safety factors, the normal forces from the three-dimensional model (Fig. 10) and the actual capacity were compared. So, here the braces work with 90 – 100 % of their capacity. But for the additional cohesion of 10 kPa, which is not put into the model, the risk is accepted.

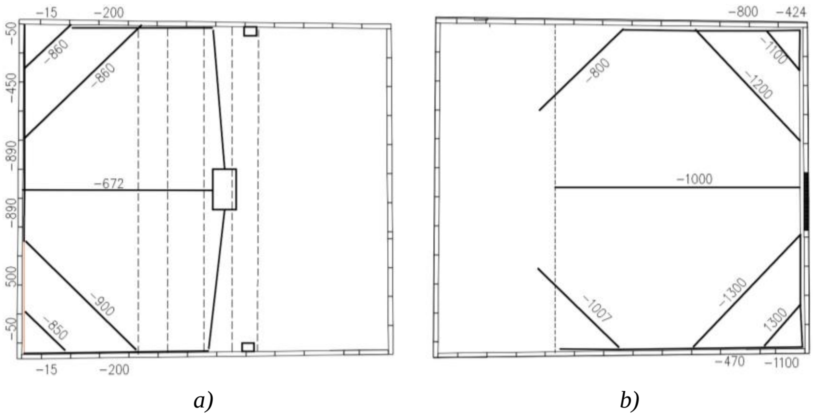


Figure 10. Braces normal forces
a) first stage; b) second stage

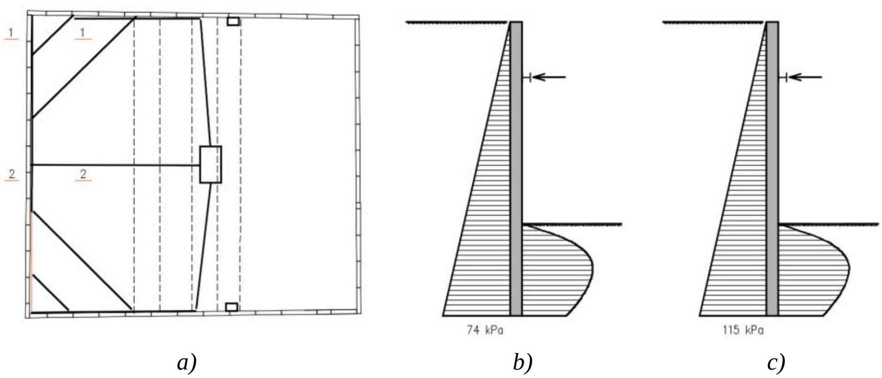


Figure 11. Spatial earth pressure
a) plan; b) section 1-1; c) section 2-2

The spatial nature of earth pressure is very well taken into account, as can be seen in Fig. 11. The values proposed by [1] for a 50 % reduction in earth pressure are approximately correct, however, for the sake of safety, it can be reduced to 75 %.

This type of construction should also be calculated against global loss of stability. For the first stage, the safety factor against loss of overall stability is 2,64, and for the second stage – 3,25.

6. Consclusion

The review of the design and execution of the retaining wall shows all the challenges that arose during the construction. Due to lack of time, data or something else, measured risks were taken. In this case, some conclusions can be drawn:

- The use of inventory steel elements allows a wide range of geometric changes to the undercuts.
- Considering the temporary nature of the retaining wall, it is possible to optimize the generally accepted type of reinforcement cage and use one that can be produced on site.
- Due to the lack of space for materials, offices and warehouses, the construction must be carried out in stages. This requires the use of new computational models, which, however, should be proven with daily monitoring.
- The FEM analysis shows a good match with the adopted reduction of German Geotechnical Society. For the sake of security, 75 % instead of 50 % can be used for the linear solution.

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ИЗСЛЕДВАНЕ НА ЕДНОРЕДОВО ПОДПРЯНА УКРЕПИТЕЛНА КОНСТРУКЦИЯ, ИЗПЪЛНЕНА НА ЕТАПИ В СОФИЯ

И. Марков[1]

Ключови думи: *шлицова стена, подкоси, укрепителна стена*

РЕЗЮМЕ

Статията разглежда шлицова стена, използвана за укрепване на масов изкоп в гр. София. Дълбочината на изкопа е средно около 8 m, размерите в план са 29/32 m. Поради стеснените условия и невъзможността за разполагане на строителна площадка извън имота, изпълнението на изкопа е осъществено на два етапа, което също представлява предизвикателство при проектирането. Предложени са различни методи за изчисление, както и резултати от мониторинга.

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