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COMPOSITE SOLDIER PILE AND JET-GROUTING RETAINING WALL STABILIZATION OF EXCAVATION PIT IN THE CITY CENTER OF SKOPJE

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Abstract
The present paper presents a finite element analysis of a deep excavation with dimensions of 52.35 × 22.8 m and a depth of 12 m, located in the highly urbanized city center of Skopje. The soil conditions are complex, 8.5 m below groundwater level, in proximity to existing high raising buildings. For this purpose, a composite soldier pile and jet-grouting retaining wall is used to ensure dry conditions and stable excavation. The results of the analysis show that the combined design approach of composite, piles and soilcrete, elements offers a hydraulic and stability solution which is effective and practical for deep excavations under challenging ground and site conditions.

Keywords
Deep excavation, jet-grouting, groundwater control, hydraulic barrier, numerical modeling.

1 Introduction

The new public administration building, located in the central urban area of Skopje, at the intersection of "Macedonia" and "Dame Gruev" street, is the subject of analysis in this paper. The excavation pit has base dimensions of 52.35 × 22.8 m (Figure 1), corresponding to a total area of 1155 m², with a depth of -11.6 m which is 8.5 m below the groundwater level.

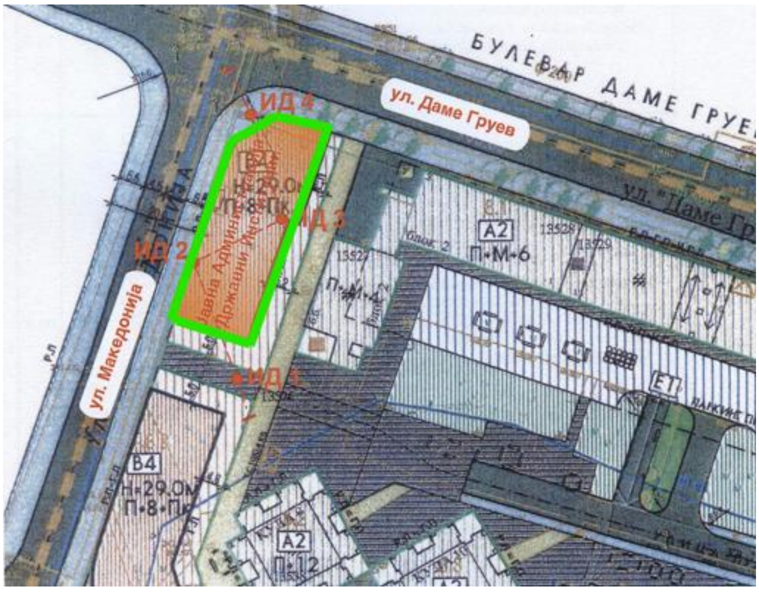


Figure 1. Location of the new public administration building.

The excavation pit is bordered on two sides by roads that must remain operational. In contrast, on the third side, there is an existing six-story residential building, which further complicates the construction conditions. The protection of the excavation pit must satisfy the requirements for both structural and hydraulic stability, given that it is a discontinuous barrier that allows direct penetration of groundwater through the side walls and the base.

2 Geotechnical conditions on the field

The geotechnical conditions of the field were determined through field investigations and tests. For that purpose, four investigation boreholes were drilled along the sides of the pit. At certain depths, Standard Penetration Tests (SPT) were performed, from which the modulus of compressibility was estimated, ranging between 32000 and 42000 kPa at depths of 8 to 12 m.

The geotechnical profile of the site includes the following soil materials: humus (H) up to 0.3 m; silty clay (ML) from 0.3 m to 2.5 m and up to 4.5 m in some locations with backfilled material mixed with construction debris; below this layer, gravel (GW) is present down to a depth of 12 m, containing approximately 40% of particles larger than 40 mm (maximum 100 mm) and with small sandy fractions. Based on additional investigations of neighboring structures, it has been determined that the gravel layer extends down to a depth of 30 m. Therefore, high site permeability is expected, necessitating the implementation of appropriate drainage measures.

Additionally, laboratory tests were conducted to obtain the material parameters, presented in Table 1.

3 Technical solution for the protection of the excavation pit

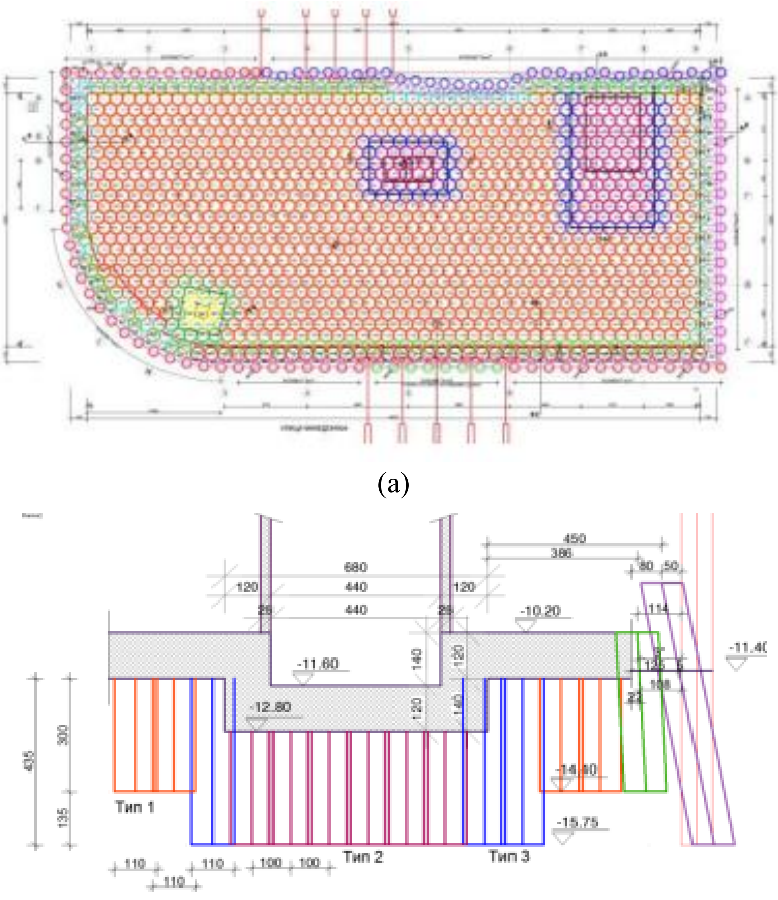
Due to the complex geotechnical conditions in the central urban area of Skopje, the allowable soil deformation criteria are very strict, with the displacements not exceeding 15 mm. Therefore, the primary solution considered for protecting the excavation pit was an anchored pile retaining wall. A retaining wall was constructed using 101 piles with a diameter of 80 cm, spaced at 140 cm intervals (Figure 2). A disadvantage of this solution is that the pile wall is discontinuous and does not provide a watertight barrier. Consequently, additional hydraulic protection measures were implemented, vertically and horizontally around the pit, using jet grouting.

Figure 2. Excavation pit with pile retaining wall.

To stabilize the wall, anchors were added at a level of -3 m at each opening between the reinforced concrete piles. Together with the horizontal barrier (carpet), the pit will be fully protected against groundwater infiltration from all sides and the base.

The piles extend from street level at 0.0 m down to a depth of 14.5 m. Above them, the first row of soilcrete columns is inclined at 11°, starting from a level of -8.5 m with a height of 6.85 m. The second row begins slightly lower at -10.5 m, inclined at 6°, reaching a depth of 14.5 m. The first row contains 108 elements, while the second row of the curtain has 111 elements (Figure 3).

The horizontal barrier (carpet) is also constructed from soilcrete elements arranged in a patterned joint layout of 87 × 110 cm over an area of approximately 970 m². The total number of elements is 1198, with a height of 3 m. To completely seal the excavation pit of 1155 m², 1.344 soilcrete elements are used, with a total length of 4893 m. The drilling length is larger by an additional 2554 m or 7447 m in total.



(a)

(b)

Figure 3. Base plan of excavation pit (a) and cross section (b).

4 Jet-grouting procedure and soilcrete elements

The jet grouting procedure was carried out in two phases to ensure optimal penetration of the grout mass and to determine the minimum erosion diameter. The injection mass, with a water/cement ratio, was injected using water to improve mixing with the local soil and larger diameter soilcrete columns. The injection pressure was set at 400 MPa, which propelled the mixture through two nozzles with a diameter of 1.8 mm at a velocity of approximately 100 km/h.

Different water–cement ratios, rotation speeds, and lifting speeds of the monitors were considered. A total of 9 test piles were excavated and investigated. After seven days, some of the ground bodies were excavated under the groundwater level (GWL) (Figure 4a), and samples were taken for laboratory testing (Figure 4b).

Uniaxial compressive strength (UCS), as well as tensile strength from Brazilian tests of the soilcrete material, were determined on representative samples. The material parameters required for the next step, for stability or deformation analysis, were precisely defined.

(a) (b)

Figure 4. Field investigation – visual inspection (a) and soilcrete specimens for laboratory tests (b).

5 Stability analysis

The global stability of the soil masses of the excavation pit has been analyzed using a numerical approach through the application of the finite element method. This approach enables a detailed assessment of stress–strain behavior in the soil and structural elements, as well as the determination of internal forces and deformations.

For this purpose, the software package PLAXIS was used, which is a well-established and specialized tool for solving geotechnical problems. Within the analysis, a two-dimensional model under plane strain conditions was adopted. The soil, as a continuous medium, was modeled as an elasto-plastic material according to the Mohr-Coulomb model. The jet-grouted elements (soilcrete elements) were also modeled using the Mohr-Coulomb model, with the material assumed to be non-porous. The material parameters used in the analysis are presented in Table 1.

Table 1. Soil properties used in the analysis

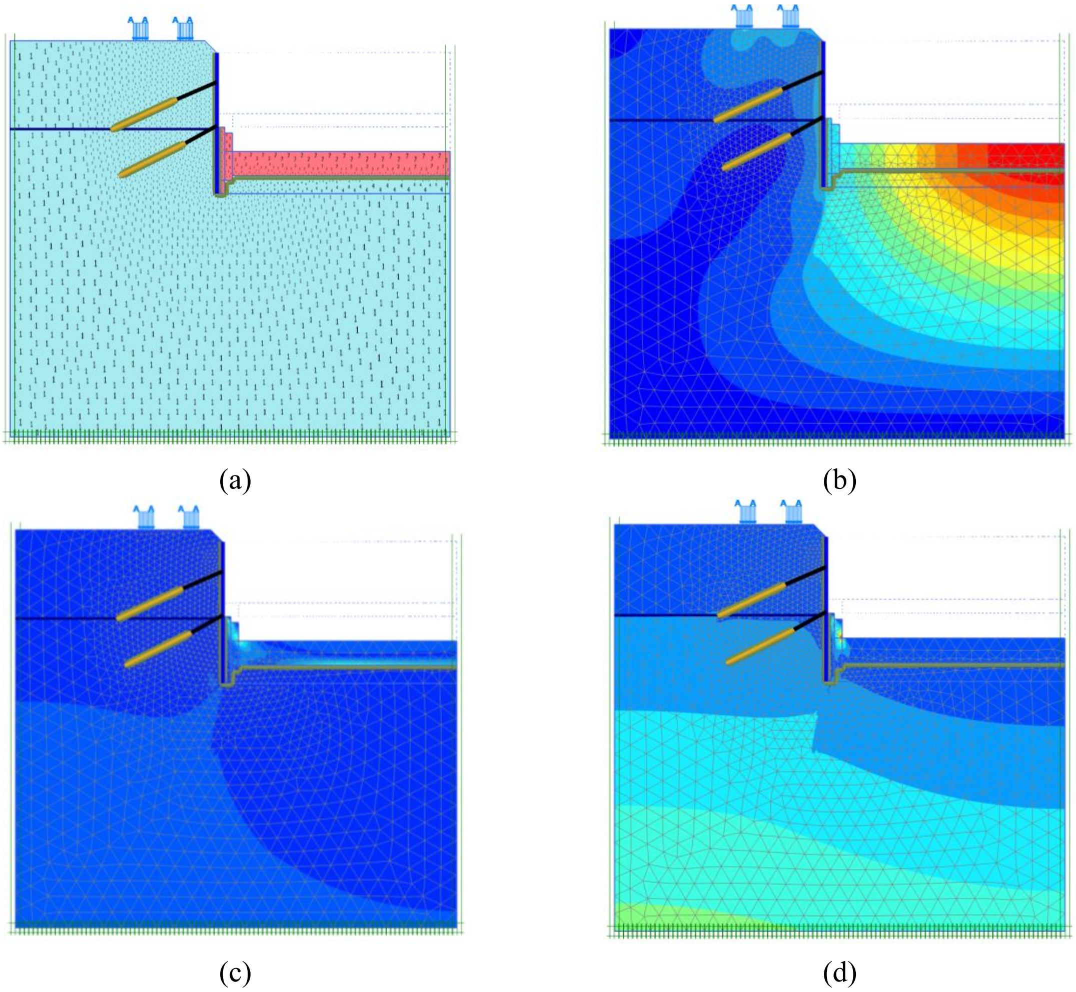
Material	γ_{unsat} [kN/m^3]	γ [kN/m^3]	c[kPa]	ϕ [°]	E_{50} [mPa]	ν [/]	k [m/s]
Sandy gravel	21.5	22	2	35	40	0.3	$1\text{x}10^{-4}$
Soilcrate	22	22	658	37	8000	0.2	10^{-8}

Special attention was given to the definition of the soilcrete material parameters based on laboratory test results. The characteristic unconfined compressive strength (UCS) after 28 days was conservatively adopted as 8 MPa, although some test results indicated values of up to 17 MPa. The Hoek-Brown model was used to transform the parameters into the Mohr-Coulomb model framework. Regarding deformation parameters, recommendations from the relevant literature were followed, with the modulus of elasticity defined using the relationship:

$$E = 1000 \cdot UCS \tag{1}$$

although laboratory test results indicated significantly higher values. The analysis was performed under static loading conditions, without considering seismic effects, given that the excavation support system has a temporary character. The analysis was carried out on previously selected representative cross-sections, which take into account different loading conditions, soil characteristics, and geometrical configurations, as well as various types of piles (depending on the pile spacing) in combination with anchor types (depending on the anchor length and corresponding capacity). To realistically simulate the construction process, a staged construction approach was applied in the analysis, consisting of four successive phases: (1) Partially excavated pit with soldier pile wall with anchors (-8.5 m depth); (2) Execution of jet-grouting elements; (3) Complete excavation of the pit (-12.5 m depth); (4) FOS (φ- c reduction) procedure.

The modeling process begins with the definition of the geometry, soil material, loading conditions, soilcrete elements, and anchors (Figure 5a). The anchor capacity is 250 kN/m’, calculated in accordance with the provisions of EN 1997-1. Accordingly, it is modeled with an inclination of 15 degrees, a bonded length of 7 m, and a total length of 12 m. In the model, the pile wall is represented by an equivalent diaphragm, taking into consideration the variations in the stiffness and dimensions. At a distance of 2.20 m from the outer edge of the piles, a crane has been installed which transmits a total design load of G = 1000 kN.



(a) (b)

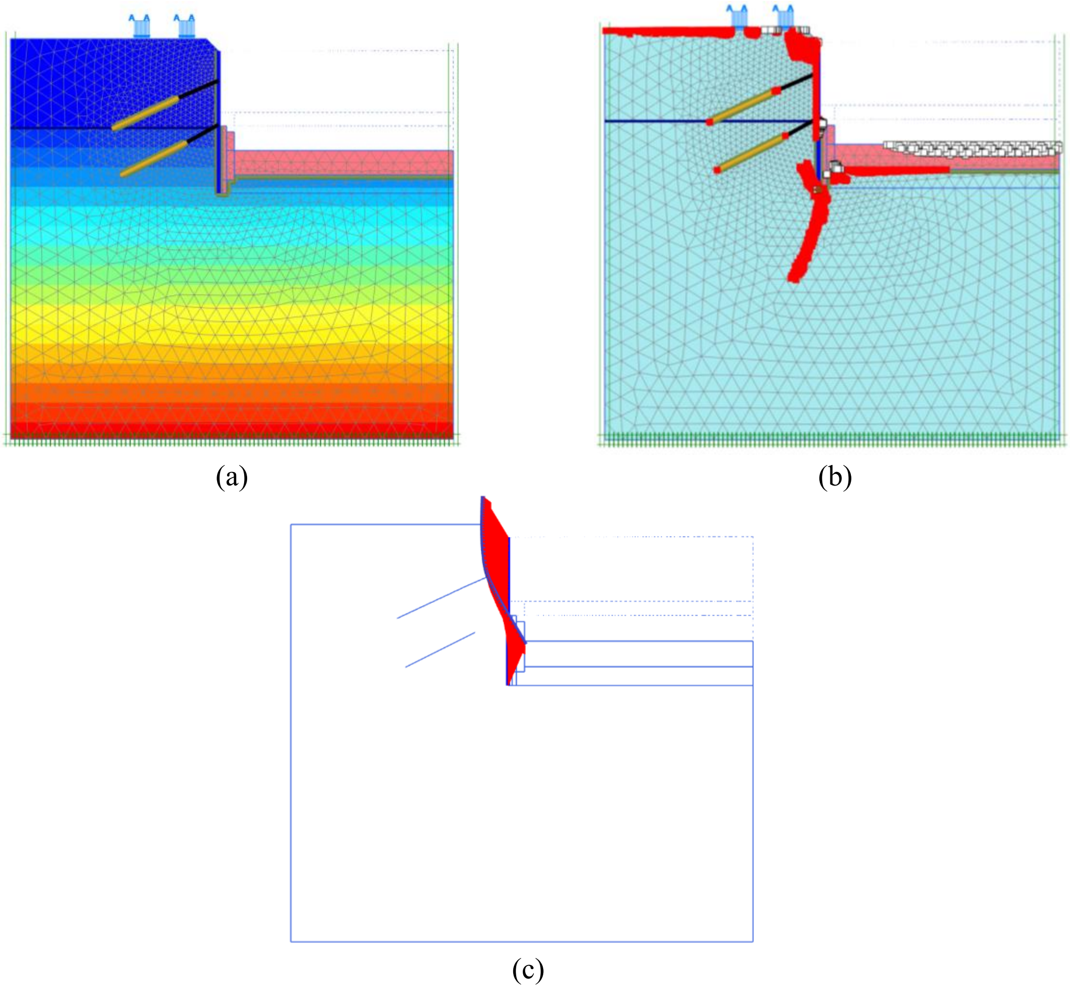
(c) (d)

Figure 5. Discretization of elements and materials (a), Total displacements |u| from the excavation phase (b), Shear stress τ from the excavation phase (c), and Vertical stresses σ_{yy} from the excavation phase (d).

The total displacements at the top of the wall are between 6 mm and 8 mm (Figure 5b). The maximum deformation of 27 mm in the upward direction is in the middle of the pit. The direction of movement is primarily a result of hydrostatic pressure, as well as partially due to unloading effects (resulting from the excavation to -3 m) in the staged construction analysis, which is not expected to occur in practice.

A concentration of shear stresses is observed at the upper corner of the interface between the curtain and the carpet (Figure 5c). At this location, a maximum value of 1721 kPa is recorded, which is the result of a local (corner) effect and is not considered a governing value. In the remaining part of the barrier, stresses are between 100 and 600 kPa. These values are within the allowable limits for a material such as soilcrete.

The maximum recorded stress acting on the structure is 190.6 kPa, occurring in the lower part of the retaining wall (Figure 5d). In the central part of the carpet, the stresses range between 100 kPa (in the central zone) and 300 kPa (near the wall).


(a) (b)

(c)

Figure 6. Active pore pressure from the excavation phase (a), Plastic and tension points from the excavation phase (b), and Total displacement |u| of the retaining construction from the excavation phase (c).

The pore water pressure is linearly distributed, starting from zero at a depth of -8.5 m and reaching 70 kPa at the top of the wall (Figure 6a). Another very important indicator governing the bearing capacity and stability of the soil is the potential for the development of plastic zones and tension points.

The sliding mechanism is illustrated by the red plastic zone at the top, in combination with a tensile zone in the middle of the excavation (Figure 6b). Although a plastic zone has developed, the overall resistance at the top has not yet been fully mobilized. This is confirmed by the wall displacement diagram shown in Figure 6c, as well as by the calculated factor of safety (FOS).

Accordingly, the displacements are characterized by a rotational mechanism with the center located relatively low (in the lower third of the wall), resulting in a top displacement of 9.5 mm, influenced by the anchor action. The rotation angle of the wall is 1/475, which is below the allowable limit of 1/500. The global stability of the system is verified using the so-called φ/c reduction procedure, resulting in a global FOS = 1.20, which exceeds the required minimum value of 1.1 for temporary structures.

All designed measures for the protection of the excavation pit were implemented in accordance with the plan; however, the expected deformations did not occur, at least not to the anticipated extent. Throughout the whole process, the site was instrumented to monitor and record deformations of the wall and the surrounding ground.

6 Conclusion

In this study, an analysis of the excavation pit protection, with a depth of 11.6 m, in the city center of Skopje is presented. The geotechnical conditions at the site are extremely challenging, with the presence of gravelly material and a high groundwater level, which necessitates ensuring both hydraulic and equilibrium stability of the excavation.

For these purposes, various protective measures were applied, including a reinforced concrete pile wall, soilcrete elements, and anchors, all designed to provide stability and minimize deformations of the surrounding structures and traffic lanes. This solution also improved the surrounding soil by creating an effective hydraulic barrier without any infiltration of groundwater.

Numerical modeling using the finite element method proved to be a powerful tool for realistically simulating the soil–structure interaction and optimizing the design, especially when combining materials with different mechanical properties. The two-dimensional model provided an accurate representation of the excavation process and system behavior, although a three-dimensional model could yield even more precise results, particularly in the corner areas of the pit.

Finally, the applied design measures and soilcrete elements ensured a stable and safe construction of the excavation pit with minimal deformations, demonstrating that this combined approach is efficient and practical under challenging urban conditions.

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