

Environmental aspects of designing a deep construction excavation

Ilian Markov, **Andrey Totsev**, Melanie Angelova, Ralitsa Dadikozyan, Stefani Zhelyazkova
University of Architecture, Civil Engineering, and Geodesy, Sofia, Bulgaria, atocev@gmail.com

Iva Miteva
University of Forestry, Sofia, Bulgaria

ABSTRACT: In recent years, climate change and carbon emissions in particular have been the subject and key topic of various scientific research around the world. Leading experts are raising the issue of the contributions of geotechnical engineering to climate change mitigation (Kiessling, 2022; Adam, 2023). The efforts of numerous governments and scientists worldwide to mitigate negative forecasts make the contribution of every aspect of the economy significant, with geotechnics being no exception. Most problems in geotechnical engineering have been solved in multiple ways, and the variations in the results obtained (by different methods) can be expressed not just by a few percent but by several orders. Environmental aspects, which were not so relevant decades ago, require that we focus on economical design. Of course, economy should not come at the expense of safety. This paper presents an interactive approach to the design and implementation of a deep construction excavation, using the observational monitoring method, when controlling for the behaviour of a retaining wall and the opportunities for realising savings with an immediate environmental effect, which has been numerically assessed.

KEYWORDS: pile wall, anchors, design methods, environmental impact.

1 INTRODUCTION

The construction of a residential building in the city of Sofia required strengthening with a three-row anchored retaining wall (Berlin type). The depth of the excavation reached 12.40 m. The anchors used are passive single-bar anchors R38 with an allowable load of 500 kN, implemented without a clearly defined bounded length during the implementation, as the bound length of this type of anchors is formed in the process of loading of the anchors, which are considered tension-loaded. The static anchorage scheme was assumed such that bending and shear are not considered. The piles were made of 2T profile IPE270 and IPE300 in the individual zones.



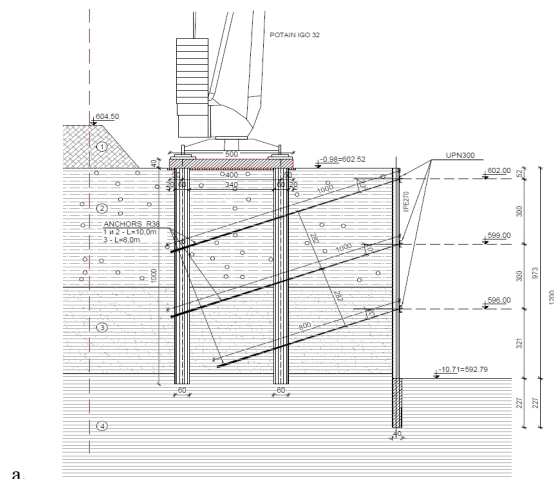
Figure 1. A retaining wall

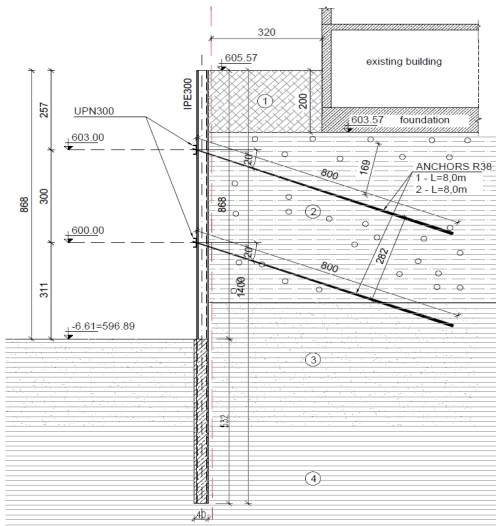


Figure 2. Load cells

2 ENGINEERING GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

According to the available geological data for the site, the following engineering soils were distinguished in the area of the site and below the excavation level to the investigated depth. Layer 1 represents a cultural layer of backfill and black clay - Smolnitsa. It has a wide areal distribution within the site. Its established thickness is 2.00 m. Layer 2 consists of deposits of dark brown clay mixed with gravel in places. This layer is exposed immediately under Layer 1. The established thickness of Layer 2 is 4.50-5.50 m. Layer 3 is represented by Pliocene clayey sands, fine-grained to sandy clays, light beige to rusty brown in colour. These are exposed at a depth of 7.40 m from the terrain elevation. The established thickness of this layer is 3.50-4.00 m. Layer 4 consists of Pliocene clays. In natural conditions of occurrence, Pliocene clays are dense, of a semi-solid consistency. This layer is exposed at a depth of 11.50-15.00 m and 17.00-20.00 m. Layer 5 consists of Pliocene gravelly clays. These occur as an alternation between the clay layers, they are unweathered in depth and area at the site. The gravels themselves are medium-sized with rounded pieces. They occur at a depth of 15.00-17.00 m. Pliocene gravelly varieties are compacted with different amounts of sandy-clay fraction. The generalised properties of individual soil varieties are shown in Table 1.





b. Figure 3. Geological profile according to the retaining structure in two typical cross sections – a.1-1 and b.2-2

Table 1. Design values of soil parameters – DA2 ($\gamma_w = \gamma_c = \gamma_r = 1,0$)

Layer	Volume weight	Internal friction angle	Cohesion	Modulus
	γ_k [kN/m ³]	ϕ_k [°]	c_k [kPa]	E_0 [MPa]
Lithology type 1	17.90	16.00	14.00	4.50
Lithology type 2	21.09	26.40	27.80	10.00
Lithology type 3	20.40	36.90	18.20	18.00
Lithology type 4	19.12	22.70	42.90	14.00
Lithology type 5	19.82	32.10	16.70	30.00

3 MODELLING A RETAINING STRUCTURE

Different approaches can be employed when designing the retaining walls of deep construction excavations. In general, these approaches are assigned to three groups: FEM with different types of nonlinear soil behaviour; subgrade reaction methods with linear and nonlinear distribution of spring stiffness (SRM) and classical methods using active and passive earth pressure. When designing the specific excavation, two approaches were used - SRM (the spring method) and FEM. In SRM, a proportionality coefficient is used to model the soil-structure interaction, considering the relationship between stresses and deformations. The main problem associated with the use of the spring method in the design of retaining walls, which is still a subject of debate in scientific and design circles, concerns the distribution of the Winkler coefficient in depth and its accurate determination depending on the experimental data obtained for the specific soil mass, as well as the magnitude, shape and distribution of the earth pressure load. In this paper, three load schemes were considered, as shown in Fig. 4 – the classical scheme; the Terzaghi-Peck schemes and EAB (Gens, 2010; Recommendations on excavation, 2008). The springs modelling the soil below the excavation bottom elevation were assumed to be constant (CW) and linearly increasing (IW) (Fig. 4). The anchors were modelled as yield spring supports with a stiffness of 25,000 kN/m³. FEM studies were performed with Plaxis using MCM and HSM (Fig. 5).

Two sections with characteristic loading were considered. Although the deepest area of the excavation is 12.40, the object

of observation were two other characteristic zones – 1-1 with a depth of 9.70 m and a stationary crane located on the terrain (Fig. 3-a) and 2-2 with a depth of 8.70 m adjacent to a hospital building (Fig. 3-b).

Table 2. Calculation results for cross section 1-1 (Depth of 9.70 m with a crane).

Design model	M_{max} [kNm]	δ_1	δ_2	δ_3	A1 [kN]	A2 [kN]	A3 [kN]
		[-0,5]	[-3,5]	[-6,5]			
CL CW	49.12	0.09	3.17	6.3	2.82	79.78	157.83
CL IW	59.65	0.09	3.06	6.77	2.78	77.14	169.88
TPL CW	36.17	1.80	7.33	7.07	46.83	183.42	176.09
TPL IW	40.33	1.80	7.28	7.31	46.81	182.07	182.21
EAB CW	31.66	1.02	5.60	5.52	21.66	140.33	137.12
EAB IW	30.26	1.02	5.57	5.68	26.86	139.43	141.19
Plaxis HSM	36.25	27.02	31.45	31.87	56.96	116.4	142.2
Plaxis MCM	38.2	28.15	33.15	37.5	67.99	129.8	132.7

Table 3. Calculation results for cross section 2-2 (at a depth of 8.70 m adjacent to an existing hospital building).

Design model	M_{max} [kNm]	δ_1	δ_2	A1 [kN]	A2 [kN]
		[-2,5]	[-5,5]		
CL CW	70	0.48	4.77	11.92	124.13
CL IW	86.16	0.27	5.59	6.39	146.64
TPL CW	68.60	7.03	5.69	170.88	141.09
TPL IW	68.60	6.95	6.01	168.74	149.80
EAB CW	43.79	4.87	3.92	119.12	96.48
EAB IW	43.79	4.83	4.10	117.95	101.24
Plaxis HSM	62.65	19.01	23.34	82.76	165.2
Plaxis MCM	106.5	11.2	19.2	73.44	124.1

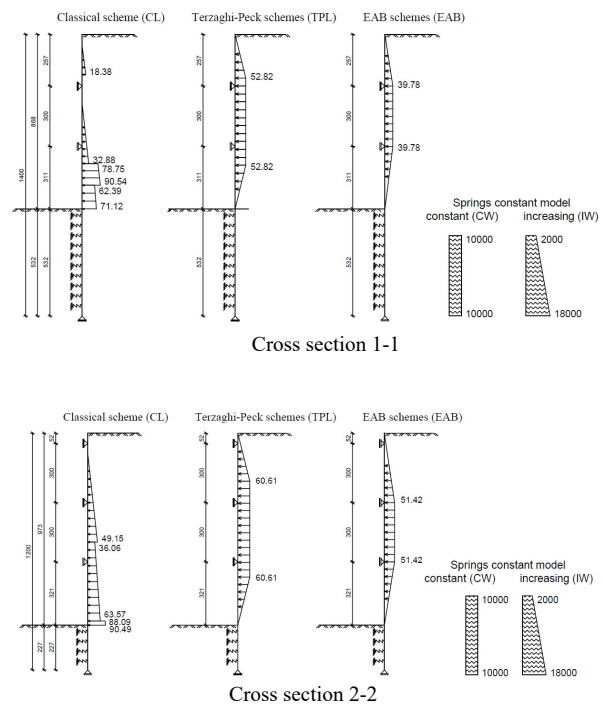


Figure 4. Load schemes and wall support

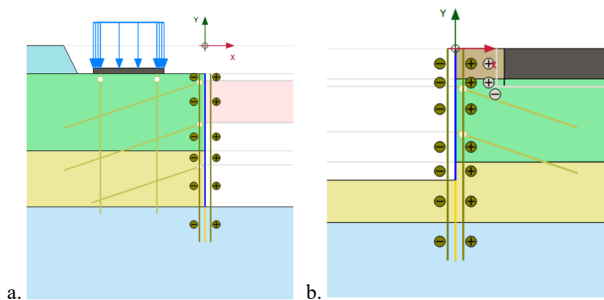


Figure 5. A solution with Plaxis

4 MONITORING OF THE RETAINING STRUCTURE

To apply the observational method, seven measuring load cells (Fig. 1, Fig. 2) were installed to record directly the changes in the forces during the individual phases of excavation.

Table 4. Monitoring results for cross section 1-1 (at a depth of 9.70 m with a crane in place)

Excavation phase	δ_1	δ_2	δ_3	A1	A2	A3
	[-0.5]	[-3.5]	[-6.5]	[kN]	[kN]	[kN]
	[mm]	[mm]	[mm]			
Excavation to level -3.50 m	9	-	-	3	-	-
Excavation to level -6.50 m	17	12	-	9	18	-
Excavation to level -10.00 m	28	24	21	14	26	22

Table 5. Monitoring results for cross section 2-2 (at a depth of 8.70 m adjacent to an existing hospital building).

Excavation phase	δ_1	δ_2	δ_3	A1	A2
	[-0.5]	[-2.5]	[-5.5]	[kN]	[kN]
	[mm]	[mm]	[mm]		
Excavation to level -3.50 m	7	-	-	-	-
Excavation to level -6.50 m	12	11	-	35	-
Excavation to level -10.00 m	19	17	16	58	41

Additionally, by means of a system of geodetic benchmarks, the displacement of the retaining wall at the top of the pile and at the levels of the anchors was monitored for the individual phases of execution. The results obtained are summarised in Table 4 and Table 5.

5 HORIZONTAL DISPLACEMENT OF THE RETAINING WALL

In the specialised literature, there are numerous observations of the horizontal displacements of retaining walls, on the basis of which some authors propose empirical methods for determining the projected displacement.

In these methods, the displacement depends on the height of the wall, the number of anchor rows and the type of soil. Figure 6 shows two empirical methods for different soils – Clough & O'Rourke's method for hard clays and sands (1990) and Mana & Clough's method for soft clays (1981). According to the proposed dependencies, a displacement within 17-19 mm is expected for hard clays and sands and a depth of the excavation of 8.70-9.70 m.

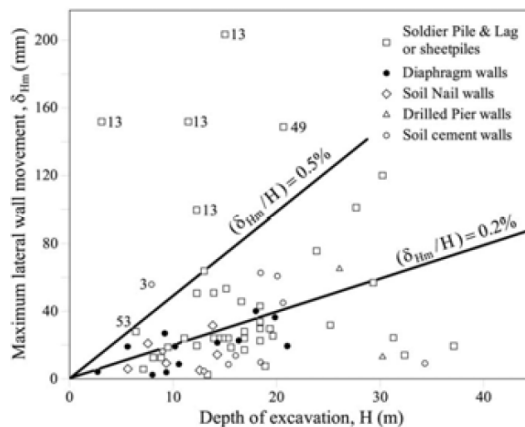


Figure 6. Determining horizontal displacements by Clough & O'Rourke's empirical method for hard clays and sands (1990)

6 DESIGN AND IMPLEMENTATION

During the design and implementation, the well-known 'most probable' parameters approach (Soga, 2025) was used. The goal of this approach is to propose an economical solution by monitoring the efforts and displacements in the structure at each phase of the implementation and, if necessary, the structure is then strengthened. In case the obtained results do not exceed the calculated (projected) results, the implementation of the project is continued. The observations carried out during the individual implementation phases of the strengthening of the construction excavation showed that the obtained results were smaller than the projected ones, i.e. the strengthening could be implemented in its most economical design version.

A comparison of the obtained results shows that the difference between the adopted (most economical) solution and the most conservative one, measured in geotechnical structures, is approximately 120,000 kg of profile steel for piles and 1000 m of anchors used.

7 ENVIRONMENTAL IMPACT ASSESSMENT OF GEOTECHNICAL STRUCTURES

There are several approaches to environmental impact assessment (EIA) in the specialised literature, with the first step being the determination of the environmental aspects. An aspect is an activity, product or service that interacts or may interact with the environment. When determining an aspect, the life cycle of the product or service should also be taken into account. The main stages of the life cycle of a product or service are extraction of raw materials, design, production, transportation, use and disposal. These steps are interrelated, and while transportation and use are directly related to identifying environmental factors for the purposes of this study design, they also indirectly affect extraction, production, and disposal.

Determining the effects of the elements on the environment and the EIA's goals is the primary step in the process. The assessment may include one or more of the following tasks: reduction of waste and rational consumption of natural resources; elimination or limiting of pollutant emissions in the environment; limitation of hazardous production, compliance with regulatory requirements for storage and warehousing of regulated quantities; prevention of the impact of particularly hazardous raw materials; minimizing any harmful impact of new technologies and products; informing the public about the problems and achievements in

environmental management. Once the purpose is defined, the assessment is carried out using one or more of the following quantitative criteria – the amount of raw materials, resources, and energy used; carbon dioxide emissions; the quantity of waste generated throughout the entire production cycle; the efficiency of using different types of energy; the amount of specific pollutant emissions – lead, zinc, etc.; investments in environmental protection. This paper discusses the strengthening method of a deep excavation during the construction of a residential building in the city of Sofia, therefore the environmental aspect is the strengthening of the construction excavation. The impacts resulting from this complex construction process include the consumption of natural resources, air and soil pollution, a long-term change in the general noise background, a change in the general condition of the environment, etc.

The purpose of the assessment was related to air pollution, and the EIA itself was carried out in relation to the amount of carbon dioxide emissions that were released during the production of structural steel, namely 5403,2 kg CO₂/m³. The results of the comparison between the most economically beneficial design solution and the most conservative one showed a difference of 120,000 kg of profile steel (IPE270 and IPE300) and 1000 m of anchors (R38N-19). The carbon dioxide emissions released during the production of steel alone were 83,276.7 kg CO₂.

From the above, it is clear that in order to safely strengthen a deep excavation, a large amount of metal is needed, which in this case generated 83,276.7 kg CO₂, compared to the traditional monitoring method the emissions were reduced by 92,626 kg CO₂. This activity was not related to mining and production, but could indirectly have an impact. For this purpose it was necessary for the steel to be obtained from verified and certified mills that recycle all products from the steel production cycle and also make efforts to minimise carbon emissions. By optimising the steel production processes and implementing innovative approaches such as CO₂ recovery, the carbon footprint could be significantly reduced (Baena-Moreno, Na) or even completely eliminated (Kiessling).

Another important aspect for determining steel consumption is the observational monitoring method, in which the most economical solution (minimal retaining wall) is implemented and the excavation is monitored, and through inverse analysis the need for additional interventions is assessed to ensure the necessary stability and safety. Traditional design methods are quite conservative and material-intensive, while the application of monitoring and the ‘most probable’ parameters approach is a framework that allows for correction of geotechnical parameters during construction, based on monitoring data. The main objectives of this type of monitoring are stability, achieving minimal emissions, while ensuring the failure-free operation of the structure. It is important to note that Eurocode 7 explicitly allows for the application of the observational method. By applying the observational method, the required steel in this type of structure is almost halved. Therefore this method is a sustainable and effective substitute for conventional design techniques since it not only guarantees structural stability and safety but also minimizes material consumption.

8 CONCLUSION

The presented case study shows the importance and advantages of using a ‘most probable’ parameters system to mitigate negative environmental forecasts. It demonstrates that when using economical design while applying monitoring during implementation, the effect on the climate is equal to the daily

footprint of almost 12,000 diesel cars. Over 90,000 kg CO₂ emissions were saved. The direct benefits of the optimal use of natural resources and reduced air pollution, the positive effect on the general noise background, reduction of construction waste and improvement of the general condition of the environment should also be taken into account, which are the subject of further studies. In summary, the application of the observational method not only ensures structural stability and safety but also significantly optimizes material use, making it a sustainable and efficient alternative to traditional design approaches.

9 REFERENCES

- Baena-Moreno, F.M., Cid-Castillo, N., Arellano-García, H., Reina, T.R. Towards emission free steel manufacturing – Exploring the advantages of a CO₂ methanation unit to minimize CO₂ emissions.
- BDS, 2004. BDS EN 1997-1:2004/NA Eurocode 7: Geotechnical design. - Part 1: General rules.
- CIRIA, 2024. Observational method guidance (P3295).
- Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise.
- EAB, 2008. Recommendations on excavation.
- Gens, A., 2010. Ground movement control of a deep excavation. NZGS course.
- Interactive Construction Material Pyramid – developed by the Royal Danish Academy, The Aarhus School of Architecture and Vandkunsten Architects.
- ISO, 2015. ISO 14001:2015.
- Kiessling, S., Gohari Darabkhani, H., & Soliman, A.-H., 2022. The Bio Steel Cycle: 7 Steps to Net-Zero CO₂ Emissions Steel Production. 10.20944/preprints202211.0078.v1.
- Na, H., Sun, J., Qiu, Z., Yuan, Y., & Du, T., 2022. Optimization of energy efficiency, energy consumption and CO₂ emission in a typical iron and steel manufacturing process. *Energy*, 257, 124822. <https://doi.org/10.1016/j.energy.2022.124822>.
- Regulation on the management of construction waste and the use of recycled construction materials, 2012.
- Science of The Total Environment, Volume 781, 2021, 146776. <https://doi.org/10.1016/j.scitotenv.2021.146776>.
- Soga, 63rd Rankine lecture, From geo-monitor to geo-adapt: leveraging distributed sensing and data analytics for performance-based design, construction and maintenance, 2025
- Terzaghi, K., Peck, R., 1967. Soil mechanics in engineering practice. New York, London, Sidney.