AN EXAMPLE OF THE PROTECTION OF A DEEP EXCAVATION IN AN URBAN ENVIRONMENT

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Abstract: *The paper presents the design of deep excavation support system in an urban environment. Excavation is carried out in the vicinity of surrounding buildings whose structural stability must be ensured during the execution of the construction works. The 60 cm thick diaphragm wall supported by the two rows (17.00 m and 18.25) of geotechnical anchors was selected as an excavation support system. The approximate floor plan dimensions of the diaphragm wall are 81x118 m, and the maximum excavation depth is 10.5 m. An additional challenge in designing the diaphragm wall is the presence of groundwater, whose maximum level is observed at a depth of approximately 5.8 m. In order to ensure the execution of construction works in dry conditions, a system of drainage trenches and wells is designed at the bottom of the pit. The diaphragm wall is designed in accordance with Eurocode 7.*

Keywords: *diaphragm wall, deep excavation, geotechnical engineering, Eurocode 7*

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1. INTRODUCTION

Because of the continuous progress of urbanization, there is often a need for more above-ground spaces for development and construction in urban areas. It resulted in the accelerated utilization of underground construction opportunities, which is especially important for developing large urban areas (Feng et al. 2022). Efficient utilization of underground spaces can improve the sustainability of urban development, i.e. contribute to the overall quality of life (Broere 2016). However, along with the many advantages of using underground spaces, it also brings specific challenges. For example, the execution of deep excavations necessarily results in ground movements, including horizontal movements and settlements. The above can threaten the safety and stability of neighboring buildings (Sun & Xiao 2021). In order to evaluate the potential negative impacts of this type of work on neighboring buildings, it is necessary to evaluate the displacements that occur as a result of deep excavation. The aforementioned can be carried out using empirical and semi-empirical methods, laboratory tests, analytical methods and numerical simulations (Yang et al. 2021). With the development of computers, the finite element method (FEM) is becoming one of the most widely used methods in geotechnical analyses of deep excavations (Chen et al. 2022). On the site of the former electric light bulb factory in Zagreb, Croatia, a residential-commercial building is planned. The building's floor plan is approximately rectangular, with dimensions of 80x117 m. The building consists of three underground and nine above-ground floors. In order to ensure the structural stability of the soil and surrounding buildings, as well as the execution of construction works in dry conditions, it is necessary to design a proper excavation support system. The design and construction of the excavation support system is an integral part of the design of buildings containing underground floors (Frydrych et al. 2021). The design process involves modelling the complex foundation-soil interaction with a series of important input parameters: the initial stress state in soil, groundwater level, soil lithology, and relative stiffness between the structure (Popa et al. 2015). An additional challenge in the geotechnical analysis of the support system is the relatively high groundwater level, which was observed at a depth of 5.8 m.

In accordance with Eurocode 7 (European Committee for Standardization 2004), the excavation support structure is categorized in Geotechnical category two. This category includes common structures and foundations without high risk or unusual or extremely difficult conditions in the underlying soil. The design of geotechnical category two structures should typically include quantitative geotechnical data and calculations to ensure that the basic requirements are met. For design in geotechnical category 2, standard procedures for field and laboratory testing and calculation may be used.

2. LOCATION

The construction pit is located at 10 Frana Folnegovića Street in the Trnje district of Zagreb (**Figure 1**). Within the construction pit's location, some of the existing buildings and installations were removed before the start of the works. Near the excavation, along its eastern side, there is a road, and along the northern, western and southern sides, there are buildings whose structural stability should be ensured during the works.

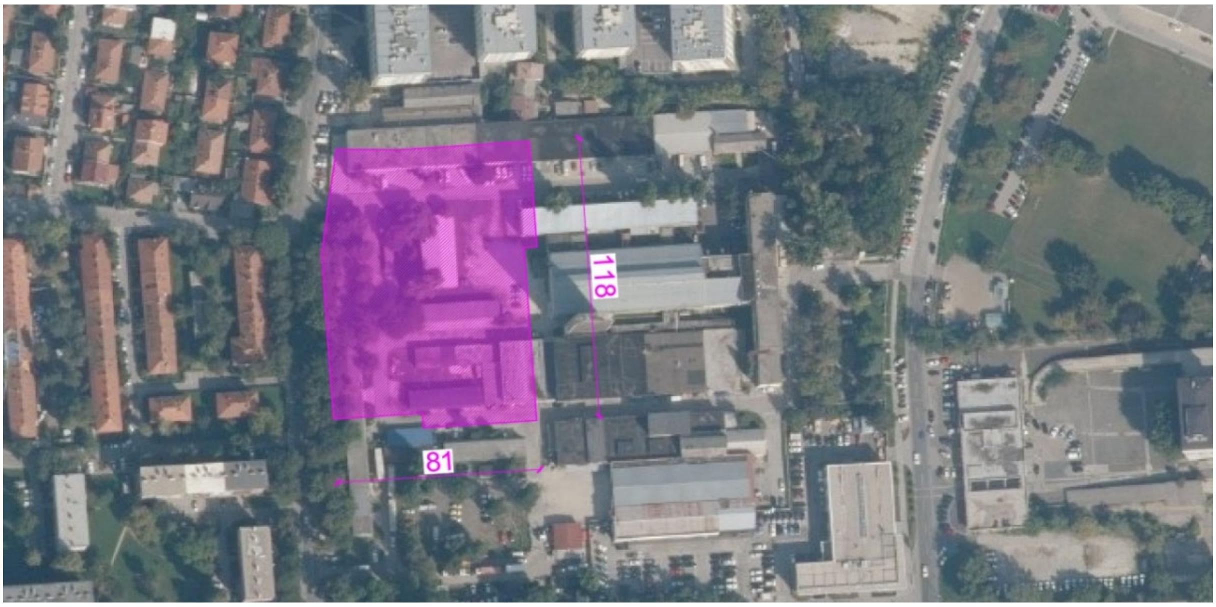

Figure 1. Location of the construction pit

Data on the maximum value of horizontal acceleration at the location were read from the "Map of Earthquake Areas of the Republic of Croatia" prepared by the Geophysics Department of the Faculty of Science and Mathematics in Zagreb in 2011. Maps with an interpreter are an integral part of the National Annex to the series of norms HRN EN 1998-1:2011/NA:2011, Eurocode 8: Design of seismic resistance of structures - Part 1: General rules, seismic actions and rules for buildings (Croatian Standards Institute 2011; 2021). **Table 1** shows the values.

Table 1. Maximum horizontal ground acceleration

RETURN PERIOD (years)	a_{max} (g.)
95	0,123
475	0,243

2.1. Geotechnical investigation works

Relevant information on the geotechnical composition of the soil, necessary for finding the optimal design of the excavation support system, was obtained from the geotechnical investigation works. In general, the program of geotechnical investigation works is designed in such a way that a sufficient amount of data is collected from the location to define:

- geotechnical model of the location with the type and characteristics of the underlying soil,
- soil strength and deformability parameters for the implementation of geotechnical limit states analyses,
- recommendation for the design and construction of foundations and excavation support system.

Geotechnical field investigation works were carried out at the beginning of September 2019. Four (4) investigation borings were drilled. The works included the following activities:

- drilling of four (4) borings, 21 m deep, with a motorized rotary drill, including continuous soil coring (**Figure 2**),
- soil relative compaction exploration using the method of the standard penetration test (SPP test), to assess the relevant properties of the soil,

- monitoring and field AC classification of the drilled core and selection of representative undisturbed and disturbed soil samples for the conduction of laboratory tests,
- during and after drilling, the occurrence of groundwater level was monitored.

Table 2. Markings and characteristics of investigation borings

BORING	WELL DEPTH (m)	SPP (pc)	US* (pc)	DS** (pc)
NB-1	21	10	1	-
NB-2	21	9	1	-
NB-3	21	10	-	-
NB-4	21	10	1	-

** US, Undisturbed Sample; ** DS, Disturbed Sample*

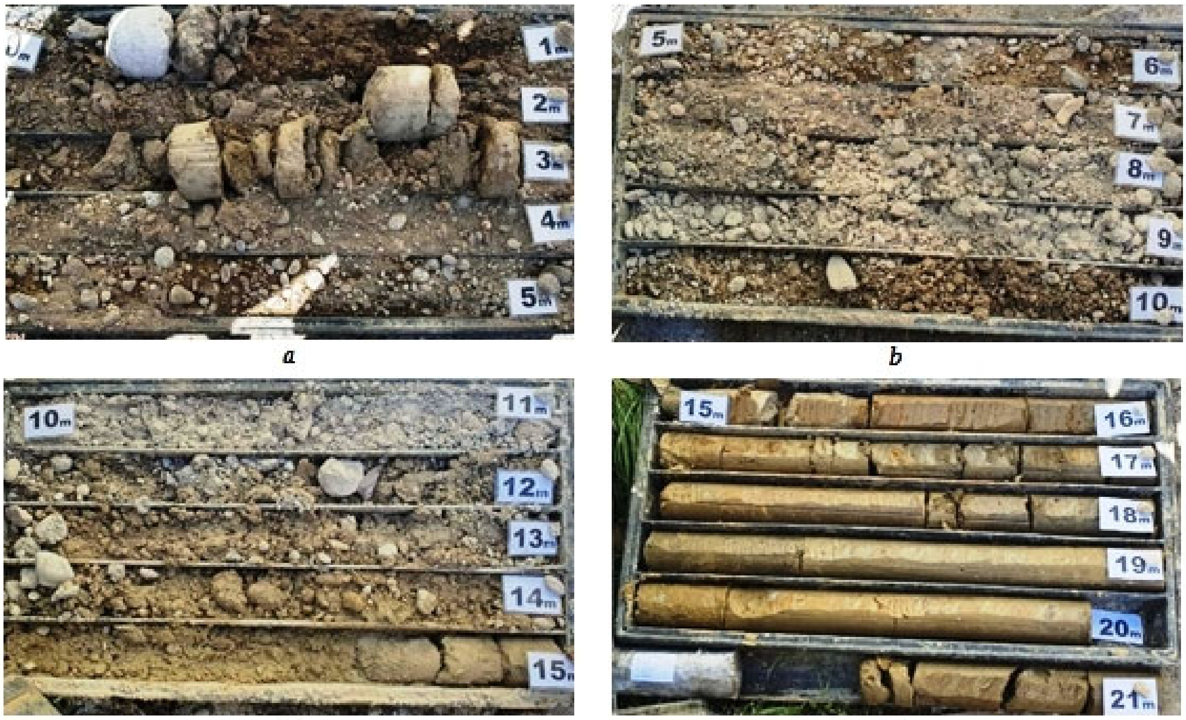

Figure 2. Drilled cores

Laboratory tests on disturbed and undisturbed soil samples were performed according to appropriate standards and in accordance with Croatian norms and included the following tests:

- identification tests to determine the general properties of the soil:
  - examination of the granulometric composition
  - consistency limits (Atterberg limits) and soil plasticity index
- identification tests to determine soil strength and deformability properties:
  - shear strength by direct shear
  - soil compressibility using an oedometer
  - uniaxial soil strength

Based on field investigations and laboratory tests, geometry, and geotechnical characteristics of the half-space of soil are defined. The soil generally consists of four layers. The first layer is silty sand, up to a maximum depth of 3.7 m. The following soil layer is a very dense well-graded gravel to the depth of the groundwater level. Below the groundwater level, up to a depth of 15-16 m, the layer of dense gravel is identified. Below 15-16 m is a 1 m thick layer of clay mixed with sand, and finally, the drilling was finished in highly plastic clay. The groundwater during the drilling was observed at 7.0-7.3 m. Later, groundwater in the previously drilled holes was observed at 5.8 m. Given the excavation depth of 10.5 m, it is evident that the elevation of the bottom of the construction pit is below the groundwater level. Based on the investigation works results, six geotechnical environments were defined as follows:

1. Embankment
2. Clayey-silty sand, SC/SM
3. Well-graded gravel, GW-1
4. Well-graded gravel, GW-2
5. Clayey sand, SC
6. High-plasticity clay, CH

Table 3. Markings and characteristics of exploratory wells

SOIL	DEPTH (m)	γ (kN/m^3)	c (kPa)	ϕ (°)	M_v (MPa)	c_u (kPa)
Embankment	0-0.6	18	5	15	4	-
SC/SM	0.6-2.5	18	6	32	8	-
GW_1	2.5-7.0	18	0	38	65	-
GW_2	7.0-15.35	18	0	33	32.5	-
SC	15.35-16.10	18	2	31	35	-
CH	>16	18	25	21	40	120

3. THE EXCAVATION SUPPORT SYSTEM – CONCRETE DIAPHRAGM WALL

The excavation is planned at 101.25 and 101.95 m above sea level, while the existing terrain is approximately horizontal at approximately 111.75 m above sea level. The excavation support system was designed considering the restrictions at the location and technology used by the selected contractor. Accordingly, a concrete diaphragm wall supported by two rows of geotechnical anchors was selected as the excavation support system. The floor plan of the construction pit is shown in **Figure 3**.

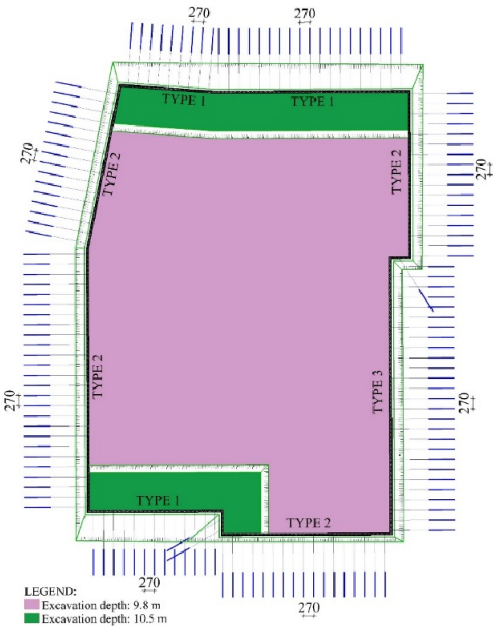

Figure 3. Diaphragm wall layout

During construction, the diaphragm wall ensures that the works are carried out in dry conditions. After completing the works, it represents a load-bearing structural element to bear external horizontal and vertical actions. Geotechnical analyzes of ultimate and serviceability limit states of all relevant construction work phases were carried out: excavation with the action of geotechnical anchors enabled, construction work advancement including connection of the diaphragm wall with ceiling slabs and the stage of the building use. The details of the diaphragm wall's connection with the building's ceilings are harmonized with the requirements given by the structural engineer. The designed diaphragm wall consists of the following:

- 60 cm thick diaphragms wall

- head beams measuring 70/70 cm
- two rows of geotechnical anchors
- guide trench, concrete C 25/30, reinforcement steel Q 335

The following materials are used for the construction of the diaphragm wall and geotechnical anchors:

- concrete C 30/37, consistency S4, D_{max} = 16 mm
- steel reinforcement B 500B
- steel for geotechnical anchors S 1670/1860 N/mm2
- injection mixture C 25/30

Due to different conditions regarding the neighboring buildings, three types of the cross-section are provided:

- TYPE 1: it is performed on parts of the construction pit's floor plan, where the plot's edge is approximately 7.5 m distant from the external contour of the diaphragm wall (**Figure 4**).
- TYPE 2: it is performed on parts of the construction pit's floor plan, where the plot's edge is approximately 3.0 m distant from the external contour of the diaphragm wall (**Figure 5**).
- TYPE 3: it is performed on parts of the floor plan of the construction pit, where the neighboring buildings are located - the eastern side (**Figure 6**).

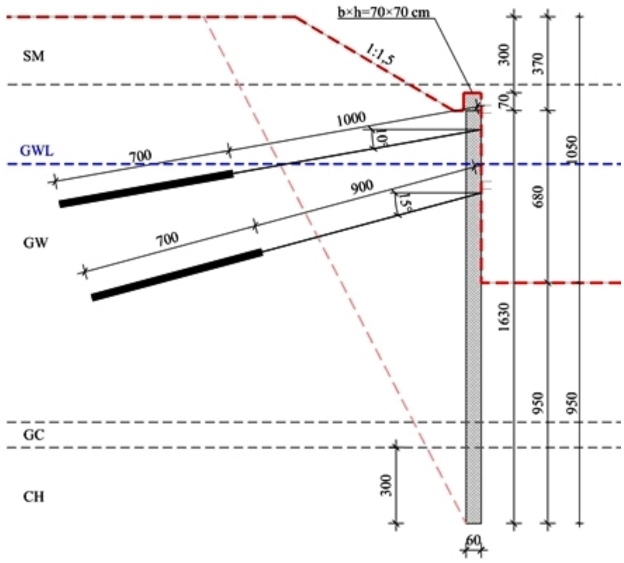

Figure 4. Cross section Type 1

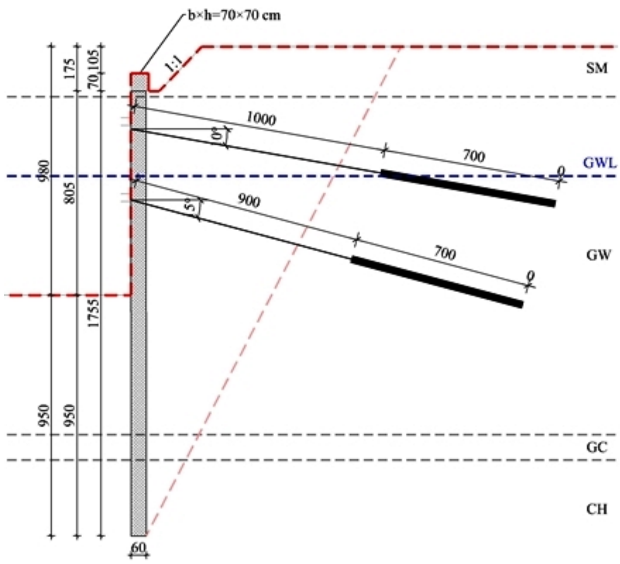

Figure 5. Cross section Type 2

3.1. Geotechnical analyzes and results

Numerical modelling of the diaphragm wall behavior in interaction with the soil (deformation analysis) was carried out using the commercial program Plaxis 2D. The calculations were performed assuming a two-dimensional deformation state. The calculation stages are aligned with the construction stages. For each calculation phase, the distribution of displacements, internal forces and all other relevant data necessary for the design of the diaphragm wall and geotechnical anchors were determined. The soil is modelled using the Hardening Soil soil model, in which the stiffness of the soil depends on the stress. The load-bearing capacity of all structural elements was verified according to regulations, i.e., Eurocode 7 (European Committee for Standardization 2004). This paper presents the results of geotechnical analyses only for cross-section type 3. **Tables 3, 4** and **5** show input parameters of the diaphragm wall, geotechnical anchors, floor slab and mat foundation.

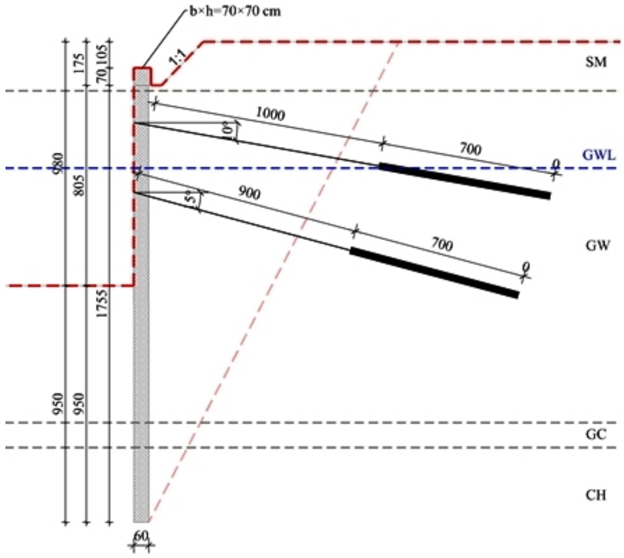

Figure 6. Cross section Type 3

Table 3. Input parameters of the diaphragm wall

IDENTIFICATION	Diaphragm wall D=60 cm
MATERIAL TYPE	Elastic
ISOTROPIC	Yes
EA_1	$18 \cdot 10^6$ kN$/m$
EA_2	$18 \cdot 10^6$ kN$/m$
EI	$540 \cdot 10^3$ kNm$^2/m$
d	0.6 m
w	3.6 kNm$/m$
ν	0.25

Table 4. Input parameters of geotechnical anchors, floor slab and mat foundation

IDENTIFICATION	GEOTECHNICAL ANCHORS	FLOOR SLAB	MAT FOUNDATION
MATERIAL TYPE	Elastic	Elastic	Elastic
EA	$176 \cdot 10^3$ kN	$3 \cdot 10^6$ kN	$30 \cdot 10^6$ kN
L_SPACING	2.7 m	2.7 m	1.0

Table 5. Input data of geotechnical anchors bond length

IDENTIFICATION	Bond length 300 mm
MATERIAL TYPE	Elastic
E	$3 \cdot 10^7$ kN$/m^2$
γ	24 kN$/m^3$
BEAM TYPE	Predefined

PREDEFINED BEAM TYPE	Massive circular beam
DIAMETER	$0.3\ m$
A	$0.07069\ m^2$
I_	$0.3976 \cdot 10^{-3}\ m^4$
L	$2.7\ m$

Table 6. Soil parameters design values

IDENTIFICATION	MATERIAL MODEL	DRAINAGE TYPE	γ	E_{50}^{ref}	E_{OED}^{ref}	E_{UR}^{ref}	c_{ref}	φ
			kN/m^3	kN/m^2	kN/m^2	kN/m^2	kN/m^2	(°)
Embankment	HS	Drained	16	4000	4000	12000	4	12.10
SM	HS	Drained	19	10000	10000	30000	4.8	26.56
GW_1	HS	Drained	19	65000	65000	195000	0	32.01
GW_2	HS	Drained	19	35000	35000	105000	0	27.45
GC	HS	Drained	19	35000	35000	105000	1.6	25.67
CH	HS	Drained	20	40000	40000	120000	20	17.07

Figure 7 shows the numerical model of the excavation support system in Plaxis. **Figures 8, 9, 10, 11** and **12** show the results of deformation analysis for cross-section type 2. **Table 8** shows the summary results of internal forces and displacements for all three types of cross-sections.

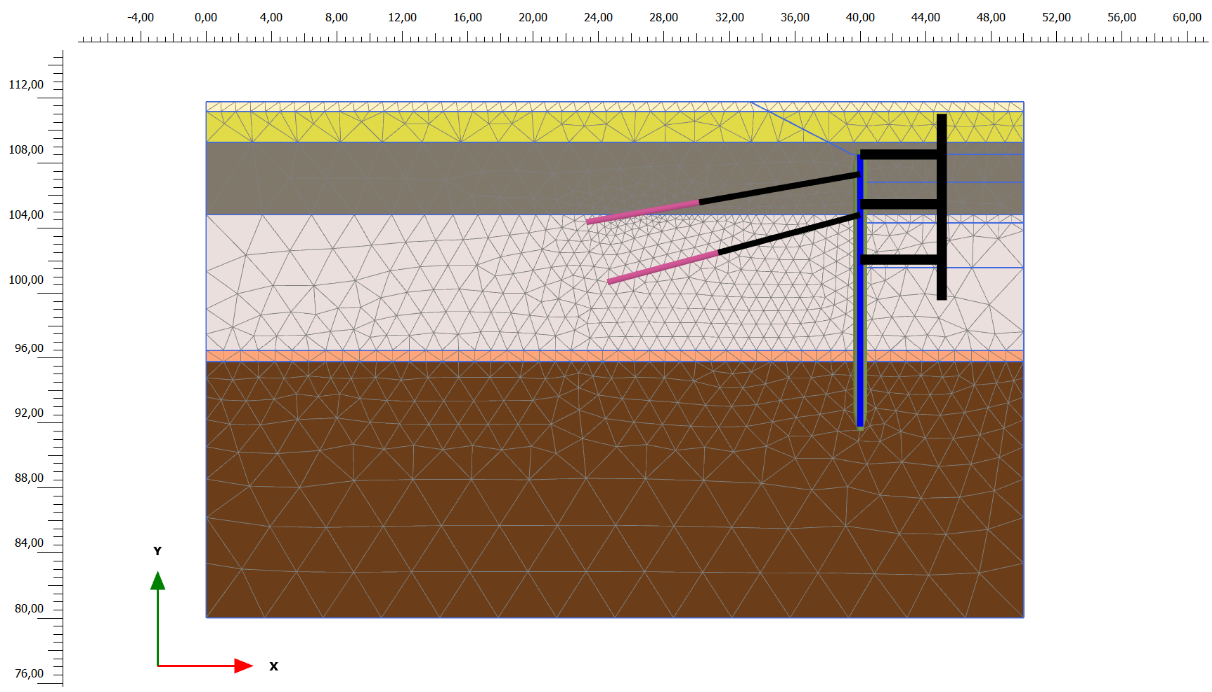

Figure 7. Plaxis model

The dimensioning of geotechnical anchors and diaphragm reinforcement is carried out for the internal forces shown in **Tables 7** and **8**. However, the procedure for their dimensioning is not presented in this paper. The maximum calculated horizontal displacement of the diaphragm wall is 2.6 cm, obtained in cross-section type 1.

Table 7. Axial forces in geotechnical anchors

STRUCTURAL ELEMENT	NODE	LOCAL NUMBER	X [m]	Y[m]	N [kN]	N_{min} [kN]	N_{max} [kN]
NODETONODEANCHOR_1_1	926	1	40.000	107.300	510.466	0.000	516.764
ELEMENT 1-1 (NODE-TO-NODE ANCHOR)	16302	2	30.150	105.560	510.466	0.000	516.764
NODETONODEANCHOR_3_1	1684	1	40.000	104.800	583.559	0.000	583.559
ELEMENT 2-2 (NODE-TO-NODE ANCHOR)	16367	2	31.310	102.470	583.559	0.000	583.559

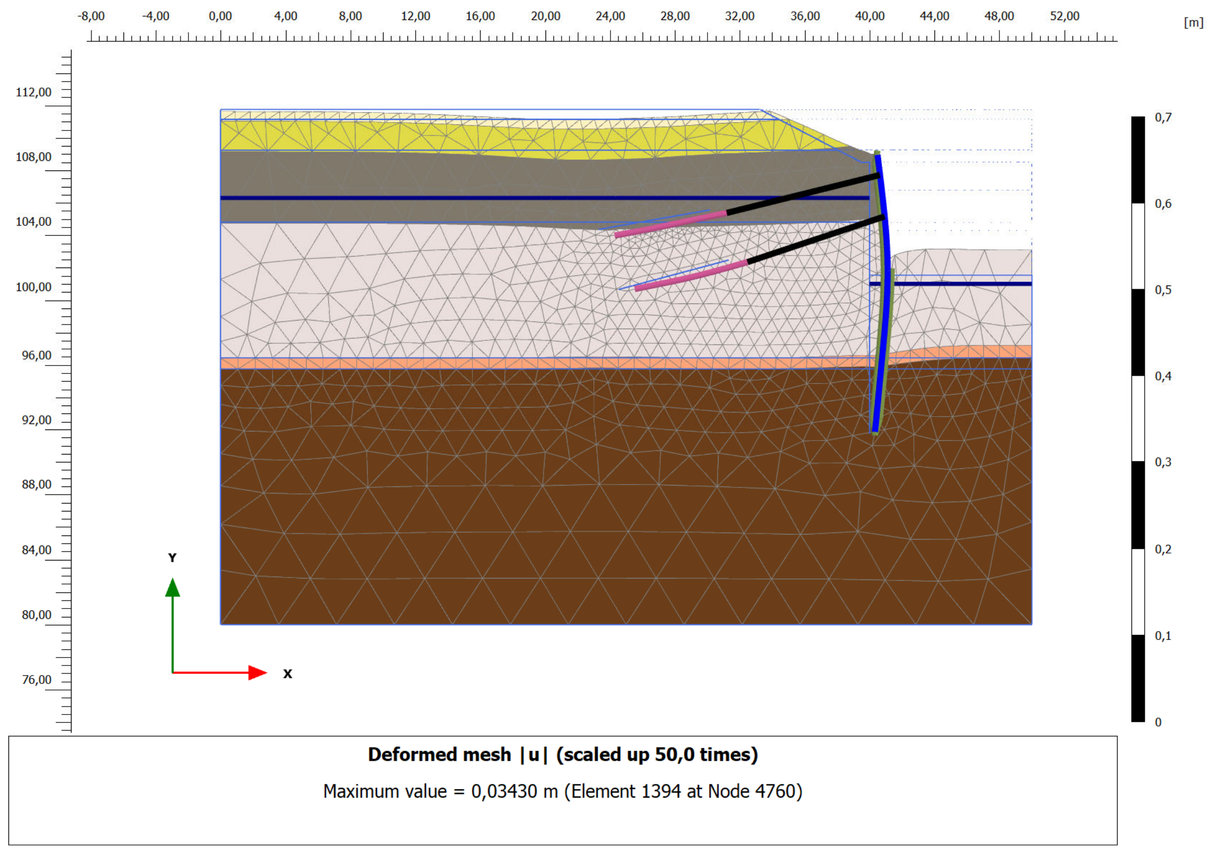

Figure 8. Horizontal displacements in the final stage of excavation

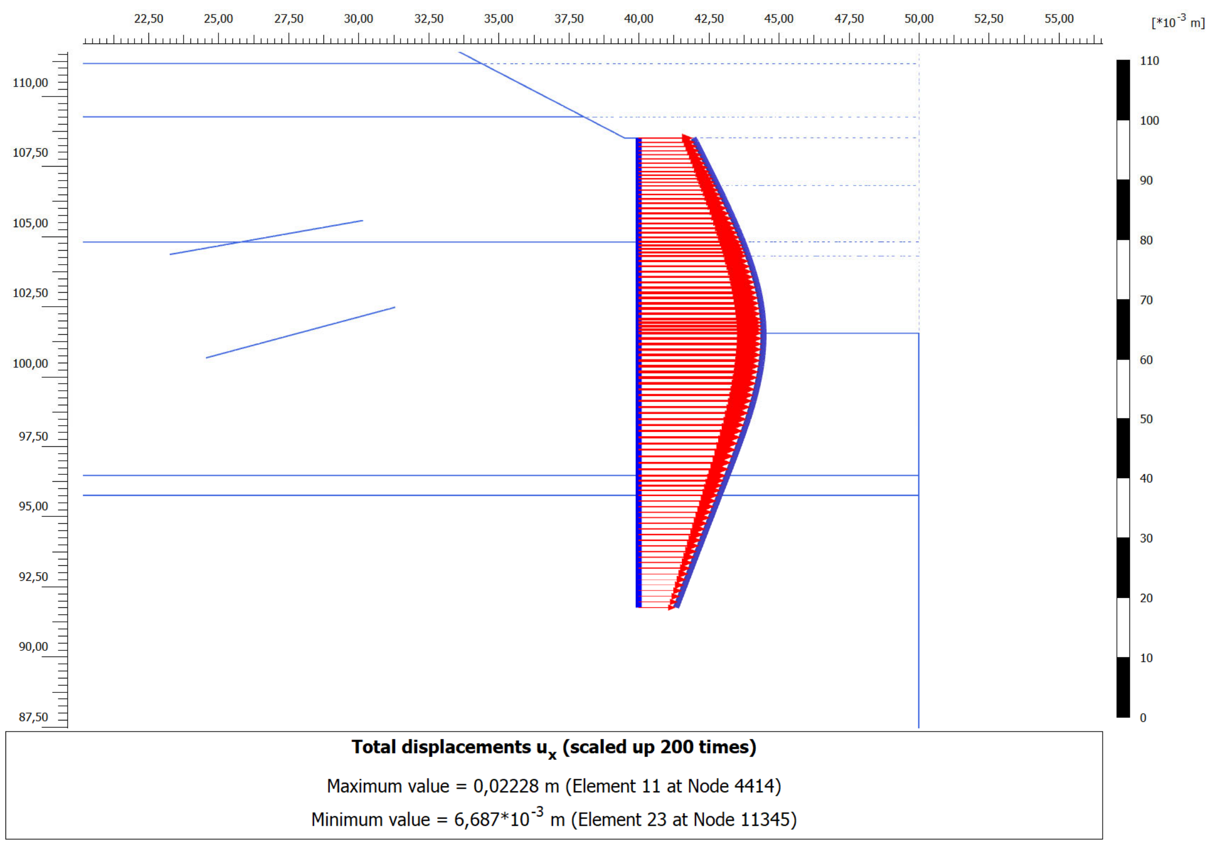

Figure 9. Horizontal displacements of the diaphragm wall

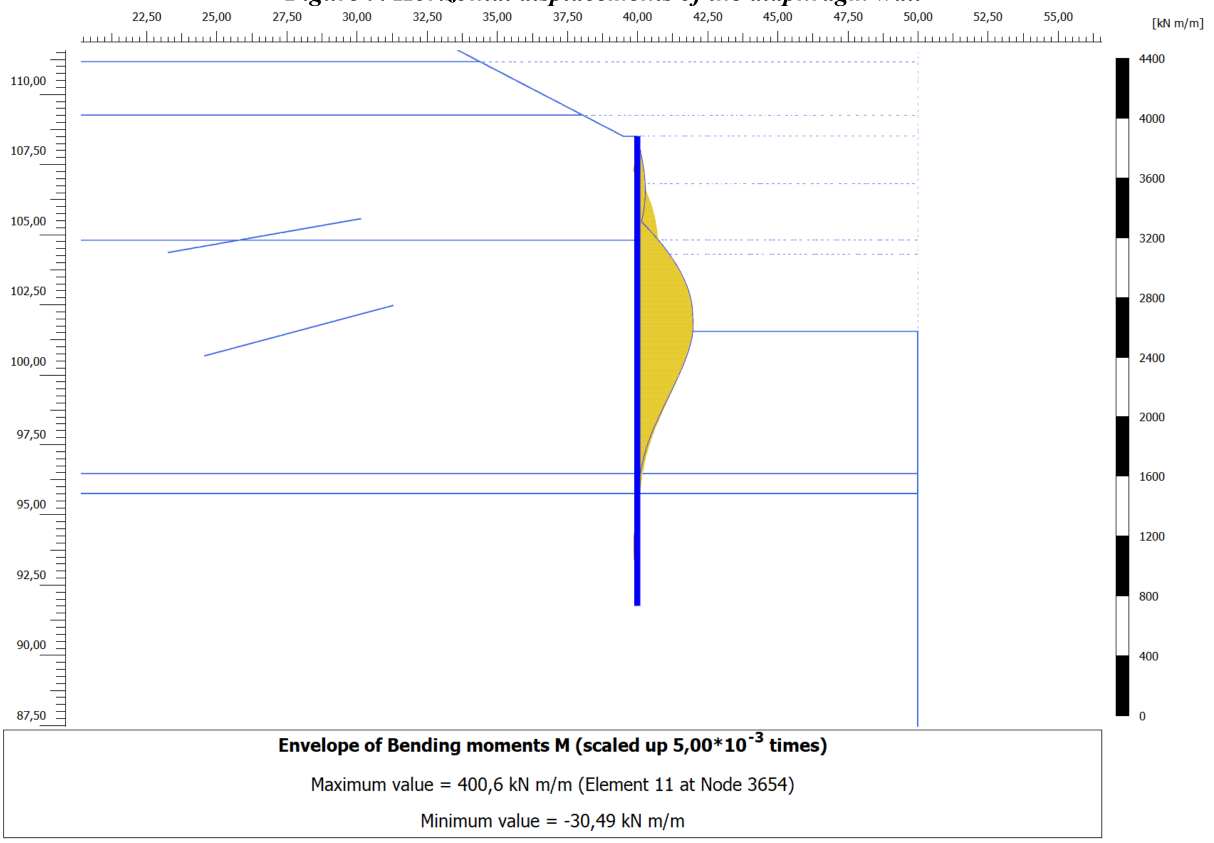

Figure 10. Envelope of diaphragm bending moments

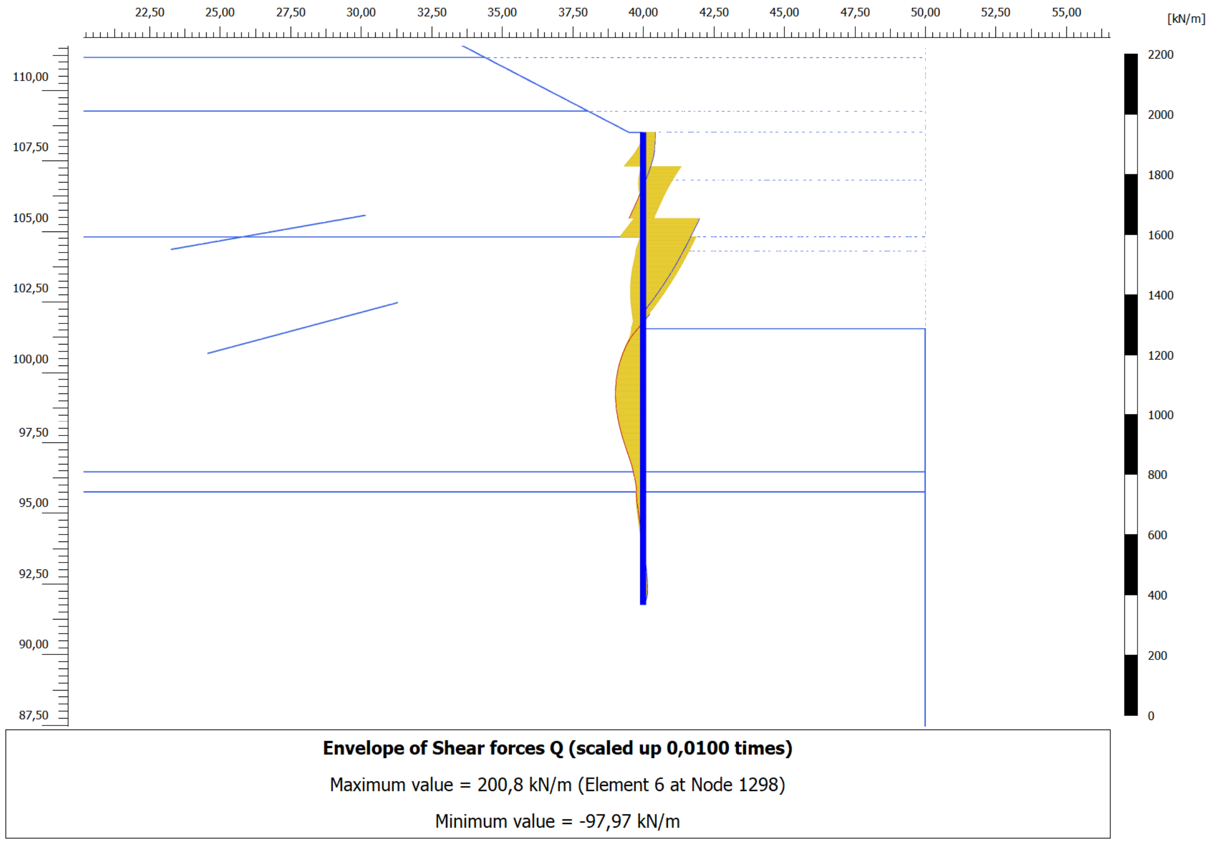

Figure 11. Envelope of diaphragm transverse forces

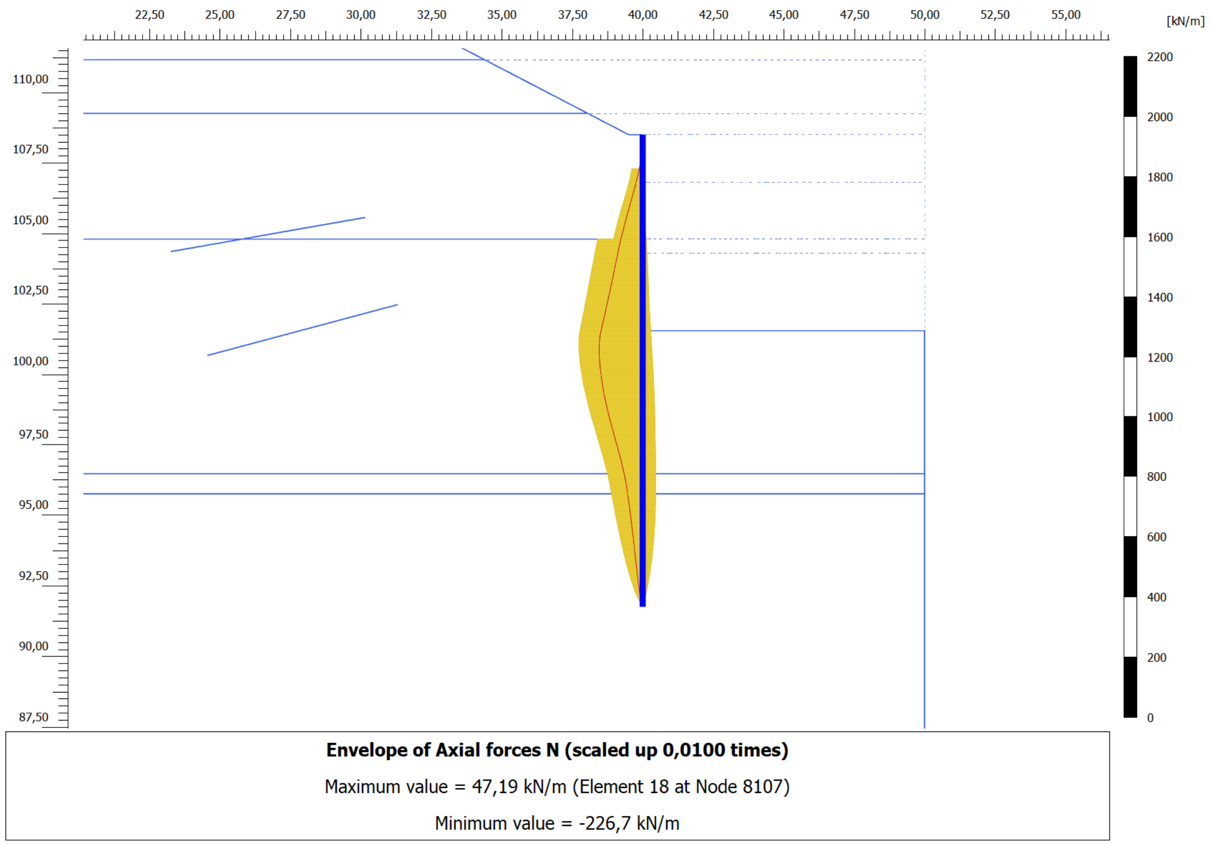

Figure 12. Envelope of longitudinal diaphragm forces

Table 8. Actions and displacements of the diaphragm

DIAPHRAGM WALL d = 60 cm	M_{maks}	Q_{maks}	N_{maks}	u_x
	[kNm/m]	[kN/m]	[kN/m]	[cm]
DESIGN SITUATION	Cross section Type 2			
PERMANENT	400,6	200,8	-226,7	2,2
	Cross section Type 1			
PERMANENT	418,8	207,9	-270,6	2,6
	Cross section Type 3			
PERMANENT	275,1	167,2	-230,8	1,4
RELEVANT VALUES	418,8	207,9	-270,6	

4. DISCUSSION AND CONCLUSION

The paper presents an example of a deep excavation support system design in an urban environment. Excavation is being carried out to construct the three underground floors of a commercial-residential building located at 10 Frana Folnegovića Street in the Trnje district of Zagreb, Croatia. The maximum excavation depth is 10.5 meters. During the geotechnical investigation, the groundwater level is determined at a depth of 5.8 m. Since the excavation is carried out in soil of high hydraulic conductivity, one of the selected support system's essential features was ensuring the execution of construction works in dry conditions. Considering relevant factors, a concrete diaphragm wall with a width of 60 cm and lengths of 17 and 18.25 m was selected as an excavation support system. Due to the different conditions in proximity to existing buildings, three types of cross-sections were chosen, shown in **Figures 4, 5** and **6**. The diaphragm wall ends in a layer of highly plastic clay (CH), reducing groundwater inflow into the construction pit. In addition, a system of drainage trenches and wells is planned at the bottom of the pit. The diaphragm wall is supported by two rows of geotechnical anchors. The length of the anchors in the upper row is 17 m (10+7), and in the lower row is 16 m (9+7). Geotechnical analyzes were carried out using the commercial geotechnical software Plaxis 2D. The results of geotechnical analyses are shown in **Figures 8-12**. Based on these results, the diaphragm wall reinforcement and geotechnical anchors are dimensioned, which is not shown in this paper. However, as the deep excavation is carried out in an urban environment, potential deviations in the behaviour of the diaphragm wall could threaten the stability of neighbouring buildings. For this reason, continuously monitoring the diaphragm's wall displacements is necessary. The purpose of monitoring is the confirmation of design assumptions and the possibility of interventions if there are more significant deviations than anticipated. The project includes the monitoring activities:

- monitoring the diaphragm wall movement using inclinometers,
- monitoring displacements of the header beam.

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