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Lecture Notes in Civil Engineering

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Geotechnical Conditions for Construction of Savski Trg Metro Station as a Part of the Belgrade Metro Line One

Nemanja Stanic, Dragoslav Rakic, Josip Isek, and Slavoljub Simic

Abstract In order to solve serious traffic congestion in Belgrade, a number of studies regarding the Belgrade Metro construction have been carried out since 1973. However, only in 2019, the routes of the future metro lines 1 and 2 were defined as a part of the General Metro Construction Project. The lines are designed to intersect at the location of Sava Square, where an interchange metro station will be built. It represents a complex geotechnical structure consisting of three different parts: a part of the metro station for line 1, a part of the metro station for line 2, and a common part for both metro lines. Due to the complexity of construction and different depths of the diaphragm walls, deeper than 40 m on the part of metro line 2, phased construction is planned. In this regard, determination of geotechnical modeling for each part separately as well as geotechnical design are presented including the analysis of phased methods of excavation, influence of pore and effective stresses on the stability of the diaphragm wall, lateral and vertical displacements as well as the interaction between diaphragm walls and reinforced concrete slabs.

Keywords Metro station · Geotechnical modeling · Displacements

1 Introduction

In order to solve traffic congestion in Belgrade, an approach to provide an underground transportation network by building metro lines has been analyzed for 50 years already. A number of studies regarding the Belgrade Metro construction have been

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carried out since 1973. However, only in 2019, the routes of future lines 1 and 2 in a total length of 42,9 km were defined. The lines are designed to intersect at the location of Savski Trg, where an interchange metro station will be built. The metro station represents a complex geotechnical structure consisting of three different parts: a part of the metro station for line 1, a part of the metro station for line 2, and a common part for both metro lines. The line 1 part and the common part will have three reinforced concrete slabs that provide constant support to reinforced D-walls, whereas the line 2 part will have four reinforced concrete slabs.

2 Determination of Geotechnical Parameters for the Ground Model Design

In order to determine geological conditions and develop geotechnical model for Savski Trg metro station, a considerable number of field and laboratory investigations were performed in 2021 and 2022. The field investigations in combination with laboratory testing were carried out in a narrow area of the future metro station, see Table 1.

The following engineering-geological units were discovered to a depth of approximately 55 m in the investigations on the site: the Middle and the Upper Miocene sediments, the Quaternary sediments, and recent anthropogenic deposits. The Middle Miocene sediments $\left(M_2^2\right)$ are comprised of the Badenian limestones, whereas the Upper Miocene is made up of the Sarmatian organogenic limestones and marly limestones $\left(M_3^1\right)$ and the Pannonian gray marls and marly clays $\left(M_3^2\right)$. In the Quaternary sediments (Q_2), riverbed facies sediments (coarse-grained sediments represented by sands and clayey gravelly sands—ak^{p}, ak^{ppr}, $ak^{pš}$ in a regular alternation with younger fine-grained sediments of silty sands and silty clays), floodplain facies

Table 1 Geotechnical investigations on the site of future Savski Trg metro station

Investigation	Line 1 (2021)	Line 2 (2022)
Engineering-geological mapping	Engineering-geological map 1: 2000	Engineering-geological map 1: 2000
Exploratory drilling	5 Exploratory boreholes in a total length of 183 m	2 Exploratory boreholes in a total length of 94 m
Piezometer boreholes	2 Piezometer boreholes 91,5 m	1 Piezometer borehole 47 m
SPT test	18 Tests	9 Tests
CPT test	3 Tests	2 Tests
Geophysical survey	Seismic refraction survey—Rp profile in a length of 150 m	/
Laboratory geomechanical testing	26 Soil samples 17 Rock samples	13 Soil samples

(these sediments comprise of gray-brown and gray clays and silty to sandy clays—ap^g, ap^{pg}, whereas, in the upper portions, the organic content gives them gray tint indicating the presence of marsh deposit from the oxbow lake facies—am). The anthropogenic (manmade) deposits lie on the surface of the entire investigated site, with a thickness of 5,5 m at the location of the future metro station (fill material—n^{pr} is composed of sandy clay and sand mixed with other construction material such as stone, brick, concrete, slag, etc.). The characteristic geological cross section (stratigraphic column) on the site of future Savski Trg metro station is depicted in Fig. 1. The results of laboratory and field penetration tests (cone—CPT and standard—SPT penetration tests) were used to determine physical and mechanical parameters for geotechnical modeling. The results clearly indicate the best rock mass quality in 25–35 m depth intervals, the Sarmatian organogenic limestones were discovered in the investigations.

Excavation will mostly involve the Sarmatian sediments given that the proposed solution to the retaining system provides for the retaining structure depth of less than 50 m in relation to the surface of the ground. The summary of particular physical and mechanical parameters for the rock masses and soil obtained from laboratory testing is provided in Fig. 2. Undrained shear strength from SPT tests resulted from $c_u = fN$, where f is dependent on the soil type and ranges from 2 to 17,5 [3, 4], whereas undrained shear strength cohesion from CPT tests resulted from $c_u = q_{c,net}/N_{kt}$ ($N_{kt} = 8$–20) for poorly consolidated clays that is, $N_{kt} > 20$ for hard and overconsolidated clays [1, 2]. The parameters enabled application of the Hoek–Brown constitutive model to the rocks, whereas the hardening Soil constitutive model was used to define

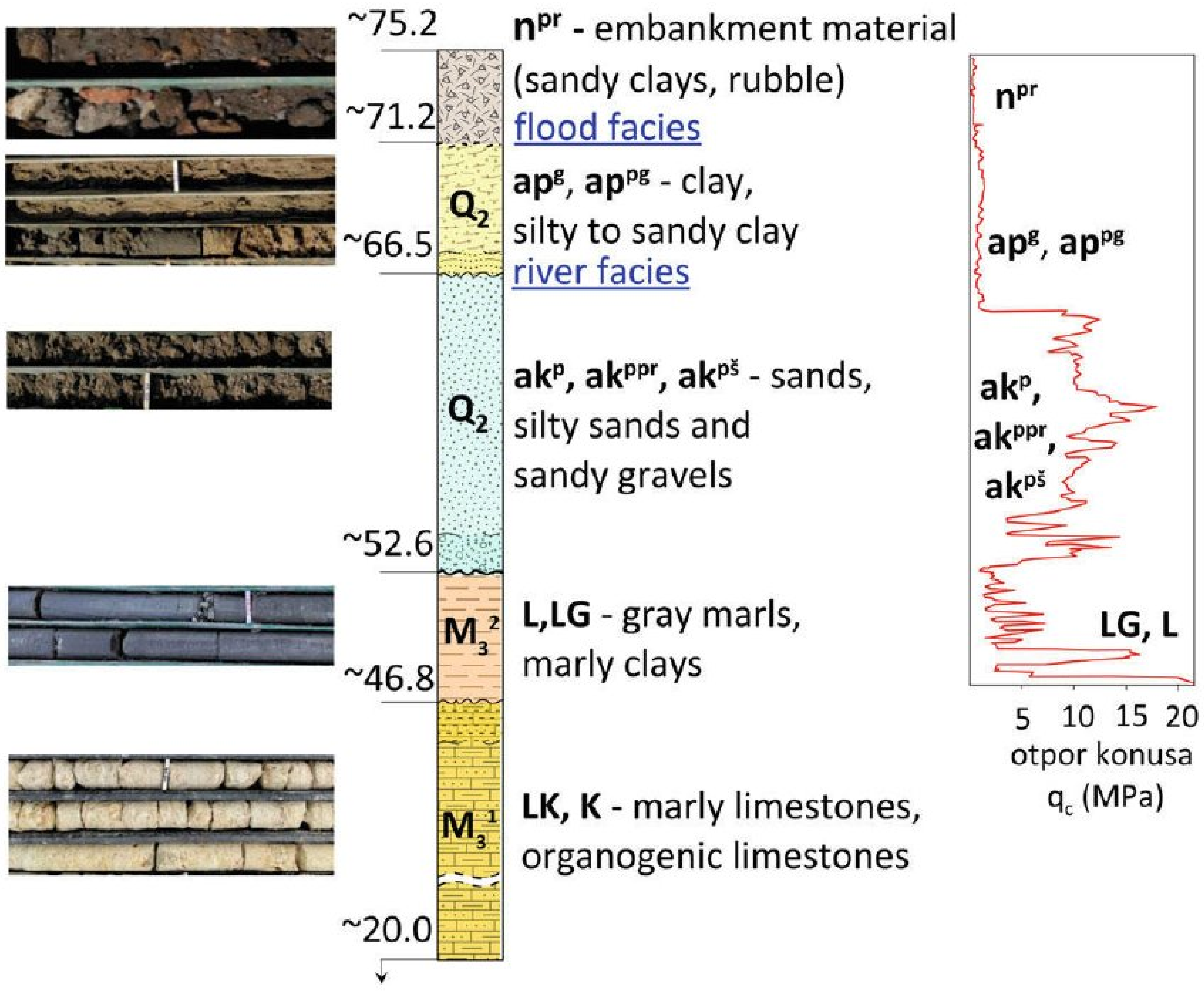

Fig. 1 Stratigraphic column with the cores on the site of future Savski Trg metro station

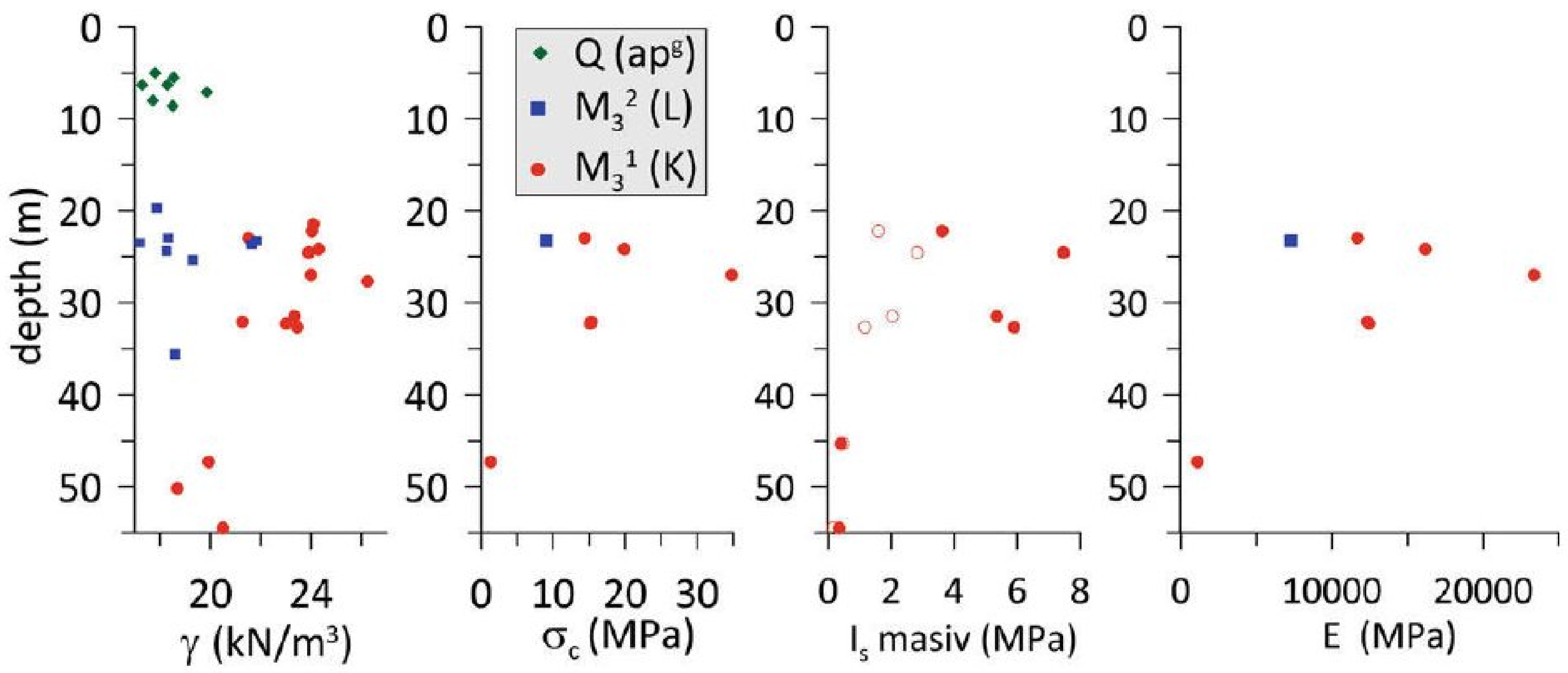

Fig. 2 Particular parameters for soil and rocks obtained from laboratory testing

Table 2 Adopted values of physical and mechanical parameters

Lithological Unit	γ(kN/m^3)	c'(kN/m^2)	φ'(^{0})	ν	E'$_{load}$/E'$_{unload}$ (MPa)	k_f(m/day)
Soil parameters						
Fill-**n**$^{\mathbf{pr}}$	19	15	18	0,3	12/36	0,432
Floodplain silty clays-**ap**$^{\mathbf{g}}$	19	20	20	0,3	5/15	0,00388
Riverbed sands-**ak**$^{\mathbf{p}}$	18,5	0	33	0,28	35/105	1,728
Pannonian gray marls-**L**	18,5	100	20	0,28	65/195	0,0000864

Rock parameters

	γ(kN/m^3)	σ'_{ci}(MPa)	m_i	GSI	ν	E'$_{rm}$ (MPa)	k_f(m/day)
Sarmatian organogenic limestones-**K**	22,5	11	11	33	0,28	350	0,6048

parameters for other units. The adopted values of physical and mechanical parameters for the identified units are provided in Table 2.

3 Geotechnical Analysis of the Metro Station Construction

Given the complexity of the structure, the metro station will be constructed in phases. The first phase involves construction of reinforced concrete diaphragm walls in the structural sections within lines 1 and 2.

Excavation and construction phases in a shallow part of the station intended for line 1 will follow. The final construction phase for shallow station sections will involve construction of the common section (shallow box).

The geotechnical analyses involved the three characteristic cross sections. Cross section A-A corresponds to line 1 box and a shallow common box. Cross sections B-B and C-C correspond to line 2 box and the common box of both lines, respectively (Fig. 3). It should be noted that all three structural units are supported by diaphragm walls of different depths: $H_A = 28.2$ m, $H_B = 45$ m, $H_C = 20.2$ m that also have RC slabs which also provide permanent support of the D-walls. Raft, bottom and top intermediate, and roof RC slabs are 0.9–1.4 m, 0.9 m, and 1.3 m thick, respectively.

Plaxis 2D Ultimate software was used in the geotechnical analyses. In the analyses, each phase was assigned a time interval ranging from min. 2 to max. 1895 days that is, until completion of the consolidation process. Since the stress condition from each stage of analysis was applied in the following stage, stress and strain changes were progressively added. The A-A cross section was analyzed by applying *bottom-up* method of construction (18 phases for L1 and 14 phases for CS). The B-B cross section was analyzed by applying *top-down* method of construction. The C-C cross section was analyzed in eight construction phases, four for each part of the structure. The construction phases involved diaphragm wall construction, groundwater lowering, excavation methods at various depths, strut installations, RC concourse, raft, and roof slab construction. In Fig. 4, the A-A geotechnical cross-sectional numerical model with displacements after the final phase of excavation for the line 1 box that is, the shallow common section for both lines is depicted. Similar modeling was also made for B-B and C-C geotechnical cross sections.

The allowable displacements of diaphragm walls were predetermined, up to 15 mm and 30 mm at the D-wall top and middle sections, respectively. Maximum horizontal displacements at the D-wall top for both structural elements of lines 1 and 2 are within the allowable range (Fig. 5), whereas maximum horizontal displacements in the middle section of the line 2 left diaphragm wall are slightly larger than the allowable range and equal 31 mm.

The analyses demonstrate that the values of bending moments and lateral forces are lower than the maximum acceptable values for each geometry analyzed. Passive earth pressure at the constrained part of the diaphragm wall was determined by

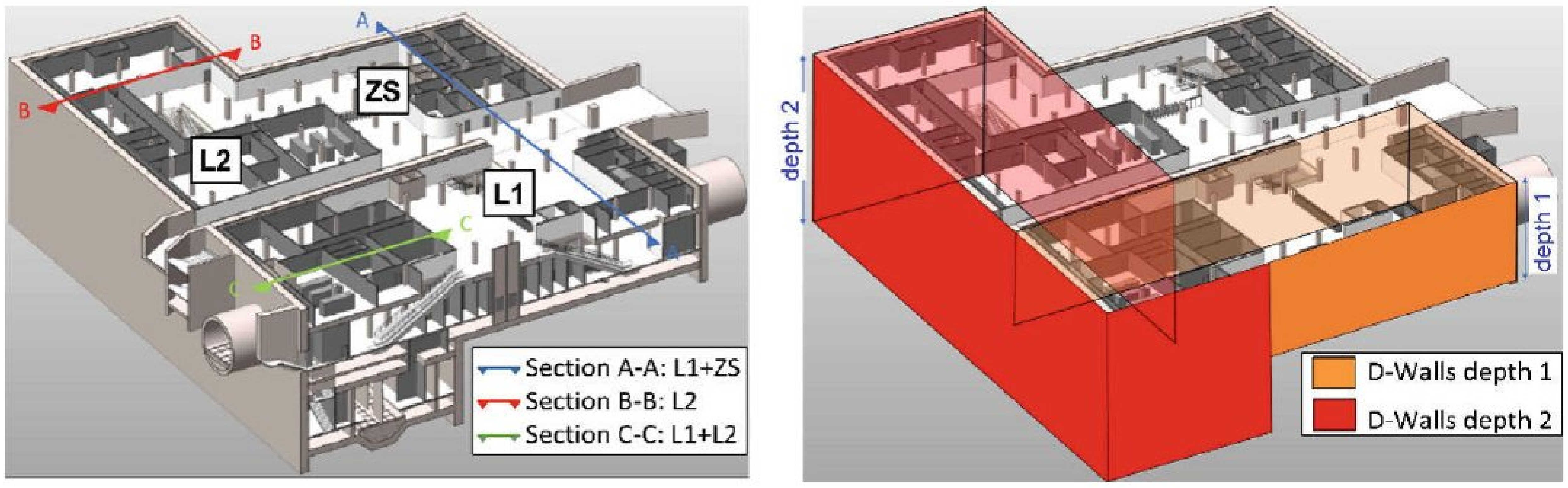

Fig. 3 Characteristic cross sections in the geotechnical analyses

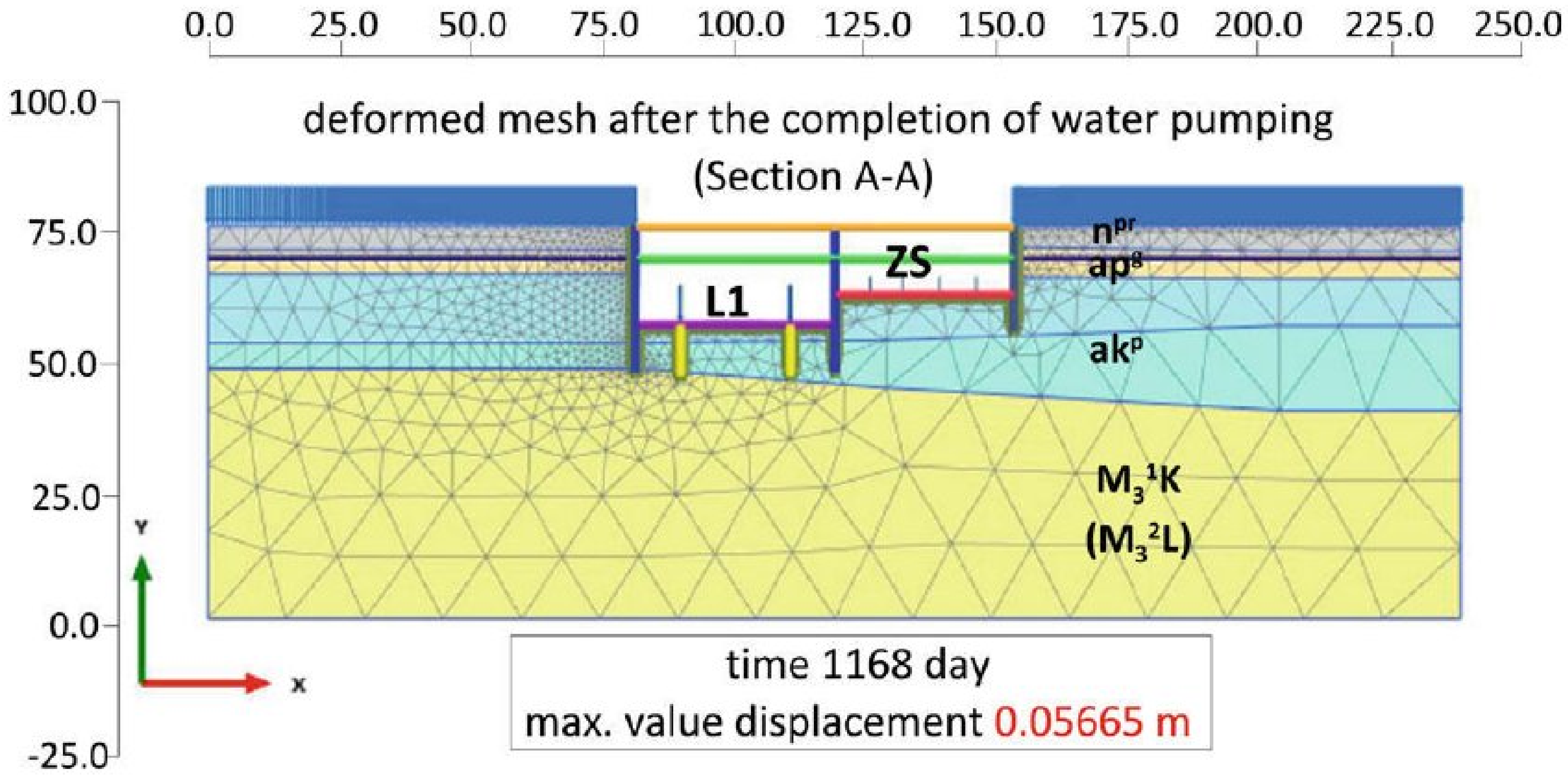

Fig. 4 Deformed mesh after the final phase of excavation for line 1 and the shallow common line 1 and line 2 box

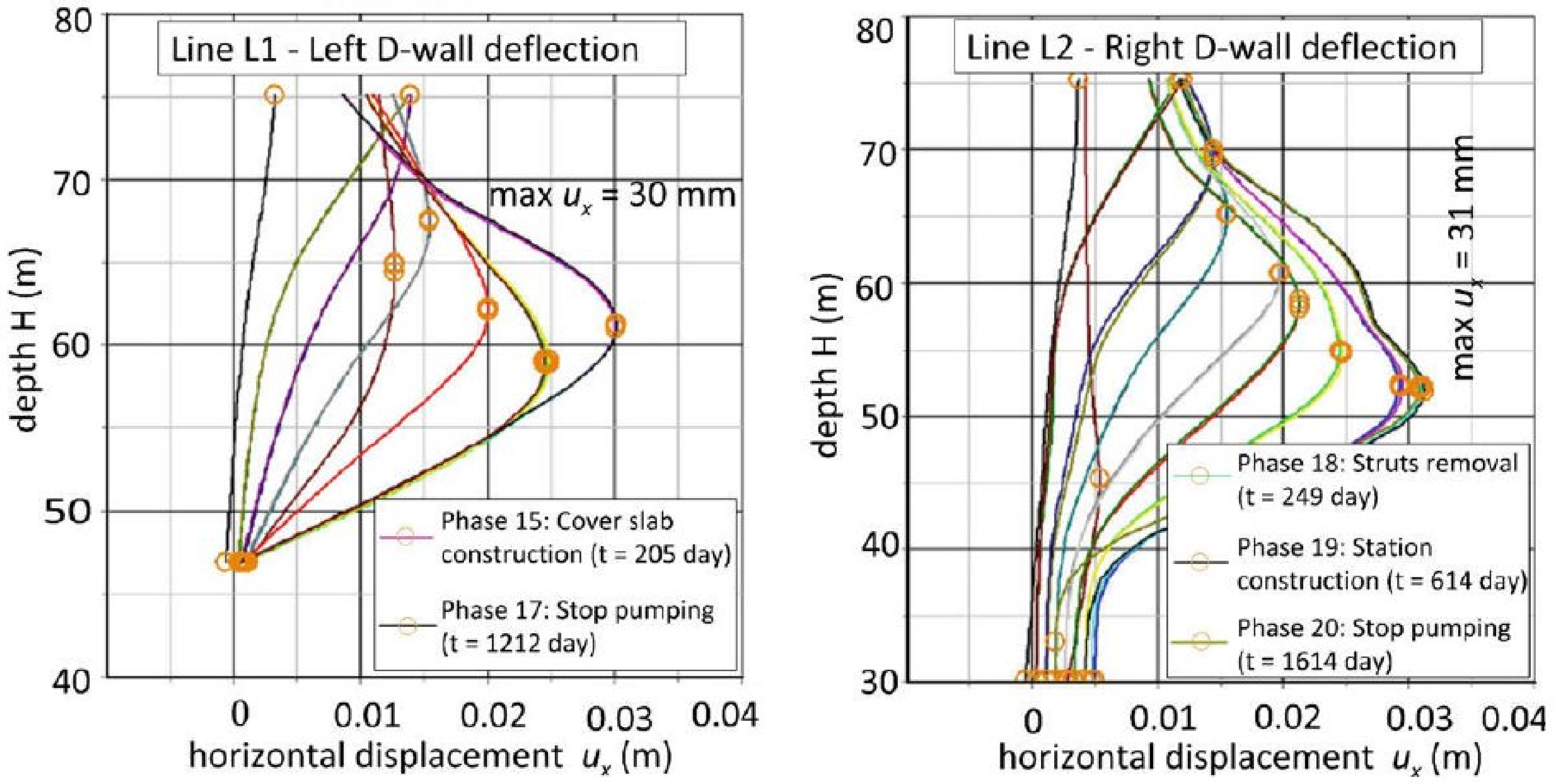

Fig. 5 Lateral deflections of D-wall at various stages for line 1 and line 2 box

using the Caqout and Kérisel theory also recommended in SRPS EN 1997-1, for the horizontal surface of the ground behind the D-wall ($\beta = 0$). The value of $\delta = 2/3\varphi'$ for the friction angle at the contact of the diaphragm wall and soil was taken into account in determination of the passive pressure coefficient K_p. The analyses verified the diaphragm wall stability because the obtained values of the factor of safety were much higher than the allowable ones ($F_s > 1.4$). Summary of the verification results for the analyzed cross sections is represented in Table 3.

The modeling design and the analysis results are provided in Table 4, where it can be seen that the D-wall overall stability was also met.

Table 3 Verification results for lateral earth pressure (GEO)

Lateral earth pressures	Line L1: A-A cross section		Line L2: B-B cross section
	Diaphragm wall	Shallow box	
E_a (kN)	2208	975,7	4592
E_p (kN)	3831	2087	20470
F_s	1,74	2,14	4,46

Table 4 Verification results for the overall stability of retaining structures for L1: A-A cross section

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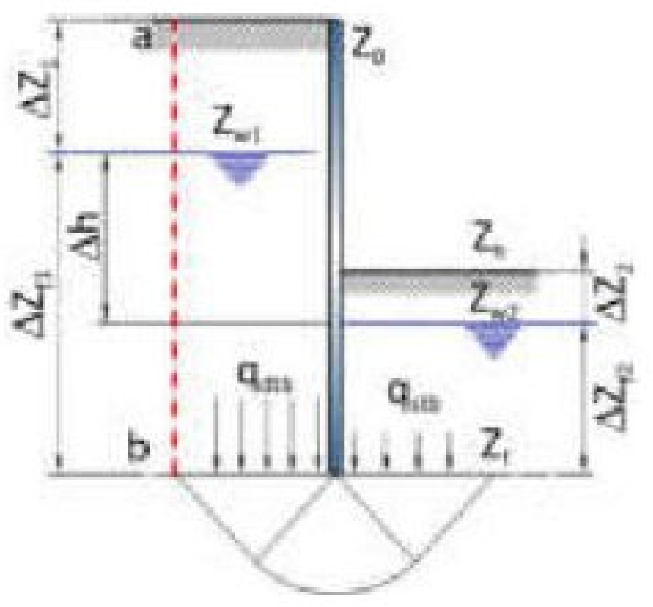
<tr><td rowspan="6">
</td><td colspan="3">D-wall stability verification—L1</td></tr>
<tr><td>q_{stb} (kPa)</td><td>q_{dst} (kPa)</td><td>F_s</td></tr>
<tr><td>1473</td><td>761,4</td><td>1,93</td></tr>
<tr><td colspan="3">Shallow box stability verification—ZS</td></tr>
<tr><td>1427</td><td>545,4</td><td>2,62</td></tr>
</table>

4 Conclusion

The results of the numerical analysis indicate the following construction methods can be used with the designed retaining system for future metro station Savski Trg: *top-down* method for line 2 structure and *bottom-up* method for line 1 structure and the shallow common line 1 and line 2 structure. The numerical analyses show that it is reasonable to use the designed retaining system, and that the structural elements meet the required criteria with regard to lateral and vertical displacements, bearing capacity, and stability.

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