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Finite Element Analysis of Microtunneling Under a Railway Track

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Abstract. Microtunneling is a trenchless construction method used to install pipelines beneath highways, railroads, runways, harbors, rivers, and environmentally sensitive areas. For railway lines, the primary objective of the method is to address the challenges posed by the installation of utilities without disrupting rail operations. The aim is to minimize the impact on railway services, ensuring the uninterrupted flow of transportation while facilitating essential infrastructure development. Traditional excavation methods often involve significant ground disturbance and pose risks to the stability of the railway track, leading to service interruptions and safety hazards. Microtunneling, on the other hand, offers a non-disruptive alternative by utilizing advanced tunneling equipment that minimizes ground settlement and vibration, reducing the risk of damage to the railway structure. The technique involves the use of remotely controlled boring machines to excavate tunnels with precision, allowing for the installation of pipelines or other utilities with minimal impact on the railway infrastructure above. The aim is to achieve a seamless integration of new underground utilities while maintaining the structural integrity and operational functionality of the railway line. Furthermore, microtunneling under a railway line contributes to sustainable development by minimizing the environmental footprint associated with construction activities. The reduced excavation and disturbance to the surrounding environment lead to lower levels of noise, dust, and disruption, aligning with modern principles of environmentally conscious infrastructure development. In this study, the installation of a sewage pipeline constructed by microtunneling under an existing railway track is investigated using geotechnical and structural FEM.

Keywords. Microtunnelling, railway track, finite element method, pipeline

1. Introduction

In recent years, the population increase and the growth of cities, have resulted in the expansion of roads, metro systems, trains, communication networks, and oil and gas pipelines. Construction projects like pipes and metro systems near railway tracks poses a significant safety risk to the railroads [1-2]. The traditional method of open trenching is very time-consuming and disruptive. Moreover, it requires a large workforce and creates safety hazards for railway traffic. Nowadays, the installation of pipelines under railways is mostly carried out by trenchless methods [3]. Microtunnelling is employed

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to avoid blocking roads and railways [4]. Microtunneling is a technique used for constructing tunnels under obstacles like railway tracks. It involves creating small-diameter tunnels without disturbing the surface above it [5]. Installing sewage pipes under railway tracks is a complex project because any disturbances in the track lead to disruption of railway operations and pose safety risks. Therefore, using microtunneling provides a good solution by being able to install sewage pipes without affecting the railway's functionality [6].

In the microtunneling work, microtunnel boring machines (MTBM) are used to install pipelines and dig tunnels with minimal damage to the surface [7-9]. MTBM is controlled remotely to enable it to penetrate the soil safely. It is usually work directed using a laser with other guidance systems to help excavate tunnel diameters. The working mechanism depends on the principle of jacking or pushing, where the tunnel is excavated, and at the same time the pipe is pushing behind it, thus reducing damage and maintaining soil stability [10]. Many studies have been conducted on the use of Microtunneling. Al-Maamori et al. studied the impact of time-dependent deformation on microtunneling in Queenston shale using finite element analysis. Their findings reveal the significance of time-lapse in controlling deformations and stresses [11]. Vakili et al. studied proposed a novel approach using slurry shield microtunneling technology to rectify tilted structures, efficiently mitigating structural settlement. Their findings offering valuable guidance for implementation by designers, owners, and contractors [12]. Sheil et al. introduced a Bayesian method to estimate jacking forces during microtunneling. Their study results show the superiority of Bayesian predictions over traditional methods like genetic algorithms, highlighting the importance of robust back-analysis techniques in capturing complex geotechnical conditions during tunnelling [13]. Alzabeebee and Keawsawasvong studied how microtunneling affects pavement settlement. Their results show that traffic load and microtunnel diameter significantly impact settlement [14]. Tyagi et al. used microtunneling method in the interceptor sewer project aimed at intercepting wastewater and conveying it to the nearest treatment plant. The project employs microtunneling due to its ease of construction and minimal disruption to the public and adjacent properties [15].

Recent literature confirms the importance of microtunneling as an efficient solution for underground infrastructure installation, such as sewer and water pipelines, utility conduits, and transportation infrastructure. The method used has several advantages over the traditional solution (trenching):

- minimal traffic disruption,
- trenchless technology eliminates the consolidation; additional railway track maintenance does not arise,
- the loads acting on the pipe are more favorable,
- smaller internal forces arise in the tube,
- reduced likelihood of pipe failure.

In this study, geotechnical and structural finite element modeling are employed to simulate and analyze the pipeline constructed under an existing railway track.

2. Project description and site condition

In the Danube-Tisza Interfluve, warm arid and warm-temperate arid climatic conditions exist [16], where from the early 1970s, a continuous, rapid decrease of groundwater level could be detected. To stabilize the ecological water demand, new storage, canals, construction and demolition of structures, and construction of standpipes have become necessary.

One segment of the complex project includes the construction of two parallel standpipes, DNA800 and DNA1200. These standpipes cross the railway line no 145. The material of the standpipes is HOBAS SN 100000, and the proposed operating pressure is 6 bar. The construction technology used for the standpipes was microtunneling, a trenchless excavation technique. The conduction length under the railway line is 20 m, and the lower part of the standpipes is 5.21 m, measured from the surface. The thickness of the soil above the pipes is 3.49 m for the larger pipe and 3.98 m for the smaller pipe. The distance between the shafts of the two tunneling pipes is 5.0 m.

Two geotechnical drillings were performed to investigate the site conditions around the existing railway line. The borehole samples were tested to determine the grain-size distribution curve, the Atterberg limits, the layers' shear strength, and the oedometric modulus. Based on the laboratory test results, the surface is covered by sand and silty sand, and the thickness of the coarse-grained material is 2.9 m. Below the sand layers, silt settled with a thickness of 1.1 m, and low plasticity clay was found up to 10 m below the surface. The properties of the soil layers are summarized in Table 1.

Table 1. Soil properties

parameters		1 – Sand	2 – silty Sand	3 –Silt	4 –Clay
γ_{unsat}	kN/m^3	17.0	18.0	19.0	17.0
γ_{sat}	kN/m^3	19.0	20.0	21.0	19.0
e_0	-	0.6	0.5	0.7	0.8
E_{50}^{ref}	MPa	15.0	14.0	10.0	5.6
E_{oed}^{ref}	MPa	15.0	14.0	10.0	5.0
E_{ur}^{ref}	MPa	45.0	42.0	35.0	22.4
m	-	0.5	0.5	0.7	0.8
G_0^{ref}	MPa	60.0	45.0	40.0	30.0
$\gamma_{0,7}$	-	8.0E-5	8.5E-5	2.0E-4	3.0E-4
c'_{ref}	kPa	1.0	5.0	20.0	15.0
φ'_{ref}	deg	29.0	27.0	19.0	14.0
ψ	deg	0.0	0.0	0.0	0.0

3. Methodology – PLAXIS 2D

The output of the geotechnical finite element software results is the characteristic values of the structures' stresses. The partial factor is applied to obtain the design value of the stresses. However, the characteristic values of the stresses determined by the software include permanent and temporary actions. Determining the design value would have to be separated, but this is not possible in finite element modeling. Considering that most actions are due to permanent loads (e.g., earth pressure), the γ_E=1.40 partial factor is typically used as an approximation between γ_G=1.35 for permanent loads and γ_Q=1.50 for temporary loads.

Regarding the limit state of serviceability, the deformations and displacements of the structures have to be analyzed; it has to be shown that their magnitude and differences do not block the structure's serviceability. A linear elastic model describes the standpipe elements installed by microtunneling, and the input parameters are summarized in Table 2. The values of the elastic modulus E, the inertia I, and the Poisson ratio ν were taken to be the same as those given by the manufacturer.

Table 2. Input parameters of the structural elements

Parameters			DN800	DN1200
Normal stiffness	EA	kN/m	2.4E+5	3.5E+5
Flexural rigidity	EI	kNm^2/m	6.4E+1	1.74E+2
thickness	d	m	0.056	0.076
Poisson ratio	ν	-	0.30	0.30

The static track load was considered as distributed load in the analysis, p=52 kPa. The dynamic load was determined by the dynamic factor Φ_{dyn} = 1.4, so the dynamic rail load p_{dyn} = 72.8 kPa was considered.

The following stages of the construction were applied:

1) Initial state, the soil environment was undisturbed, but the railtrack load was active due to the operating transportation.

2) Excavation of the soil, subsequently, both the protection pipe and the service pipe elements were installed in one step.

3) Contraction of the tunnel's reinforced concrete wall.

4) Operating condition, the rail load was simulated, considering both static and dynamic loads separately.

Figure 1 illustrates the generated finite element mesh using the geotechnical finite element software. The model contains 206255 nodes, and the average element size is 0.07 m. The model's width is 26 m, and its depth is 10 m.

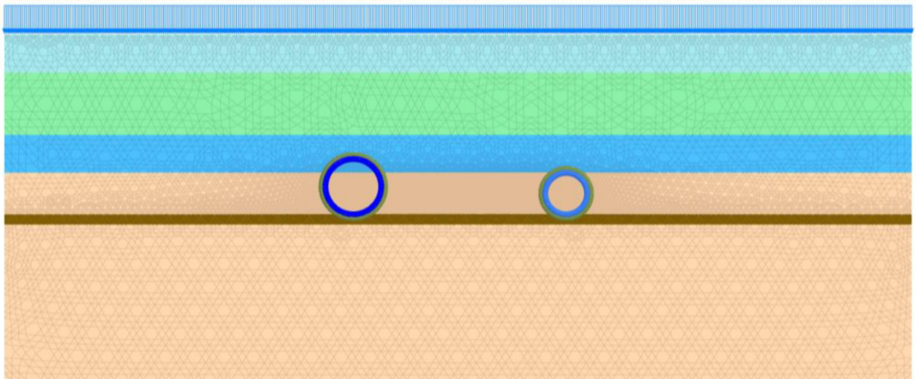

Figure 1. The applied finite element mesh in the initial case (PLAXIS 2D)

4. Methodology – AxisVM

In the structural finite element model, the tube under investigation was constructed from 1D beam elements supported by 2-2 point supports in the vertical and horizontal axes of symmetry. Because of the supports, the 2 points in the vertical axis of symmetry can only displace in the vertical sense, while the 2 points in the horizontal axis can only displace in the horizontal sense. The inclusion of the supports is also necessary to maintain the stability of the model, despite the fact that the loads presented later are in equilibrium by themselves. In all cases, the radius of the pipe is equal to the radius interpreted as half the wall thickness. The material properties summarised in Table 3 were used uniformly in the modelling, while the geometric data specific to the models considered are summarised in Table 4.

Table 3. The applied properties

Parameters			
Elastic modulus	E	N/mm2	11000
Poisson ratio	v	-	0.30

Table 4. Geometrical parameters

	1. case	2. case	3. case	4. case
Outer diameter of pipe [mm]	1229	1229	1720	1720
Pipe wall thickness [mm]	56	56	78	78
Cover [m]	2.84	3.56	3.50	4.00

The track loading was based on the LM71 load model without “destination” factor, which assumes a static load of 52 kN/m^2 on the upper plane of the earthwork. The basic value of the dynamic factor was determined based on a formula typical of carefully maintained tracks, calculated at its maximum value, so that the basic value of the factor is 1.67, reduced according to the degree of covering depth. Knowing the surface load, a stress spread of 2:1 (vertical: horizontal) was used to determine the vertical earth pressure at the top of the pipes under the vehicle load. Considering the vertical vehicle load, the horizontal load on the pipe can also be determined. Based on the manufacturer's structural analysis, the angle of friction of the soil is uniformly 25°, so that a multiplier of 0.58 for the resting earth pressure was considered for all the cases considered. The factor of safety applied to the vehicle load is 1.45 in the ultimate limit state (LM71 load model) and 1.00 in the serviceability limit state. The load was applied in the AxisVM program as a projective distributed load, applied as a predicted load on the quarter of the girder.

The vertical load from the cover, was determined by multiplying the volume weight by two times the cover depth. Based on the manufacturer's structural analysis, the soil bulk density is uniformly 20 kN/m^3. The value of the horizontal earth pressure was given by the product of the cover pressure at pipe height multiplied by the resting earth pressure, which value is constant along the pipe height. The factor of safety applied to the load from the backfill was 1.35 in the ultimate limit state and 1.00 in the serviceability limit state. The load was applied as a projection distributed load in AxisVM X6, applied as a predicted load on the quarter of the support.

5. Results

The geotechnical finite element software, Plaxis 2D, and the structural finite element software, AxisVM were used for the calculations. A comparative analysis with the manufacturer's conventional method was also conducted. Results from different software packages exhibited consistency. Figure 2 shows the total displacements around the pipelines using the geotechnical software. The maximum settlement is s_{max}=2.8 mm and it appears above the larger pipe. Around the smaller pipe, the maximum displacment is s_{max}=2.2 mm. Close to the surface, the displacement is less than $s<1.0$ mm.

The results are summarized in Table 5. PLAXIS 2D indicated the smallest values considering the deformations, and the AxisVM resulted in slightly higher displacements. The difference is likely because the geotechnical finite element software considers the soil-structure interaction, by contrast AxisVM does not. It requires users to apply approximations during model construction and load application. Regarding the maximum normal force, AxisVM displayed ~20% and PLAXIS 2D produced ~30% higher values than the conventional method applied by the manufacturer. Regarding bending moment, the conventional method produced the highest value, AxisVM presented slightly lower values, and PLAXIS 2D software provided values approximately one-third of the others.

A crucial future task is to develop even more precise models, with the ultimate objective of generating 3D models. The work of Ézsiás et al. [17] and Fischer [18] serves as a good foundation for this, particularly in describing the multi-layer fractured structure.

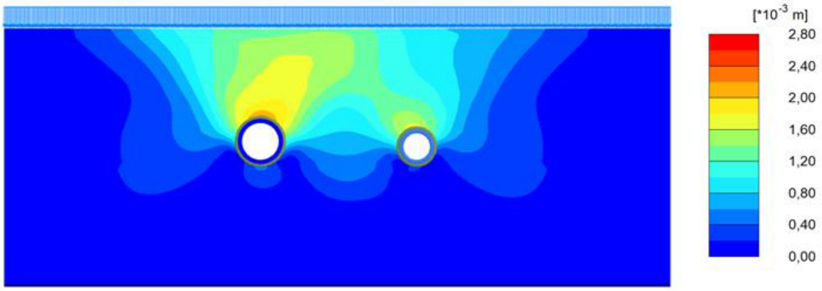

Figure 2. The total displacements of the final stage (PLAXIS 2D)

Table 5. Calculated displacements and internal forces

	PLAXIS	**AxisVM**
max. displacement [mm]	2.8	3.65
max. bending moment [kNm]	3.5	10.16
max. axial forces [kN]	135.5	113.48

6. Conclusions

This study investigates the installation of two parallel pipelines constructed by microtunneling under an existing railway track using geotechnical and structural finite element software. The study was conducted based on soil properties obtained from site investigation. The input parameters of the structural elements were given by the manufacturer. Based on the results of the numerical simulations, it was stated that the geotechnical software produced the smallest displacements; the difference between the Plaxis and AXIS simulations was ~30%. The bending moment obtained from the geotechnical model was approximately one-third of the AXIS model. Related to the maximum normal force, there was a slight difference; the Plaxis model produced the larger value. Based on the analysis, the benefit of the geotechnical model considering the soil-structure interaction was highlighted. A detailed monitoring program during construction would be beneficial to validate the simulations.

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