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Research paper

Longitudinal settlement trough estimation during TBM tunnelling in quaternary deposits

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Abstract: The article presents the spatial issue of the settlement trough estimation above tunnel performed by the mechanized TBM EBP machine. This issue is most often modeled and analysed in the selected 2D cross-sections and spatially interpolated for the entire tunnel section along and across. The authors attempt a broader spatial analysis of monitoring data for a selected monitoring sections of a railway tunnel performed with a large-diameter TBM in a Quaternary deposits with a relatively small overburden of approximately 1D. The paper presents transverse settlement trough in selected monitoring sections and a longitudinal settlement trough above the tunnel axis. The results were analyzed as the percentage of settlements depending on the area of the origin – the front of the TBM, the shield length and the tail zone. Representative results were obtained for consolidated Quaternary deposits.

Keywords: TBM tunnelling, longitudinal settlement trough, geotechnical monitoring, volume loss

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1. Introduction

The analysis of the settlement trough developed over tunnels made by mechanized boring machine is a spatial issue. This phenomenon is most often modeled in the selected 2D cross-sections and spatially interpolated for the entire tunnel section along and across. In the practice of monitoring studies during the construction phase, it is often difficult to obtain a comparable spatial distribution. Typically, the task of the monitoring system is to detect limit values at individual points or, at most, cross-sectional monitoring sections.

In the article, the authors attempted a spatial analysis of monitoring data for a selected greenfield section of a railway tunnel made by a large diameter TBM EPB in Quaternary deposits with a relatively small overburden of approximately 1D. The area of tunnelling works is located in central Poland, in a large urban agglomeration with compact urban development, mostly historical, dating back to the 19th century on the surface. Most of the buildings are in poor technical condition, therefore the correct estimation of settlements is crucial for the safety of the project. Analysis and interpretation of monitoring data for the first phase of tunnel drilling from the greenfield area was carried out, both in cross-sections and in the longitudinal section in the axis of the TBM. On this basis, further scenarios for the development of the settlement trough were forecast. Figure 1 below shows the view of the TBM EPB machine and the basic drilling parameters.

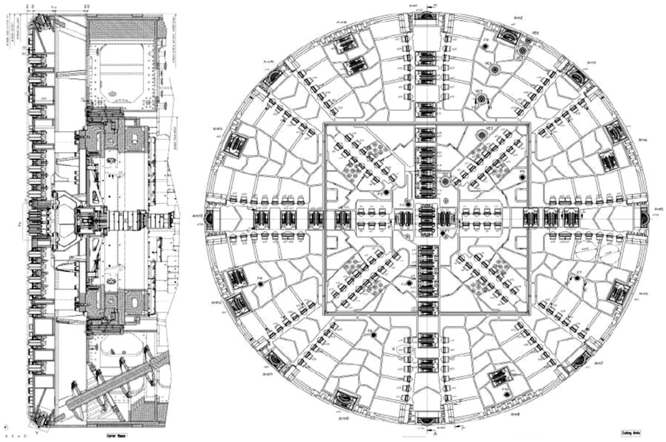

Fig. 1. Front view of the 13 m diameter TBM EPB machine in the Project [3]

In the presented Project [3], a single tunnel with double-track was designed, for which the following parameters of the TBM EPB were applied:

- TBM diameter 13 m
- Internal tunnel diameter 12 m
- Thickness of the tunnel lining 0.5 m
- Length of the shield 11 m
- Max working pressure 3 bar
- Average overburden thickness 14–15 m

The total length of a tunnel bored with such a machine is 2,350 m.

2. Soil conditions

In the presented area, the Quaternary deposits are 40 to 100 m thick series of sandy interstadial sediments and bouldary clay complexes representing successive glaciations. There are Quaternary sediments along the tunnel line, mainly Pleistocene, related to the Central Polish glaciation, and partly Holocene-Pleistocene [3]. Groundwater occurs relatively high level and is partially pressurized by the clay layer. The stabilization level occurs approximately 6 m below the ground surface.

Based on the analysis of the results of geotechnical investigation, geotechnical cross-sections were separated in each monitoring section. Below are presented two selected monitoring sections 1 and 2, for which the subsoil contains: I – man-made embankments, II – upper sand deposits (MSa, siSa, FSa), III – intermediate bouldary clay deposits type A (sisaCl, sasiCl, siCl+co), IV – lower sand deposits (MSa, CSa). Below, in Fig. 2, the arrangement of layers for both selected cross-sections, level of tunnel works and the designation of each type of the material are presented. For each layer, the design geotechnical parameters for the Hardening Soil model with Small Strain Stiffness (HSS), representative for the analyzed tunnel sections, are given in Table 1. In-situ and laboratory tested parameters of each layer were calibrated, with special attention to soil modulus E_{OED}; E_{50}; E_{UR}. The calibration based on the numerical 2D study, for compliance of the calculated settlement trough with the measured one in the monitoring sections, selected for calibration. In the first stage (initial analysis) all the calculations were done with basic in-situ parameters. In the next step, the values of the modules of the dominant geotechnical layer were variants. This was done for layers no. III and IV which are the dominant in the cross-sections where the TBM drives.

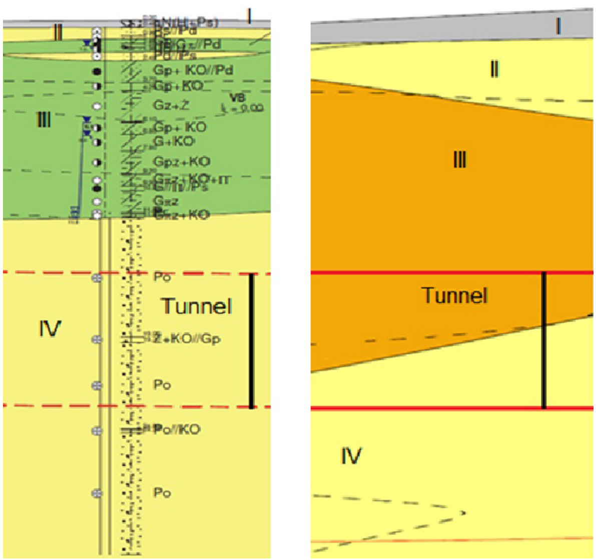

Fig. 2. Geotechnical cross-sections for selected monitoring sections presented in the paper [3]

Table 1. Geotechnical parameters of the presented layers

Soil layer	Bulk density	Poisson ratio	Stiffnes modulus	Oedometer modulus	Unloading-reloading modulus	Lateral pressure coefficient at rest	Effective friction angle	Dilatation angle	Effective cohesion	Over consolidation ratio
	γ	ν	E_{50}^{ref}	E_{oed}	E_{ur}^{ref}	K_0^{nc}	Φ’	ψ	c’	OCR
	kN/m^3	[–]	kPa	kPa	kPa	[–]	[°]	[°]	kN/m^2	[–]
I	18.0	0.2	5509	5509	22040	0.40	19	0	0	1.0
II	18.0	0.2	50000	50000	150000	0.43	35	0	0	1.0
III	21.0	0.2	7968	7968	31870	0.61	23	0	10	1.0
IV	18.5	0.2	58750	58750	176300	0.43	35	0	0	1.0

3. Settlements monitoring outcomes

The analysis of transverse and longitudinal settlements was studied for the first sections of the tunnelling works in the greenfield area. Fig. 3 shows extensive surface monitoring, which consisted of approximately 20 advanced sections. Each section consisted of 8 to 11 surface benchmarks – mirrors on which automatic measurements were performed with an automatic total station instruments [4]. Additionally, manual measurements were carried out for verification purposes of an automatic ones. In selected cases, downhole inclinometers were also installed. Two monitoring sections were selected for the detailed analysis in this article. This sections are marked on Fig. 3 with numbers 1 and 2.

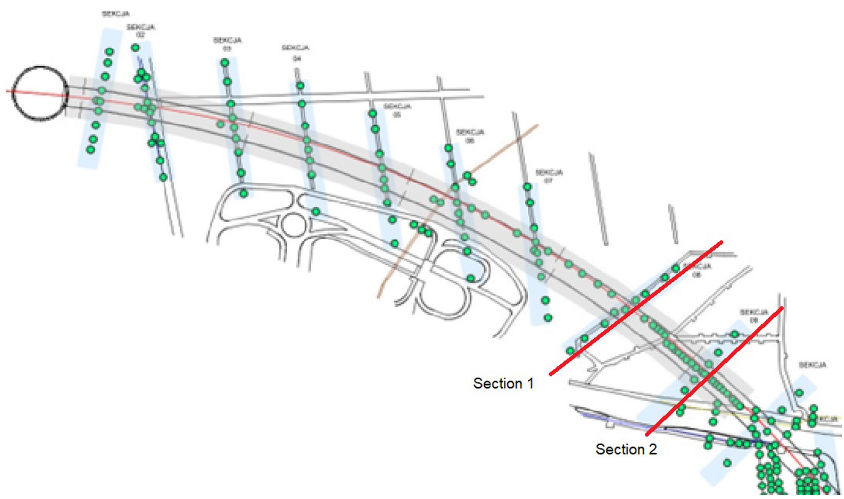

Fig. 3. Monitoring sections and surface monitoring points

Detailed results are presented for selected sections. Fig. 4 and 5 show the development of the transverse settlement trough during TBM tunnelling in section 1, and Fig. 6 and Fig. 7 shows the development of the settlement trough in section 2. Based on the results of the geodetic measurements in the monitoring sections and additionally tachymetric measurements, the following ranges of the maximum depth of the transverse settlement trough were found:

– 8–18 mm in section 2;
– 22–30 mm in section 1.

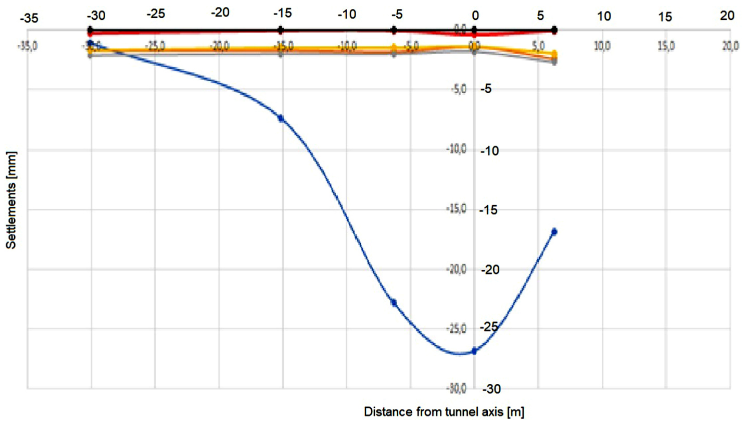

Fig. 4. Settlement trough in monitoring section 1 – manual readings

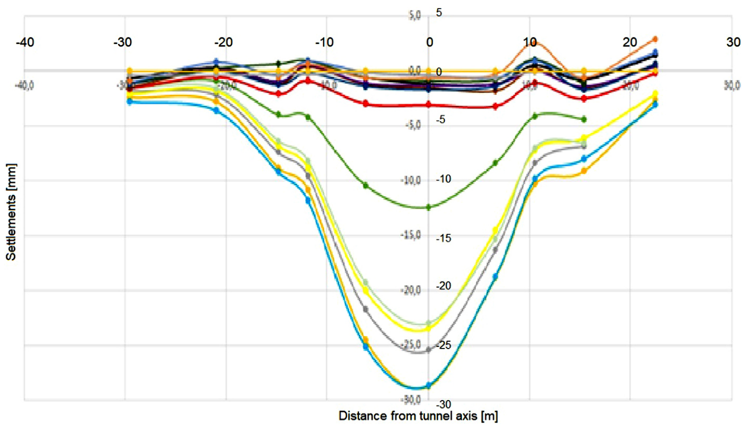

Fig. 5. Settlement trough in monitoring section 1 – automatic total station measurements

Based on the analysis of the settlement trough for each monitoring section, the values of volume loss V_L and the ranges of the transverse settlement trough were determined. This was supplemented by the average value of the K parameter. For the analyzed section 1 – $V_L = 0.51\%$ and $K = 0.38$ with a trough width of approx. 40 m. For the section 2 – $V_L = 0.31\%$ and $K = 0.45$ with a trough width of approx. 50 m.

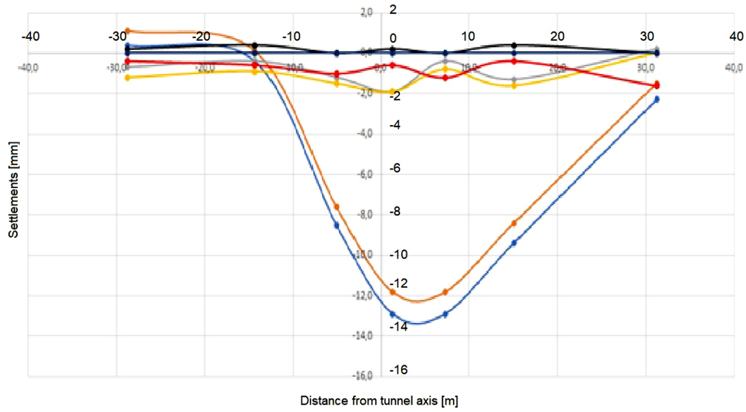

Fig. 6. Settlement trough in monitoring section 2 – manual readings

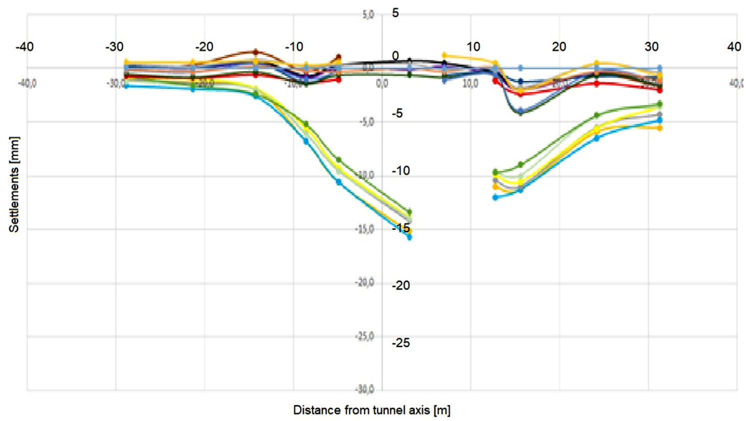

Fig. 7. Settlement trough in monitoring section 2 – automatic total station measurements

4. Longitudinal settlement trough estimation

The analysis of the depth and extent of the transverse settlement trough in the analyzed monitoring sections was supplemented with an analysis of the development of the settlement trough along the tunnel. For this analysis tachymetric measurement points located above the tunnel axis were considered. The values of maximum settlements in the tunnel axis between 5 selected sections were assumed for the analysis. Approx. 30 measurement points located in the tunnel axis were installed between these sections. The maximum settlements diagram along the tunnel axis is shown on Fig. 8.

The analysis of the graph shows that large spatial variations in settlements are obtained in the greenfield area. This depends mainly on the type of deposits in the overburden of the tunnel – a variable sand/clay scheme, with higher settlements occurring in sections with a predominance of sand in the profile. The face support pressure is also important, the underestimation of which significantly affects the amount of settlement. This may also be directly related to the remains of unidentified, historical elements in the ground, which causes unpredictable settlement variability. Changes in the thickness of the overburden related to the morphology of the urban area are also important.

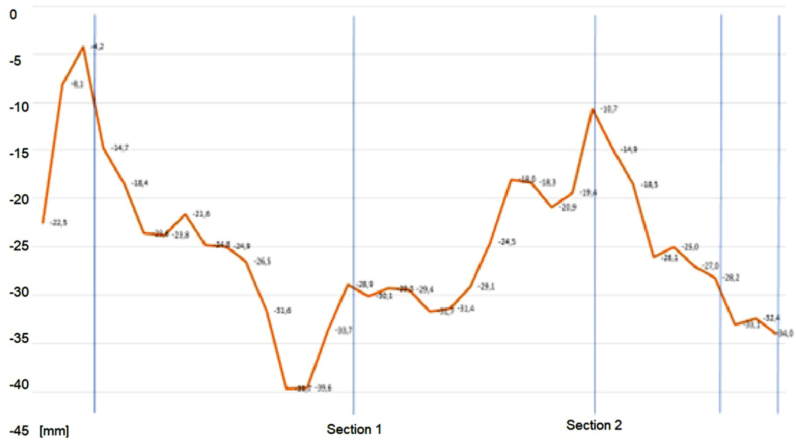

Fig. 8. Longitudinal settlement trough in the axis of tunnel between 5 monitoring sections

Additionally, development of the longitudinal settlement trough in each section was analyzed, considering several factors:

- the date of the cutting head – machine front – passed under each section;
- the date of the TBM tail passed under each section;
- the date of occurrence of the maximum settlement in each monitoring section;
- the final date of the settlement's stabilization in the section.

Tachymetric measurement points located in the axis of the tunnel were selected for detailed analysis and non-average readings were considered. Raw data from the monitoring charts shows Fig. 9 and Fig. 10.

Analyzing the distribution of the settlement trough along the TBM drive, it was found that the maximum value of the settlement is observed not immediately after the TBM machine (head and tail) passes under the measuring section, but after a few or a dozen days after the first measurement in the section. This coincides with the data from the publications of Anagnostou & Kovari [1] and Leca & New [2], who stated that in the case of tunnel works performed with the traditional methods (manual or partially mechanized shields), 70–80% of surface settlements are the result of deformations occurring at the head of the working chamber. In the case of excavations done by mechanized tunnelling, this value drops below 70%, depending on the boring method (Anagnostou & Kovari [1]).

The percentage share in subsidence on the ground surface, depending on the ground disturbance, is on average (Leca & New [2]):

- at the tunnel face 10–20%,
- along the shiel 40–50%,
- in the tail void 30–50%.

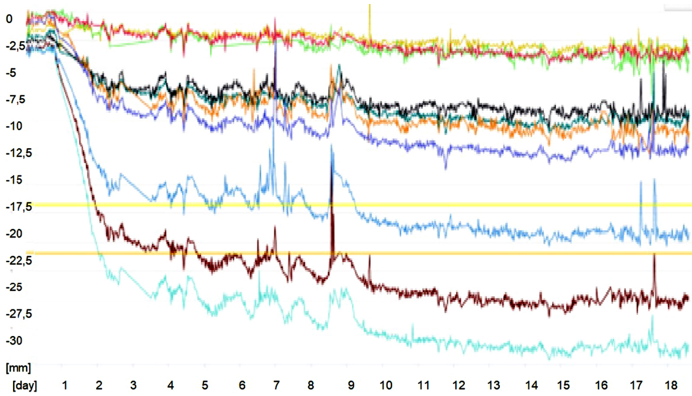

Fig. 9. Longitudinal settlements in time over tunnel axis in the monitoring section 1

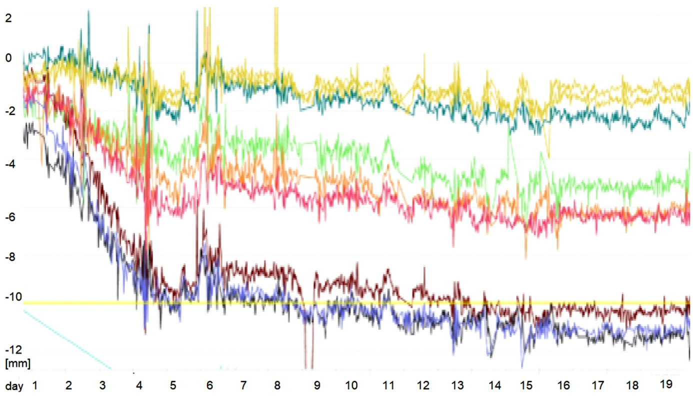

Fig. 10. Longitudinal settlements in time over tunnel axis in the monitoring section 2

In most soils, the amount of settlement at the ground surface is approximately equal to the volume loss of soil at the face. This situation is illustrated on Fig. 11. The summary of settlement in the head, tail and after stabilization is presented in Table 2, and the percentage distribution of settlement values along the shield's path in the axis of the analyzed tunnel is presented in Table 3.

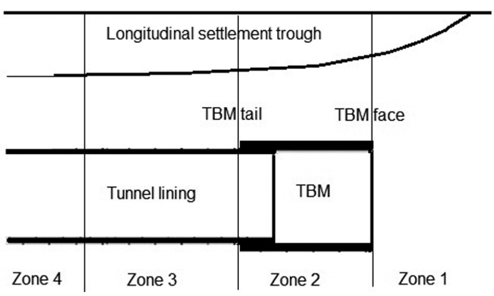

Fig. 11. Longitudinal settlements over tunnel depending on the TBM machine part [2]

Table 2. Settlements comparison for each part of the TBM machine and its position in relation to monitoring sections

TBM position vs monitoring section	**Day/Hour**	**Settlements [mm]**	**Distance of TBM face from the monitoring section [m]**
Section 1			
TBM face – zone 1/2	Day 1 Hour 18.54	–3.2	0
TBM tail – zone 2/3	Day 2	–16.3	11
Max settlements – zone 3	Day 15 Hour 16.08	–29.7	25
Settlements stabilization – zone 4	Day 19	–29.7	61
Section 2			
TBM face – zone 1/2	Day 1 Hour 13.18	–5.6	0
TBM tail – zone 2/3	Day 2 Hour 10.00	–7.1	
Max settlements – zone 3	Day 13 Hour 9.54	–11.4	62
Settlements stabilization – zone 4	Day 18	–11.3	69

Table 3. Percentage of the settlement in the front and tail of the TBM in relation to the max value

Section	**TBM face [mm] [%]**	**TBM tail [mm] [%]**	**Max settlements [mm]**
Section 1	–3.2; 10%	–16.3; 44%	–29.7
Section 2	–5.6; 49%	–7.1; 13%	–11.4

5. Conclusions

The analyzed greenfield area was monitored in the Project by several monitoring sections and a number of benchmarks for tachymetric measurements located in the axis of the TBM tunnel. As a part of the presented results, the transverse settlement trough was analyzed – its depth and range, as well as the longitudinal settlement trough in the selected sections. Based on the arrangement of the monitoring sections in relation to the tunnel (some sections were located obliquely) and the location of measurement points (some points were located on rigid surfaces such as sidewalks or streets), two representative sections are presented in the article. Based on the deformation measurements in the sections, the value of volume loss V_L and the calculation parameter K were determined, resulting from the depth and extent of the trough. Based on the analysis of the measurement results in the analysed sections, the following is stated:

- the settlement values obtained for a TBM shield with a diameter of 13 m in Quaternary soils, with an overburden of approximately 1D, vary from 30 to 40 mm if the machine drives properly (design V_L) and the shield face is sufficiently supported;
- the range of the settlement trough in the analysed sections is approximately 60 m;
- average volume loss V_L values calculated on the basis of the observed settlement trough vary from 0.3% to 0.5%;
- the value of the K parameter determined on the basis of the soil profiles in the monitoring sections, or their vicinity is on average approximately $K = 0.4$;
- settlements along the shield route reached their maximum value when the face of the TBM was located at a distance about 25 m to 60 m behind the monitoring sections, which means that observations of the settlements should be made at least 10 to 15 days after the face of the TBM passes under each section (taking into account possible stops and interventions during this period);
- the percentage of the settlements over the TBM face was about 40% to 60% (only in one section it was 10%), which is consistent with literature data for similar conditions;
- the percentage of the total settlements in the tail of the TBM vary from 13% to 44%;
- the percentage distribution of the settlements in the face and tail of the TBM may indicate too low pressure in the working chamber of the machine and insufficient support of the face in some monitoring sections of the TBM advance;
- while ground conditions change to predominance of non-cohesive soils (mainly sand), the maximum settlements values might be higher;
- with lower values of the soil overburden above the TBM (below 1D), the settlement trough is deeper, which means – while the tunnel grade is made shallower, a greater impact of tunnel works on the ground surface can be expected.

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Analiza rozkładu wzdłużnej niecki osiadania przy drążeniu tunelu tarczą TBM w gruntach czwartorzędowych

Słowa kluczowe: tarcza TBM, niecka osiadań wzdłużnych, monitoring geotechniczny, strata objętości

Streszczenie:

W artykule przedstawiono przestrzenne zagadnienie niecki osiadania nad tunelami drążonymi tarczą zmechanizowaną typu EBP TBM. Zagadnienie to modeluje się najczęściej w wybranych przekrojach poprzecznych 2D i interpoluje przestrzennie dla całego odcinka tunelu wzdłuż i w poprzek. Autorzy podejmują próbę szerszej analizy przestrzennej danych monitoringowych dla wybranego odcinka testowego tunelu kolejowego drążonego tarczą dużej średnicy 13 m w gruntach czwartorzędowych przy stosunkowo małym nadkładzie gruntu wynoszącym ok. 1D. W ramach analizy przedstawia się poprzeczne niecki osiadań w wybranych sekcjach monitoringowych oraz nieckę podłużną nad osią tunelu. Wyniki poddano analizie podziału procentowego osiadań w zależności od miejsca ich powstawania – czoło tarczy, płaszcz, strefa “ogonowa”. Uzyskano wyniki reprezentatywne dla skonsolidowanych gruntów czwartorzędowych.

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