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Research paper

Subsidence trough asymmetry calculations in twin tube TBM tunnelling

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Abstract: The impact of TBM EPB tunnelling was assessed with respect to the observed values of settlements as the results of extensive monitoring system of the subsoil and ground surface. The aim of the analysis using empirical methods was to determine the real scale of impact and to determine the formula for the asymmetric subsidence trough observed during the passage of two TBMs in quaternary cohesive soils. Based on field measurements, authors propose the polynomial formulation for the depth and shape of the asymmetric subsidence trough prediction over twin tube TBM tunnel.

Keywords: TBM tunnel; settlements calculation; subsidence through asymmetry

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1. Introduction

Ground surface settlement is one of the main issues associated with tunnelling in urban areas. The shape of the subsidence trough above tunnel excavations was examined by Schmidt 1969 [20] and Peck 1969 [17] who showed that the Gaussian curve well represents the settlements of the surface. Peck proposed analytical formulation commonly used until today. This formulation was developed by Oteo 1979 [13], Oteo and Sagaseta 1982 [14], Clough and Schmidt 1981 [3], Attewell and Woodman 1982 [1], Verruijt and Booker 1996 [21], Loganathan and Poulos 1998 [8]. They are calibrated on the basis of the measurement data from numerous case studies related to the tunnelling using different type of TBMs Kuszyk and Sieminska-Lewandowska 2018 [6], Mair 2011 [9], [10], O'Reilly 1982 [16], O'Reilly 1988 [15]. Using Peck equation [17] or empirical methods the depth and subsidence trough expansion over single tunnel can be asset. In case of twin tube tunnels the superposition of two single subsidence throughs is the most commonly used solution Leblais et all [7], O'Reilly 1982 [16], ITA-AITES [22]. This results with symmetric subsidence trough over twin tunnels. Moreover, it does not take into consideration the geotechnical conditions, methods of construction and time delay between the construction of each of two tunnel tubes. The theoretical prediction of the ground settlement over twin tube tunnel using empirical methods very often is not validated by field measurements.

The evaluation of tunnelling induced settlements related to TBM tunnelling and the impact on existing buildings and underground infrastructure is the most important aspect of the ongoing TBM tunnelling projects in Poland. The convenience of the Gaussian equation and superposition of two probability distribution single curves used by the designers leads to the predictions that may not be apparent in field data. There is a lack of data base of real values of the depth and expansion of subsidence trough as well as design recommendations dedicated to local quaternary deposits represented by consolidated glacial clays and compacted glacial sands. The ITA-AITES [22] guidelines could be used but should be adapted to the local geotechnical conditions.

Regarding future and ongoing tunnel projects in Poland it is becoming more and more common that twin tunnel construction will be in close proximity to each other. For most of them a time delay of 1 or 2 months will occur between the construction of the first tunnel (TBM1) and the second tunnel (TBM2). The drive of the TBM2 causes ground movements in the soil above the tunnel, which had been already disturbed by the TBM1. As mentioned above, the total settlement profile found by addition of the two curves estimated for single tunnel may not be accurate. In order to validate this hypothesis and to find the most probable formulation for the shape of subsidence trough the extensive monitoring of ground surface over two tube tunnel construction was performed and analysed. The test sections were located in urban area, in typical Quaternary, post-glacial, consolidated deposits of Central Poland. The machine used was 6,5 m diameter EPB TBM. Due to homogenous soil conditions the drive of both TBM machines was not interrupted by maintenance and unexpected stops. The final shape of the ground displacement profile was not disturbed by construction sequences. Based on extensive field measurements, authors propose the polynomial formulation for the depth and shape of the subsidence trough over twin tube tunnel.

2. Settlements monitoring outcomes

The twin tube metro tunnel of total length of 502 m was constructed using EPB TBM of 6.5 m in diameter. The distance between the tunnel axis was about 14,0 m. One 0,3 m thick ring of the segmental lining was composed of 5 segments. The technical data of the EPB machine were as follow:

• Outer diameter of the segmental lining	6,0 m
• Inner diameter of the segmental lining	5,4 m
• Distance between tunnel axis	14 m
• Maximal torque	1,8 ÷ 3,8 MNm
• Face pressure support	2,5 ÷ 3,4 bar
• Cover	5 ÷ 8 m bgl

During the construction stage the monitoring system was designed to check surface displacements during TBM drive [6]. The deformation control system based on:

- devices for deep horizontal deformation measurements (inclinometers INC);
- devices for deep vertical deformation measurements (extensometers EXT);
- ground benchmarks (GP) for surface deformation measurements;
- piezometers (PIEZ) located in saturated soil to control water level changes along tunnels;
- benchmarks, mirrors and crack-meters on the buildings located in the area of the TBM influence for structure control and cracks propagation.

Complete monitoring sections no. D1101 and D1113 for the analyzed metro tunnels were also installed. The scheme of typical monitoring section along metro line presents Fig. 1 [6]. For full section there were installed: 3 inclinometer pipes with electric probes (INC), 2 extensometers with triple rod (EXT), 4 piezometers with Casagrande filter (PIEZ), 5 ÷ 7 ground benchmarks. In the analyzed sections 5 to 7 ground benchmarks were installed. The results of measurements in the form of collective graphs for each of the 8 selected measurement sections no. D1101, D1103, D1104, D1106, D1111 presents Fig. 2-6. The settlements are presented cumulatively from the beginning of the measurements (approx. 2 months in advance in relation to the passage of the TBM1), until the TBM passed and the settlements stabilized (up to approx. 7 ÷ 8 months). The measurements frequencies varied depending on the distance of the TBM face in front of each cross-section and behind.

At each graphs the range of the maximum settlement considering the long-term settlements that occurred is marked with a dashed red line. The axis of symmetry of the metro tunnels was indicated as the reference point (the centre of the graphs), and the minimum values of the settlements are in the axes of each tunnel (TBM1 and TBM2).

In most cross-sections, the development of the subsidence trough increasing over time. The outcomes show the occurrence of settlements over the northern tunnel - right side of the graphs (TBM1 passed first) and then irregular increase in settlements over the south tunnel - left side of the graphs, which was done later (TBM2).

Table 1. Maximum settlements measured for each tunnel in the axis [mm]

Monitoring section	First tunnel TBM1	Second tunnel TBM2
D1101	1,8	2,3
D1103	1,1	4,2
D1104	1,5	7,7
D1106	1,6	6,3
D1111	1,1	8,2

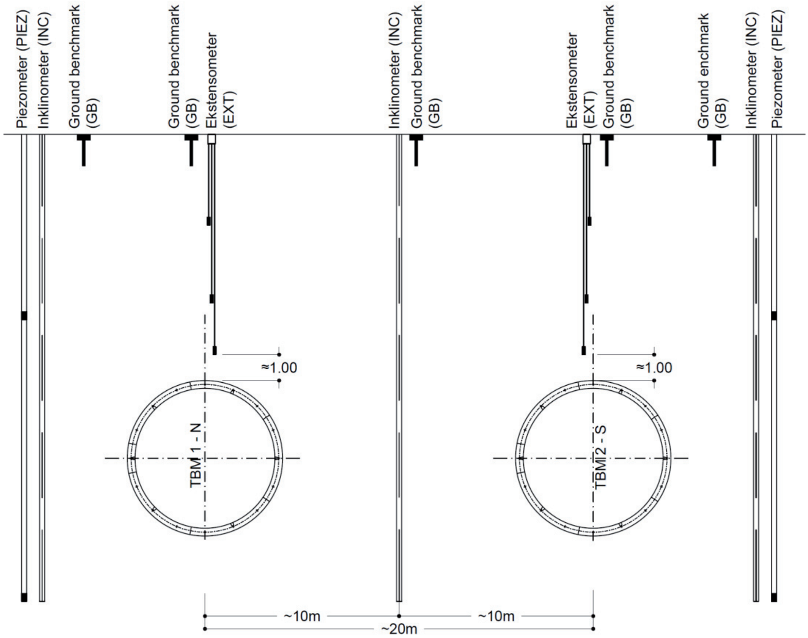

Fig. 1. Typical full monitoring section [6]

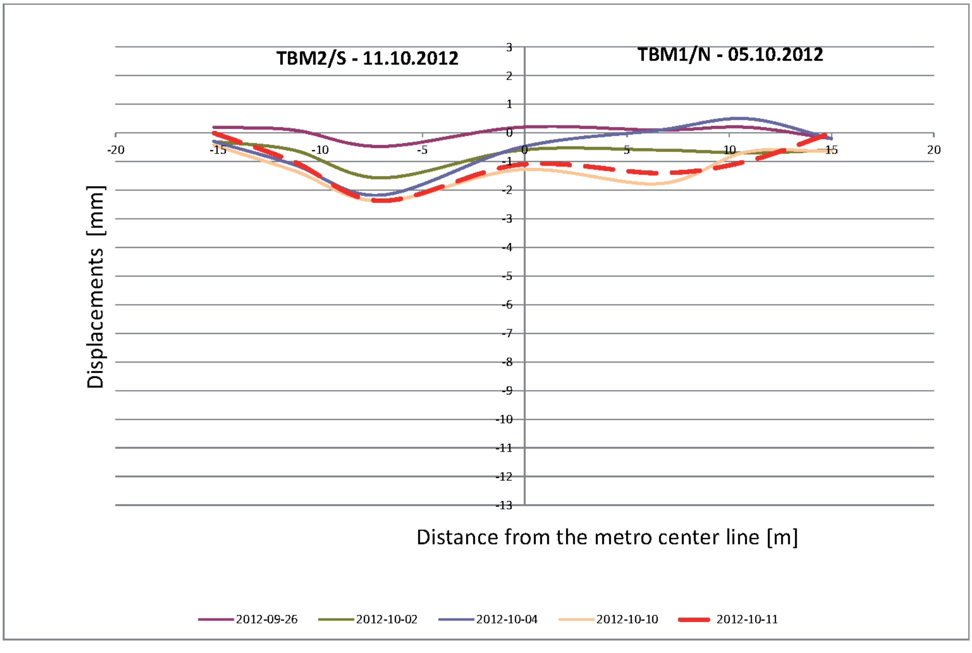

Fig. 2. Monitoring outcomes in section D1101

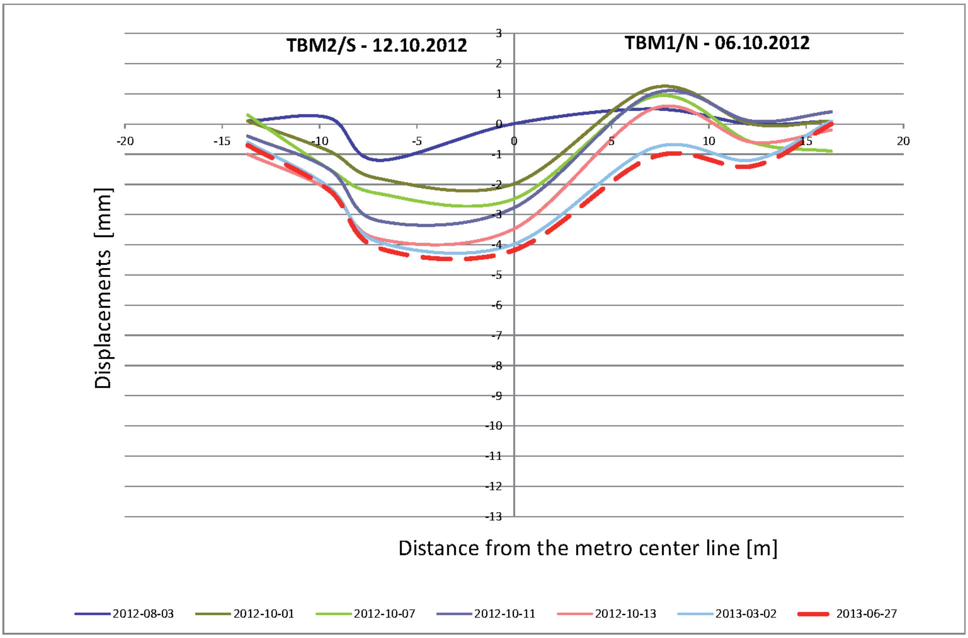

Fig. 3. Monitoring outcomes in section D1103

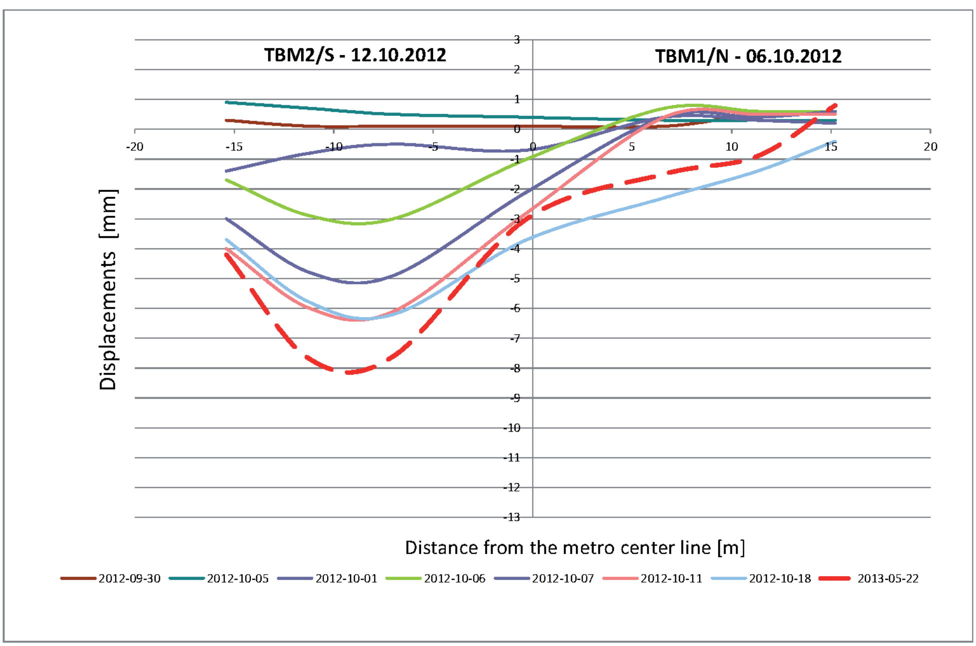

Fig. 4. Monitoring outcomes in section D1104

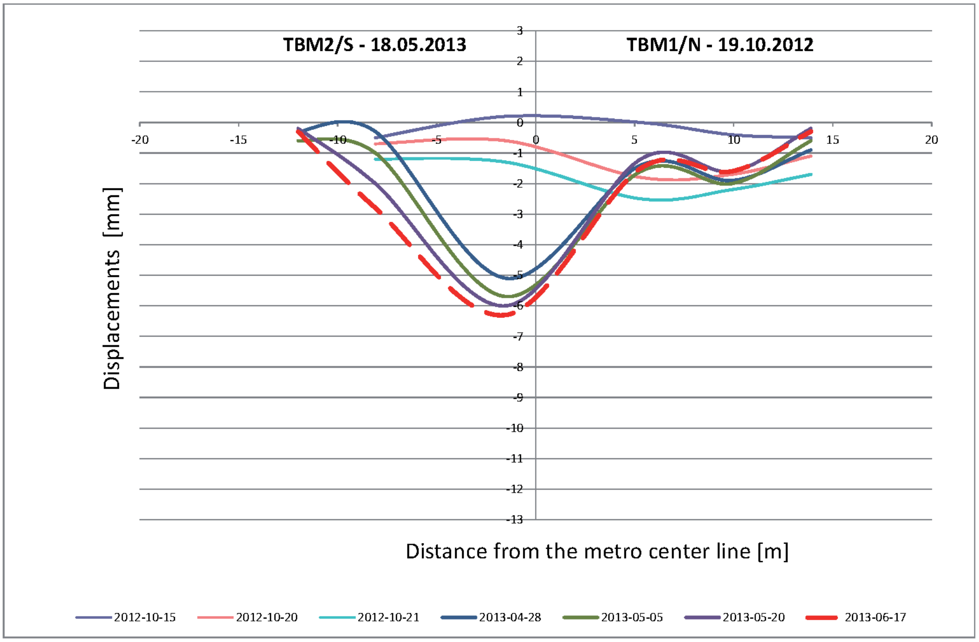

Fig. 5. Monitoring outcomes in section D1106

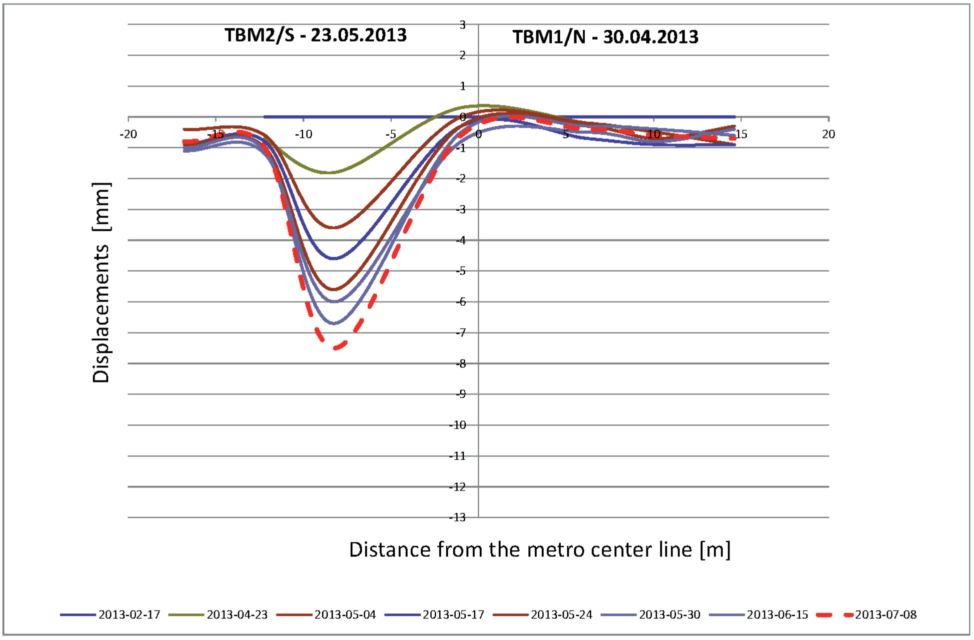

Fig. 6. Monitoring outcomes in section D1111

3. Calculation methodology

3.1. The calculation method description

Based on experimental data, authors present the formula for determining the depth and shape of the subsidence trough over two tunnels made by EPB TBM type (maintaining the technological spacing) in typical Quaternary, post-glacial, consolidated deposits of Central Poland. The formula takes into account the fact that the subsidence trough is not symmetrical and the applied superposition of two single troughs does not reflect the real situation on the ground surface, despite the fact that it is a common design practice resulting from simplifications and the lack of appropriate experimental data. For this study the semi-empirical Oteo method [13], [14] was used, considering the diameter and depth of the tunnel, in which the subsidence trough equation is:

$$s = \Psi \frac{\gamma D^2}{E}(0{,}85 - \nu)\exp\left(\frac{-y^2}{2i^2}\right) \tag{1.3}$$

$$i = \eta\left(0{,}57\frac{H}{D} - 0{,}21\right)D \tag{2.3}$$

where:

Ψ – empirical factor determine by the monitoring observation – 0,4 clay, 0,5 sand, 1,0 manmade deposit [-], D – tunnel diameter [m], η - technological factor dependent on D and H 0,75 ÷ 1,25 [-], H – tunnel depth [m], E – Young modulus [MPa], γ – unit weight [kN/m^3], ν – Poisson ratio [-], y - distance of the considered point from the tunnel axis [m], i - trough width parameter [-], s_{max} – maximal settlements in the axis of the tunnel [m]

Analysing the results of soil displacement measurements on the tunnel sections and partially modifying the Oteo formula for the normal distribution over a single tunnel, authors developed the polynomial formula describing the subsidence trough over twin tube tunnels in the Quaternary postglacial deposits of Warsaw.

The ideal polynomial distribution with characteristic points is presented in Fig. 7. The individual points of the proposed polynomial are described by first and second order derivatives. Derivative of individual characteristic points 1 ÷ 7 of the curve were assigned the corresponding values x and y according to Fig. 7

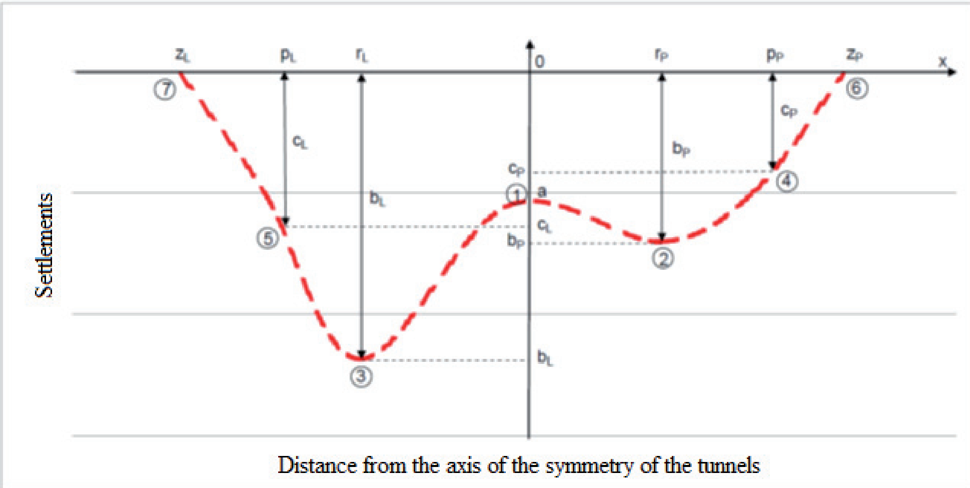

Fig. 7. Polynomial distribution of asymmetric settlements trough for twin tunnels

Below is a list of conditions for each of the 7 characteristic points of the polynomial curve of the settlements distribution:

Point 1 – polynomial maximum:

$$W'(0) = a \qquad W''(0) = 0 \tag{3.3}$$

Point 2 – polynomial minimum:

$$W'(r_P) = b_p = 0{,}5\Psi_P \frac{\gamma_P D^2}{E_{oed}^P}(0{,}85 - \nu_P) \qquad W''(r_P) = 0 \tag{4.3}$$

by Oteo [13] with modification

Point 3 – polynomial minimum:

$$W'(r_L) = b_L = \Psi_L \frac{\gamma_L D^2}{E_{oed}^L}(0{,}85 - \nu_L) \qquad W''(r_L) = 0 \tag{5.3}$$

by Oteo [13] with modification

Point 4 – point of inflection:

$$W'(p_P) = c_p \qquad W''(p_P) = 0 \tag{6.3}$$

Point 5 – point of inflection:

$$W'(p_L) = c_L \qquad W''(p_L) = 0 \tag{7.3}$$

Point 6 – trough limit:

$$W'(z_P) = 0 \qquad (8.3)$$
$$W''(z_P) = 0$$

Point 7 – trough limit:

$$W'(z_L) = 0 \qquad (9.3)$$
$$W''(z_L) = 0$$

where:

r_L i r_P – points located in the axis of each tunnel L - left, P - right; z_L i z_P – range of the subsidence trough [m] – defined observationally $z_L=2r_L$ and $z_P=2r_P$; Ψ – factor depended on the excavated soil and relaxation of the subsoil caused by time delay in the TBM1 and TBM2 pass – defined observationally for glacial deposits $\Psi_p = 0{,}9$ and $\Psi_L = 0{,}7$; D – diameter of the tunnels [m]; γ, ν – soil parameters – weighted average value in the soil profile for each tunnel L and P; E_{oed} – oedometer modulus weighted average value in the soil profile for each tunnel – $E^P_{oed} = E_{oed;UL}$ relaxation modulus from empirical approach $E_{oed;UL} = 3\ E_{oed}$ or extract by laboratory methods or found by backward analysis or from in-situ Menard pressuremeter test or as deformation modulus E extract with small deformations $\varepsilon \leq 0{,}01\%$; c_L, c_P – points of the settlements trough inflection – interpolation or from Mathematica - Interpolating Polynomial: [{{0,-a,0},{r_P,-b_P,0},{r_L,-b_L,0},{p_P,-c_P,Automatic,0},{p_L,-c_L,Automatic,0},{z_P,0,0},{z_L,0,0}}, x]

3.2. The results of calculations

To verify the proposed method, in sections: D1101, D1103, D1104, D1106 and D1111, settlement calculations of the subsidence trough over twin TBM1 and TBM2 tunnels were performed. The polynomial points, marked with a triangles in the figures, were marked on the settlement curve, determined by numerous commonly used empirical methods [1], [2], [3], [6], [8], [12], [13], [17], [18], [19], [21]. The monitoring system and the results of empirical methods calculation were presented in Kuszyk and Sieminska-Lewandowska [6]. There were compared with the results of the measurements on the monitoring sections – dashed line. The graphs on the Fig. 8 ÷ 12 show the results of the calculations in five analysed cross-sections, considering the geotechnical model and soil parameters.

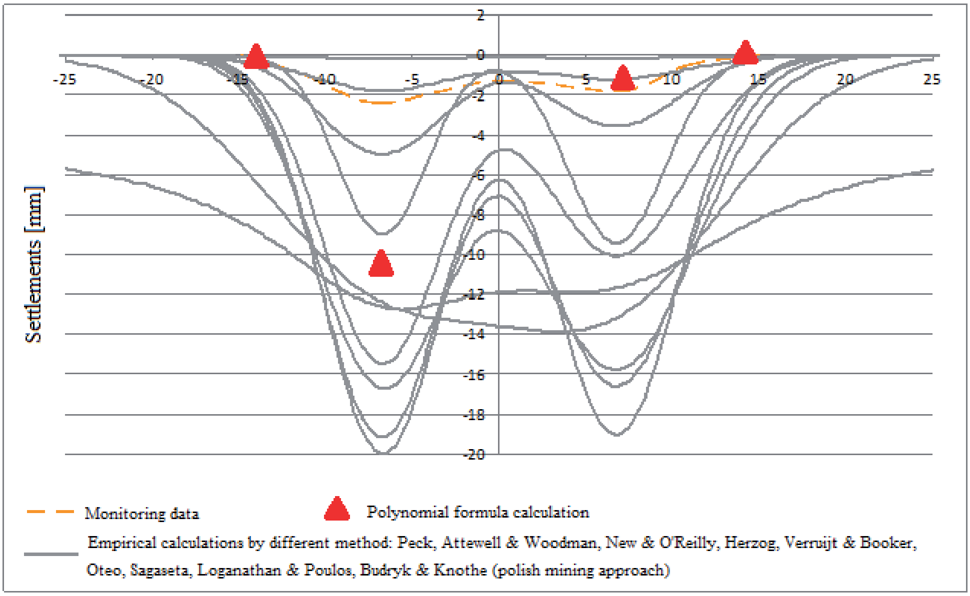

Fig. 8. Calculated deformations by polynomial for twin tunnels in section D1101

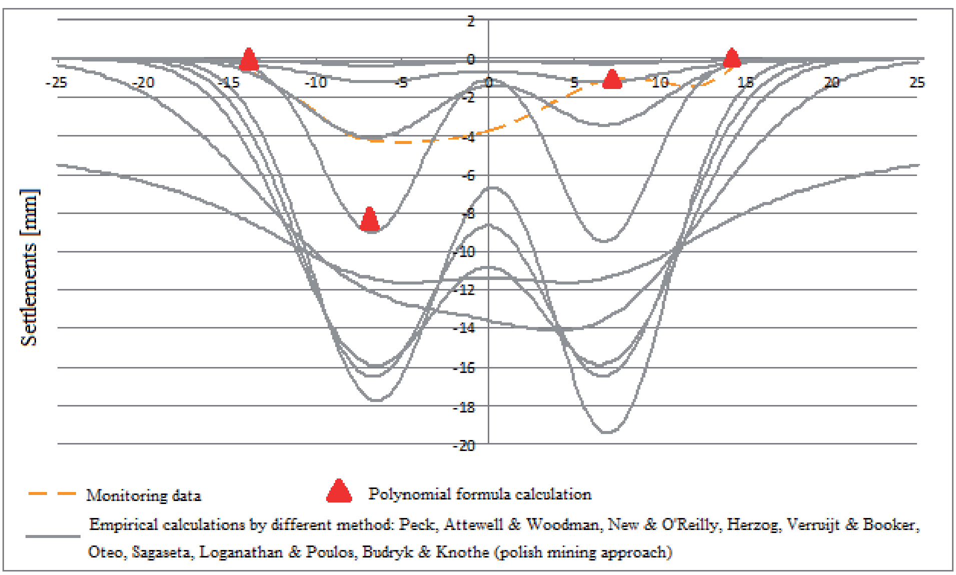

Fig. 9. Calculated deformations by polynomial for twin tunnels in section D1103

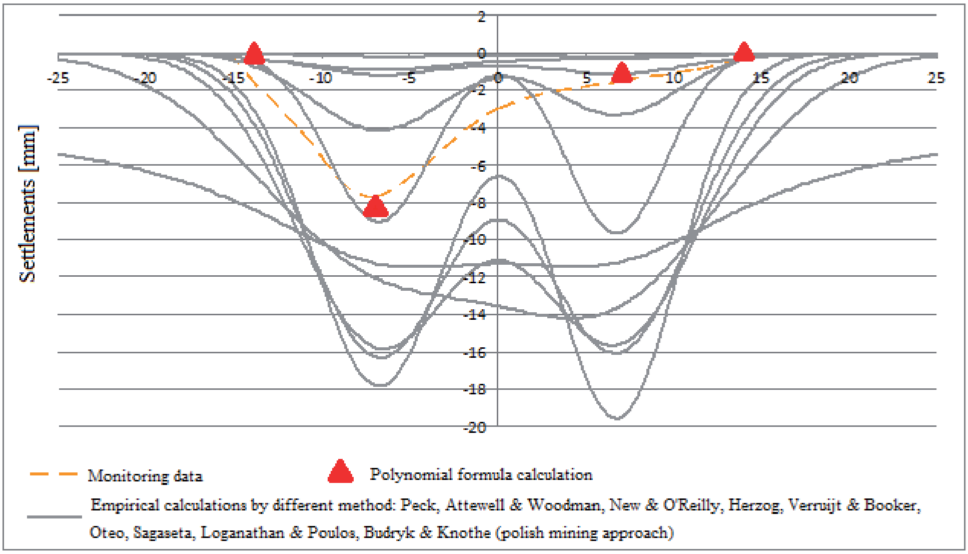

Fig. 10. Calculated deformations by polynomial for twin tunnels in section D1104

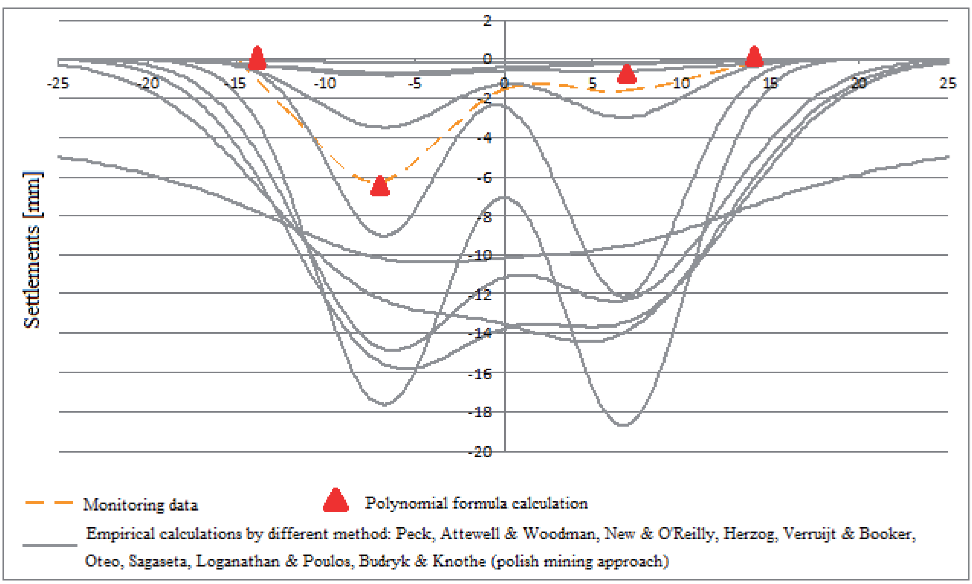

Fig. 11. Calculated deformations by polynomial for twin tunnels in section D1106

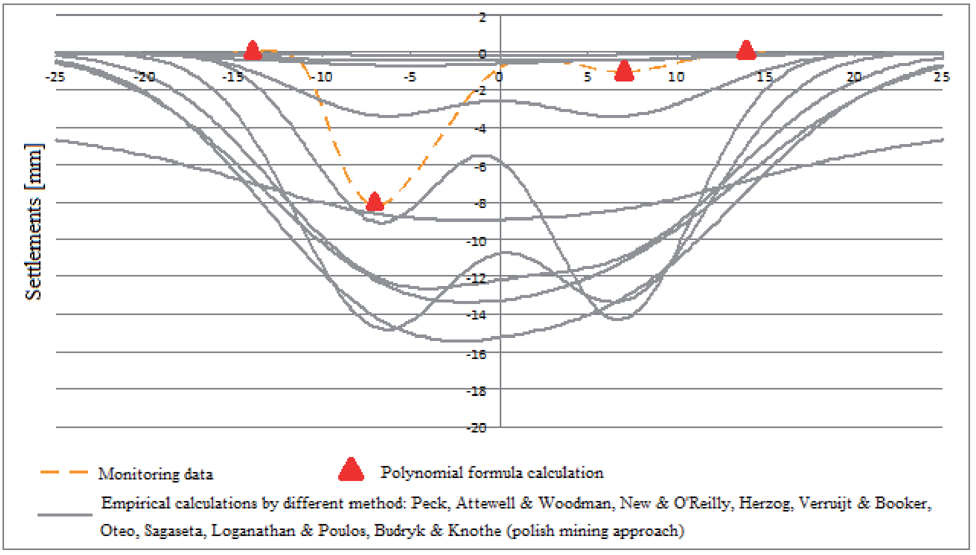

Fig. 12. Calculated deformations by polynomial for twin tunnels in section D1111

As can be seen from the graphs, the results were very convergent, especially in the sections D1104, D1106 and D1111 and partial compliance in sections D1101 and D1103. In each of the analysed cross-sections, both in the real measurements and the empirical calculations done by the proposed polynomial formula, there is an asymmetry of the settlements trough resulting from the time delay of the TBM 1 and TBM 2 drive.

4. Conclusions

Since the empirical formulas given in the literature [22] refer to the determination of the subsidence trough range over a single tunnel, the results were superposed taking into account the distance between two metro tunnels constructed by EPB TBM machine. Authors presented several monitoring sections (D1101, D1103, D1104, D1106 and D1111) due to the relatively homogeneous arrangement of geotechnical layers - Quaternary postglacial cohesive soils. Also, the monitoring outcomes were not disturbed and give image of the shape and extention of the asymmetry of the subsidence trough. Real displacement over first tunnel reaches 0 to 5mm and for second one up to 8mm, range of the settlement trough is about 30m from metro line axis. Analyzing the results of the measurements of ground displacements in the monitored sections and partially modifying the Oteo formula for the normal distribution over a single tunnel, the authors developed the formula of a polynomial describing the settlements trough over twin tunnels constructed by EPB TBM in Quaternary postglacial deposists. This settlements trough created over twin tunnels is not symmetrical, so the superposition of two single troughs resulting from empirical calculations is not always correct and does not reflect the real situation on the ground surface. The passage of the second TBM (with a time and technological delay) causes an increase in settlements in relation to the neighboring trough, already constructed tunnel and gives the final, asymmetrical arrangement of both troughs

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Obliczenia asymetrycznej niecki osiadania nad dwoma tunelami drążonymi tarczą EPB TBM

Słowa kluczowe: tunele metra, obliczanie osiadań, asymetryczna niecka osiadania, tarcza EPB TBM

Streszczenie:

Analiza niecki osiadania nad tunelami drążonymi tarczą TBM jest istotnym elementem oceny oddziaływania robót tunelowych na terenach silnie zurbanizowanych. W obliczeniach niecki wykorzystuje się metody pół-empiryczne, empiryczne i numeryczne weryfikowane doświadczeniami z monitorowania przemieszczeń rzeczywistych obiektów. W praktyce najczęściej stosowane są metody empiryczne, które definiują kształt niecki osiadania nad pojedynczym tunelem jako krzywa Gaussa modyfikowana przez Pecka, Schmidta, O'Reilly, Oteo i innych. W przypadku budowy dwóch tuneli, metodą superpozycji sumuje się krzywe wyznaczone dla pojedynczego tunelu uzyskując symetryczną nieckę osiadania. Działanie takie jest obarczone błędem wynikającym z faktu, że tunele drążone są w odstępie technologicznym oraz czasowym, a budowa pierwszego z nich powoduje zmiany stanu naprężenia w podłożu podczas budowy drugiego tunelu. Potwierdzają to wyniki pomiarów na odcinku doświadczalnym budowanym tarczą EPB TBM w typowych, czwartorzędowych gruntach polodowcowych Polski. W artykule przedstawiono propozycję metody sformułowanej na podstawie modyfikacji wzoru Oteo, uwzględniającej niesymetryczność niecki osiadania. Wyniki obliczeń zaproponowanym wielomianem zostały porównane z wartościami osiadania wyznaczonymi stosowanymi metodami empirycznymi oraz z wynikami pomiarów w skali naturalnej w monitorowanych przekrojach badawczych. Uzyskana zgodność świadczy o przydatności metody w czwartorzędowych gruntach polodowcowych w przypadku drążenia dwóch tuneli metra tarczą EPB TBM.

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