Numerical analysis of the impact of construction of an underground metro line on the urban environment – a case study from the Vistula Valley in Warsaw

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Numeryczna analiza wpływu budowy metra na środowisko zurbanizowane – przykład z Doliny Wisły w Warszawie. Prz. Geol., 64: 219–229.

A b s t r a k t. Budowa tunelu metra w środowisku zurbanizowanym jest złożonym procesem inwestycyjnym, który ma wpływ na istniejącą zabudowę oraz dalszy kierunek zagospodarowania przestrzennego. Artykuł przedstawia analizę wpływu budowy II linii metra na obszar terenu w rejonie Skarpy Warszawskiej. Dla rozwiązania określonego w tytule zadania wykorzystano metodę elementów skończonych (MES). Pierwszym etapem symulacji numerycznych było odtworzenie stanu początkowego, a następnie realizacja południowego tunelu II linii metra. W kolejnym etapie odtworzono wykonanie północnego tunelu metra. Obliczono rozkład naprężeń w podłożu oraz skumulowane osiadania w strefie oddziaływania tuneli metra. W celu weryfikacji poprawności modelu numerycznego, otrzymane wyniki porównano z wynikami geodezyjnego monitoringu. Dzięki przeprowadzonym obliczeniom określono pionowe przemieszczenia budynku, którego fundamenty znajdują się 4,80 m nad tunelem metra. Przemieszczenia te są równe 8 mm w miejscu analizowanego punktu na ścianie budynku. Taka wielkość osiadań nie wpływa ujemnie na stateczność budynku, nie jest naruszony stan nośności. Niemniej jednak może nastąpić obniżenie funkcjonalności budynku, przekroczenie stanu granicznego użytkowalności. W trakcie obliczeń wyznaczono, metodą redukcji parametrów wytrzymałościowych, współczynnik stateczności skarpy (SF = 1,1). Otrzymany wynik świadczy o zagrożeniu procesami geodynamicznymi (tzn. powierzchniowymi ruchami masowymi) i potrzebie prowadzenia stałego monitoringu. Zaprezentowana analiza pokazuje skuteczność MES w analizie wpływu budowy tunelu metra oraz prognozowaniu jego konsekwencji na środowisko zurbanizowane.

Słowa kluczowe: *osiadania, stateczności skarp, obliczenia numeryczne, tunel metra, Skarpa Warszawska*

A b s t r a c t. Underground construction in urban areas is a complex investment, impacting existing buildings. The paper presents a case study of the 2nd metro line, in close proximity to the Warsaw Slope. To analyze the aforementioned issue, the finite element method (FEM) was used. First, the initial state was generated. Next, the southern tunnel of the metro construction was simulated. Then, the northern tunnel of the metro construction numerical model was prepared. Based on this simulations and cumulative settlements of a particular building above the metro were calculated. The results were confirmed by land surveys. The calculations show the maximum vertical displacement of 8 mm below the building's foundations. This value does not affect the stability of the building or the slope nearby. Nevertheless, it can impact serviceability. Such settlements can generate cracks in buildings. Furthermore, the value of the calculated safety factor of the Warsaw Slope in this section is 1.1. Hence, slope changes require continuous observations. The numerical procedures presented show the usefulness of FEM and its suitability for the purposes of building an extension of the 2nd metro line.

Keywords: *settlements, slope stability, numerical calculations, metro tunnel, Warsaw Slope*

The increase in population causes huge changes in the natural environment. Urban development creates urban areas in which natural soil and water conditions are crucial factors in geotechnical engineering. A major aspect of civil engineering in urban areas is underground passenger transport networks. This necessarily interferes with the natural stress state of the soil and induces superficial settlement. Particular problems occur when a tunnel passes beneath a slope and buildings. Overly high values of soil settlement can trigger landslides.

There are mainly two types of soil settlement caused by subway tunnel construction. The first is short-term subsidence caused by moving, i.e., Tunnel Boring Machine (TBM) and the second is long-term due to the consolidation of cohesive soils and creep dependent on the type of soil. Short-term settlements are the most important in the deformation process due to their magnitude (Kuszyk & Siemińska-Lewandowska, 2009). These settlements are caused by the stability of the face, the pace of tunnel construction, installing individual casing rings and then filling cavities between the casing and soil mass (Kuszyk & Siemińska-Lewandowska, 2009). The finite element method (FEM) is used for numerical simulation of settlement and slope stability as well. An example of numerical methods being used to analyze an underground construction is described in an article by Bitetti et al. (2012). For stability analysis, many examples can be found (Kaczyński et al., 2008; Kaczmarczyk et al., 2014; Kaczmarek & Dobak, 2015; Kaczmarek & Popielski, 2015). A number of simulations showed that the important elements of numerical analysis are: exact geometry model and parameterization of soil (Potts & Zdravkoić, 2001). An extensive description of tunnel construction by numerical simulations was published by Potts & Zdravković (2001).

In the article, several Finite Element simulations were presented in reference to the 2nd line of the Warsaw Metro.

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The purpose of this study is to investigate the displacement of a building above the metro and to answer the question if the settlements may impact the stability of the Warsaw Slope, which is situated opposite.The numerical model was created with use of archival electrical tomography results (Kaczmarek et al., 2016), geotechnical report (Wysokiński, 2013) and survey monitoring data concerning the displacements of the ground and the buildings. The actual process of tunnel excavation was simulated in 5 construction stages.

SITE DESCRIPTION

The area subject to research is located in the Powiśle district of Warsaw, between two metro stations: Nowy Świat – Uniwersytet Station and Centrum Nauki Kopernik Station (Fig. 1). The numerical analysis concerns the area of 6 Dynasy Street. Within this region, the multi-story buildings and a section of the Warsaw Slope are potentially at risk. Furthermore, the Warsaw Slope, which may be affected in the event of major settlements, is located in close proximity. The slope is one of the characteristic morphological elements of the Warsaw landscape. It is a natural border between the plateau and the Vistula River Valley. In the urban area of interest, a newly built subway tunnels pass beneath the slope and then eastwards 4.8 m below the foundation of the building. The analyzed section of the underground is part of the central section of the 2nd metro line. The construction of the 2nd metro line began on 16.08.2010 and ended on 03.08.2015. The current length of the underground section is 6.1 km, with seven metro stations.

Settlement analysis was performed in a cross-section perpendicular to the subway tunnels and parallel to the slope edge. The other cross-section used for the analysis of the slope stability was made parallel to the metro tunnels (Fig. 2).

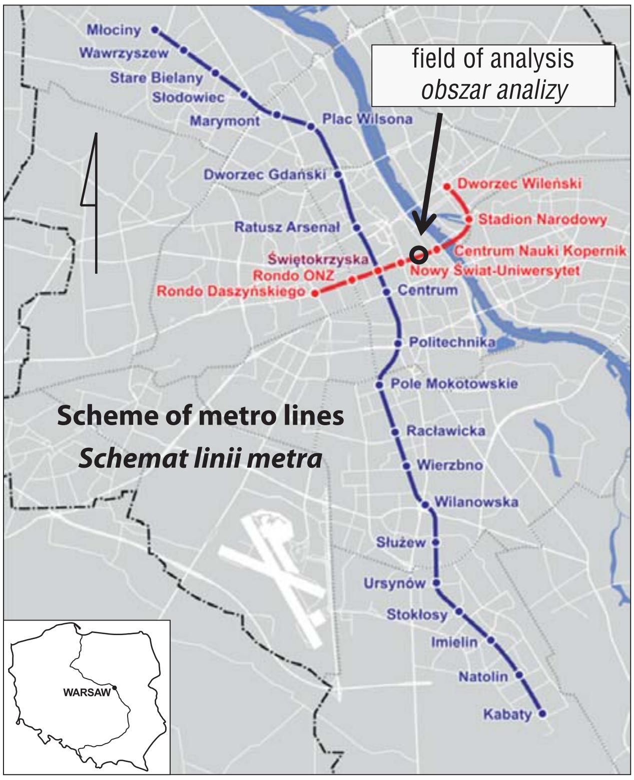

Fig. 1. Location of the research area (www.ztm.waw.pl)
Ryc. 1. Lokalizacja obszaru badań (www.ztm.waw.pl)

Fig. 2. Location of numerical simulation sections and underground tunnels
Ryc. 2. Lokalizacja przekrojów obliczeniowych oraz tuneli metra

The building, which is located approx. 4.8 m above the metro tunnels, has four floors above ground and one basement level. The foundations consist of unreinforced concrete set in fill which overlies river deposits and Mio-Pliocene clays. The top of the foundations is approximately 3.7 m below ground level. As part of the 2nd line project, two running tunnels were excavated under the corner and center of the building. First, the southern tunnel of the metro was constructed and then the northern tunnel. The metro tunnels intersects three layers with its foundations in Mio-Pliocene clay.

The crown of the analyzed slope is part of the moraine plateau. Both the crown and the foot of the slope consist of various soil types. The geometry of the slope was obtained from survey measurements (Kaczmarek et al., 2016). Trigonometric levelling, using Leica TA30 robotic total station, helped to determine the height of the slope (approx. 17.5 m) and its inclination (approx. 36°). The geological model was prepared using archival materials (Wysokiński 1999, 2013). The continuity of soil layers in the geological model was determined by electrical resistivity tomography (Kaczmarek et al. 2016).

The complex soil profile indicates eight distinct layers: the upper several-meter-thick layer consists of clayey sand. In the crown under this layer, there is a 1.0-m-thick tills layer. Below, there is a several-meter-thick layer of fluvioglacial medium sand. Next, there is a second 10.5-meter-thick tills layer. Subsequently, there is a Mio-Pliocene clay layer, which extends over the entire geological section of the analyzed area. The slope consists of fill near the surface and colluvium below it. In the Vistula Valley there is a fill layer approx. 3 m thick. This layer is used as a foundation layer for the multi-story building at 6 Dynasy Street. Enormously high displacements of this soil may cause damage to the building, which would be highly undesirable. Below, there is a thin layer of fluvial silt and a thin layer of medium sand, and the underlying Mio-Pliocene clay. Silt, sand and clay layers are located in the area where the metro tunnel is constructed. Table 1 shows a comparison of the soil layer parameters. During the calculation the dilation angles of soils were equal 0, according to common approach

Table 1. Comparison of the soil parameters (Dłużewski, 1997; PN/B-03020, 1981; Wysokiński, 2013)
Tab. 1. Zestawienie tabeli parametrów gruntów (Dłużewski, 1997; PN/B-03020, 1981; Wysokiński, 2013)

No. Nr	Layer *Warstwa*	Parameters / *Parametry*					
		Physical *Fizyczne*		Strength *Wytrzymałościowe*		Elastic *Sprężyste*	
		Soil unit weight above phreatic level *Ciężar objętościowy gruntu* γ_{unsat} [kN/m^3]	Soil unit weight below phreatic level *Ciężar objętościowy gruntu w warunkach całkowitego nasycenia wodą* γ_{sat} [kN/m^3]	Friction angle *Kąt tarcia wewnętrznego* φ [°]	Cohesion *Kohezja* c [kPa]	Young's modulus *Moduł Younga* E [MPa]	Poisson's ratio *Współczynnik Poissona* ν [-]
I	fill (clayey sands) *nasyp (piaski gliniaste)*	18.6	21.6	22.1	16.4	80	0.30
II	colluvium (sandy clay) *koluwia (glina piaszczysta)*	20.5	22.0	22.0	9.0	20	0.30
III	silt *mady*	14.3	18.8	36.0	0.1	5	0.40
IV	medium sand *piasek średni*	17.5	19.0	32.0	0.1	100	0.25
V	till (sandy clay) *glina zwałowa (glina piaszczysta)*	22.0	22.5	22.0	20.0	40	0.30
VI	medium sand *piasek średni*	17.8	21.1	38.0	0.1	100	0.25
VII	till (sandy clay) *glina zwałowa (glina piaszczysta)*	19.6	22.3	32.0	16.0	45	0.25
VIII	clay *ił*	20.0	21.0	9.0	30.0	30	0.35

Table 2. Material properties of the plates
Tab. 2. Parametry materiałowe elementów konstrukcyjnych

Plates *Płyty*	Normal stiffness *Sztywność ściskania* *EA* [kN/m]	Flexural rigidity *Sztywność zginania* *EI* [kNm^2/m]	Weight *Ciężar* *w* [kN/m/m]	Poisson's ratio *Współczynnik Poissona* ν [-]
Metro lining *Obudowa metra*	$1.4 \cdot 10^7$	$1.43 \cdot 10^5$	8.4	0.15
Buildings *Budynki*	$1.0 \cdot 10^{10}$	$1.0 \cdot 10^{10}$	25.0	–
Wall *Mur*	$5 \cdot 10^5$	8000	–	–

for numerical simulation with use of the Coulomb-Mohr material model (Cudny & Binder, 2005).

The phreatic level is located 4.7 m below the ground surface in the Vistula Valley. This water level is unconfined and remained unchanged during the construction of the tunnels (piezometric monitoring by ZTM Warszawa, 2015). The reasons for this are deep drainage, surface drainage and foil insulation spread over the slope. Hence, the pore pressure distribution is hydrostatic.

In addition to soil parameter sets, three plate type (construction elements) data sets were created on the basis of ILF, 2010; Plaxis, 2010. The properties for these plate elements of numerical model are listed in Table 2. The list of parameters depends on the type of material behavior, which is elastic in the case of construction elements.

In the tunnel boring machine (TBM) method the soil is generally over-excavated, which means that the cross sectional area occupied by the final tunnel lining is always smaller than the excavated soil area. Although measures

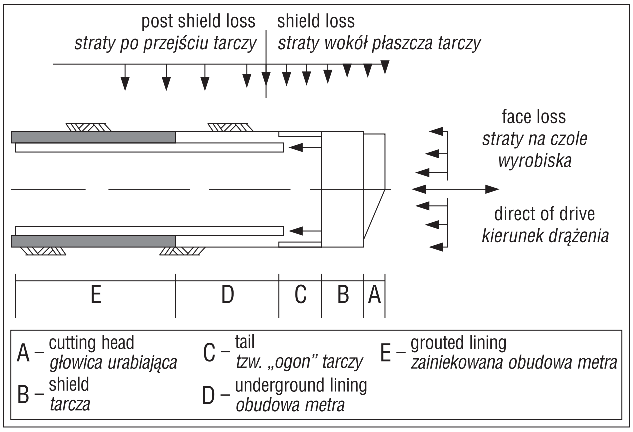

Fig. 3. Sources of volume loss in the TBM method (Potts & Zdravković, 2001)
Ryc. 3. Źródło strat objętości w przypadku TBM (Potts & Zdravković, 2001)

are taken to fill up this gap, it is impossible to avoid stress re-distribution and deformations in the soil as a result of the tunnel construction process. Thus, volume loss (V_L) is related to higher cutting volume of soil than the volume of the tunnel.This value is influenced by:

– loosening the soil in the surrounding zone of TBM work,

– loss of soil around the tunnel shield.

It is noteworthy that the TBM diameter is larger than the diameter of the tunnel and hence V_L becomes enlarged. A schematic diagram of the TBM driving process is presented in Figure 3.

The circular tunnels considered in this case study have a diameter of 6.1 m and are located at an average depth of 8.5 m below the terrain surface (Fig. 4).

It is noteworthy that the colluvium (layer II; Fig. 5) on the plateau is the former landslide shelf (Wysokiński, 2013). The buildings near 4, 6 and 8 Dynasy Street have been damaged as a result of mass movements (Wysokiński, 2013). Consequently, the building at 6 Dynasy Street was reinforced by braces prior to 2008.

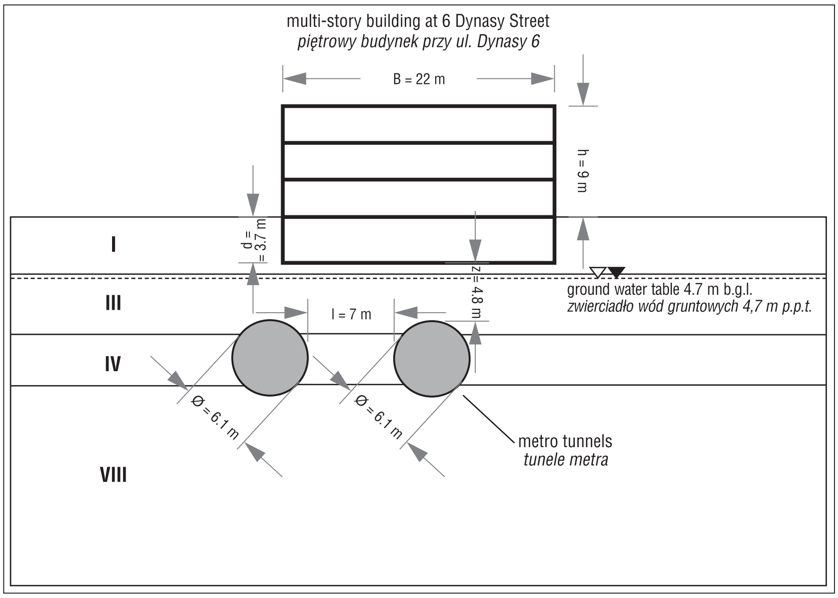

Fig. 4. Geometry of the tunnels project with soil layers numbered
Ryc. 4. Projekt tuneli metra z numerami warstw geologicznych

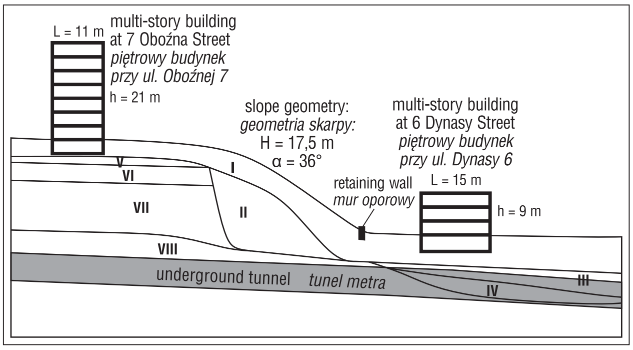

Fig. 5. Schematic diagram of the slope
Ryc. 5. Schemat skarpy

NUMERICAL SIMULATION PROCEDURES

The case study investigates the settlements induced by the construction of the shield tunnels in the layered soil. The shield tunnel is constructed by excavating soil at the front of a tunnel boring machine (TBM) and installing a tunnel lining behind it. This issue can be solved by numerical methods (i.e. FE technique) or by analytical techniques, which often give faster, cheaper and more satisfactory results. The advantage of numerical methods is that they are not limited by tunnel construction conditions (Potts & Zdravković, 2001). The non-numerical approach is based on different unconnected elements. For example, loads are determined by an elastic solution and movement of soil by empirical solutions. Therefore, empirical predictions are limited to greenfield situations. The actual conditions, especially in urban areas, are complex, involving pore pressure changes, plasticity, lining deformations and existing structures (Potts & Zdravković, 2001; Barański et al., 2008). On the other hand, the finite element method makes it possible to simulate the construction sequence, deal with complex hydraulic and ground conditions and consider adjacent structures (Plaxis, 2010). It can also be used to analyze intermediate and long term conditions with multiple tunnels (Potts & Zdravković, 2001).

Tunnel excavation is a three-dimensional engineering process. Where ground surface response is crucial to the analysis, then a plane strain representation of the transverse section is required (Potts & Zdravkovic, 2001). Several two-dimensional analyses were performed with Plaxis software to analyze the tunneling-induced soil behavior. The monitoring data was used in the back-analysis. In the finite element approach, the tunnel excavation and its impact on settlements were modelled by the volume loss control method by means of tunnels diameter contraction increment established arbitrarily at a level equal to 0.8%. This value is based on literature (Kuszyk & Siemińska-

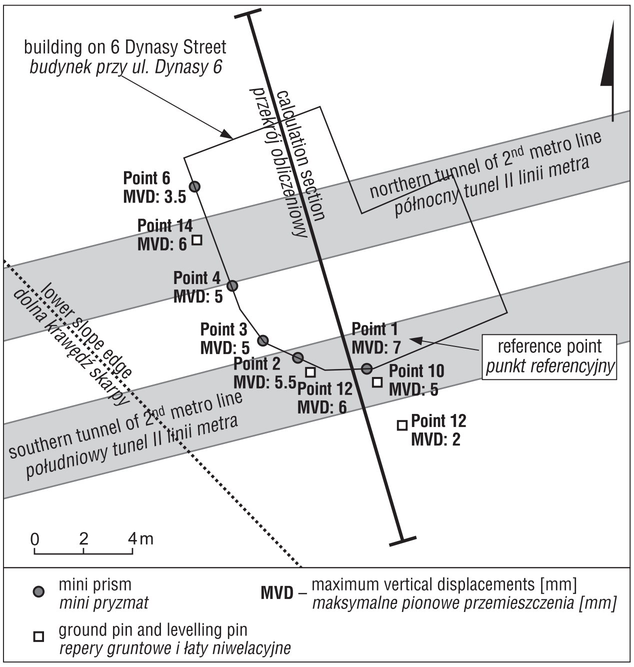

Fig. 6. Survey monitoring of a building at 6 Dynasy Street
Ryc. 6. Monitoring geodezyjny budynku przy ul. Dynasy 6

-Lewandowska, 2009). Due to the shortage of data, injection work was not taken into account in the numerical simulations.

During the underground construction process, the building was monitored by the metro contractor. The results presented below (Fig. 6) were used to verify the numerical simulations of the tunneling-influenced response of the building.

The change in subsidence over time was simulated by staged construction. First, the southern metro tunnel was simulated, then the northern tunnel.This approach is con-

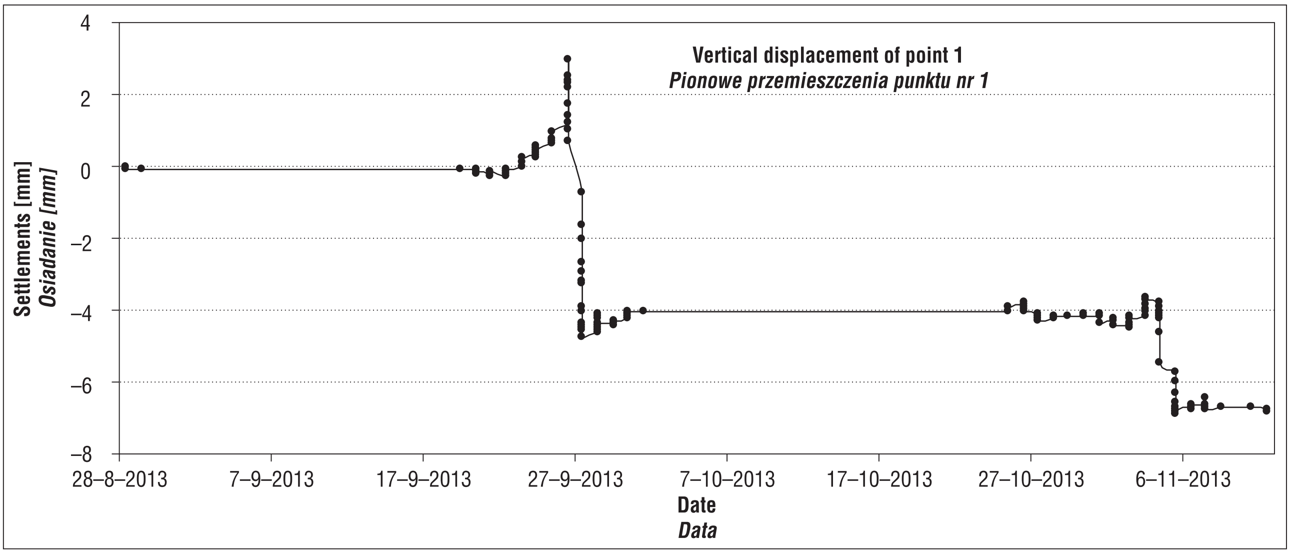

Fig. 7. Settlements of point 1 (mini prism) located on the building at 6 Dynasy Street against time (ZTM Warszawa, 2015)
Ryc. 7. Osiadania w czasie punktu 1 (mini pryzmat) położonego na rogu budynku przy ul. Dynasy 6 (ZTM Warszawa, 2015)

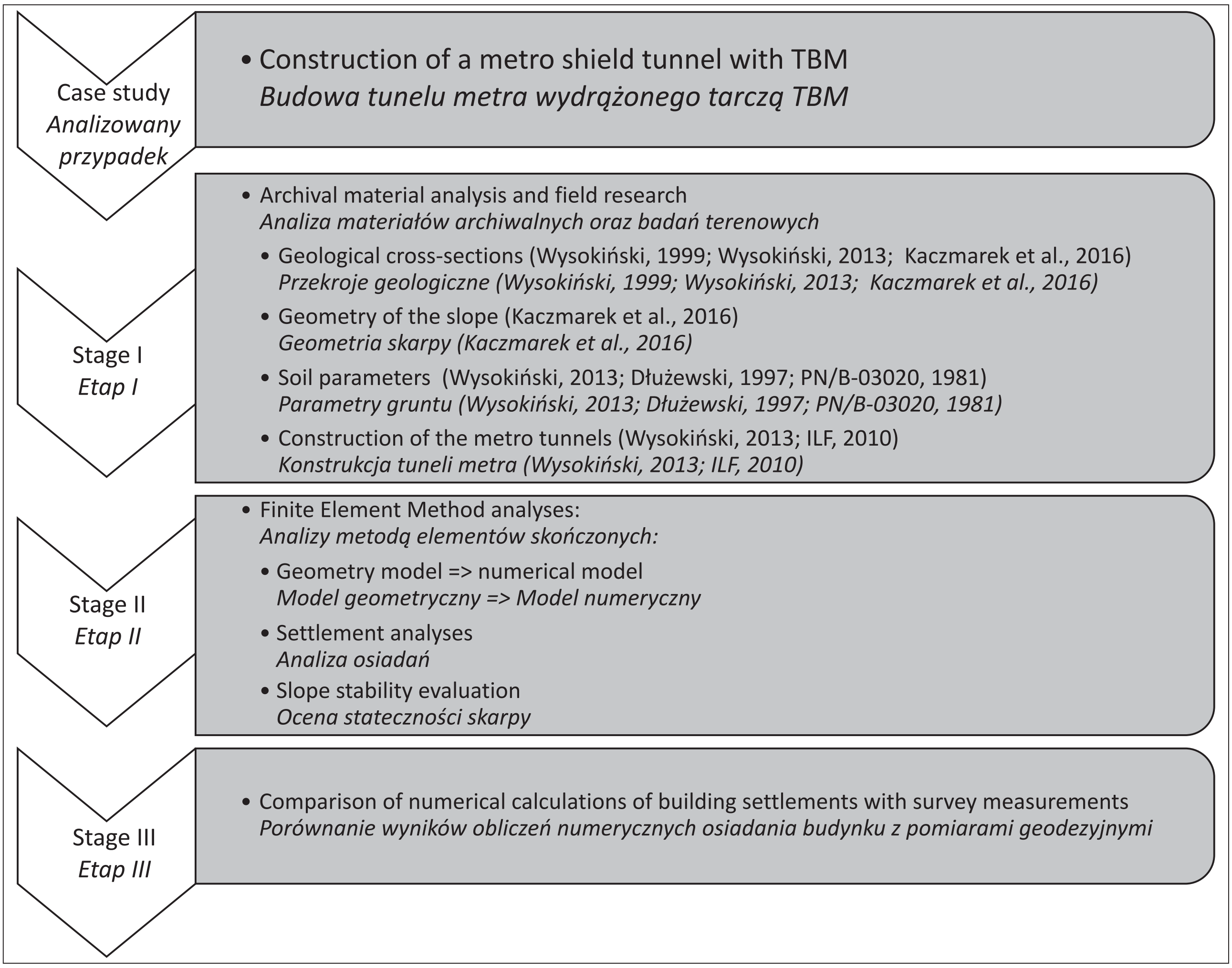

Fig. 8. Workflow of numerical simulation
Ryc. 8. Schemat symulacji numerycznych

Table 3. Numerical simulation procedure of settlement analysis
Tab. 3. Procedura analizy osiadań, z wykorzystaniem symulacji numerycznych

Stage number **Numer etapu**	**Description** **Opis**
1	Restore the original state before underground construction *Odtworzenie stanu początkowego przed budową metra*
2	Simulation of the southern metro line construction: *Symulacja budowy południowego tunelu metra*:
	– activating the tunnel lining with proper material properties and deactivating the soil clusters inside thetunnel; *aktywacja elementów obudowy tunelu o odpowiednich parametrach materiałowych oraz dezaktywacja gruntu w środku tunelu;* – activating draining the water within it – dry tunnel; *aktywacja odwodnienia – suchy tunel;* – modeling the soil-tunnel interaction by assigning modified properties, with reduced strength parameters (R_{interf} = 0.1); *model interakcji gruntu-tunelu, za pomocą przypisania zmniejszonych parametrów wytrzymałościowych (R_{interf} = 0,1);* – *defining tunnel contraction to simulate volume loss.* *zmiana geometrii tunelu dla symulacji utraty objętości.*
3	Simulation of the northern metro line construction: *Symulacja budowy północnego tunelu metra:*
	– activating the tunnel lining with proper material properties and deactivating the soil clusters inside the tunnel; *aktywacja elementów obudowy tunelu o odpowiednich parametrach materiałowych oraz dezaktywacja gruntu w środku tunelu;* – activating the water drainage within it – dry tunnel; *aktywacja odwodnienia – suchy tunel;* – modeling the soil-tunnel interaction by assigning modified properties, with reduced strength parameters (R_{interf} = 0.1); *model interakcji gruntu-tunelu, za pomocą przypisania zmniejszonych parametrów wytrzymałościowych (R_{interf} = 0,1);* – defining tunnel contraction to simulate volume loss *zmiana geometrii tunelu dla symulacji utraty objętości.*

firmed by the immediate subsidence observation (Fig.7; ZTM Warszawa, 2015).

The two maximum subsidence values are caused by the presence of the TBM, firstly in the southern metro line, then in the northern metro tunnel.

Construction elements of the metro tunnel do not influence the stability of the slope. Nevertheless, the low value of the safety factor (near *SF* = 1), in combination with large settlements, give cause for concern. Figure 8 below shows the analysis workflow.

Finite Element analysis for both displacements and slope stability simulations was conducted using refine calculation mesh in the expected stress concentration zones. These zones occur in close proximity to tunnels, buildings and soil layer where the landslide surface is located. In the cases analyzed, a 15-node element mesh model was used as the basic element type. The FE model of building settlements was performed using 2199 elements and 18,087 nodes. The model is 66 m wide and 39 m high. Further more, the mesh for the slope stability analysis has 850 elements and 7069 nodes. The FE model of the slope is 132 m long and 64 m high. The need for greater computational accuracy led to the higher number of elements and finer mesh of the settlement model. Boundary conditions of analyzed models were defined as full fixity at the bases of geometries and roller conditions at the vertical sides. In his geotechnical report, Wysokiński (2013) pointed out an increased hazard of high subsidence, posing a danger to public safety. In addition, high-ground settlements could trigger a landslide mechanism on the Warsaw Slope located opposite the building.

Staged construction simulation was used to analyze the impact of the tunnels on settlements. The initial conditions were simulated by means of material unit weight, pore water pressure and the coefficient of earth pressure at rest. Furthermore, in relation to the constitutive models used, additional parameters were specified to model soil behavior. After generating the initial condition, the process of tunnels lining were activated and the soil inside was removed. The underground construction elements were simulated by means of shell elements in the FE model. Deactivating the soil inside the tunnels affects soil stiffness, soil strength and effective stress (Plaxis, 2010). Secondly, water pressure inside the tunnels was deactivated. Table 3 shows the procedure used to simulate the settlement process.

The evaluation of slope stability was performed using a safety factor (*SF*), which is the ratio of stability forces to destabilization forces. The value of *SF* = 1 is the threshold value, where *SF*<1 indicates slope instability. In the FE software, this value was obtained by the iterative shear strength reduction method, named c-φ reduction method (Zimmermann et al., 1987). In this method, the Coulomb failure condition is used. In the software used, this approach is obtained by cohesion and friction angle tangent reduction in the same proportion. As a result, the global safety factor is calculated (Plaxis, 2010):

$$SF = \frac{c}{c_r} = \frac{tg\varphi}{tg\varphi_r}$$

Where:
SF – safety factor [-],
c, φ – actual cohesion [kPa] and friction angle [°],
c_r, φ_r – reduced cohesion [kPa] and reduced friction angle [°] at the slope failure moment.

RESULTS

Numerical simulations were used to perform the analysis of the re-distribution stress field in the soil and the basin subsidence, which caused settlements of the building at 6 Dynasy Street. In addition, the state of stability of the Warsaw Slope was tested. Overly high values of subsidence at the buildings in the Vistula Valley can indirectly influence the stability of the slope, which is located in close proximity (several meters).

SETTLEMENTS

The impact of the metro tunnels construction on the geological environment had its rendition on the stress field. This resulted in the forces acting on subway elements. In addition to the inducted stress relief, the soil movements were generated. Due to soil compression and the process around tunnel excavation (volume loss of soil), settlements above the tunnel took place. The greatest bending moments of the tunnels occurred in this phase.

Figure 9 shows the shadings of cumulative relative shear stress field. The maximum stress values occur between the underground tunnels, as well as in the foundation corners.

In Figure 10 the results of the decrease in volume were summarized. The value of forces acting on the two parts of the underground tunnels, where the maximum values are around 700 kN/m, was maximized. The internal forces vector acting on the tunnels is dependent on geostatic and building load.

Figure 11 shows the total maximum bending moments after the soil volume loss. The vertical axis of the tunnels

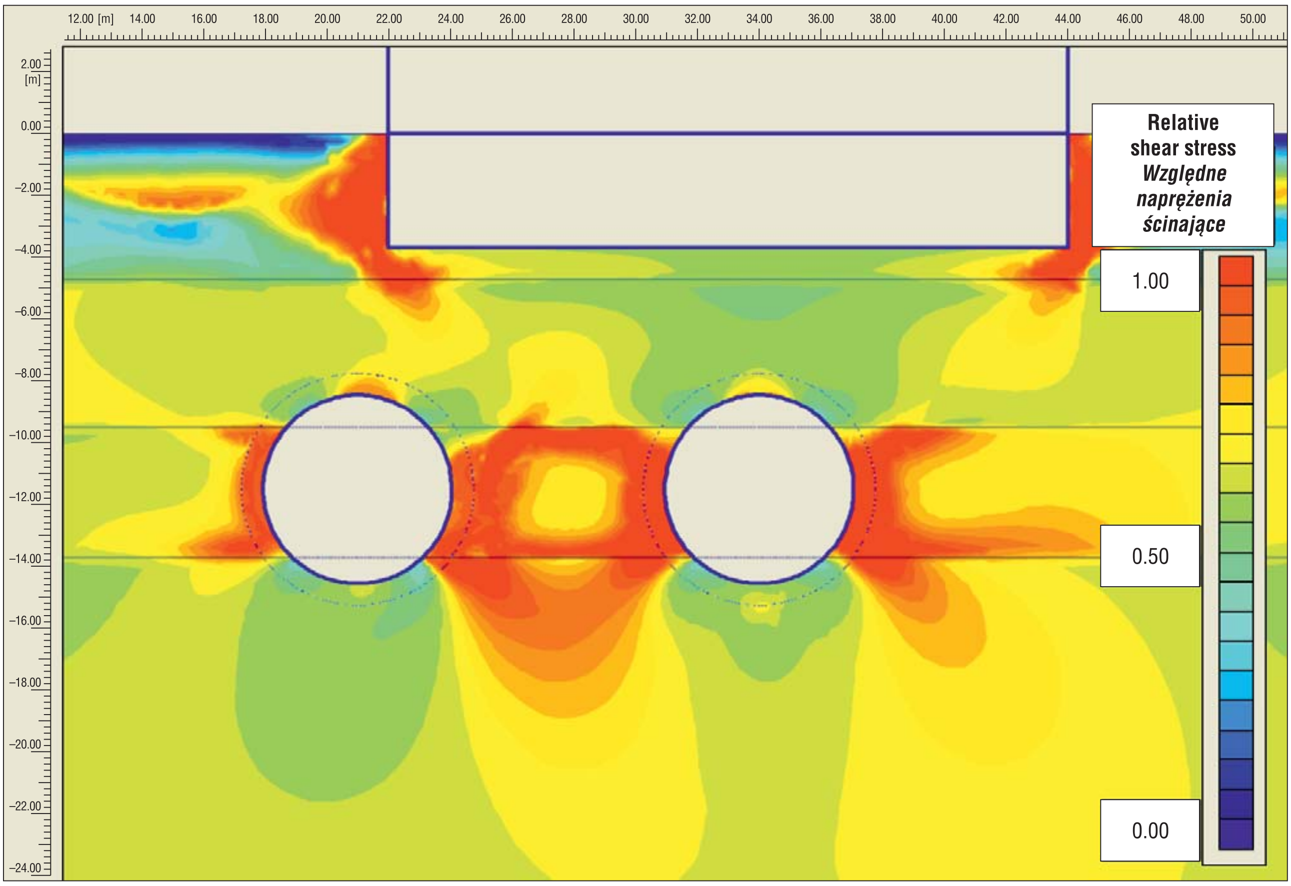

Fig. 9. Relative shear stresses (normalized by maximum stress) in construction zone in the cross-section plane to the metro line
Ryc. 9. Naprężenia ścinające w wartościach względnych (znormalizowanych według maksymalnych naprężęń) w obszarze budowy metra w płaszczyźnie przekroju poprzecznego do linii metra

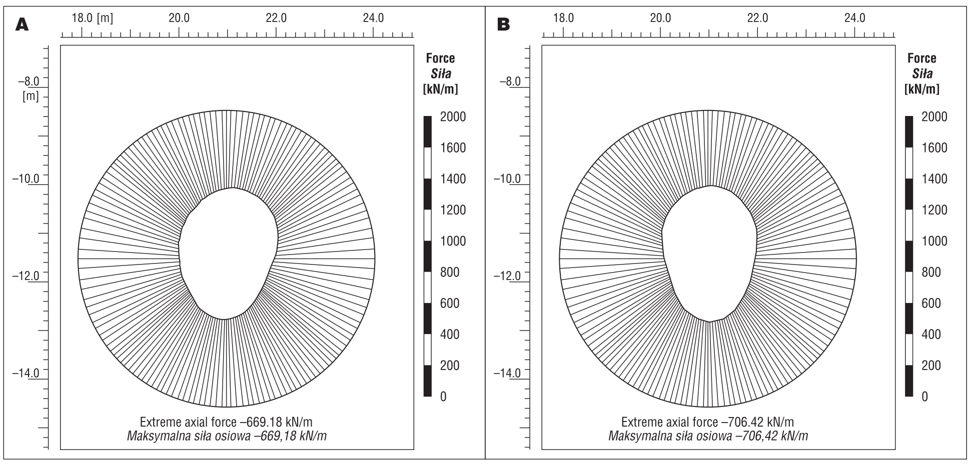

Fig. 10. Axial forces acting on: **A** – southern tunnel; **B** – northern tunnel
Ryc. 10. Osiowe siły działające na: **A** – południowy tunel; **B** – północny tunel

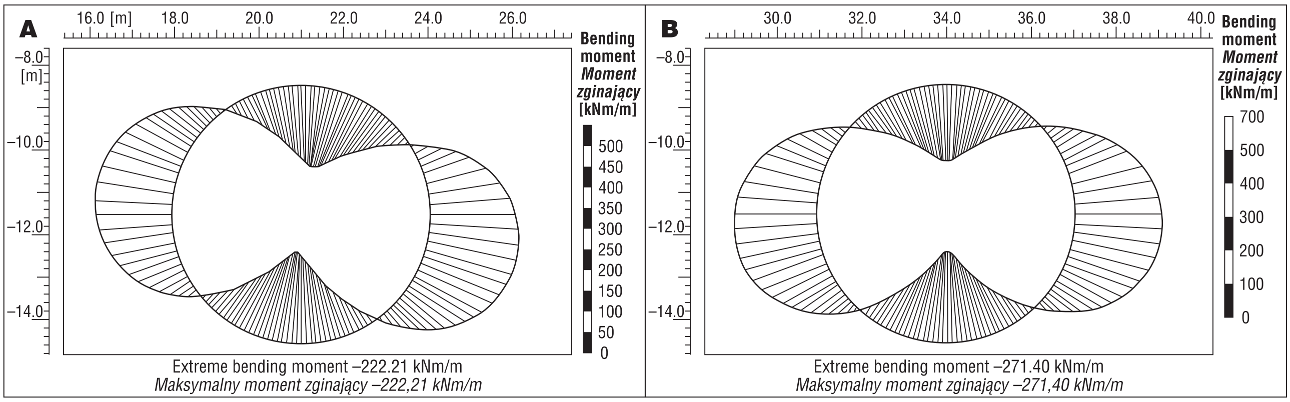

Fig. 11. Bending moments for metro construction below building: **A** – southern tunnel; **B** – northern tunnel
Ryc. 11. Momenty zginające konstrukcji metra pod budynkiem: **A** – południowy tunel; **B** – północny tunel

dominate in the compression, as well as in the horizontal axis stretching at the same time.

The values of the total displacements (cumulated horizontal x-axis and vertical z-axis displacements) obtained in the first stage of calculations are 18.1 mm in the proximity to the subway tunnel, while the maximum total displacement value under the building is approx. 5 mm (Fig. 12A). The total maximum values of the displacements are 19.2 mm in the analyzed numerical sections. The total value of vertical displacements of the building at 6 Dynasy Street is 8 mm (Fig. 13A). The total displacements in the near-terrain surface zones are mainly vertical, therefore the displacements in these places can be simply assumed as the vertical settlements. The size and range of the settlements obtained in the numerical simulation in the corner of the building are in good agreement with land survey data. Both figures 12B and 13B show changes in building contour geometry, which can be estimated by means of total displacement vectors of individual FE nodes. Due to the staged construction of the metro tunnels, in the first phase the set-

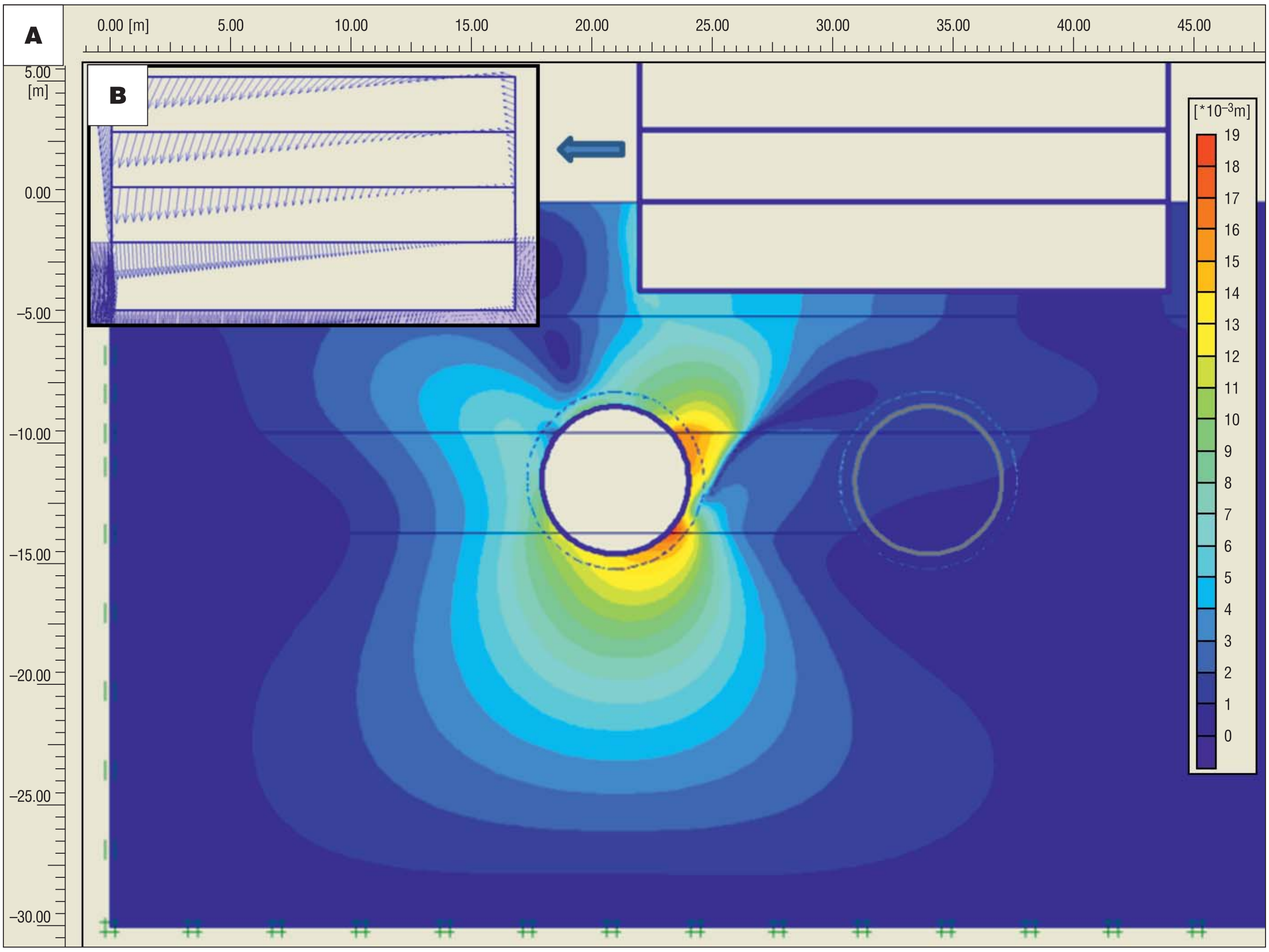

Fig. 12. A – total soil displacements induced by the southern metro tunnel; **B** – displacement vectors of the building at 6 Dynasy Street
Ryc. 12. A – zsumowane przemieszczenia gruntu spowodowane budową południowego tunelu metra; **B** – wypadkowe wektory przemieszczeń budynku przy ul. Dynasy 6

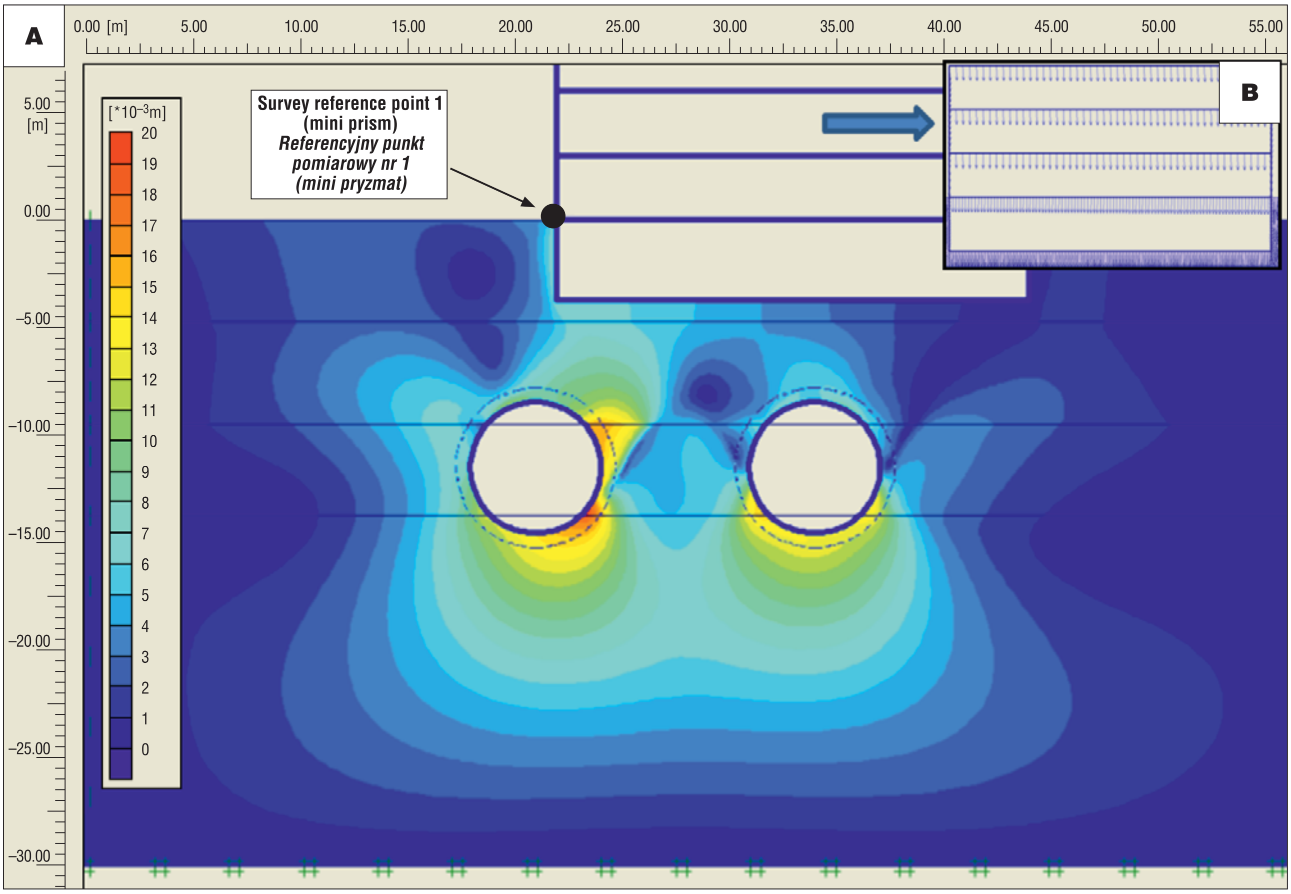

Fig. 13. A – total soil displacements induced by the two metro tunnels; **B** – displacement vectors of the building at 6 Dynasy Street
Ryc. 13. A – całkowite przemieszczenia gruntu spowodowane budową dwóch tuneli metra; **B** – wektory przemieszczeń budynku przy ul. Dynasy 6

tlements and inclination of the building were minimized. In the second phase (northern tunnel of the metro) the settlements were uniform for the building section.

The divergence between the results of the numerical simulations and land survey monitoring may be caused by (i) the fact that the value of the building load was estimated, and (ii) not taking into account the impact of the injection zone. This approach was dictated by the lack of precise data.

According to Polish Standard PN-B-03020 (1981), as well as criteria proposed by Popielski (2012), the displacement results obtained by the numerical simulations and survey monitoring of the building at 6 Dynasy Street are borderline acceptable. Therefore, it is reasonable to monitor the changes occurring in this area.

ANALYSIS OF SLOPE STABILITY

In order to obtain a full description of the analyzed issue, numerical simulations of slope stability were conducted. The strengthening wall was taken into account in the numerical model. Because of surface and deep water drainage, as well as slope surface isolation by a plastic film and the low groundwater level, the simulation does not take water flow into account.

The simulation reveals *SF* = 1.1 which indicates stability. Nevertheless, this result indicates an alarmingly small safety margin. The small *SF* value is confirmation of information found in the literature on recent (before 2008) landslide movements (Wysokiński, 2013) as well as current field observations that show slow creep of soil (twisted branches of trees). This calculation result also confirms the suitability of the aforementioned steps taken to protect the slope.

High ground settlements of the building near the slope foot can trigger the landslide mechanism opposite the Warsaw Slope. Slope inclination has the greatest impact on the *SF* value in the analyzed area. Figure 14 presents a deformed mesh, due to the loss of slope stability, which indicates the potential range of landslide.

During the loss of stability, simulated mass movements revealed slip surfaces at a depth of 4–5 m below the surface, which is largely parallel to the ground surface. Figure 15 illustrates a potential slip surface of the Warsaw Slope in the analyzed area.

Subsidence induced by metro tunnels does not pose a threat to the stability of the slope. Nevertheless, the low value of SF requires continuous monitoring of changes occurring in the slope area. It is noteworthy that the dynamic factor (metro trains) can cause consolidation and further settlements (Potts & Zdravković, 2001).

SUMMARY

This paper presents a case study of the 2nd metro line in the proximity to the Warsaw Slope. The numerical simulation provides detailed information about the impact of metro tunnels construction on urban area settlements.

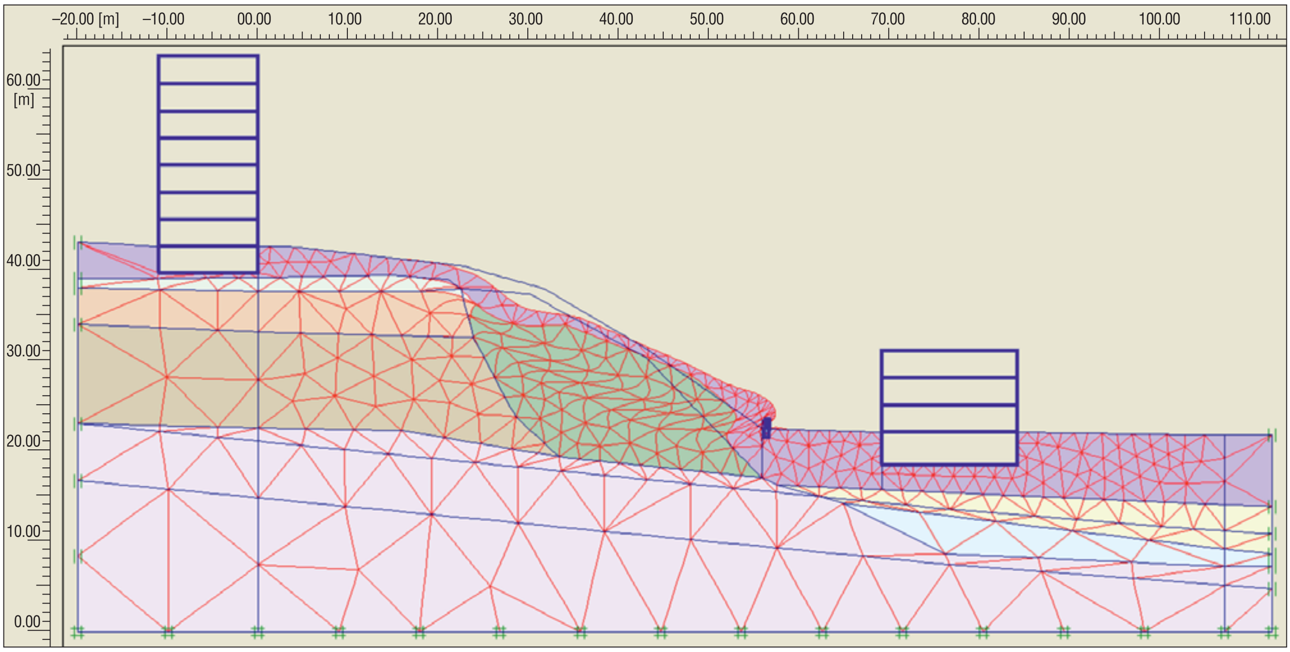

Fig. 14. Deformed mesh model affected by potential landslide
Ryc. 14. Zdeformowana siatka modelu przez powstanie potencjalnego osuwiska

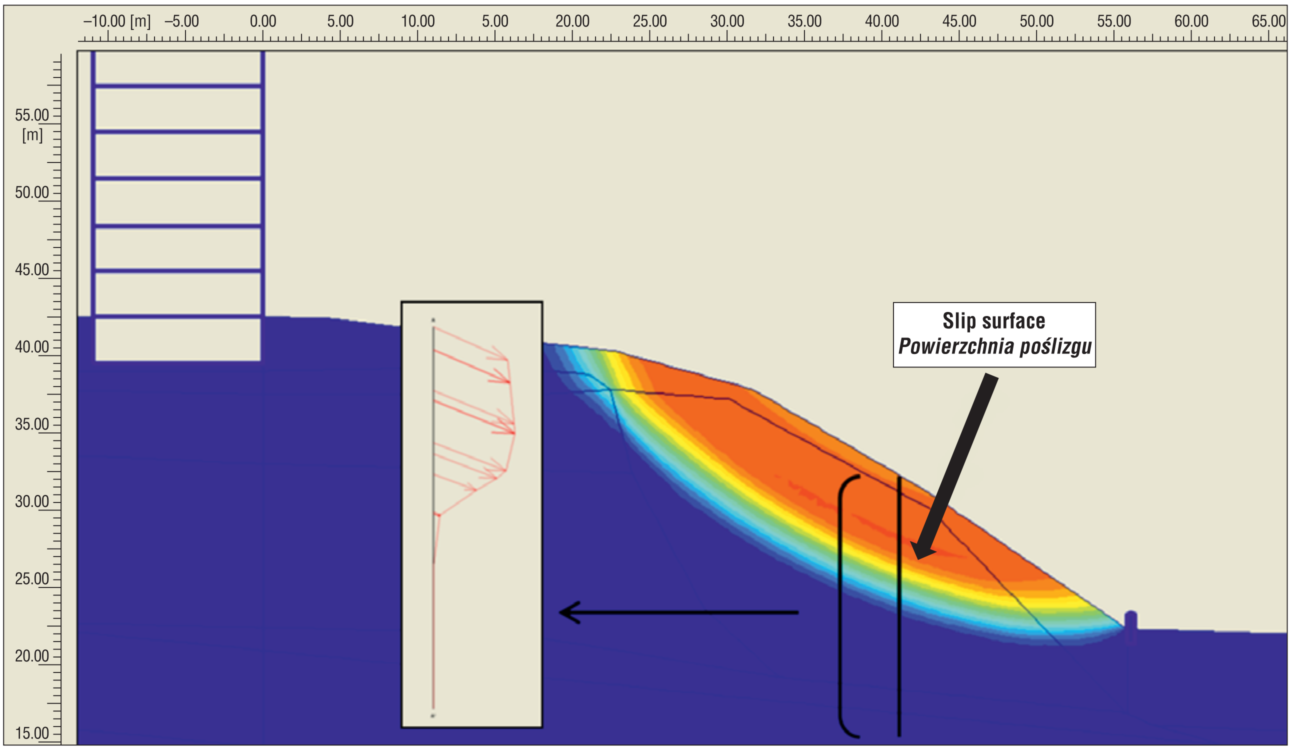

Fig. 15. The visualization of potential slip surface with a section showing vectors of displacement
Ryc. 15. Obraz potencjalnej powierzchni poślizgu z wektorami przemieszczeń w wybranym przekroju

Stress redistribution in foundation soil induced by metro excavation generates further ground and building settlements. The numerical approach allowed us to estimate the size and range of the subsidence. The total value of maximum displacements was 19.2 mm with the maximum vertical displacement value of 8 mm below building foundations and within a range of a few meters from the corner of the building. Furthermore, the forces and bending moments acting on the underground tunnels construction were calculated. The stress field obtained by simulations indicates the places most affected by the metro construction. These places were in the proximity to metro tunnels bases, which are below the corner of the building. The results of the numerical simulations are in good agreement with land survey data.

The Warsaw Slope is located opposite to the building at 6 Dynasy Street and above the 2nd metro line. Highly irregular subsidence in the area of the slope can lead to a reduced safety factor and induce a landslide. Since stability calculations using the strength reduction method show *SF* = 1.1, constant monitoring of displacements and changes occurringin the slope is required.

The presented case study shows the usefulness of numerical methods in investigating potential hazards when constructing extensions to the 2nd line of the Warsaw Metro. The issue of assessing settlement induced by metro tunneling is in fact a soil-structure interaction analysis, in which soil parameters and geology strata should be taken into account.

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