Complex Analysis of the Impact of Construction of an Underground Metro Line on the Urban Environment – a Case Study from the Vistula Valley in Warsaw

Łukasz Kaczmarek

*Department of Engineering Geology, University of Warsaw, Poland
E-mail: lukasz.kaczmarek@uw.edu.pl*

Abstract. 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 (Kaczmarek, Popielski 2016; Kaczmarek *et al.* 2016). First the digital terrain model was analysed. Next the prospection of electrical resistivity imaging (ERI) were performed. In addition results of archive boreholes were correlated to ERI outcome. Then complementary laboratory tests (e. g. triaxial CU tests) were carried out. Furthermore the prisms located on the Warsaw Slope were measured with tacheometric technique. This results were merged to archive monitoring observations of slope surface deformation and near building settlements. Based on previous steps the finite element method (FEM) simulations were performed. Thanks to numerical analysis cumulative settlements of a particular building above the metro tunnel were calculated. The values of vertical displacements does not affect the stability of the building or the slope nearby. Nevertheless, it can impact serviceability. 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 presented case study shows the usefulness of complex research analysis and its suitability for the purposes of building an extension of the 2nd metro line.

Keywords: slope stability, settlements, electrical resistivity imaging, surveying, triaxial tests, finite element method.

Conference topic: Case studies.

Introduction

Urban areas are places of complex interactions of many anthropogenic and natural components which require accurate analysis (Dundulis *et al.* 2006). One 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 extensive description of a tunnel construction by numerical simulations was published by Potts and Zdravković (2001).

In the article, several Finite Element simulations were presented in reference to the 2nd line of the Warsaw Metro (Kaczmarek, Popielski 2016). 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 (ZTM Warszawa 2015) concerning the displacements of the ground and the buildings.

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. The construction of II Metro Line cuts the slope perpendicularly in the area of 6 Dynasty Street, in Powiśle district. Within this region, the multi-story buildings and a section of the Warsaw Slope are potentially at risk. 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 tunnel passes 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.

Methods

Figure 1 shows scheme of performed tests in order to analyse the tunnel construction's influence on the urban environment in Vistula Valley in Warsaw

In the first stage, landslide activity in the area of metro tunnel construction in the past was established. On the basis of the author's own research and a number of publications (Wysokiński 2013; Kaczmarek, Dobak 2015), the most important factor influencing the slope stability (which is high slope angle of approximately 36°) was

identified. This kind of morphology of the research area causes increased threat of landslide's reactivation in the case of interactions with metro tunnel construction, resulting in horizontal and vertical displacements of the researched area.

The analysis of electrical resistivity tomography prospection (Figs 2 and 3) indicates the lack of landslide slip surface. Due to prospection geological strata was designated.

Fig. 1. Scheme of evaluation of the second metro line construction impact on the urban environment

Fig. 2. Results of geophysical prospection (ERI) perpendicular to the extent of the slope. Additionally on the right there is scheme of Warsaw Slope

Fig. 3. Results of geophysical prospecting (ERI) parallel to the extent of the slope. Additionally on the right there is metro tunnel scheme

Fig. 4. Settlements of point 1 (mini prism) located on the building at 6 Dynasy Street against time (ZTM Warszawa)

In the third stage, the quantities of vertical and horizontal displacements was obtained. On the Warsaw Slope vertical quantities were up to 25 mm, whereas the horizontal were up to 16 mm. Surveying indicate maximum vertical displacement of 8 mm below the building's foundations (Fig. 4). Furthermore this results can be correlated with individual stages of the investment's realization. A characteristic stage is the first TBM's passage of the tunnel's southern part, which is directly under the slope. The next stage is the second TBM's passage of the metro tunnel's northern part. It is important that the author's tachimetric measurements made in two cycles with an interval of 2.5 weeks indicate the stoppage of controlled points' displacements.

The last research stage was made with the use of inclinometer subsurface measurements indicated the lack of displacements below the slope's surface, near its lower edge.

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 5 presents a potential slip surface, due to the loss of slope stability, which indicates the potential range of landslide.

Performed calculation indicate Warsaw Slope factor of safety ($SF = 1.1$).

The values of the total displacements (cumulated horizontal x-axis and vertical z-axis displacements) obtained in the first part of calculations are 18.1 mm in proximity to the southern part of the underground tunnel, while the maximum total displacements value under the building is approx. 5 mm. The total maximum values of the displacements for the southern and northern parts of metro tunnel are 19.2 mm in the analyzed numerical sections. The total value of vertical displacements of building at 6 Dynasy Street is 8 mm. The total displacements in the near terrain surface zones are mainly vertical, therefore the displacements in this 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. Figure 6 shows displacement field and vectors. Due to the staged construction of the metro tunnel, in the first phase the settlements and inclination of building were minimized. In the second phase (northern line of the metro) the settlements were uniform for the building section.

Fig. 5. A - Total soil displacements induced by the second metro line tunnel; B – displacement vectors of the building at 6 Dynasy Street (Kaczmarek, Popielski 2016)

Fig. 6. Total soil displacements induced by the second metro line tunnel; B – displacement vectors of the building at 6 Dynasy Street (Kaczmarek, Popielski 2016)

Conclusions

To sum up, it is claimed that the influence of II metro line's construction below Warsaw Slope is visible because of the deformations. Nevertheless, this influence is so small that it does not pose a threat to slope's stability, as well as the buildings in its neighborhood. The metro implementation's influence assessment shows a high usefulness of complementary research methods, which allow for a broad and reliable analysis of investments' implementation in complex urban conditions.

References

- Dundulis, K.; Gadeikis, S.; Gadeikyte, S. 2006. An environmental investigation scheme used in Lithuanian urban areas, in *The 10th IAEG International Congress*, 6–10 September 2006, Nottingham, United Kingdom.
- Kaczmarek, L.; Dobak, P.; 2015. Stability conditions of the Vistula Valley attained by a multivariate approach – a case study from the Warsaw Southern Ring Road, *Geologos* 21(4): 249–260.
<http://dx.doi.org/10.1515/logos-2015-0020>
- Kaczmarek, L.; Popielski, P. 2016. Numerical analysis of the impact of construction of an underground metro line on the urban environment – a case study from the Vistula

- Kaczmarek, L. 2016. *Complex analysis of the impact of construction of an underground metro line on the urban environment – a case study from the Vistula Valley in Warsaw* Valley in Warsaw, *Polish Geological Review* 64(4): 219–229.
- Kaczmarek, Ł.; Woźniak, M.; Mieszkowski, R.; Dybciak, T. 2016. Electrical Resistivity Imaging and land surveying of underground construction impact on the Warsaw Slope, *Studia Quaternaria* (in press).
- Kuszyk, R.; Siemińska-Lewandowska, A. 2009. Ocena rozwoju niecki osiadań nad tunelem drążonym tarczą zmechanizowaną [Evaluation of the subsidence progress above the metro tunnel created by Tunnel Boring Machine], *Górnictwo i Geoinżynieria* 33(3/1): 229–237 (in Polish).
- Potts, D. M.; Zdravković, L. 2001. *Finite element analysis in geotechnical engineering*. London: Thomas Telford.
- Wysokiński, L. 2013. *Geotechnical raport of metro tunnel construction D13 in the proximity of Warsaw Slope by TBM*. ITB, Warszawa (in Polish).
- ZTM Warszawa. 2015. *Website of DDC monitoring data dissemination system* [online], [cited 15 March 2016]. Available from Internet: www.ddsmonitoring.com