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Geomorphological and geophysical analysis of the Warsaw slope stability conditions in the Ursynów district
Geomorfologiczna i geofizyczna analiza uwarunkowań stateczności skarpy warszawskiej w rejonie Ursynowa

Key words: slope stability, the Warsaw slope, electrical resistivity tomography, numerical methods, the Southern Beltway of Warsaw
Słowa kluczowe: stateczność skarpy, skarpa warszawska, tomografia elektrooporowa, metody numeryczne, Południowa Obwodnica Warszawy

Introduction

This paper shows stability analysis of the Warsaw slope in the selected section of Ursynów (Fig. 1). The analyzed fragment of the slope is located on the border of two neighboring districts: Ursynów from the West, and Wilanów from the East. The issue of a proper management of this area should therefore be of interest and cooperation between local authorities in both districts.

In June 2010, there was a reactivation of landslides in the analyzed territory. It resulted in significant damage and displacements observed on the walls of two buildings at the st. Orszady.

The geological conditions in this area were analyzed based on cross-section profiles that run through st. Kieda-

FIGURE 1. Location of the field of study in the city of Warsaw. A – field test (Google, 2014)
RYSUNEK 1. Lokalizacja terenu badań na tle miasta Warszawy. A – obszar badań (Google, 2014)

cza (cross-section I–I'), st. Płaskowicka (II–II'), st. Kokosowa (III–III') and through the crossing of st. Kokosowa and st. Orszady (IV–IV'). Locations of these sections are shown in Figure 2.

In order to select representative areas for conducting stability evaluation along the selected analytical profiles, the problem of stability conditions was preceded by geomorphologic analysis and site inspection. Static load from the buildings was also taken into account as well as load caused by currently restrained vehicle transport. Geophysical electrical resistivity tomography (ERT) was used to identify the allocation of geomorphologic layers and adaptation of a suitable calculation model.

Prospect of archival research in the analyzed area

In the literature there can be found numerous publications on stability of the Warsaw slope, written by Wysokiński

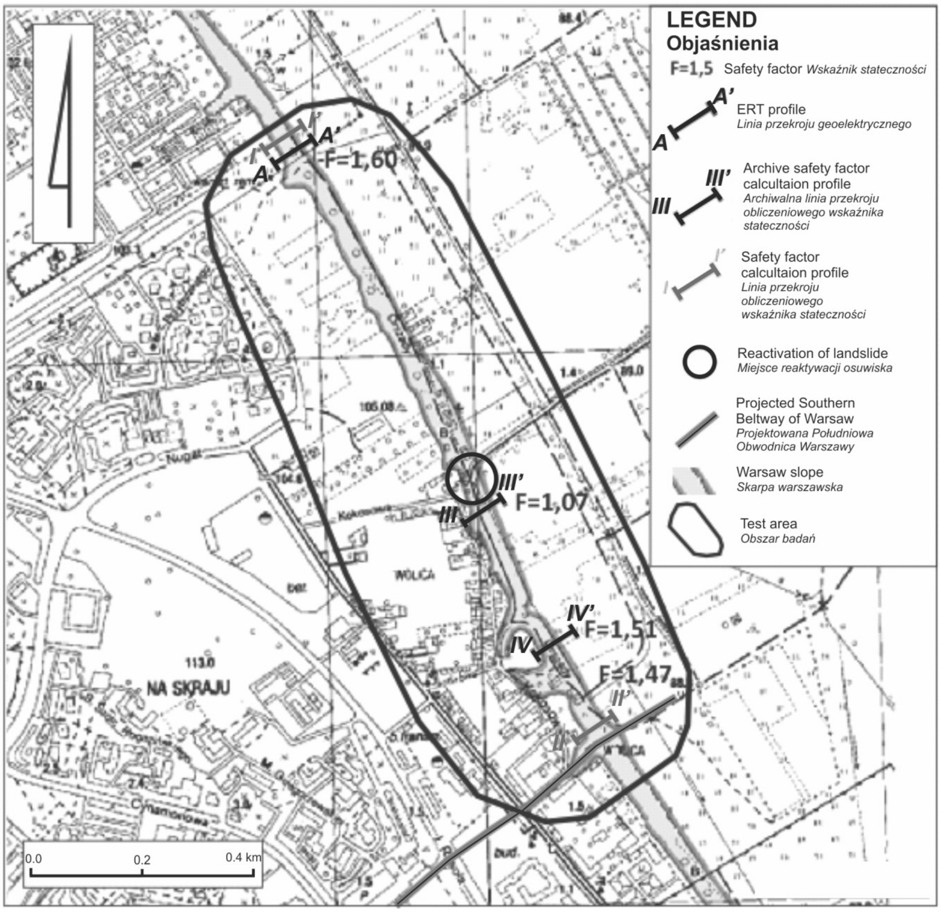

FIGURE 2. Location of the field of research and analyzed cross-sections
RYSUNEK 2. Lokalizacja obszaru badań oraz analizowane przekroje

(1991, 2011), among others, as well as the results of specialized studies of geo-engineering properties of soils conducted by Kaczyński (2008). Due to large interest in development investments in the border region between the districts of Ursynów and Wilanów, many expert studies have been conducted, by inter alia, Koda et al. (2005), Koda, Bąkowski and Rabarijoely (2007) and Mieszkowski (2012). In addition, the documentation for the proposed Southern Beltway of Warsaw (Grzelewski, Pabich and Socha, 2009) can also serve as a valuable material for the preparation of the analytic model.

Geomorphology of analized area

Located to the West of the Vistula river, the Warsaw slope is the erosion edge of the Warsaw Plain (Kondracki, 2011). To the East of the slope, the Middle Vistula River Valley is located (Kondracki, 2011). This was formed mainly by lateral erosion of the Vistula river. In the analyzed area three types of morphologically different areas can be distinguished:

– Moderately diverse and vertically flat alluvial Pleistocene terrace of the Vistula river (Sarnacka, 1992). Height differences are less than 3 m, terrain inclination less than 5% (GUGiK, 1992).
– A relatively flat glacial upland (Sarnacka, 1992). Height differences are larger here, but do not exceed 5 m, landform inclination greater than 5% was not observed (GUGiK, 1992).
– Referring to archival studies (Grzelewski et al., 2008, Kaczyński, 2008) steep area of the slope has relative height of approximately 12.5 m and maximum height of approximately 15 m. Based on the topographic map in scale 1 : 10 000 (GUGiK, 1992) it is noted that the drops are roughly 47% (tilt angle 24%), up to a maximum of 60% (tilt angle 31%).

Terrain relief in elevation area is shown in Figure 3. This illustration also shows the preferred runoff direction of snowmelt and rainwater, which is an important element in assessing the hydrodynamic conditions of the slope stability. Rainwater in the analyzed terrain conditions has a dominant impact on the depth and oscillation of the groundwater level. High groundwater level and its frequent changes may adversely affect the stability of the slope.

In the analyzed area covering the Warsaw slope in the Ursynów section, the distance to the Vistula river is approximately 4.5 km. The absolute height of the slope in this location ranges from 89 to 104 m above sea level. During the field inspection, formed at the foot of the slope, a buttress reminiscent of a “shelf” shape was noticed with inclination from 3° to 5° and height from 3 to 4 m. A number of ravines cut through the slope in the upland section, shaping a relief suitable for development of a local road. Currently, one of the major factors forming the relief of the area in discussion is human activity and numerous anthropogenic forms: building and communications development, terrain alignment, leveling the incantation of the slope and hillsides, as well as super-structuring the face of the slope with anthropogenic land (mounds, rubble and garbage).

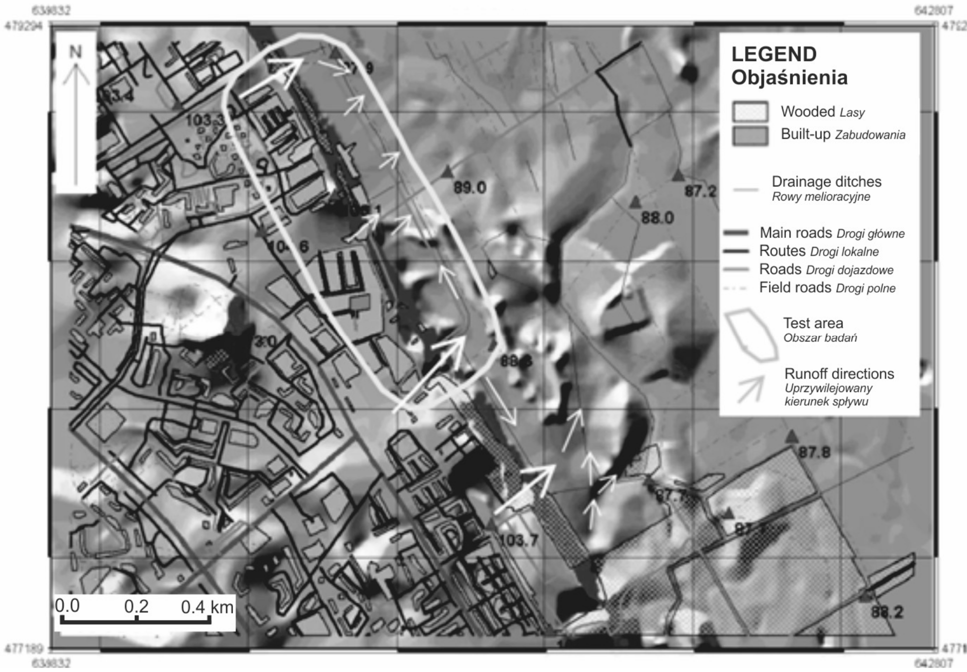

FIGURE 3. Runoff directions on the relief map
RYSUNEK 3. Mapa rzeźby terenu z zaznaczonym uprzywilejowanym kierunkiem spływu

Geology of selected fragments of the slope

Slope is a geomorphologic form conditioned by its geological structure. Sediments that form the slope also affect it's geometry, resistance to denudation process, height, and above all – landslide activity.

The analysis of the geological structure of the studied area is based on two representative cross-sections (own work) and data taken from the Geo-engineering Atlas of Warsaw (Frankowski et al., 2000 unpublished). This sources indicate the dominance of glacial cohesive soils (sandy-clayey silt, clayey sand) of the Warta Glaciation (Fig. 4, layer 5) and the Odra Glaciation (Fig. 4, layer 6) forming the upland.

In the plateau and in the valley, underneath the cohesive sediments, incohesive sediments of the Mazovian Interglacial are present (Fig. 4, layer 7). In the Holocene (Fig. 4, layers 2,3,4), in the valley, there are deposits of medium sand, sandy-clayey silt with gravel and recent facies of organic soils. On the surface however, there may be non-engineered fill (to a depth of approximately 2.5 m below ground level, Fig. 4, layer 1). During the geophysical survey, the presence of Pliocene clays was also confirmed, at the depth of approximately 20 m below ground level. Large inclination of the slope is due to cohesion and relative high values of the internal friction angle. In terms of slope stability, the areas where cohesive and loose soils

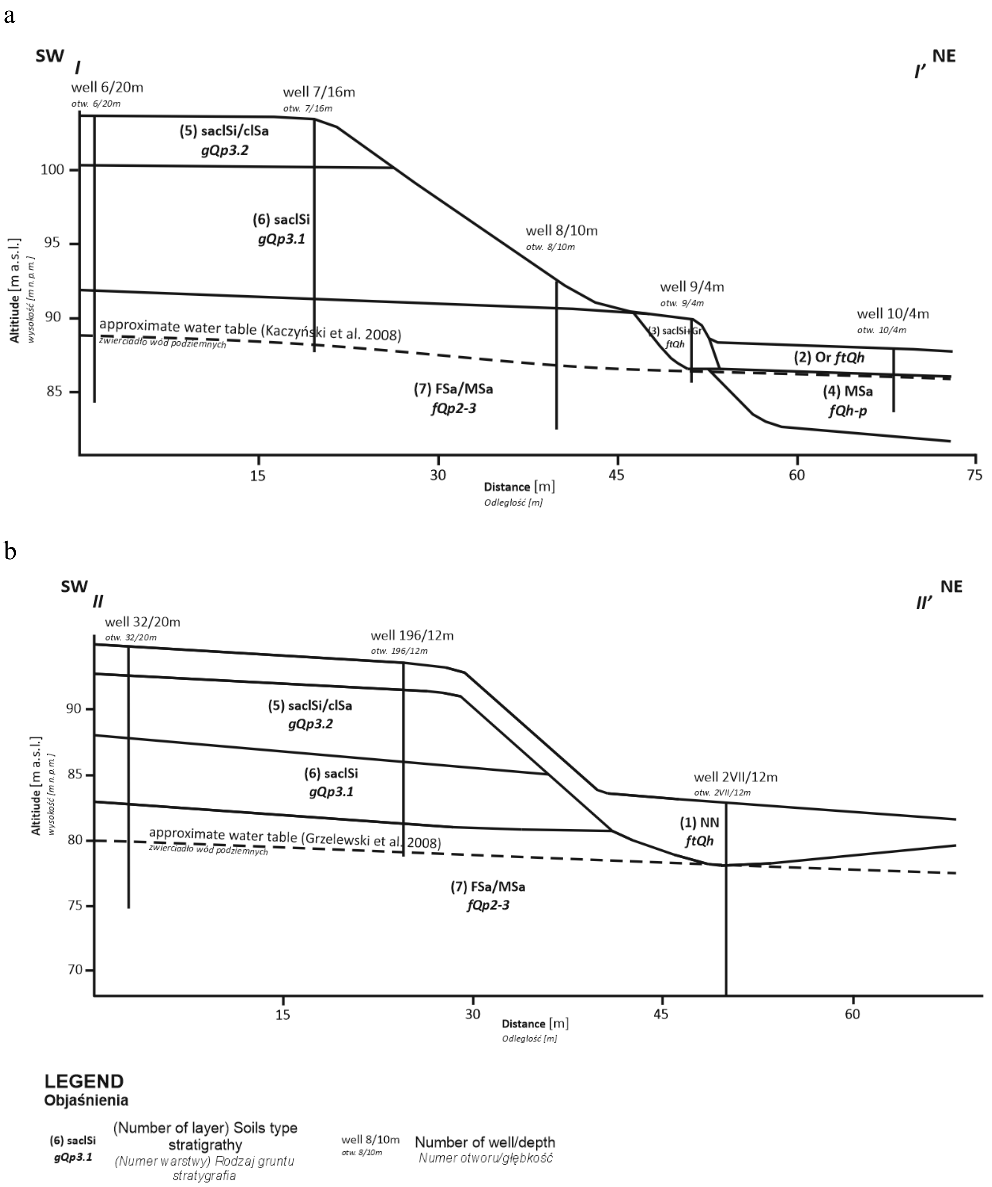

FIGURE 4. Geological cross-sections through the Warsaw slope. A – st. Kiedacza (line I–I'; B) – st. Płaskowicka (line II–II')
RYSUNEK 4. Przekroje geologiczne przez skarpę warszawską: A) przy ulicy Kiedacza (linia przekroju I–I'; B) – przy ul. Płaskowickej (lnia przekroju II–II')

meet are potentially dangerous. During the rain, when the water begins to soak and infiltrate, increasing the humidity of the contact surface, a natural, predisposed slip surface is creating, which is the deciding factor in destabilization of the slope.

Soil parameters responsible for slope stability: density, cohesion and internal friction angle for each layer, were assessed based on archive materials and are present below (Table 1).

Methodology

The electrical resistivity tomography (ERT) method was introduced by the Schlumberger brothers in the early XX century. The theoretical description of the method has been presented, among others, by Keller and Frischknecht (1966) and in Polish literature by Szymanko and Stenzel (1973). A geophysical prospection was conducted in the area represented by a cross-section in the location map

TABLE 1. Summary of the characteristic parameters of the soil (Grzelewski et al., 2008; Kaczyński, 2008)
TABELA 1. Zestawienie parametrów charakterystycznych gruntu (Grzelewski et al., 2008; Kaczyński, 2008)

Number of layer Numer warstwy	Soils type (abbreviation) by PN-EN ISO 14688-1: 2006; PN-EN ISO 14688-2: 2006; Rodzaj gruntu (skrót) według PN-EN ISO 14688-1: 2006; PN-EN ISO 14688-2: 2006;	Deposit genesis, stratigraphy (abb.) Geneza, stratygrafia (skrót)	Unit weight of soil Ciężar objętościowy γ [kN/m^3]	Internal friction angle Kąt tarcia wewnętrznego φ [^{o}]	Cohesion Spójność c [kPa]
1	Non-engineered fill* (NN)	Anthropogenic, Holocene (ftQh)	16.0	10.0	28.0
2	Organic (Or)	River, Holocene (ftQh)	12.0	5.0	10.0
3	Sandy-clayey silt with gravel (saclSi + Gr)	Glacial, Holocene (ftQh)	20.0	11.0	10.0
4	Medium sand (MSa)	River, Holocene-Pleistocene (fQh-p)	19.6	33.0	0.0
5	Sandy-clayey silt and Clayey sand (saclSi/clSa)	Glacial, Wartanian Glaciation (gQp3.2)	21.8	34.0	7.0
6	Sandy-clayey silt (saclSi)	Glacial, Odranian Glaciation (gQp3.1)	22.3	32.0	8.0
7	Fine sand and medium sand (FSa/MSa)	Fluvioglacial, Mazovian Interglacial (gQp3.1)	19.9	35.0	0.0

*Soil not directly usable as a substrate structure, possible use of stabilization/Grunt niezdatny do użycia jako warstwa konstrukcyjna, możliwe wykorzystanie do stabilizacji podłoża.

(Fig. 2). Selection of the field of study was based on terrain accessibility and lack of accurate information about the continuity of the geological structure in this region. Geophysical measurements acquired with ERT survey made it possible to trace the distribution of electrical resistivity of soils in the slope and it's vicinity.

Results

The resulting cross-sections with their interpretation are shown in Figure 5. On cross-sections obtained by ERT method, performed in order to conduct in-depth interpretation of electrical resistivity (including links with lithology), respective profiles of boreholes are marked. The measurements were made by using an electrode system in accordance with gradient and Schlumberger scheme, with spacing between the electrodes amounting to 2 m along the profile line, which allowed prospection depth of around 30 m on the section line of 80 m in length. It should be notified that a proper interpretation of ERT results requires compliance with the results of geological drilling and cross-section profiles based on conducted measurements.

In the geo-electric image five geological layers can be distinguished, sediments with different various electrical resistivity:

– Geological layer I: sandy-clayey silt of Wartanian and Odranian Glaciation present in the top of the slope and is characterized by resistance of 20 m to 80 Ωm.
– Geological layer II: dry, fine sand. Located approximately 10 Ωm from the crest's ordinate, they are characterized with very large resistances of 100 to 900 Ωm.
– Geological layer III: medium and fine irrigated sands. The ceiling is at the depth of 25 m below ground level, under the crest of the slope and continues into the foothill of the slope to a depth of approximately 5 m. Resistances up to 80 Ωm.

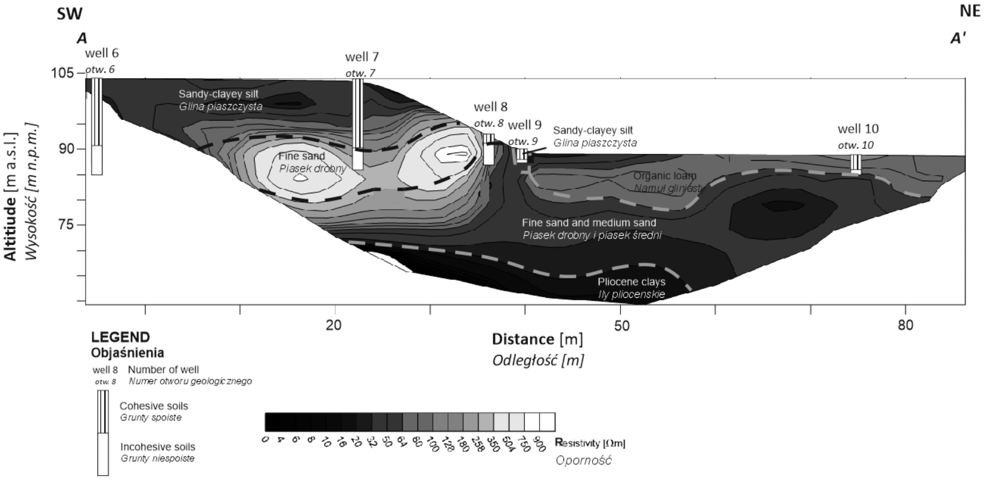

FIGURE 5. Electro resistivity profile cross-section made by st. Kiedacza
RYSUNEK 5. Przekrój elektrooporowy wykonany przy ul. Kiedacza

– Geological layer IV: sandy-clayey silt. The land is situated in the lower part of the slope. Resistance of 20 to 60 Ωm. Thickness up to 4 m.
– Geological layer V: organic loam. These sediments are located at the foot of the slope, which rest on the geological layer III. Thickness about 5 m, resistances from 80 to 100 Ωm.
– Geological layer VI: Pliocene clays. At a depth of 35 m below ground level, under the crest of the slope and about 20 m below ground level, under the foothill. Layer of very small resistances, less than 20 Ωm.

Particularly noteworthy is the presence of highly resistant anomaly in the electrical cross-section: geological layer II. Such area may indicate the occurrence of non-cohesive sediments, periodically watered. They are assumed to be fluvoglacial sands. In addition, underground waterflow may be present below overlay of cohesive composites. This is one of the factors that may affect the development of dynamic movements: the creation of landslides. It is also worth noting the fact of registering a composite geological layer interpreted by the results of ERT survey as Pliocene clays, which had not been drilled with archival drillings and are not present in respective geological cross-sections (Fig. 4).

Analysis of slope stability

Landslide activity in the described portion of the Warsaw slope can be constantly observed. In order to reduce the load on the slope the two-way traffic has been closed on the street running from the base of the slope (st. Orszada). In addition, drainage systems were built and the base of the slope has been reinforced with gabions and a retaining wall. A significant change is the modification of the geometry of the slope in order to reduce of the angle of inclination. Currently, mass movements in most parts of the slope are stopped. However, local surface movements can be observed, which can be derived from:

– Deformation of the tree stand;
– The presence of deluvial and colluvia soils;
– Recent devastation of the construction that reinforces the slope.

In the area shown in the analyzed cross-section, building development is diversified, which is reflected in the load on the slope. Cross-section I is located in the undeveloped area, while the cross-section II is near the road.

The Southern Beltway of Warsaw is meant to go through this area, and therefore in stability calculation the load from vehicles transport has been taken into account at a level of 20 kN at a distance of 3 m from the upper edge of the slope and with a seismic coefficient $K_S = 0.1$. In archival calculations for the cross-sections III and IV, the assumed value of static load caused by building development ranges from 130 to 200 kPa. Values for the safety (stability) factor (*F*) for selected sections of the Warsaw slope are summarized in Table 2. Calculations are based on the Bishop's metod (Bishop, 1955), which is widely used for the numerical analysis of the stability factor for slopes and hillsides (Fredlund and Thode, 2011). An example of the calculation results (safety factor and slip surface) for the cross-section II is presented in the Figure 5. Parameters for numerical calculations are shown in Table 1.

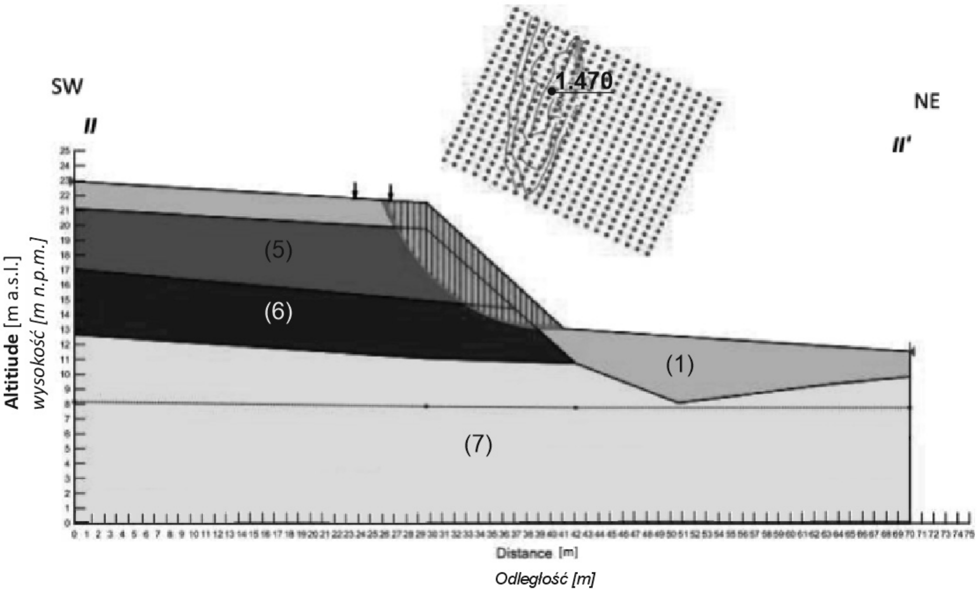

FIGURE 5. The results of stability calculation (safety factor and slip surface) by Bishop method for cross-section II
RYSUNEK 5. Wynik obliczenia stateczności (współczynnik bezpieczeństwa i powierzchnia poślizgu) metodą Bishopa dla przekroju II

TABLE 2. Results of the slope safety evaluation
TABELA 2. Wyniki oceny wskaźników równowagi skarpy

Cross--section number Numer przekroju	Location of analytic cross-section Lokalizacja analizowanego przekroju	Safety factor, *F* (evaluation of slope stability) Wartość współczynnika bezpieczeństwa, *F* (ocena stateczności)	Possibility of a landslide according to Wysokiński (1991) Prawdopodobieństwo powstania osuwiska wg Wysokińskiego (1991)	Source Źródło
I	st. Kiedacza	1.60 (slope is stable)	very unlikely	author calculations
II	st. Płaskowicka (site of the proposed POW)	1.47 (slope is stable)	unlikely	
III	st. Orszady (near the reactivation of the landslide in 2010)	1.07 (slope in state of equilibrium limit)	likely	Mieszkowski, 2012
IV	At the church of Bl. Bojanowski (intersection of st. Kokosowa and st. Orszady)	1.51 (slope is stable)	very unlikely	Koda et al., 2007

Conclusions

Based on the survey and archival materials it can be concluded that under current circumstances the Warsaw slope in the area in question is generally stable, with scarce manifestations of local and seasonal landslide activity. However, safety factor rating obtained by calculations is close to or slightly above ($F > 1$) the equilibrium state which can be described as "unstable". For example, the coefficient ($F = 1.07$) in the vicinity of landslide, which resulted in severe damage to neighboring buildings, indicates a need for constant monitoring. Geomorphology of the area in study is an important factor affecting the stability of the Warsaw slope in the section of Ursynow by determining the rainwater runoff directions and the geometry of the slope: height and inclination angle which has a significant impact on the safety factor. The geological structure does not indicate the presence of low-capacity layers. Stabilized groundwater level is below the base of the slope (Grzelewski et al., 2008), which does not exclude, however, periodic flows within the interbedding section and cracks in the massif of the slope. Performed geophysical study proves that the ERT is a suitable method for comprehensive evaluation of slope stability. The resulting anomalies with elevated values of electrical resistance may suggest an area of potential landslide activity. Another issue in the future will be evaluating the impact of vehicle load in relation to the location of the proposed Southern Beltway of Warsaw (st. Płaskowicka). This issue can be closely examined in in terms of the adopted design solutions, most particularly the drainage of rainwater and geometry of the slope. It should be noted that the variation of the safety factor may be associated with additional load from the buildings located in the impact zone of the slope and dynamic factors related to the intensification of vehicle transport. Positioning the source of additional load (both dynamic and static) too closely to the upper edge of the slope may result in mass movements of the surface: creep type or local activation of landslides.

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Summary

Geomorphological and geophysical analysis of the Warsaw slope stability conditions in the Ursynów district. Reactivation of mass movements in the Warsaw slope, which resulted in a major construction failure of two buildings, indicate a need to update the geomorphologic analysis and evaluation of slope stability in that area. The area is located near the st. Orszady and st. Kiedacza and is at risk due to increase in the development intensity and the future localization of the Southern Beltway of Warsaw. The analysis of slope stability in this study was preceded with a review of the archive for a proper assessment of geological and geo-morphological conditions. Next, measurements by using electrical resistivity tomography were conducted. The final stage of the study are stability calculations of the slope performed in accordance with Bishop's method. The results of this study allowed to evaluate the possibility of a landslide.

Streszczenie

Geomorfologiczna i geofizyczna analiza uwarunkowań stateczności skarpy warszawskiej w rejonie Ursynowa. Reaktywacja procesów osuwiskowych na skarpie warszawskiej, w wyniku których doszło do poważnej awarii konstrukcji dwóch obiektów budowlanych, unaoczniła potrzebę aktualizacji analiz i oceny stateczności skarpy w tym obszarze. Obszar położony przy ulicach Orszady i Kiedacza jest zagrożony na skutek wzrostu wskaźnika intensywności zabudowy, a w przyszłości lokalizacji projektowanej Południowej Obwodnicy Warszawy. Przeprowadzona w niniejszej pracy analiza warunków stateczności skarpy została poprzedzona przeglądem materiałów archiwalnych pod kątem oceny warunków geologicznych oraz geomorfologicznych. Następnie wykonano pomiary tomografią elektrooporową (ERT). Ostatnim etapem prac były ob-

liczenia współczynnika stateczności (F) metodą Bishopa. Rezultaty przeprowadzonych badań pozwoliły na ocenę stopnia zagrożenia procesami osuwiskowymi.

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