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POTENTIAL LANDSLIDE HAZARD IN A ZONE OF STABILISED EARTHEN EMBANKMENTS ILLUSTRATED BY WYSOKA GÓRKA IN CHEŁM

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Abstract. Plant cover is an important element in the management of earthen structures and slopes improving their aesthetic values and limiting their vulnerability to denudation processes. With regard to landslide hazards, an important aspect in the presence of plants is the effect of their root systems on the shear strength of the substrate and, consequently, on slope stability. The aim of the study was to determine the impact of the tree cover at the Wysoka Górka archaeological site on the stability of the earthen embankment on Góra Katedralna in Chełm (Lublin Province). These architectural elements originate from the times of Chełm's glory in the first half of the 13th century, when it became the capital of Halych-Volhynia Duchy and a residence of Prince Danylo Romanovych (Isaiecić 1999).

The research involved identification of the geological structure of the embankment (surveying, measurement of the filtration coefficient) and laboratory determination of the geotechnical parameters of the soil (particle size distribution and soil compressive strength measured in a triaxial compression apparatus). In the next stage of the study, stability was calculated with limit equilibrium methods in the GeoStudio program. Standard calculations of the embankment stabili-

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ty were performed and the stability coefficient for the slope devoid of vegetation and the tree-covered slope were compared assuming zero suction pressure. The shear strength parameters of soil reinforced by plant roots were adopted following the recommendations specified by Hubble *et al.* (2013). The authors performed a probabilistic analysis in order to determine the probability of critical values of the safety factor (<1.0) and comparative stability calculations, taking into account hydrological effects for the tree-covered and tree-devoid (after felling the trees) embankments (Sonnenberg *et al*. 2010, Simon and Collison 2002).

The results of the stability calculations demonstrated that the presence of viable plant roots in the substrate increased slope stability, and the presence of tree stands at the bottom of the embankment appeared to be more favourable. Modelling the slope stability with consideration of the effect of atmospheric factors has shown that the presence of woody vegetation contributed to increased water infiltration into the embankment, resulting in reduction of suction pressure. In turn, tree felling led to reduction in suction pressure due to inhibition of evapotranspiration.

Keywords: landslide, earthen embankment, slope stability

INTRODUCTION

Each investment related to the construction of an earthen embankment should be preceded by thorough geological identification of the substrate and the construction should be carried out with care and due diligence. After completion of the investment, proper operation, regular checks, and dewatering of the embankment structure are essential as well. Formation of landslides within embankment slopes is as common as in the case of the Carpathian slopes or river valleys. Landslides are most frequently caused by unregulated ground and water relations in the substrate, construction of embankments on inappropriate grounds, inadequate densification of embankments, or their excessive inclination (Trojnar 2009).

Plant cover is an important element in the management of earthen structures and slopes improving their aesthetic values and limiting their vulnerability to denudation processes. With regard to landslide hazards, an important aspect of the presence of plants is the effect of their root systems on the substrate shear strength and, consequently, on slope stability. The aim of the study was to determine the impact of the tree cover at the Wysoka Górka archaeological site on the stability of the earthen embankment on Góra Katedralna in Chełm (Lublin Province), in light of the recent damage to the Piłsudski and Kościuszko Mounds in Kraków in 1997.

STUDY AREA

The analysed Wysoka Górka object (archaeological site) is an artificial stone-earthen embankment in the form of a cylindrical mound (relative height approx. 10 m, slope inclination approx. 30°, culmination surface area approx.

25 ares) overlying the culmination of Góra Katedralna (225.4 m a.s.l.) in the south-eastern peripheral part of the Chełm Hills mesoregion (Chałubińska and Wilgat 1954, Fig. 1).

As revealed by previous archaeological investigations, the area used to be a site of pagan worship (Ruszkowska 2000). The surface of the embankment covers the remnants of an early Middle Age settlement with elements of palatial and sacral buildings, ruins of a stone tower, and a stone wall (Buko 2010, Buko *et al*. 2014).

In 2012, a 24-metre long crack appeared at a boundary of an exposed wall and the slope cover. The width of the crack ranges from 5–10 cm (in the eastern part of the slope) to 13–17 cm (in the southern part). The widest crack, i.e. 35-cm wide, has been found in the central part. The average depth of the crack is approx. 9 cm and its maximum value is 77 cm.

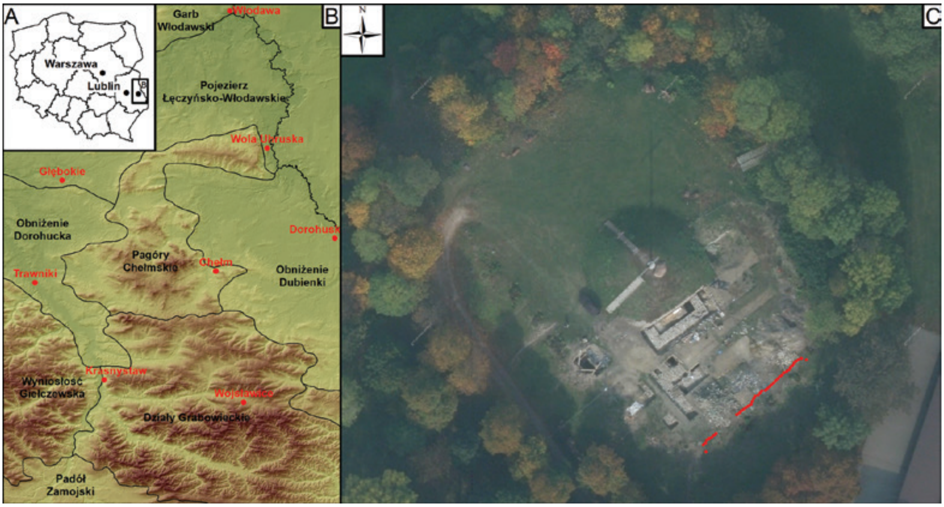

Fig. 1. Location of the crack in the embankment of Wysoka Górka (Wzgórze Katedralne, Chełm, geoportal.gov.pl; C) on the Administrative Map of Poland (A) and the Physiographic Division of Lubelszczyzna (Chałubińska and Wilgat 1954; B)

ARCHAEOLOGICAL CONTEXT OF WYSOKA GÓRKA IN CHEŁM

The early medieval residential and defensive complex in Chełm with the prince’s residence (royal residence from 1253), temples, and bishop’s palace as the main elements, was erected in the 30s of the 13th century. In its north-western part, i.e. the so-called Wysoka Górka, there is a prince’s residence, which has aroused archaeologists’, historians’, and architects’ interest for nearly 100 years (Fig. 2). As described by Jakub Jan Susza, one of the first archaeologists in Poland, the first excavations in Poland were carried out here already in the

17th century, and old walls and human skeletons were uncovered while searching for Christian roots (Pawlak 2014).

Fig. 2. Archaeological excavations in Wysoka Górka (Góra Katedralna, Chełm; photo by M. Bogacki, edited by T. Dzieńkowski)

The research results indicate that the present Wysoka Górka hill is at least a 5-m high anthropogenic embankment covering relics of six stone buildings. The first phase involved construction of a stabilisation-compensation embankment, on which a glauconite sandstone building was erected using the *opus emplectum* technique. The absence of signs of use and the unfinished walls suggest a construction disaster shortly before the completion of the investment. As shown by ^{14}C labelling, reconstruction was undertaken approximately in the mid-13th century. A new phase 2 settlement surrounded by a wood-earth rampart was built on stabilised ground elevated by 2 m. The centre of the settlement, which may have covered a substantially greater area in phase 2, was occupied by a residential-defensive tower explored in 2012 and another stone building. The new building was uncovered in the SW part of the settlement. As indicated by stratigraphic data, its construction was associated with phase 3, when land development had most likely been changed. The intensive use of the place is confirmed by the objects uncovered at the site, i.e. handcrafted rock crystal, silver jewellery, glass bracelets, iron fittings and buckles, coins, stone and metal crosses, as well as thousands of clay vessels.

METHODOLOGY

The research conducted in 2012–13 involved identification of the geological structure of the embankment (surveying, measurement of the filtration coefficient at the archaeological excavation site) and laboratory determination of the geotechnical parameters of the substrate (particle size distribution determined with the laser diffraction method, consistency limits, and soil compressive strength measured with a CIU triaxial test). Strength parameters of the embankment building material were tested using a triaxial test apparatus, multistage tests (CIU TEST) (Hormdee *et al.* 2012). In the first phase of the test, the sample was soaked up to the Skempton parameters equal to 0.95 or above. Consolidation and shear of sample proceeded in triplicates at different effective stress values on one sample. Cohesion equal to 0 kPa can be connected with the high content of sand fraction (40.2%), relatively small content of clay fraction (13.0%), as well as the occurrence of single rock crumbs.

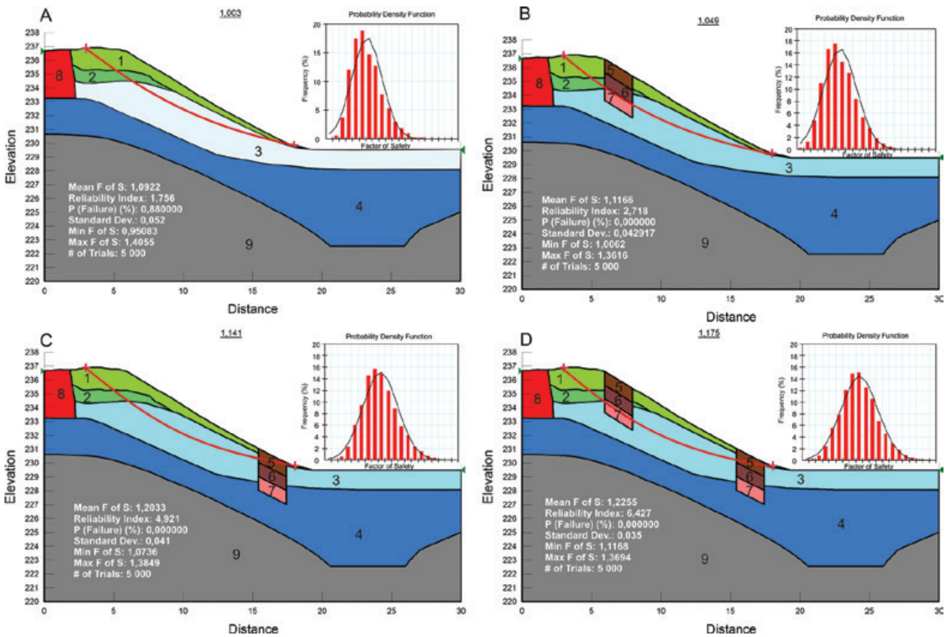

Fig. 3. Probabilistic analysis of the stability of Wysoka Górka in the absence of a tree (A), in the presence of a tree in the top part (B), in the presence of a tree in the bottom part (C), and in the presence of two trees (D). 1–4 – embankment; 5–7 – tree (root system structure); 8 – wall; 9 – cracked chalk rocks

The main part of the study consisted in calculation of stability using limit equilibrium methods in the GeoStudio program. The calculations were performed in three stages.

In the first stage of the analysis, standard calculations of the embankment stability were performed, comparing the stability coefficient for a slope devoid of vegetation and a tree-covered slope and disregarding the impact of suction pressure on the shear strength of the substrate. The analysis was carried out in four variants (Fig. 3):

1) calculations taking into account no plant cover on the embankment,
2) calculations taking into account trees growing at the top of the slope,
3) calculations taking into account trees growing at the bottom of the slope,
4) calculations taking into account trees growing at both the top and the bottom of the slope.

The aim of this part of the analysis was to determine the optimal location of the tree cover on the examined slope, which could potentially be used as a bioengineering treatment for improvement of the balance the analysed earthen structure (Kokutse *et al*. 2016, Bischetti *et al*. 2010).

The strength parameters of the substrate reinforced by plant roots were based on the recommendations specified by Hubble *et al*. (2013), who distinguished three zones of the root impact on the substrate. The authors suggested that roots in the subsurface soil zone reinforce the soil by 10 kPa; in the second zone, the ground reinforcement effect of roots is 5 kPa, whereas the effect is reduced to 2.5 kPa in the deepest zone. It was assumed that the depth of the tree roots was 1.5 m. It was also assumed that the radius of the root system impact around the tree was 1.0 m. This distance is usually recommended (Böhm 1979) in examinations of plant root systems (Table 1).

Table 1. Geotechnical properties used for modelling of Wysoka Górka slope stability

Name	Fraction content [%]			Name acc. to PN-EN 14688-1:2006	Unit weight	Natural moisture content	Plastic limit	Liquid limit	Plasticity index	Filtration coefficient	Cohesion	Internal friction angle
	Sa	Si	Cl		[kN/m^3]	[%]	[%]	[%]	[%]	[m/s]	[kPa]	[°]
embankment 1					19.5					8.50E-06		
embankment 2					20.0					6.50E-06	0.0	
embankment 3					20.5					4.50E-06		
embankment 4	40.2	46.8	13.0	saclSi	21.0	21.7	35.0	52.9	17.9	2.50E-06		26.5
tree 1					19.0					8.50E-05	10.0	
tree 2					19.5					5.50E-05	5.0	
tree 3					20.0					2.50E-05	2.5	

In the second stage, a probabilistic analysis was performed to determine the probability of critical values of the safety factor (<1.0) and the reliability index. Normal distribution of the values of the strength parameters of the substrate and the substrate reinforced by roots was assumed. Three basic parameters were employed for description of the embankment stability: the mean safety factor, probability of stability loss, and reliability index shown in Table 2.

The third part of the analyses consisted in calculations of stability taking into account the hydrological effect for the tree-covered and tree-devoid (after felling the trees) slopes. These calculations included the influence of meteorological conditions (air temperature, air humidity, sum and duration of precipitation, and wind velocity) on changes in the effective stress state in the embankment described with a modified Coulomb-Mohr strength theory (Fredlund *et al*. 1978), taking into account the effect of suction pressure forces on the substrate.

It was assumed in the calculations that the presence of vegetation increases soil water permeability (Sonnerber *et al*. 2010, Simon and Collison 2002). In turn, it was assumed in the analysis of the stability of the slope with cut down trees that the treatment caused decomposition of organic matter (root decay), which contributed to increased soil permeability and to a reduced effect of soil reinforcement with roots. Additionally, meteorological conditions prevailing in the area were used in the analyses. To identify the relationships between the slope stability and meteorological conditions in the region, meteorological data provided by the IMiGW Lublin-Radawiec synoptic station were analysed. The data available on the WeatherOnline website (http://www.weatheronline.pl/weather/maps/current) showed the daily total precipitation, maximum and minimum air temperature measured at a standard height of 2 m above the ground level, and wind speed recorded between January 2011 and the end of March 2013. The data were incorporated in the GeoStudio program as input data, thereby ensuring similarity of the stability analyses to actual conditions. Higher values of annual precipitation totals were noted in 2012 and then, in the preceding year. In 2013, the total precipitation in January, February, and March was substantially higher than in 2011–2012. The highest daily precipitation value, i.e. over 27 mm/day was noted on October 27, 2012. Slightly lower daily sums up to 25 mm were recorded in June 2011. In 2012, the maximum air temperatures were by approx. 0.5 degree higher than in 2011, and the highest temperatures recorded that year in July and August exceeded 33°C.

RESULTS

The results of stability calculations performed in the first stage of the analysis showed that the slope without plant cover was characterised by a safety factor of 1.003. Slightly more favourable stability conditions were revealed in the variant with the presence of trees in the top part of the embankment (FS=1.049). The stability coefficient in the case of the presence of trees at the bottom of the embankment was 1.141. In turn, the stability coefficient for the slope with trees growing in its upper and lower parts was the highest, i.e. 1.175. The results indicate that, from a mechanical point of view, the most effective impact of vegetation cover on slope stability is noted when plants are located at the bottom of the slope. This is related to the fact that the most unfavourable slide plane in the bottom part of the slope was located in the upper part of the soil profile characterised by the highest root density, i.e. in a zone with the greatest impact of roots on soil shear strength. However, it should be noted that the values of the safety factor obtained for each calculation variant do not largely exceed 1.0. This implies that the embankment is in a state of limit equilibrium; therefore, a slight change in the stress or slightly worse strength properties of the substrate may contribute to loss of stability of the analysed earthen structure.

Table 2. Safety level of the building with reference to the safety index value (U.S. Army Corps of Engineers 1999)

Building construction	Reliability index (safety) β
High	5
Good	4
Above average	3
Below average	2.5
Poor	2
Unsatisfactory	1.5
Risky	2

As in the case of previous analysis, the probabilistic stability calculations showed the most unfavourable equilibrium conditions in the case of the vegetation-devoid slope. The value of the safety factor in this case was 1.76, which indicated that the safety of the structure is at a level between poor and unsatisfactory (see Table 2) although the mean value of the stability coefficient was 1.09.

The calculated probability of stability loss was 0.9%. In the remaining cases, the reliability index ranged from 2.8 (a tree in the top part of the embankment) to 6.4 (the slope with trees in the top and bottom part); the probability of loss of stability in each case was zero. Therefore, the results of the investigations indicate that the presence of vegetation cover on the embankment does not impair its stability; they also suggest that the structure of the embankment is not appropriate, as the safety factor is lower than 1.3, which corresponds to values recommended for hydrotechnical embankments. It should be noted, however, that the strength criterion adopted for the analysis presented above actually takes into account two soil stress states: waterlogged ground and fully saturated ground above the water table. In the analysed object, there was no groundwater table in the immediate vicinity of the earthen embankment structure and no excessive humidification of the substrate, which could indicate its saturation even in the most unfavourable conditions prevailing during the field observations.

Therefore, the further analyses included the strength criterion for unsaturated substrate, which reflects changes in the substrate stresses accompanying changes in the substrate moisture caused by atmospheric factors or fluctuations in the groundwater table. Stability was calculated for the period between January 01, 2011 and March 31, 2013, when the cracks in the embankment structure were noted. The calculation results revealed that the felling of the trees on the embankment had an impact primarily on the humidity conditions (suction pressure distribution) in the surface ground layer (Fig. 4 and 5), which is mainly associated with limitation of the evapotranspiration process.

The stability analysis performed in the third part of the study took into account the influence of meteorological phenomena on water circulation within the embankment. Compared to previous calculations, the influence of suction pressure on the shear strength of the substrate was included. The results of the calculations showed that the felling of the trees on the embankment mainly contributed to changes in the humidity conditions (suction pressure distribution) in the surface soil layer (Fig. 4 and 5), which is mainly associated with limitation of the evapotranspiration process.

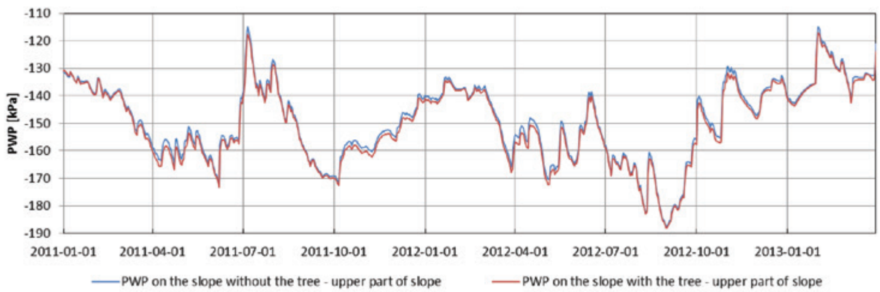

Fig. 4. Distribution of pore water pressure (PWP) in the tree-covered and tree-devoid embankments. Measurement in the top part of the embankment according to the Vadose/W model

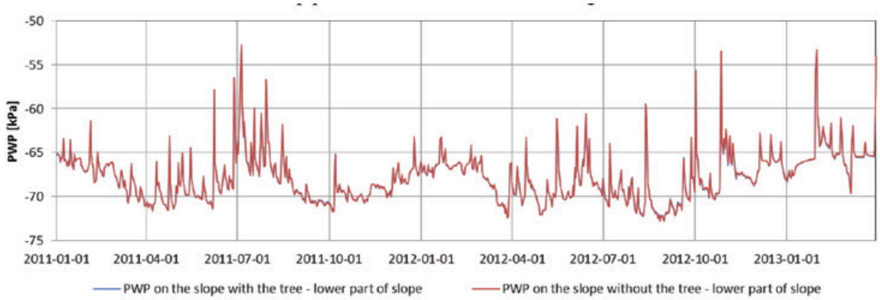

Fig. 5. Distribution of pore water pressure (PWP) in the tree-covered and tree-devoid embankments. Measurement in the bottom part of the embankment according to the Vadose/W model

The stability calculations did not reveal any significant effect of the slope cover on the stability, mainly because the most unfavourable slide plane determined by the Slope/W program was located deep. In the analysed period of observations, the lowest value of the safety factor was 2.96 in the case of the tree-covered embankment and 2.95 for the embankment deprived of the plant cover (Fig. 6). The lowest safety factor values coincided with the probable period of ground cracking (autumn 2012 and spring 2012).

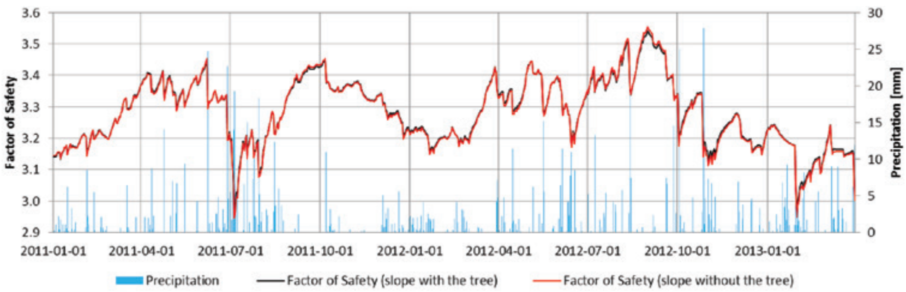

Fig. 6. Distribution of the stability coefficient of the slope in the eastern part of Wysoka Górka in relation to the precipitation sum

CONCLUSIONS

The results of the stability calculations have shown that the presence of plant roots in the ground increases slope stability and the location of trees in the bottom part of the embankment is more favourable. Modelling of the slope stability, based on the effect of atmospheric conditions, has demonstrated that the presence of the tree cover increased water infiltration into the embankment, resulting in reduction of suction pressure due to limitation of the evapotranspiration process. The amplitude of changes in the suction pressure in the top part of the object is four-fold greater than that in the bottom part (74kPa/20kPa) in the measurement period. The differences in the suction pressure values on the tree-covered and tree-devoid embankments are on average only 1.5 kPa. The infiltration flow calculations have shown that infiltration of precipitation water into the embankment is a rapid process and does not promote water retention within the embankment. More unfavourable suction pressure values are noted in winter (Fig. 4 and 5), which is associated with water retention in the ground.

The stability calculations have shown a significant influence of suction pressure on the results of the safety factor calculations. The minimum FS values obtained with the classical strength theory were close to 1.0, whereas the lowest stability coefficient values obtained with the strength theory of unsaturated substrates were approx. 2.9. Therefore, it can be concluded that the analysis did not show a significant adverse effect of tree felling on the stability conditions of the Wysoka Górka archaeological site.

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