

THE PROBLEM OF CHOOSING AN EFFECTIVE ROAD STABILIZATION METHOD ON BUILT-UP LANDSLIDE AREAS

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ABSTRACT

The aim of the article was to present feasible and effective road stabilization method on built-up landslide areas. The study has involved a landslide area situated in a designated municipality of Nowy Sącz district, in the Małopolska region. In the studied area, in the lower part of the slope, a landslide has formed, through which a road is running, leading to residential and farm buildings located further up. Bearing in mind the economic aspect, whereas also looking for the most effective way to stabilize the road in the studied area, we have analysed a number of possible technical solutions, which included: a French drain, anchor micropiles with reinforced concrete top plate, and ground anchors. The stability coefficient of the stabilized landslide has been chosen as the indicator of the effectiveness of the applied technical solution, which should take the value of no less than 1.5 after landslide stabilization. Based on the calculations we have conducted, we can conclude that the French drain is not sufficient, and neither is using the anchor micropiles on their own. Only a combination of these two solutions, along with additional anchoring, provides an effective protection of the area.

Keywords: Carpathian flysch, landslide, slope stabilization, stability analysis

INTRODUCTION

The surface movements are the most common geodynamic threats, often having the characteristics of a natural disaster. They include various processes and phenomena whose common feature is the destruction of the existing geological structures, and moving them down the slope under the influence of gravity forces. The occurrence and intensity of the processes that take place depends on the interaction between geo-environmental conditions and the factors initiating and supporting their proliferation. The results of the mass movements are the changes in the relief of the terrain, the destruction of buildings, roads, as well as other elements of technical infrastructure that

are found within the range of these processes. Mass movements and their effects pose a serious threat not only to all types of buildings and structures, including hydro-technical structures, but also to the integrity of communication routes. They occur mainly on mountain slopes, on the slopes of river valleys, on steep shores of lakes, and on the coast of seas. Landslides in Poland occur mainly in the area of the Polish Flysch Carpathians, less often in the Sudety (Sudeten) Mountains, the highlands, and the coastal belt (Barański, 1978). According to the data quoted in subject literature (Bronowski et al., 2016) over 39 thousand landslides have been observed on the Polish side of the Western Carpathians. The number of landslides, the activity of which used to be slight,

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increased significantly over the last 20 years. The main reason for their renewed activity lies in the intense precipitation and fluctuations in the level of groundwater (Starkel, 2006) (Wójcik et al., 2006). Landslides pose a serious problem for the economy. Communication routes, high-voltage lines, gas pipelines and other transmission lines are particularly at risk. Landslide processes, apart from changes in the terrain, cause very significant losses, which can be described as economic and social costs. Economic losses may be direct if they involve financial losses resulting from the damage or complete destruction of infrastructure elements as well as the destruction of agricultural crops and forest resources. Indirect economic losses result from the necessity of incurring additional costs related to the extension of travel time due to detours or traffic obstructions on the damaged road sections, the need to provide substitute utilities for the duration of repairing electricity networks, gas pipelines, waterworks etc. Social losses are also very grave, and they may include diseases such as myocardial infarction (heart attack), neurosis and depression, often associated with the destruction of livelihood and all possessions.

In the present article, the analysis of selected technical solutions was undertaken, related to the problem of the most effective way of securing the slope of the

landslide, which was created in the embankment of the access road to residential buildings. The landslide crossed the municipal road, and its further progression might cause the complete destruction of that road. Economic human activity and periodically intensive rainfall caused additional imbalances within the landslide in question. Taking into account the economic aspect, whereas finding the most effective way possible of stabilizing the road in the studied area, the application of several technical solutions has been considered and analysed, including French drainage, anchor micropiles topped with reinforced concrete cap, and ground anchors. As an indicator of the effectiveness of the technical solution used, the stability coefficient was taken into account, the value of which should not be less than 1.5.

CHARACTERISTICS OF THE LANDSLIDE AREA UNDER ANALYSIS

The studied area is located in the village of Popardowa, in the Nawojowa municipality, within the Nowy Sącz district of the Małopolska region (see: Figure 1). The embankment is located in the area of the Popardowa Wyzyna hamlet, and it crosses the municipal road between Frycowa and Popardowa at kilometre 1+850 – 2+040. The landslide has formed



Fig. 1. Location of the landslide (Google Maps)

at the bottom of the slope, and it reaches the riverbed of a stream of no name, which is a right-bank tributary of the Kamienica Nawojowska River. The landslide has the length of about 35 m and a width of about 70 m.

The landslide begins with an escarpment of about 2 metres, on the section between buildings No. 66 and 78. Below the landslide slope, the surface is clearly irregular (undulating), there are numerous depressions and bumps as well as small slopes and cracks. Within the colluvium, small outflows and wetlands are visible. The road running within the analysed landslide area belongs to the “L” class roads (see: Figure 2).



Fig. 2. View of the landslide area

Based on geological and engineering documentation (Prokopczuk and Krok, 2012) and on the analysis of archival materials, it was found that the studied area is composed of sedimentary rocks of the Cretaceous and Paleogene eras, consisting of alternating sandstones and shales, that is, typical flysch formations. The landslide is located within the area of the Magura nappe in the Outer Carpathians. Narrow banks of sandstones and shales of the Eocene and the Paleocene-Eocene inseparable hieroglyphic layers occur within the substrate of the escarpment. Also found were grey clay shales and fine grey-coloured sandstones. Sandstone shoals have a thickness of up to 10 cm, while shoals of shale have a thickness of

up to several dozen centimetres. In the area of the slope, the Paleogene deposits of the deeper substrate are covered with Quaternary sediments, developed in the form of aerosols outside the area of landslides as well as debris and colluvial clay. Colluvial deposits are mainly clayey shale debris, sandstone-shale and sandstone debris as well as whole sandstone and slate packages. The thickness of these forms is considerable, and it ranges from 1.7 m in the stream bed in the lower part of the landslide to approx. 13.4–14.3 m in the middle part and 12.7 m in the upper part of the landslide. Within the colluvial formations, a number of distinct slip planes were observed as well as small reflections among the shale fragments. The surface of the slip in the analysed landslide is the surface of the roof of the shale rock interstices on which a layer of groundwater accumulates. This water causes excessive waterlogging of the loamy rubble of the weathering cover, leading to the loss of their cohesion, and to downhill movement. Based on the geological and engineering documentation, four possible courses of slip (sliding) planes were designated, marked A, A', B, and B' respectively (see: Figure 3), for which a lateral stability analysis was carried out further in the present study. For the calculations, the values of physical and mechanical parameters of the soil were used, designated for the needs of the geological and engineering documentation (Prokopczuk and Krok, 2012), the summary of which is presented Table 1.

Table 1. Selected geotechnical parameters of loam rubble soils

Parameter	Symbol	Value
Bulk density [$\text{g} \cdot \text{cm}^{-3}$]	ρ	2.12
Angle of internal friction [°]	φ	10.0* (13.0**)
Cohesion [kPa]	c	7.0* (13.0**)

* for sliding planes A and A'

** for sliding planes B and B'

[source: Prokopczuk and Krok 2012]

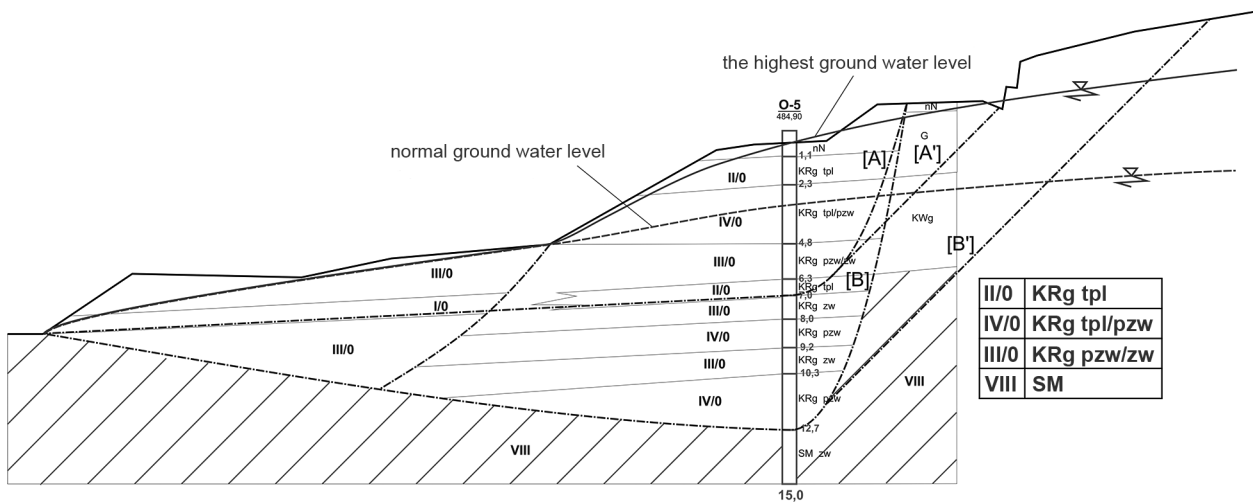


Fig. 3. Landslide cross section with designated sliding surfaces A, A', B, B'

DESCRIPTION OF SELECTED METHODS OF LANDSLIDE STABILISATION

Corrective actions taken in the event of disturbance of the slope's stability should first of all eliminate the causes that have led to the threat. When designing reinforcements, it is necessary to consider, as far as possible, all extreme situations and impacts that could arise during their operation. In order to improve the stability of the landslide, it is first and foremost necessary to regulate the water conditions, and to eliminate the possibility of accumulation of water within the escarpment. Reinforcements should be selected, taking into account the geological conditions, the height of the slope, possible inflow of water from the surroundings, and possible shocks (Barański, 1978).

The following technical solutions have been proposed for the particular road on the landslide described herein: water drainage located in the lower part of the landslide, which is to be implemented by means of filtration abutments (see: Figure 4), additionally supported by a French drain located under the reinforced concrete top plate. The top plate itself, enclosed on the outside with gabion baskets, has been placed in direct contact with the access road, and founded on micropiles. As a support element, ground anchors were used, passing at a proper angle through the said top plate (see: Figure 5). The influence of each of these systems has been analysed separately in terms of changes to the stability factor, which is presented in the following sections of this article.

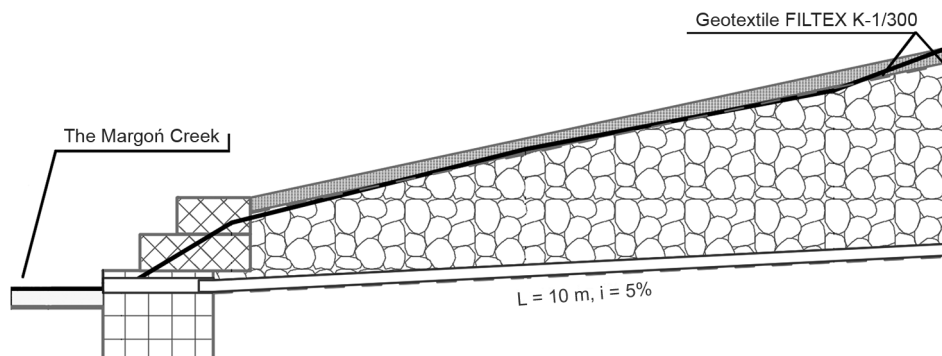


Fig. 4. Filtration abutment at the toe of the slope

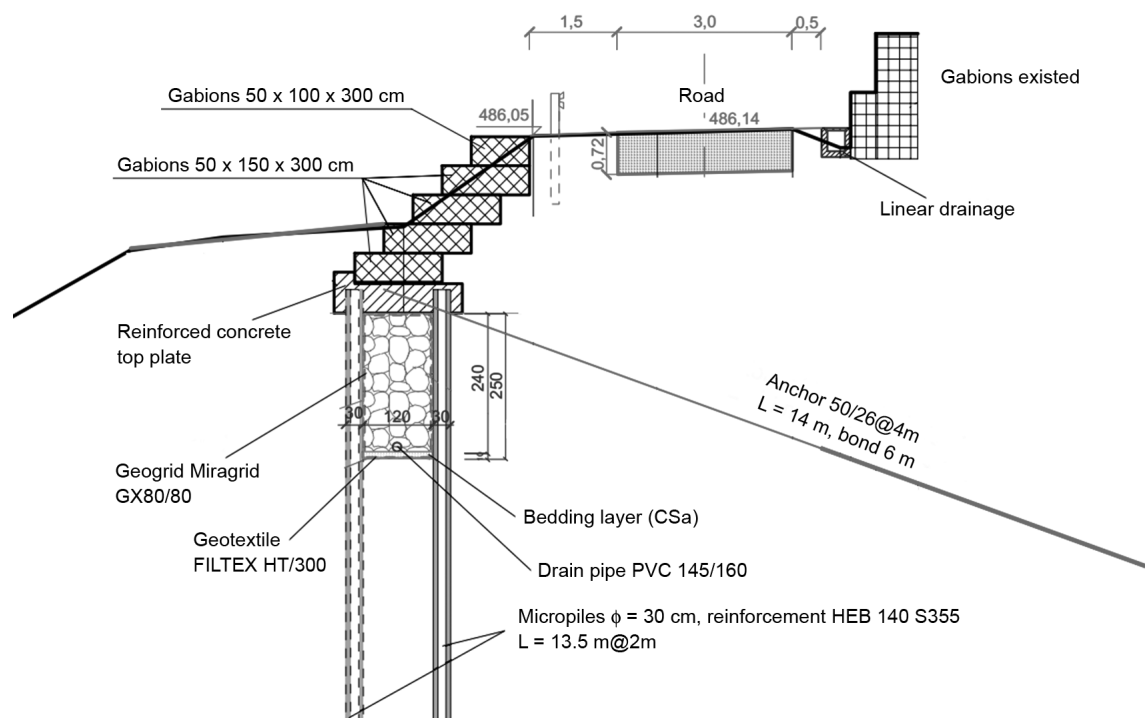


Fig. 5. Reinforcement used in vicinity of the road

Because the technical condition of the road in question did not allow temporary reinforcement while maintaining the existing structure, it was first necessary to dismantle and modify the foundation.

It should be noted at this point that one of the major problems occurring within the communication network running through landslide areas, which have already experienced deformation of the rock mass, is the extensive destruction of the road foundation structure along with the wear layer and accompanying infrastructure (for instance, displacement of the road barrier). Therefore, in most cases there is no justification for introducing only landslide reinforcements without comprehensive modernization of the road lane together with the accompanying infrastructure. This of course impacts the costs of the entire undertaking. In the case of landslides, the optimum technical solution would be to use a technology that combines soil stabilization with its protection, along with surface water and deep-water drainage, and with a simultaneous structural strengthening that meets the requirements of landscape architecture and environmental protection.

THE CHARACTERISTICS OF SELECTED METHODS OF STABILITY ANALYSIS

The stability coefficient is a measure of slope stability. Because the value of this parameter determines the efficiency (and the correctness) of the reinforcement structure, it should be noted that obtaining the value of this parameter according to the appropriate calculation algorithm will be decisive to the acceptance, modification or rejection of a given design solution. In a sense, this problem is related to the very method of calculating the stability coefficient, which should, as closely as possible, take into account the mechanism of loss of stability and thus lead to obtaining the most accurate value of the stability coefficient. The infiltration of rainwater and its impact on the water flow conditions in the soil profile (soil saturation status) also play an important role (Zydroń, 2016). Unfortunately, in most cases, the total reconstruction of the mechanism and the path of landslides remain unattainable, and the real process that accompanies it is drastically simplified and – according to some researchers (Zabuski et al., 2009) – it can even be erroneously consid-

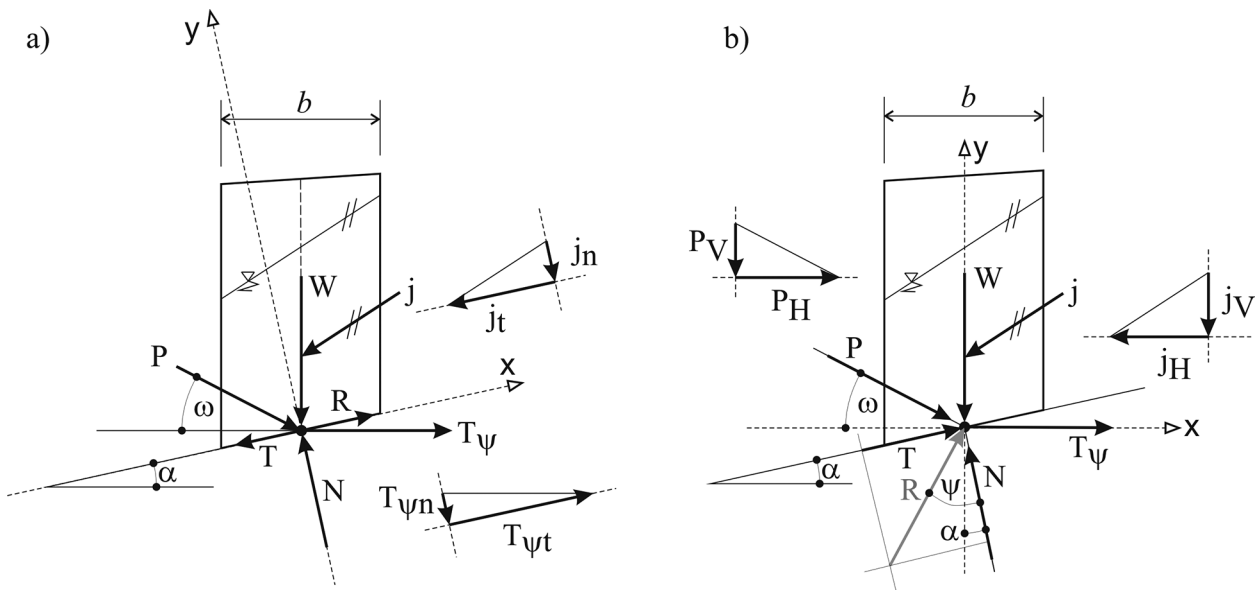


Fig. 6. Group of forces acting on the designated soil slice in the methods: a) M-P, b) M-B

ered. Two methods of slices (developed on the basis of border equilibrium) were used for the calculations: the Morgenstern-Price method (M-P) (Morgenstern and Price, 1965) along with the modification (Zhu et al., 2005) and the Maslov-Berer method (M-B) (Sozański, 1977). The choice of methods was dictated by the fact that in the analysed landslide, the course of the slip surfaces (slide planes) is non-circular, which made it impossible to use such popular methods as the Fellenius method, or the Bishop method. It should also be mentioned that the methods used are two computational systems that are at extreme ends of the spectrum from the perspective of theory. The M-B method is a simple one in terms of application, leading to a solution without the need to resort to iterative techniques or specialized calculation software. The M-P method is a complicated one, requiring the use of an iterative mechanism and adequate filtering of the obtained results (Baran et al., 2013), therefore it is difficult to use it without a proper calculation tool. As part of this article, we have limited ourselves to writing out key equations (1 ÷ 4) for driving and the resisting forces, modified to the form that would take into account the applied stabilization techniques. On the basis of these equations, the target equations for particular methods have been developed, and some insights were included in the analysis of the calculation results.

For the Morgenstern-Price method, resisting forces (R) according to (1) and the driving forces (T) according to (2) are determined by adopting a local coordinate system anchored in the centre of the slice base and rotated so that the horizontal axis is parallel to its base (see: Figure 6a). This leads to this direction being called the tangent (projections of appropriate forces in the index are given the symbol “ t ”), in contrast to the standard or normal direction to the base of the slice (the “ n ” index):

$$R = [W \cos \alpha + P \sin (\omega + \alpha) + T_{\psi n} + j_n] \tan \phi + (1) \\ + cb \sec \alpha + T_{\psi t}$$

$$T = W \sin \alpha - P \cos (\omega + \alpha) + j_t (2)$$

The Maslov-Berer method assumes that the reference system is anchored in the middle of the slice’s base and is classically oriented (see: Figure 6b), hence the vertical force projections receive the “ V ” index, and the horizontal ones, the “ H ” index, according to (3) and (4):

$$R = (W + j_V) \tan \alpha - (W + P_V) \tan (\alpha - \psi) + T_{\psi} (3)$$

$$T = W \tan \alpha - P_H + j_H (4)$$

where:

- W – weight of the slice,
- P – force at the anchor,
- j – flow pressure,
- T_{ψ} – holding force from micropiles,
- ω – anchor insertion angle relative to the level,
- ϕ – angle of the internal friction of the ground in the slip plane,
- c – soil cohesion (consistency) in the slip plane,
- α – inclination angle of the base of the slice,
- ψ – substitute angle of the internal friction of the ground in the slip plane,
- b – width of the slice.

RESULTS AND DISCUSSION

Having obtained the courses of the slip planes and the values of the relevant physical and mechanical parameters, calculations of the stability coefficient for different variants of the applied reinforcements were performed. The calculations were based on the equations of the M-P and M-B methods, using the Scilab (www.scilab.org), a free-of-charge environment for numerical calculations. The results of these calculations were summarized in table 2. When analysing the obtained values, one will immediately notice the fact of a significant increase in the value of the calculated coefficient due to the draining of the area, for both calculation methods.

Table 2. Calculated values of stability coefficient

Sliding plane	Maslov-Berer method			Morgenstern-Price method		
	without drainage orstabilization*	with drainage without stabilization	with drainage and stabilization	without drainage orstabilization	with drainage without stabilization	with drainage and stabilization
A	0.955	1.384	2.772	0.957	1.666	3.318
A'	0.967	1.371	2.764	0.985	1.420	2.824
B	0.962	1.273	1.955	0.955	1.777	3.020
B'	0.976	1.174	1.694	0.997	1.088	1.595

* stabilization = micropiles and ground anchor application

This is caused by the hydrodynamic pressure. It should be remembered that from the point of view of the theory, the hydrodynamic pressure is directly proportional to the hydraulic head (slope) and the volume of soil on which it is acting. Thus, halving the hydraulic head causes a change in the hydrodynamic pressure, reducing it by half. If the position of the filtration curve is reduced (lowered) along with the reduction of the hydraulic head, these two changes, when overlapping, cause a significant decrease in the hydrodynamic pressure (see: Figure 7). Since in both the M-P and M-B methods, the factor of the hydrodynamic pressure had been used, this has led to the corresponding, visible change in the stability coefficients before and after the application of drainage. The only deviation from this correlation was recorded in the case of the slip curve B'. When analysing the diagram (see: Figure 7), it can be concluded that due to a significant decrease in the filtration curve (greater hydraulic head) in the area of slices No. 1 through No. 4, there is a significant increase in the hydrodynamic pressure, hence as a result of lowering the water table in the remaining part of the slope, the aforementioned stability coefficient has not increased much.

In the regulation by the Minister of Transport and Maritime Economy of March 2, 1999 (Journal of Laws, item 43, 430), regarding technical conditions, which should be met by public roads and their location, paragraph §144 passage 2 states that the stability coefficient should not be less than 1.5. According to the guidelines (Wysokiński, 1991), the probability of a landslide can be determined on the basis of the obtained value of the said coefficient. Therefore, corrective actions on landslides as well as on the technical infrastructure located in such areas must be designed so that after appropriate reinforcements are introduced, the said coefficient must be not less than 1.5. As can be observed (see: Table 2), the use of drainage alone in the case of slip curves A and B facilitates obtaining the appropriate stability coefficient acquired by the M-P method. The M-B method in this case is more rigorous. In the case of slip planes A' and B', the stability coefficient calculations, performed with both the M-P and M-B method, emphasize the need for additional stabilization operations on the landslide. Because the slip plane B' is the longest one, which is accompanied by a considerable landslide capacity in

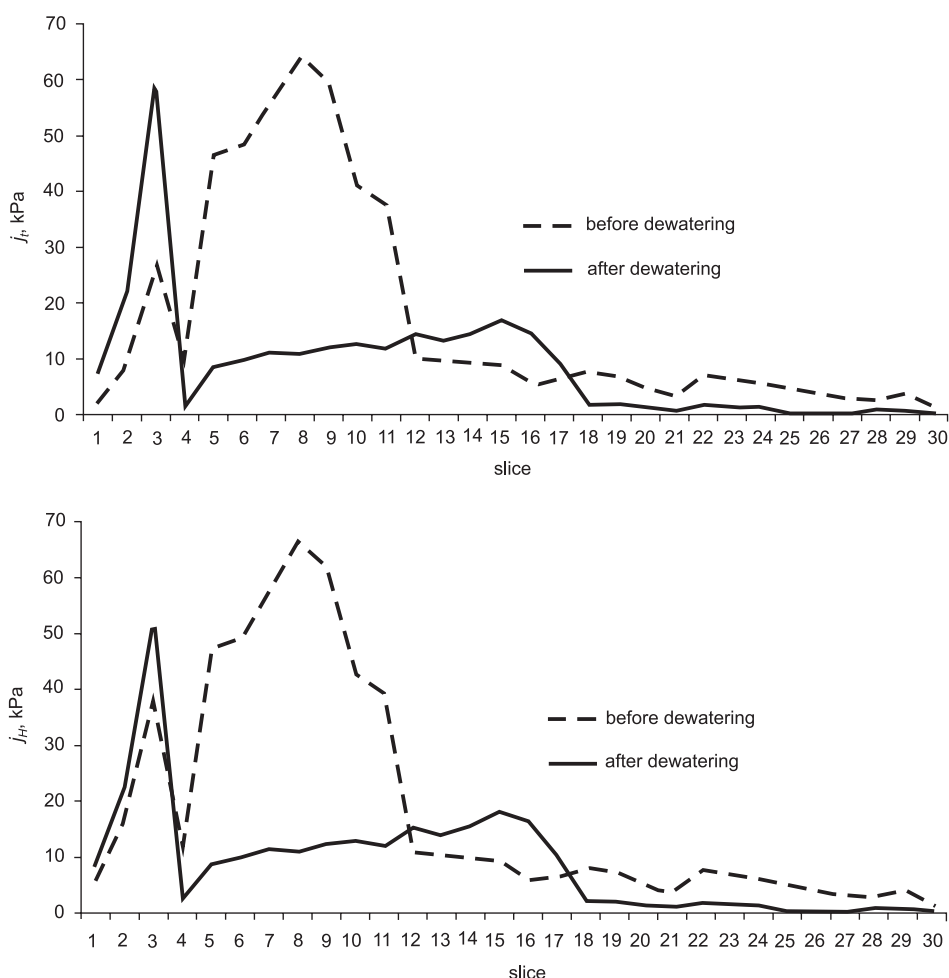


Fig. 7. Change of tangent (j_t) and horizontal (j_H) hydrodynamic pressure components before and after draining, according to the M-P method

terms of volume and weight, hence the target for this plane was the verification of the used protection and stabilizing solutions.

CONCLUSIONS

1. After heavy rainfall or thaw, the landslide loses its stability, and we are dealing with complete soil waterlogging (catastrophic state), as indicated by the stability coefficient values. In this state, the escarpment does not satisfy the stability condition for any of the adopted variants of the curve, and this will result in increasing landslide activity and in the destruction of the road running over the escarpment.
2. In the authors' opinion, the slip plane analysed as B' is the least favourable, since in this case the stability coefficient according to both methods, after the drainage has been applied, takes the lowest values.
3. Surface and deep drainage combined do not constitute a sufficient solution that would prevent the escarpment from sliding. In the Maslow-Berer method, the standard stability condition is not met for any of the slip curves, whereas in the Morgenstern-Price method for curves A and B, it can not be unambiguously stated that lowering the water table by means of drainage will maintain the balance of the analysed slope.

4. Appropriate protection of the landslide in question is possible by means of combined techniques – drainage, anchoring and the introduction of micropiles. This is confirmed by calculations using both the Maslov-Berer and Morgenstern-Price methods.
5. The use of anchoring of the top plate is necessary in order to provide an additional support thereof, and also due to the occurrence of additional forces binding the rock mass.

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PROBLEM WYBORU SKUTECZNEJ METODY STABILIZACJI DRÓG NA ZABUDOWANYCH OBSZARACH OSUWISKOWYCH

ABSTRAKT

Celem artykułu było przedstawienie możliwie najkorzystniejszej metody stabilizacji dróg na zabudowanych obszarach osuwiskowych. Przedmiotem badań został objęty obszar osuwiskowy, znajdujący się w wybranej gminie powiatu nowosądeckiego – województwo małopolskie. Na przedmiotowym obszarze utworzyło się w dolnej części stoku osuwisko, przez które przebiega droga, prowadząca do położonych wyżej obiektów mieszkalnych i gospodarczych. Mając na względzie aspekt ekonomiczny, przy jednoczesnym możliwie skutecznym sposobie stabilizacji drogi na badanym terenie, przeanalizowano zastosowanie kilku rozwiązań technicznych do których należały: drenaż francuski, mikropale kotwiące zwieńczone oczepem żelbetowym oraz kotwy gruntowe. Jako wskaźnik skuteczności zastosowanego rozwiązania technicznego wzięto pod

uwagę współczynnik stateczności stabilizowanego osuwiska, którego wartość nie powinna być mniejsza niż 1,5 po stabilizacji osuwiska. Na podstawie przeprowadzonych obliczeń stwierdzono, że drenaż francuski nie jest wystarczającym rozwiązaniem, tak samo jak zastosowanie samych mikropali kotwiących. Dopiero połączenie wspomnianych rozwiązań wraz z zastosowaniem dodatkowego kotwienia pozwala na skuteczną ochronę tego terenu.

Słowa kluczowe: flisz karpacki, osuwisko, stabilizacja skarp, analiza stateczności