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PROTECTING INFRASTRUCTURE LINES FROM INCREASING GEOTECHNICAL RISKS DUE TO CLIMATE CHANGE IN HUNGARY

Fruzsina Kápolnainé Nagy-Göde, Balázs Vásárhelyi, Ákos Török
[1] *Budapest University of Technology and Economics, Faculty of Civil Engineering, Hungary*

Abstract

Nowadays, the increasing weather extremes represent a potential daily hazard for roads and railway lines. Due to increasing traffic volumes, we encounter challenges during the design of new roads and road widening works that may require rock excavation. However, in Hungary's soft, highly fragmented rock environment, weather conditions significantly weaken the mechanical properties of rock walls. Therefore, laboratory rock tests representing weathering effects are essential for determining the feasible slope angle and designing the necessary reinforcement. Another characteristic risk category for infrastructure in Hungary is that many transport routes run along coastal areas prone to surface movement. In recent years, rainfall-induced landslides have repeatedly blocked roads along the shores of the Danube and Lake Balaton, making travel impossible. In addition to installing safety systems on high banks, we strive to minimize damage and make progress in predicting movements by operating and analyzing monitoring systems. The study provides examples and solution strategies from Hungary for these two types of infrastructure threats, highlighting that climatic hazards are increasingly exacerbating the fact that road and railway construction and maintenance tasks go hand in hand with geotechnical and engineering geological challenges. In the case of rock wall excavation necessary for road widening, the research methodology is based on empirical SMR and Q-Slope methods, laboratory testing of rock samples includes mechanical testing of air-dry, saturated, and freeze-thaw cycled samples, based on which a functional relationship helps to determine the safe slope angle on site during construction. The high bank analysis presents the identification and validation of the shear zone threatening the railway line and its surroundings in the event of extremely slow surface movement on the shore of Lake Balaton through LEM, VEM and probabilistic stability analysis modelling and inclinometer measurements, which is analyzed in conjunction with rainfall data series to develop a protection strategy.

Keywords: climate change, geotechnical hazards, laboratory tests, stability analysis, in situ examinations

1 Introduction

The strategic protection of road networks from natural hazards is a crucial and relevant field of research, in line with efforts to optimize traffic and costs in road network operations [1], which represents a significant manifestation of cooperation between road engineers and geotechnical engineers. Landslides are becoming increasingly common worldwide, mainly due to changing weather conditions caused by climate change, heavy rainfall [2], and increasing human intervention [3].

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Scientific research has significantly increased over the last 20 years in relation to the slow slope movements, the acceleration of which is typically related to precipitation events. The topic has been receiving increasing attention since 2013. In addition, the number of publications on the subject in 2024 was more than ten times higher than in 2004 [4]. According to global analysis, increasingly frequent surface movement events claim countless human lives and cause billions of dollars in material damage [5]. Arup company conducted a global assessment of landslide risk on behalf of the World Bank and GFDRR (Global Facility for Disaster Reduction and Recovery) using landslide susceptibility data provided by NASA and an innovative machine learning model for the period 1980 to 2018. They estimated that the average annual number of rainfall-induced landslides is increasing by 1-2% per year [6]. Before the 2000s, there were around 300, 000 rainfall-induced landslides worldwide each year, but by 2018, this number had risen to 600, 000. The average annual number of slope movements caused by precipitation in Hungary is 40, which, given the country's topography and size, highlights the relevance of this issue. The greatest danger of climate change in terms of geology is that precipitation is increasingly falling in short, intense showers and thunderstorms, and the number of days with unprecedented amounts of precipitation and the length of dry periods are increasing. In Hungary, the number of rainy days per year is ~17 days less than it was at the beginning of the 20th century [7]. In Hungary, we have recorded more than 2, 000 surface movement events affecting 28% of settlements. More than 10% of the country's road and rail network runs through areas at risk of movement [8]. Figure 1 is a recent example from Hungary, where in 2022, landslide in the Danube Bend made land transport completely impossible, forcing travelers to take the route by boat.

Figure 1 The landslide that covered the railway tracks and main road in the Danube Bend in 2022 [9]

2 Site descriptions

The surface geology of Hungary is dominated by soils, but there are also smaller areas of carbonate and volcanic rocks on the surface. However, these are mostly mechanically weak and fragmented, making them highly susceptible to weathering. The paper presents a volcanic rock environment and a sedimentary sequence.

2.1 Northern Hungary – first-class main road (21) to Slovakia

The site of the first case study is a part of first class national main road 21 in northern Hungary. The road section runs through the Zagyva Valley, in the northeastern part of the Mátra Mountains, with the Cserhát Hills to the west. Main road 21 is an important transit and border crossing route towards Slovakia. Polish tourist traffic also uses this road to reach the Adriatic Sea. It connects to the M3 motorway, an important international east-west transit route. (i.e. the M3-M1 line).

Among other things, these factors justified the expansion to four lanes a few years ago. During the expansion of Route 21, significant rock mechanics problems were encountered on the section between Tar and Mátraverebély, where it became necessary to construct a rock cut exceeding 20 meters in height locally. The main reason for the difficulties encountered on the section under investigation is that the main road approaches the Zagyva River, so due to the instability risks posed by the proximity of water, widening towards the rock face/ cutting seems to be safer and more cost-effective. This intervention results in a steep and high slope, at least in Hungarian terms. (At the most critical planned section, this means approximately 65° and a height of 23 meters.) The risk is increased by the extremely soft and fragmented rock environment. The area is mainly characterized by Miocene volcanic formations, which are the result of active volcanic activity in the region 20-11 million years ago, while the areas near the Zagyva River are covered by Neogene and Upper Pleistocene-Holocene sediments. The immediate surroundings of the sample area are characterized by the Dacite Tuff Formation of Tar and Andesite Formations of Nagyhársas. Figure 2 shows this soft, fragmented rock environment during the initial stage of rock excavation.

Figure 2 Soft rock environment at the widening of the main road 21, Hungary

2.2 Central Transdanubia - railway line in the eastern basin of Lake Balaton

Lake Balaton is Hungary's most important tourist region and destination besides Budapest. The railway runs around the lake on a single track, which makes it difficult to replace with other means of transport, making it an extremely important route. However, in many places it runs along high banks that are prone to landslides. The eastern basin is the part of the lake shore most endangered by the movements. The case study presented below also takes place in this area, specifically in the urban area of Balatonakarattya, where the most memorable Hungarian landslide occurred more than 100 years ago, in May 1914, when a passenger train was pushed into Lake Balaton (figure 3) by collapsing earth. Thanks to the train driver's appropriate reflexes and well-timed braking, all 180 passengers survived the accident.

Figure 3 Railway accident caused by landslide on the shore of Lake Balaton in 1914 [10]

Before and after this memorable incident, there were other accidents, so engineers had to redesign, relocate, rebuild, and protect with various safety systems, but even today, there are still minor movements in this region from time to time, which are naturally explained by the geological and morphological characteristics of the area and are influenced and accelerated by environmental factors. These characteristics and factors are briefly described hereinafter.

The high bank is made up of sediments of various grain sizes. These were formed 5-10 million years ago, when the Pannonian Lake, a shallow sea remnant separated from the Tethys Ocean, spread across the Carpathian Basin. The constantly changing size and water level of the lake formed a series of sediments several kilometers thick. Today, these ancient layers, consisting of sediments of various grain sizes: sand, silt, and clay, form the most famous high banks along Lake Balaton. It is important to note that although Ice Age loess was later deposited on top of these layers, it is only a few meters thick in some places and has been eroded away in the area under investigation. Previous movements have disrupted the original stratification, causing the layers to mix. As a result, pore water pressure can build up in the sandy layers, reducing stability in the groundwater flowing toward the lake, because clay lenses block their path. It was already established in the last century that surface movements follow periods of precipitation [11].

3 Methodology

In both case studies, on-site, laboratory, and computer tests serve the purpose of providing pre-developed engineering solutions for the risks inherent in weather conditions during construction or subsequent monitoring. They facilitate intervention and on-site decision-making thanks to preliminary explorations, tests, research results, considering the specific conditions of the site. At the same time, they use an extendable methodology.

3.1 Examination of soft rock environments along roads

The aim of the research was to examine how the solid rock of the rock face reacts to rainy and winter weather conditions. In addition to the engineering geological analysis of deep-drilled core samples taken from the area, rock mechanical measurements were performed on air-dry, water-saturated, and various numbers of freeze-thaw cycles, the results of which were used in different modelling studies. When calculating the expected safety of the slope, empirical SMR [12] and the Q_{slope} [13] methods and FEM modelling were applied.

3.2 Examination of the environment along routes running along coastlines prone to landslides

We first documented the on-site signs of surface movements, then built models by processing drilling data, which we used to perform LEM, FEM, and probabilistic stability analyses. A complex geotechnical monitoring system was also built in the area. Elements of this system include inclinometers that record subsurface displacement and piezometers that measure pore water pressure, which have been measured every three days for three years. We analyzed these data series in conjunction with rainfall databases.

4 Results

4.1 Protection of roads from soft rock environments

As a result of saturation and freeze-thaw cycles, 38% of the test specimens completely disintegrated, 46% remained in a testable condition, and a total of 16% remained intact until the destructive tests were performed. Even those samples that had not completely lost their strength after saturation and freeze-thaw cycles showed a significant decrease in strength. By simulating extreme weather conditions in the laboratory, the porosity and water absorption of the samples increased significantly, while the propagation velocity of UH decreased.

Using the measured results, the cohesion and internal friction angle of the rock were determined, which also showed a decreasing trend. These processes can be explained by the appearance and growth of cracks and strong weathering processes. We observed the decrease in the modulus of elasticity and the constancy of the modulus ratio.
The Slope Mass Rate gives the stability of rock slopes based on empirical principles, with the following components of the rock mass: Rock Quality Design RQD value, distance between joints, condition of joints, presence of groundwater and pore water, and compressive strength. These components are summarized in a score, which is reduced depending on the fragmentation of the rock slope and human intervention. The SMR method is not sensitive to the destructive effects of weather. Its impact can only be detected in the calculation through increased fragility. However, the method is extremely sensitive to the directions of the discontinuity. According to the SMR value, in the specific case, the estimated safety factor can be as high as 5 in very favorable circumstances, 2.5 in appropriate conditions, but only 1.6 in unfavorable situations, and as low as 1.1 in very unfavorable ones. The environmental effects are much better illustrated by the Q_{slope} method. The factors of the empirical method are as follows: Rock Quality Design RQD value, joint sets number, joint roughness number, joint alteration number, environmental and geological condition number, three strength reduction factors of the slope: physical condition number, stress and strength number, major discontinuity number and the orientation factor. According to the Q_{slope} value, the slope would remain stable at a maximum angle of 51.5°. The planned slope angle is 65°, which falls within the range of unstable slopes (figure 4), insurance or redesign is necessary.

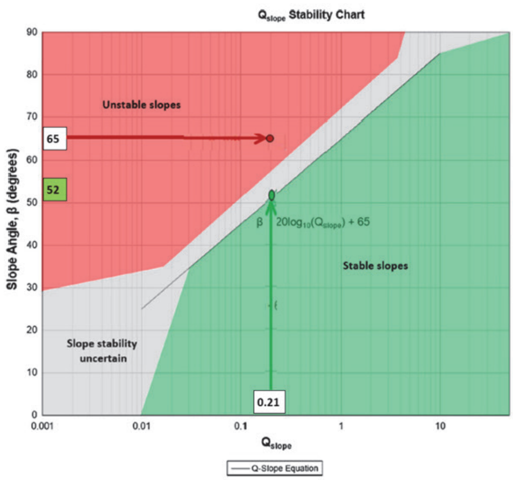

Figure 4 Q_{slope} value on a section of Hungarian main road 21 [14]

Furthermore, we created graphically illustrated functional relationships, in which, in one case, the horizontal axis represents the different orientations that can be determined during on-site implementation, while in the other case, also on the horizontal axis, the signal numbers given in the Q_{slope} tables represent the changing state of the joints, which are subject to weather conditions, while in both cases the maximum safe slope angle can be read from the vertical axis as a function of the above. Based on the planned geometry of the slope and the shear strength values determined in the laboratory under various conditions, the erosion of the upper layers of the slope is the expected failure, which can occur after as few as 20 freeze-thaw cycles. The results obtained help to apply the “design as you go” principle during construction, using predetermined function relationships enabling on-site decision-making and intervention.

4.2 Protection of coastal infrastructures

On the shores of Lake Balaton, we recorded numerous signs of slope movement, such as trees with curved trunks. Computer models based on different theories, in line with this and the literature, have shown several failure modes, an example of which can be seen in figure 5 from the probability-based calculation. The yellow curves represent the safety factors of potential slip surfaces below 1.4. Of these, the darker shades indicate lower safety, that is, a higher probability of failure, which is identified in local erosion events along the shoreline. Based on the analysis of all possibilities, that means the sum of all potential failures, whether minor or serious, the worst possible combination of input parameters causes 4.28% probability of slope failure. In addition, the value of the reliability index is 2.8, which does not meet the required minimum of 3.

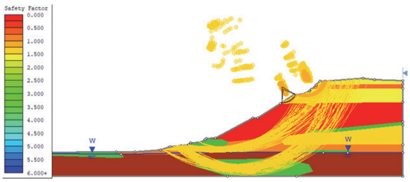

Figure 5 Failure modes of high bank Balatonakarattya from Slide2 [4]

Further modelling has established that the probability of deep circular movements occurring is related to the water level of the lake, which is regulated. However, the smoother sliding surface at the foot point is related to the effects of precipitation, as the inclinometers installed there show an acceleration of movement at a depth of approximately 7.5 meters following these events. Based on these correlations, it became possible to analyze the relationship between rainfall events and shear zone movements. We have determined that above-average precipitation amounts cause accelerated movement in the shear zone, which can be seen in the changes in the slope of the time-displacement graph (figure 6).

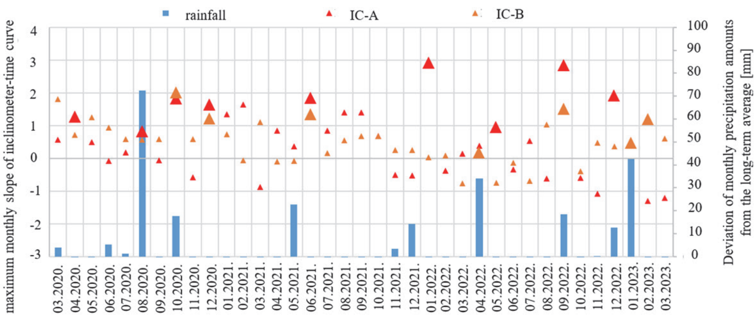

Figure 6 Accelerations in landslide following above-average precipitation events

Using innovative methods of data analysis, seasonal characteristics, categories that can be used as a basis for predictions, and status ratio numbers were also created [4].

5 Conclusion

The two case studies from Hungary, provide examples of how geotechnical tools help in the protection of roads and railway lines against the hazards of climate change. The following observations were outlined. In the case of rock slopes necessary for the expansion of traffic routes, we have shown that empirical stability calculations and computer stability modelling can be exploited to create various functional relationships for on-site decision-making by simulating weather effects under laboratory conditions. We have shown in the case of coastal public transport routes that are prone to movement, that if a shear zone and movement process can be verified, and we have a sufficiently frequent series of displacement data available, then, when analyzed together with precipitation time series, we can take significant steps toward discovering the time delay with which precipitation has an acceleration effect on landslide, thus contributing to forecasting strategies.

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