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Dynamics of landslides located in lithologically diverse rocks of the Carpathian flysch based on instrumental monitoring

Summary of doctoral dissertation:

The doctoral dissertation raises an important issue: the impact of atmospheric precipitation on the dynamics of landslides. Currently, the largest scope of instrumental monitoring of landslides is carried out by the Polish Geological Institute - National Research Institute as part of the Landslide Protection System (SOPO) project. This monitoring is based on a three-part system of deep and surface measurements and registration of the groundwater table in relation to precipitation as a factor activating landslides. Data collected as part of monitoring works were the basis for the development of this dissertation.

In the dissertation, eleven were selected from among the landslides monitored as part of the SOPO project, which according to the author, represent a wide spectrum of factors determining the development of landslides in the Carpathians. These are landslides that differ in size, slope angle, number of slip surfaces and type of movement. These are landslides that showed continuous activity during monitoring and were reactivated only after heavy rainfall. These landslides are located in different parts of the Carpathians and developed in different lithological and structural conditions of the Carpathian flysch. The landslides are located in the area of the following tectonic units: Skolska, Podląska, Silesia and Magura. The landslide in Mała developed partly on Miocene transgressive sediments in the Carpathians.

The aim of the study was to determine the impact of atmospheric precipitation on the dynamics of landslides, which depends mainly on the geological conditions in which these landslides developed. An attempt was made to correlate rainfall data with changes in the groundwater table and displacement increases on the analyzed landslides.

To achieve the set goal, the author analyzed the impact of atmospheric precipitation on changes in groundwater levels and the dynamics of landslides. Author compared precipitation data from rain gauges installed in the area or vicinity of the studied landslides, data on changes in groundwater levels, displacements in inclinometer holes, displacements of geodetic points installed in the landslide area, and data on the geological structure of landslides obtained from cartographic works, drilling works and archival materials.

In the first stage of the work, landslides, their geological substrate and hydrogeological conditions were described. The results of surface and underground monitoring were analyzed.

The second element of the analysis was an attempt to correlate rainfall data with changes in atmospheric conditions and displacement increments in inclinometer columns. Determining the

moment of initiation of these movements comes down to determining the time when the most unfavorable meteorological conditions occurred, resulting in a clear change in the hydrogeological situation. Assuming this assumption, selected time periods were analyzed in detail for each landslide, in which the impact of atmospheric precipitation on ground conditions was compared. For the selected measurement intervals, an attempt was made to indicate the time and rainfall situation causing a change in the dynamics of these landslides.

The analysis of precipitation shows that high values occur mainly in spring and summer. There is a large difference between the minimum and maximum rainfall values in individual months. The highest monthly rainfall was recorded in May 2010 at the IMWM rain gauge (Kalwaria Zebrzydowska) not far from the landslide in Lanckorona. It was 432 mm, while the average for this month was 321 mm. This exceptional meteorological situation in 2010 extended into the first half of June, and its effect was a very large number of cases of reactivation of old landslides and creation of new ones, mainly in the southern part of Poland. In the later period of the analysis, such a situation did not occur again. Also noteworthy are the high average values of monthly rainfall sums in June (173 mm) and July (197 mm) 2013 , as well as in May (197 mm) and July (179 mm) of 2014 and May 2019 (195 mm). Each of these periods was associated with a general increase in landslide activity.

Combining the cumulative displacement curves into one scale shows that the analyzed landslides behaved in two ways. The first group was characterized by small displacements recorded in inclinometer columns in the range of up to 40 mm (in the period between 10 and 12 years). These are landslides in Milówka, Lanckorona, Żegocin, Rożnów Zagórze, Łowczówek (western part of the landslide) and Ruszelczyce (central part), where significant displacements were recorded in the spring of 2010.

The second group is characterized by an almost continuous nature of displacements with changes in dynamics depending on the amount of rainfall. In this group, the greatest dynamics was observed in the I1 measurement column in Kasinka Mała, where an approximately constant displacement dynamics of 4.5 mm/month was recorded. On the remaining landslides in Witanowice, Grybów, Skołyszyn, Mała, Ruszelczyce, Łowczówek (eastern part) and Ruszelczyce (western part), the average displacement speed was from 0.3 to 3 mm/month.

The values of displacements leading to the shearing of the measuring column varied in the range from 38 mm for column I2 in Witanowice to 232 mm for column I2 in Ruszelczyce. This discrepancy in values is mainly due to the thickness of the shear zone and the plasticity of rock formations in the shear zone.

An important issue discussed in the work is the general relation of the dynamics of landslides to the rock base on which they formed and the composition of colluviums derived from these formations. The water permeability of rock formations seems to be particularly important because changes in hydrogeological conditions influence changes in the values of mechanical parameters and stresses in rocks and the water load on the landslide slope.

The reactivation of the landslide in Milówka in 2010 occurred after three days of rainfall totaling 251 mm. In 1960, the landslide in Lanckorona was also reactivated by three days of rain with a total of 88 mm, which was the culmination of a monthly rainfall of 280 mm. Much more unfavorable conditions triggered this landslide in 2010, when a four-day rainfall culmination of 220 mm ended the exceptionally rainy month of May. The reactivation of the landslide in Rożnów-Zagórze in May 2010 was caused by rainfall with a monthly total of 300 mm and a three-day culmination of 137 mm. For each of these landslides, reactivation took place in a meteorological situation including both a long period of almost continuous rainfall lasting several days, as well as a culmination with torrential rain, which, according to the author, had a dominant role in the activation of landslides composed of flysch formations with a predominance of sandstone. Later small movements recorded during monitoring were associated with intense rainfall lasting several days with an intensity of several dozen mm/day. The landslide in Żegocin behaved similarly to the landslides described above, but due to its small size, incidental increases in activity occurred more often.

Landslides in Witanowice, Grybów, Sławęcin and Mała, where sandstone-shale or clay deposits predominate, showed continuous activity, with different displacement values in individual measurement intervals. An increase in dynamics usually occurred during periods of long-term, heavy rainfall, when monthly rainfall totals approached 100 mm, but determining the rainfall threshold and the approximate moment of acceleration is difficult.

The landslides in Kasinka Mała, Łowczówek and Ruszelczyce are extensive forms composed of zones of various activity. Within these landslides, both permanent displacements and minor incidental activity were observed in inclinometer columns throughout the analyzed period. The increase in the dynamics of the less active zones of these landslides was associated with intense rainfall that lasted for several days or occurred several times at short intervals. In the case of permanently active zones, two- or three-day precipitation exceeding 60 mm resulted in higher displacement values in the measurement interval.

The analysis carried out allowed for the following conclusions to be formulated:

1. Landslides in areas composed mainly of clay rocks, where the infiltration of atmospheric waters is difficult, had a long response time to rainfall. These landslides showed approximately constant activity that was difficult to correlate with fluctuating precipitation. The increase in dynamics usually occurred during periods of long-term, heavy rainfall. A quick response to rainfall could only result in a significant water load on landslides close to the stability limit.
2. Landslides where in the geological substrate sandstones, mudstones or conglomerates have a similar or dominant share in comparison to clay formations, the reactivation was of an "impulse" nature. Displacements on these landslides were recorded mainly after exceptionally heavy precipitation or torrential rains. Activation was mainly associated with a rapid change in water conditions within the colluviums. On these landslides, the so-called "reaction time" to

precipitation was short and amounts to several dozen hours. Better filtration properties also caused the landslides to reach equilibrium faster after the rainfall stopped.

3. Geodetic methods should be used as basic ones due to low financial outlays, ease and speed of interpretation of results and the possibility of implementation in almost any area. Point information about surface displacements is based on repeatable measurements, usually of several points.
4. Inclinometer measurements are characterized by high precision of displacement registration. They provide information about the depth of the slip surface and the direction of displacement. However, they involve a lot of work and financial resources. Inclinometer measurements are justified in areas where accurate knowledge of the dynamics and depth of the slip surface is necessary for infrastructure safety control or geotechnical design needs for slope stabilization.
5. The durability of the inclinometer column depends on the dynamics of displacements. The values of displacements after which the column is sheared depend on the thickness of the shear zone and the plasticity of rock formations in the shear zone.
6. Many years of observations have shown that recording the groundwater level is justified mainly for landslides located in permeable formations or with a high degree of fissures. The impact of precipitation on the groundwater table is then visible, which may be used in determining precipitation thresholds and creating an early warning procedure. In landslides formed in clay formations, due to the nature of the dynamics and poor correlation with precipitation, monitoring of deformations seems to be more important.