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## Impact of meteorological conditions on stability of selected slopes in the Wiśnicz Foothills

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**Abstract:** *Impact of meteorological conditions on stability of selected slopes in the Wiśnicz Foothills.* Mass wasting is one of the most important processes influencing the shaping of mountain slopes. Most programs for testing mass wasting are limited to short-time, single observations, and to surface measurements of the big phenomenon ignoring shallow landslides occur resulting in slope covers, or on its border with the rock solid. That is why, when analyzing the causes of mass wasting processes, it is extremely important to assess the influence of meteorological conditions on water circulation in the landslide slope system and the status of stresses in a soil medium that is connected with it. The aim of this work was to determine the course of changes in stability conditions for two selected slopes, connected with meteorological conditions in the period of 2009–2013 on the area of the Wiśnicz Foothills. Numerical analysis were subjected to two slopes in villages the Królówka and the Łychów. Meteorological data for analysis, i.e. air temperature and soil humidity, wind speed, precipitation sum and length, were taken from the station Jagiellonian University in Łazy. To determine the course of changes of stability factor used capabilities Geostudio 2007 (Slope/W, Vadose/W, Seep/W). The work is a pre-development servant indicate the formation of shallow landslides present in silt. Results of the stability calculations confirmed the common opinions that conditions of slope balance are very strongly connected with atmospheric precipitation, but it was also shown that they also depend significantly on thermal conditions. These calculations showed that in the period 2009–2013 the most unfavorable conditions of stability were obtained in May 2010, which is a confirmation of the situation observed in reality.

**Key words:** factor of safety, landslide, Wiśnicz Foothills

### INTRODUCTION

Mass wasting is one of the most important processes influencing the shaping of mountain slopes built from the Carpathian flysch. There are probably more than 20 thousand landslides in the Carpathians (Mrozek et al., 2000). The interest in slides has increased in the last years, which is primarily connected with formation and activation of slides after the flood in 1997 and with the “landslide catastrophe” from 2010. Comprehensive, full-scale tests on the mechanisms of landslide movements were conducted only on few objects. Such tests are time-consuming, and obtaining full information on the range and causes on loss of stability sometimes requires several years of measurements and analyses. Most programs for testing mass wasting are limited to short-time, single observations, and to surface measurements of the phenomenon. Participants of these tasks often focus on large structural landslides which reach to deep-lying Paleogene, and older, rocks, but not on

shallow landslides occurring on the border between slope covers and solid rocks and within range of slope covers which dominate among the currently occurring mass wasting processes (Margielewski, 2008). It is believed that such a state is caused by changes in land management by man, which changes the way water circulates in the slope system, from deep to surface. That is why, when analyzing the causes of mass wasting processes,

## CHARACTERISTICS OF THE STUDY AREA

The Wiśnicz Foothills spreads from the valley of the Raba river to the valley of the Dunajec river, covering an area of approximately 700 km<sup>2</sup> (Starkel, 1988, Kondracki, 2009, Fig. 1). The main rocks the area of the foothills is made of are Krosno Beds, menilite shales, Ciężkowice Sandstones, red shales, and Upper and Lower Istebna Beds of the



FIGURE 1. Location of the studied slopes on the elevation model background of the Wiśnicz Foothills

it is extremely important to assess the influence of meteorological conditions on water circulation in the slope system and the status of stresses in a soil medium that is connected with it. The aim of this work was to determine the course of changes in stability conditions for two selected slopes, connected with meteorological conditions in the period of 2009–2013 on the area of the Wiśnicz Foothills (Pogórze Wiśnickie).

Silesian and Sub-Silesian units (Skoczyła-Ciszewska and Burtan, 1954). They are covered with a few-meter layer of Pleistocene deposits, i.e. loess and loess-like formations as well as silt saprolites of the Carpathian flysch (Olewicz, 1968, Święchowicz, 1991, Kaszowski and Święchowicz, 1995, Marks et al., 2006).

The relief of the region of the Wiśnicz Foothills is an example of a mature erosion-denudation relief with a character of

low and medium foothills. The main elements distinguishable in the relief are two levels of flats: higher (350–420 m a.s.l.) and lower (300–320 m a.s.l.) (Starkel,

The greatest number of landslides has been recorded in the eastern part of the Wiśnicz Foothills, with density up to 28 landslides per km<sup>2</sup> (Fig. 2).

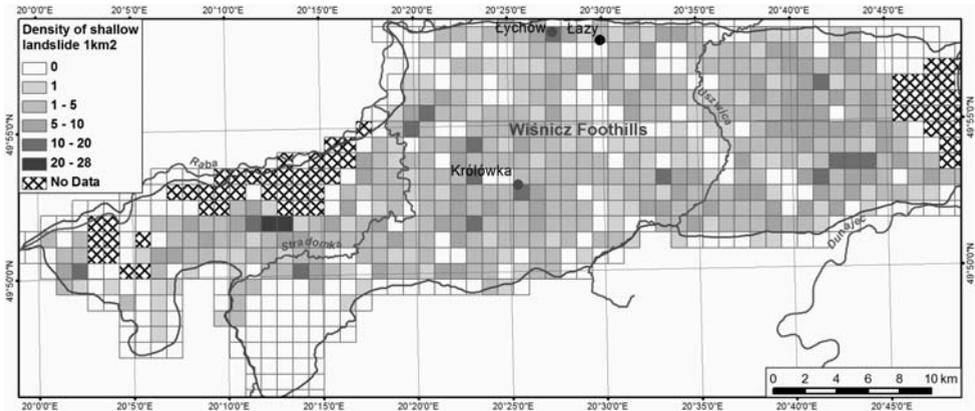


FIGURE 2. The density of shallow landslides caused to the slope covers the Wiśnicz Foothills (source: SOPO, statement: Demczuk)

1972). The higher level is crossed by narrow depressions with a character of erosion-denudation valleys and ravine forms.

According to Landslide Counteracting System (LCS) (in Polish System Ochrony Przeciwsuwiskowej – SOPO; Polish Geological Institute, <http://www.pgi.gov.pl/>), there are about 3.5 thousand landslides in the Wiśnicz Foothills, from which about 2 thousand landslides are soil (earth) landslides and landslides formed within slope covers (a slide layer present at the contact between slope covers and bedrock). The average density of occurrence of shallow landslides (up to 10 m deep) (Ziętara, 1968) in this region is about 3 landslides per km<sup>2</sup>.

#### CHARACTERISTICS OF METEOROLOGICAL CONDITIONS BETWEEN 2009 AND 2013 COMPARED TO A MULTI-YEAR

The course of precipitation conditions at the station in Łazy in recent years has been indicating a slight increase in annual totals of precipitation. The lowest precipitation in the analyzed multi-year was observed in 2003 (slightly more than 400 mm), which is about 60% of the mean total precipitation at this station. Similarly, low precipitation amounts were recorded in 1993 and 2011 – respectively 74 and 75% of the mean annual precipitation (Fig. 3).

The highest annual total of precipitation in the period 1989–2013 was

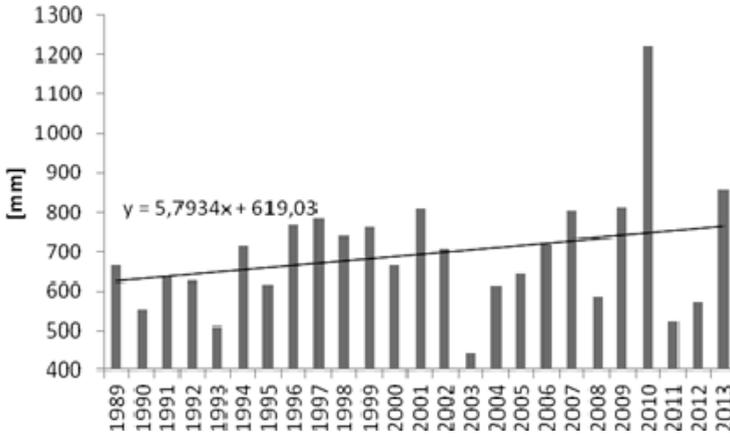


FIGURE 3. Course of annual totals of precipitation at the station in the Łazy in the years 1989–2013

recorded in 2010 – over 1,200 mm. High annual totals of precipitation were recorded also in 2001, 2007, and 2013 – more than 800 mm. In 3 years of the last 5-year period (2009–2013), the total of precipitation exceeded 100% of the mean total of precipitation from the period 1989–2013.

The highest precipitation totals in the Łazy were recorded in the months of the warm season – between April and Sep-

tember (Fig. 4). In March, April, August, September, October, and December the mean precipitation total for the period 1989–2013 is higher than the mean precipitation total of the analyzed 5-year period (2009–2013). In the remaining months, monthly precipitation totals are higher than the multi-year mean. In the period 2009–2013, the mean precipitation total in June was more than 50 mm higher than the mean monthly total for

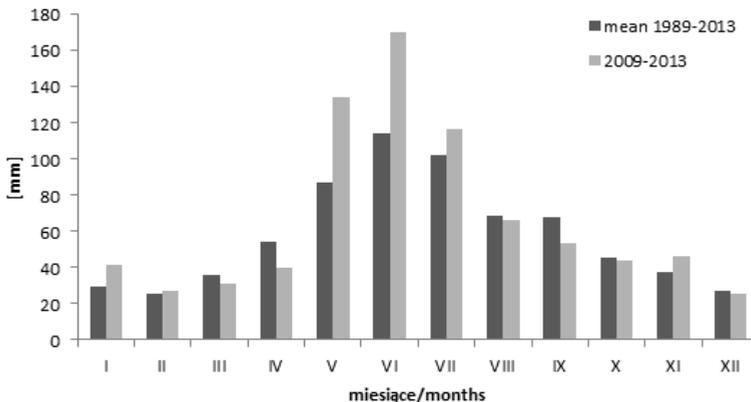


FIGURE 4. Monthly course of precipitation mean and totals value at the station in the Łazy in the years 1989–2013

the entire 24-year period. In May, the mean total from the last 5 years is more than 60% higher compared with the multi-year period 1989–2013.

The average number of days without precipitation at the station in the Łazy in the period 1989–2013 is about 214 days per year (Fig. 5). On average,

were 16 days with precipitation above 50 mm, 11 days in the last 10-year period, and 7 days in the years 2009–2013. The highest number of days with precipitation exceeding 50 mm was recorded in 2010 (4 days).

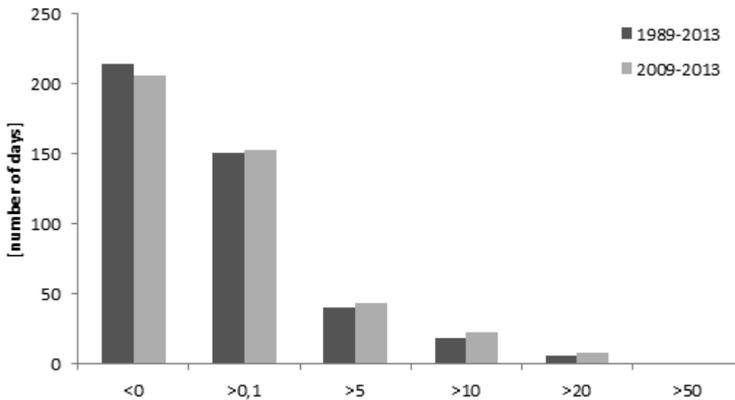


FIGURE 5. Number of days with precipitation at individual ranges in the Łazy in the years 1989–2013

there were fewer days without precipitation in the analyzed period 2009–2013 than in the entire period 1989–2013. In the remaining ranges of 24-hour precipitation totals, the number of days is higher in the last 5 years than in the entire period. In the last 5-year period, the number of days with precipitation above 10 mm was higher than the mean by more than 4 days, whereas with precipitation above 20 mm – slightly over 1 day. A considerable increase in the number of days with 24-hour precipitation total above 50 mm has been observed in the last 10 years. In the entire period of meteorological observations at the station in the Łazy there

Synoptic conditions of high precipitation at the station in the Łazy between 15 and 18 May 2010 were connected with the moving low-pressure system near the Mediterranean Sea. The movement of lows in the north-eastern direction was associated also with it being filled. An inflow of air masses with a very high moisture content from north-west and south-west caused high precipitation totals. The precipitation total in the period between 15 and 18 May 2010 was above 187 mm, and the highest 24-hour precipitation total occurred on 16 May – above 110 mm. Precipitation observed in that period had a character of long-term pre-

precipitation lasting more than 22 h a day, with the intensity of approximately 0.08 mm a minute.

The depth of the 0°C isotherm in soil depends on several factors: air temperature, soil moisture content, vegetation cover, or occurrence of snow cover. When soil freezes, the 0°C isotherm moves in the direction from smaller to greater depths. This course is reversed in thawing periods (spring).

Soil freezing was observed at the station in the Łazy in all the analyzed years of the period 2009–2013 (Fig. 6).

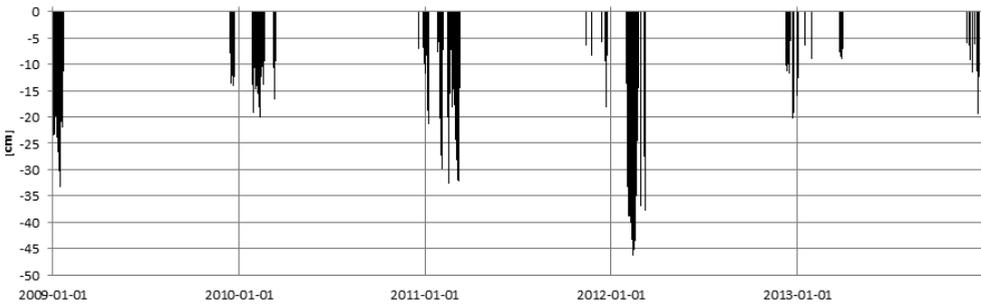


FIGURE 6. Course of 0°C isotherm depth in soil at the station in the Łazy in the years 2009–2013

The greatest lying depths of the 0°C isotherm were observed in winters 2011–2012, when on 13 February 2012 the 0°C isotherm lay at the depth of 46 cm under soil surface. Similar values for the depth of freezing in soil were observed in winters 2008–2009 and 2010–2012 – more than 30 cm. Definitely the lowest depths of freezing were recorded in the years 2009–2010 and in the last two winters in the period 2009–2013 where the location of the 0°C isotherm did not exceed 20 cm.

## SCOPE AND METHODOLOGY OF THE WORK

The work involved tests on two slopes located in the Królówka near the Nowy Wiśnicz and in the Łychów near the Bochnia on which signs of mass wasting were observed. The field works included geodetic measurement, geological drillings and measurements of water permeability of surface layers of the slopes using a double ring infiltrometer. The laboratory works involved determination of the grain-size distribution, permeability coefficient, and the shear strength of

the soils. Grain size tests were conducted using a laser particle size analyzer. Permeability tests were performed in a triaxial compression apparatus made by the British company VJ Tech, under a steady hydraulic gradient according to a procedure described in (PKN-CEN ISO/TS 17892-11:2009). Determination of the shear strength was conducted in a triaxial apparatus made by VJ Tech using the CIU method (PKN-CEN ISO/TS 17892-9:2009). Soil saturation was conducted using back pressure until obtain-

ing a value of the Skempton coefficient equal to, at least, 0.95. On the other hand, sample compression was carried out using stage shearing of soil, the so-called multistage test, which enables to determine the strength parameters of soil based on tests from one sample. After saturation, the samples were consolidated until obtaining the assumed value of effective stresses, then compressed until setting of the value of ratio of principal stresses ( $\sigma_1/\sigma_3$ ), which generally did not exceed 5% of deformations of a sample. In the following stages, the samples were consolidated by increasing the value of effective stresses. The last stage of compression was conducted until obtaining 20% of deformation of the sample, and interpretation of the test results was conducted by assuming a criterion of soil failure corresponding to the maximum value of stress deviator.

The analysis of stability conditions was conducted using the GEO-SLOPE software package with the use of SEEP/W (GEO-SLOPE, 2010a), VADOSE/W (GEO-SLOPE, 2010b) as well as Slope/W modules (GEO-SLOPE, 2010c). The Seep/W module was used for establishing the conditions of the initial status of stresses in the slope in consideration of the mean annual precipitation from the 1987–2013 multi-year. These calculations utilized the results of the laboratory tests, whereas retention properties were determined using the simplified method (Aubertin et al., 2003). In the next stage

of the work, the Vadose/W model was used to determine the impact of meteorological conditions (precipitation amount, temperature, air humidity, and wind speed) and land cover (depth of the plants root system) on changes of pore pressure within the slopes in the period 2009–2013. Thermal parameters of the soils (thermal conductivity, thermal capacity) were established based on equations provided in the user's manual for the (Vadose/W 2012) software, whereas results of measurements from the station in Łazy near Bochnia were used to determine the boundary thermal conditions in the soil profile. The last part of the study involved stability calculations of the analyzed slopes using Janbu's method (Janbu, 1954) for the assumed slide planes, taking into account the influence of matric suction on the shear strength of the soil. The calculations resulted in obtaining the values of stability coefficients as a variable dependant on the amount of precipitation, evapotranspiration, and matric suction of the surface formations. Landslides (the landslide in the environs of the Królówka was formed in May 2010; no data on the time the landslide in the environs of the Łychów was formed) occurred on the analyzed slopes, and that is why it was assumed that results of calculations which give, in the analyzed period, at least one value of the factor of safety below 1.0 would decide on correctness of the performed calculations.

## RESULTS OF THE FIELD AND LABORATORY TESTS

Based on the field tests, the characteristic longitudinal profile of the slope in the Królówka, in whose lower parts there were visible traces of mass wasting processes, was separated. The land cover consists of meadows, and single trees occur only in the lower parts of the slope. In this part of the slope there is also a local asphalt road which is enclosed from one side by a drainage ditch, and a small flow from the other. Based on a macroscopic analysis conducted under field conditions, four geotechnical layers within the slope were separated. Granulometric tests showed that silt which lie at a maximum depth of 2.2 m below land surface level constitute the surface formations, and below them there is clayey silt. On the other hand, the lowest lying layer consists of sandstones and shales of the Krosno Beds, which were found in the upper part of the analyzed section at the depth of 2.7–3.2 m below land surface level and in the bottom of the stream channel. During the field tests there was no occurrence of underground water in the layers of the slope cover. The landslide was formed the 15 of May 2010.

Geo-engineering conditions of the slope in the Łychów were slightly different, having a significantly changed relief due to slopewash and ravine erosion processes. Site investigations conducted in 2012 showed high mois-

ture content in the soil masses in the lower part of the slope, and presence of numerous transverse cracks formed in consequence of subsidence of soil masses was found. Results of the field and laboratory tests showed that slope covers substantially consist of silt, and below them there is bedrock which, according to the Detailed Geological Map of Poland 1 : 50 000 (Skoczylas-Ciszewska and Burtan, 1954), consists of red shales of the Silesian unit. Geodetic measurements and geomorphological mapping showed a considerable change in the relief of the slid part of the slope in comparison to its remaining part. Backward fallen colluvial masses and numerous steps occurred in the deformed part of the slope, indicating that the slip of soil masses had the nature of rotational movement (Dikau, 1996). At this stage of the research it was impossible to unambiguously determine whether the formed landslide had was a single movement or if it was multi-stage. Therefore, two slide planes were assumed for the stability analyses. The first of them began in the upper part of the slope and finished in its lower part, and the second one covered the foot of the slope. In the second case it was assumed that the landslide might have initiated in the lower part of the slope, and then propagated up the slope. Basic geotechnical properties of the soils are presented in Table 1, and Figure 7 shows the computational schemes of the analyzed slopes.

TABLE 1. Geotechnical parameters of soils from slopes in the Królówka and the Lychów

No	Fraction content (%)			Name acc. to PN-EN ISO 14668-2:2004	Volumetric density (g·cm <sup>-3</sup> )	Natural moisture content (%)	Plastic limit (%)	Liquid limit (%)	Plasticity index (%)	Filtration coefficient (m·s <sup>-1</sup> )	Internal friction angle (°)	Cohesion (kPa)
	sand	silt	clay									
Królówka												
1	12.6–13.6	77.3–79.1	8.3–9.1	Si	1.91–2.07	20.8–23.6	17.8	30.7	12.9	4·10 <sup>-8</sup> –2·10 <sup>-6</sup>	22.8	0.5
2	9.3	80.1	10.7	clSi	2.11	21.74	16.8	26.3	9.5	1·10 <sup>-8</sup>	32.0	4.0
3	3.4	79.8	15.0	clSi	2.03	22.3	15.8	32.0	10.4	1·10 <sup>-9</sup>	23.5	0.5
4	5.2	81.2	15.5	clSi	2.15	28.8	21.6	35.1	25.0	1·10 <sup>-9</sup>	23.5	0.5
5	sandstones and shales (Krosno Beds – Oligocene)											
Lychów												
1	0.0	91.1	8.9	Si	1.85–1.92	12.6–16.1	17.8	24.8	7.0	3·10 <sup>-6</sup> –6·10 <sup>-6</sup>	25.6	0.0
2	0.0	93.8	6.2	Si	2.04–2.06	19.5–20.4	18.8	27.8	9.0	6·10 <sup>-8</sup>	22.8	6.3
3	0.0	91.4	8.6	Si	1.91	21.5	17.5	26.7	9.2	4·10 <sup>-9</sup>	30.8	2.8
4	red shales (Eocene)											

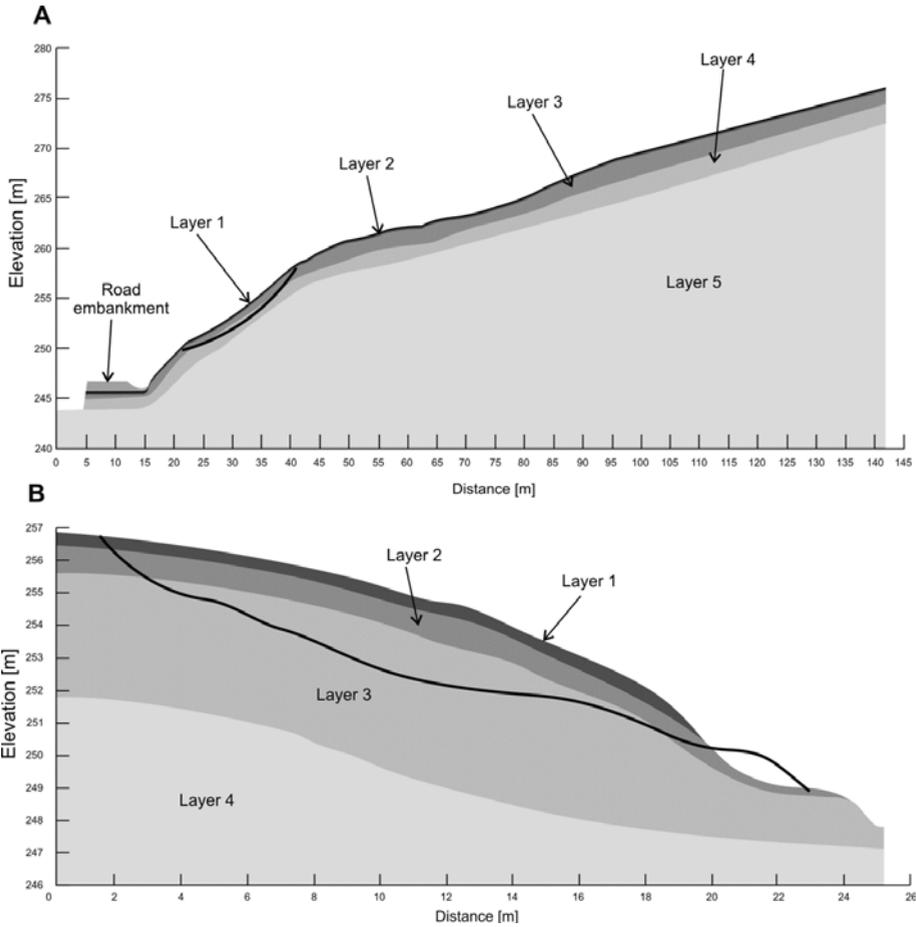


FIGURE 7. Reconstructed geological sections of slopes in the Królówka (A) and the Łychów (B) with marked (thick line) present land profile

**RESULTS OF STABILITY CALCULATIONS**

Factors determining slope stability include, among other factors, the shape and inclination of a slope as well as physical properties of formations that build them. Active factors, among which time of duration and amount of precipitation are of great importance, cause changes in stability (Gil, Kotarba, 1977, Gil, Starkel,

1979). Precipitation water infiltrates into soil and causes changes in pore pressure, which has fundamental importance for slope stability. Figure 8 presents results of calculations of pore pressure within the analyzed slopes at selected depths of the soil profile located in the central part of the slope.

It is noticeable that there were considerable pore pressure fluctuations in the analyzed period, whereas the charac-

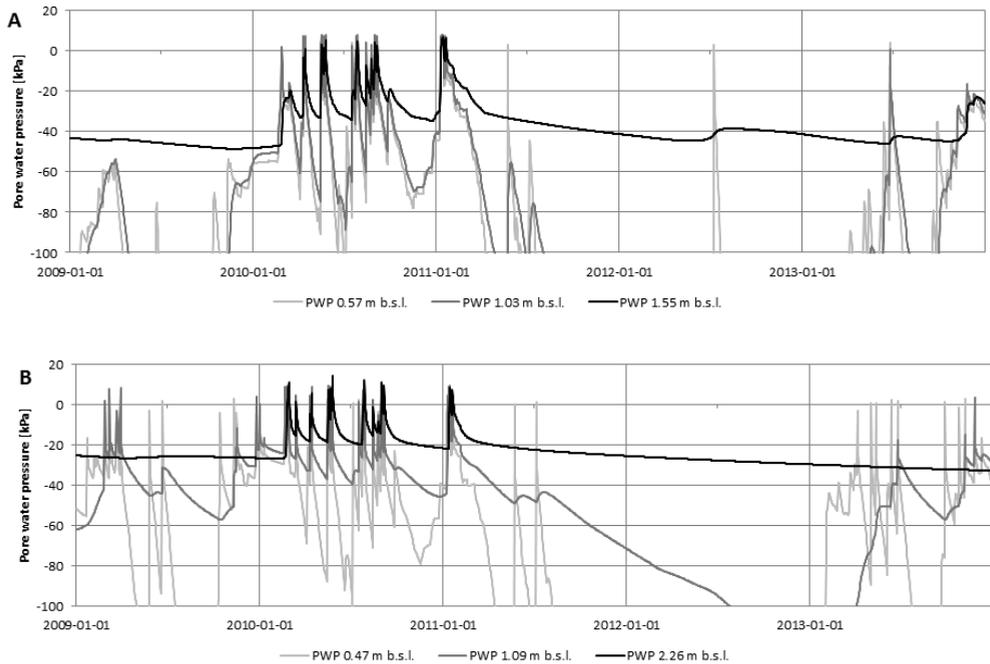


FIGURE 8. Results of calculations of pore pressure within slope in the Królówka (A) and the Łychów (B) in the period 2009–2013

ter of these changes was similar for both slopes. In general, smaller pore pressure changes pore in the surface zone of the slope (approx. 1 m below land level) were obtained for the slope in the Łychów, which is probably connected with water permeability of slope formations in this area. Calculations showed that in most of the analyzed period, slope covers are not fully saturated, and the highest values of suction pressure were obtained in 2012, which was connected with low precipitation in the first half of that year. On the other hand, the highest values of pore pressure were obtained in 2010 when there was very high precipitation and a considerable intensification of mass wasting processes in the Polish

Flysch Carpathians. The obtained calculation results also indicate that the relatively high values of pore pressure (low values of suction pressure) occurred on the slope in the Łychów in the winter period, which is visible especially at the beginning of 2009 and 2010, where autumn and winter precipitation totals were 258.7 and 290.5 mm, respectively. On the other hand, in 2011 and 2012 the precipitation totals were about twice smaller than in the above-mentioned periods. On the other hand, high values of pore pressure were not obtained in winter 2013 despite relatively high precipitation (295.8 mm). It is probable that small precipitation in the second half of 2012 was of great significance in

that case. In general, high values of pore pressure or moisture contents in soils in the winter period are a phenomenon commonly observed in nature (Harris et al., 2011, Bittelli et al., 2012, Sorbino and Nicotera, 2013, Rianna et al., 20), or they arise from calculations (Lu et al., 2013) and are connected with water freezing and thawing processes in soil pores or with spring melts.

The obtained results of calculations of pore pressure are reflected in stability calculations (Fig. 9). The presented data show that in the period 2009–2013 there were over a dozen days when the factor of safety values were below 1.0. This value indicates that there is high

probability of subsidence of soil masses. More critical values of the factor of safety (14 cases) were obtained in the case of the slope in the Królówka, whereas in the Łychów there were seven such cases. Six cases of such type were reported for the slope in the Królówka in January 2011, where soil and air temperatures were positive (between 3 and 8°C) and it rained. Within a day, the 0°C isotherm rose by 35 cm to the land surface (the soil thawed very quickly). Similar results of stability analyses for the winter period are presented in the work of Bittelli et al. (2012). These authors pointed out that low values of the stability coefficient at this time of year may result from high precipitation and at the same time

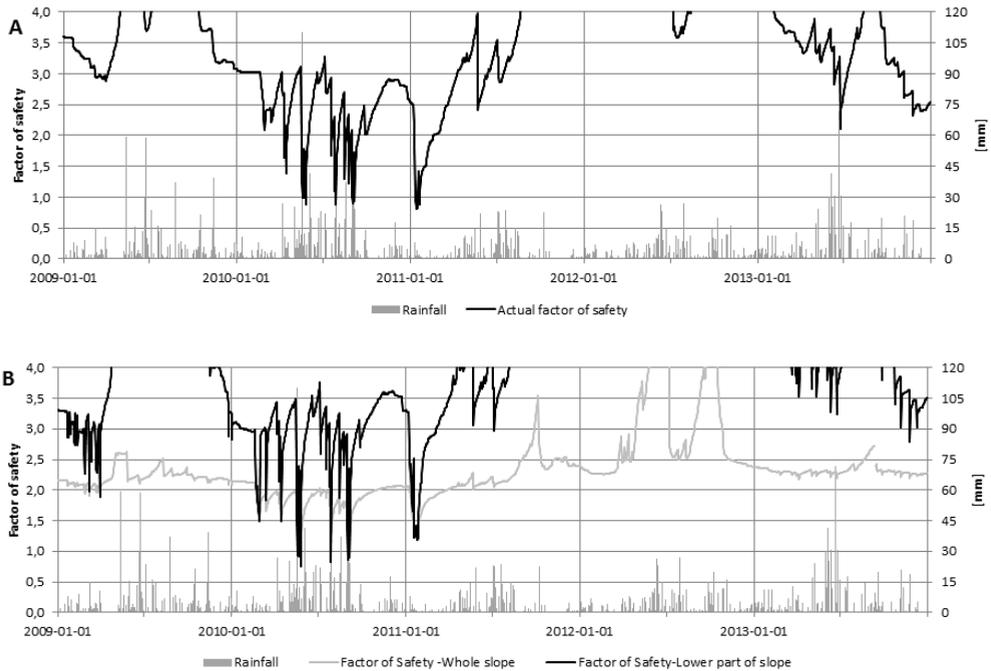


FIGURE 9. Dependence of safety factors on amount of precipitation in the Królówka (A) and the Łychów (B) in the period 2009–2013

can be indicative of slope-creep processes. In the case of the analyzed slope, the amount of precipitation in a 14-day period preceding the obtainment of critical values of the stability coefficient was, however, low and did not exceed 40 mm. When analyzing the obtained results it may be noted, however, that prior to the period with low level of the factor of safety (before 11 January 2011) a phenomenon of ground frost occurred (Fig. 5), which favors water accumulation in the soil profile. Other cases of obtaining critical values of the factor of safety are primarily associated with May 2010. In that month there were 4 days when values of the safety coefficients were below the critical value and they were connected with a precipitation total from 14 days of antecedent period which amounted to over 200 mm. Other cases of obtaining low values of the factor of safety took place between July and September 2010, but the total of antecedent precipitation amounted to 91–128 mm.

Results of stability calculations for the slope in Lychów were different. Critical values of the factor of safety were obtained only in the vegetative period in May (4 days), July (1 day), and September (2 days) of 2010, and precipitation total in the 14-day antecedent period was at least 90 mm.

#### ANALYSIS OF CALCULATION RESULTS

The obtained results suggest that in the case of both slopes the amounts of so-called threshold precipitation, which

initiates mass wasting, cannot be unambiguously determined. This is because statistical analysis of the results of stability calculations did not show a significant relationship between values of the factors of safety determined from calculations, and the amount of precipitation expressed as a 24-hour precipitation total, 14-day precipitation in the period preceding loss of slope stability or precipitation intensity. In the case of both slopes the calculation results showed that the most unfavorable conditions of stability occurred in May 2010, where on 17 May the accumulated amount of 2-week precipitation reached over 200 mm. This value is also given in literature (Rączkowski and Mrozek, 2002, Gil and Długosz, 2006) as threshold precipitation that initiates mass wasting processes in saprolite formations in the Polish Flysch Carpathians. On the other hand, Gorczyca (2004), based on results of several-year observations of mass wasting processes in the Łososina River basin (particularly in 1997), stated that intensification of such type of processes required precipitation above 70 mm which was preceded by intensive precipitation of approximately 170 mm. Therefore, it may be stated that the obtained results of stability calculations coincide with results of field observations conducted for the region of the Polish Flysch Carpathians.

However, it should be noted that the stability calculations showed also that conditions favoring the loss of stabil-

ity occurred in January 2011, where the amount of antecedent precipitation was very little. In that month, as well as in the previous one, monthly precipitation totals slightly exceeded mean precipitation values from the multi-year. Analysis of air temperatures showed that in December 2010 and at the beginning of 2011 over a dozen days with minimum temperature below 0°C were recorded, and soil temperature at land surface was also negative. On the other hand, days for which the obtained factor of safety was below 1.0 were preceded by an increase in soil temperature above 0°C, which, with the melt of water accumulated in the profile and simultaneous occurrence of precipitation of 10 mm, was a probable cause of the reduction of the factor of safety below the critical value. Amount of antecedent precipitation similar to the one in January 2011 occurred in January 2010, but changes in the stability coefficient were very small in that period. In this case both in December 2009 and January 2010 there were lower soil temperatures – they were negative practical-

ly in that entire period, which limited the possibility of precipitation infiltrating into the soil, and the precipitation was transformed into fast surface flow.

In order to determine the impact of climatic conditions on the slope stability in winter period, an additional stability analysis was carried out with a simulation of thermal conditions prevailing in the winter period of 2011–2012, where the lowest temperatures from the analyzed multi-year were recorded, and for the remaining part of the year (spring–autumn) amounts of precipitation from 2010 were specified. Results of the simulation showed that at the time of soil thawing (beginning of March 2012) the factor of safety was by about 2.5 greater than the one calculated in an analogous period of 2010, and the specified amount of precipitation was unable to reduce the factor of safety to the critical value. The factor of safety came down below 1.0 only twice in the forecast period, not before September (Fig. 10). It may therefore be stated that, apart from precipitation, also thermal conditions of

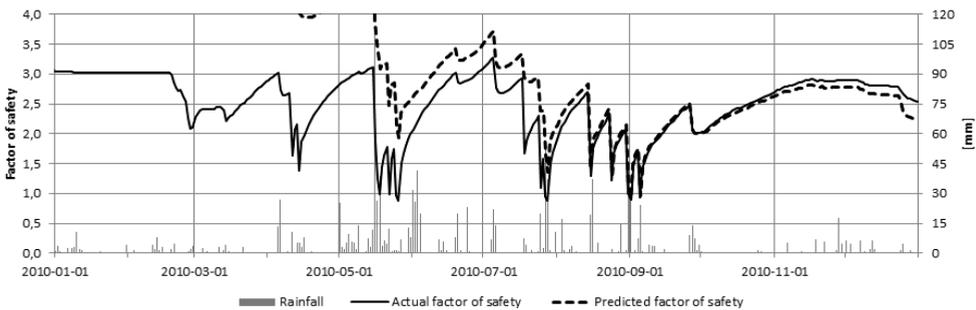


FIGURE 10. Forecast of changes in the factor of safety in 2007 at the same precipitation depending on ground frost depth

soil in the winter period, associated with ground frost depth, have significant influence on the conditions of slope balance. Precipitation occurring in that period leads to formation of a snow cover which, in the period of melts, constitutes additional source of water supply to the soil profile, thereby causing a reduction of slope stability. This process can be observed in spring 2010 and 2011, but is negligible in the case of 2012 when winter precipitation in 2011 and spring precipitation in 2012 were generally significantly smaller than monthly means from the multi-year.

## CONCLUSIONS

The work presents results of stability calculations of two landslide slopes from the Wiśnicz Foothills, located in the Królówka and the Łychów. In both cases of slopes, slope covers substantially consist of dusty deposits of low or medium plasticity. In general, these formations are characterized by medium and low water permeability, whereas values of this parameter were lower for layers from the slope in the Łychów. Results of the stability calculations confirmed the common opinions that conditions of slope balance are very strongly connected with atmospheric precipitation, but it was also shown that they also depend significantly on thermal conditions. These calculations showed that in the period 2009–2013 the most unfavorable conditions of stability were obtained in May 2010, which is a

confirmation of the situation observed in reality. Amount of precipitation in the 14-day period preceding the occurrence of critical conditions of stability reached approximately 200 mm. On the other hand, in the further part of that year there were substantially 2 more days where the factor of safety values lower than 1.0 and they were connected with antecedent precipitation amounting to 90 mm. In these cases, water accumulation in the soil profile from the earlier period of that year probably had a significant influence on the amount of precipitation and stability conditions, whereas the most favorable stability conditions were obtained in 2012, where there was very little precipitation, and additionally that period was preceded by year 2011 which had been low on precipitation.

Weather conditions of high precipitation in the area of the Carpathian Foothills between 15 and 18 May 2010 were connected with the moving low-pressure system near the Mediterranean Sea. The movement of lows in the north-eastern direction was associated also with it being filled. An inflow of air masses with a very high moisture content from north-west and south-west caused high precipitation totals. The total precipitation between 15 and 18 May 2010 was above 187 mm, and the highest 24-h precipitation total occurred on 16 May – above 110 mm. Precipitation observed in that period had a character of continuous rains lasting more than 22 h a day, with the intensity of approximately 0.08 mm a minute.

In the case of 16 May 2010 the inflow of air masses was observed from north-west and south-west. It was cool maritime polar air with high moisture supply and very hot and humid maritime tropical air. Similar synoptic conditions accompanied high precipitation totals in May 2014 and July 1997 when floods and high intensification of landslide processes occurred in the south of Poland.

High precipitation totals are usually connected with development of regions with low pressure over the northern coasts of the Mediterranean Sea. The movement of lows occurs from south-west to north-east. Development and vanishing of low-pressure areas are very dynamic. In each of the cases the development of low-pressure areas is accompanied by atmospheric fronts that separate masses of hot and humid air from masses of air with a significantly lower temperature and high humidity – from the Atlantic. Such combination of air masses causes high precipitation totals. Intensity of precipitation is average, but its long duration leads to it causing geomorphological effects.

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**Streszczenie:** *Wpływ warunków meteorologicznych na kształtowanie się warunków stateczności wybranych zboczy Pogórza Wiśnickiego.* Jednym z najważniejszych procesów wpływających na kształtowanie stoków górskich zbudowanych z fliszu karpacciego są ruchy masowe. Tylko na nielicznych obiektach prowadzono kompleksowe, pogłębione badania mechanizmów inicjacji ruchów osuwiskowych. Badania takowe są czasochłonne, a zadowalające i wiarygodne wyniki osiąga się po co najmniej kilkuletnim okresie pomiarów i analiz. Większość programów badań ogranicza się do krótkich, jednorazowych obserwacji i pomiarów powierzchniowych. Uwaga uczestników tych projektów skupia się na dużych osuwiskach strukturalnych obejmujących swoim zasięgiem głęboko zalegające skały trzeciorzędowe, pomijając płytkie osuwiska zachodzące na granicy zwietrzliny i skał litych oraz w zasięgu samej zwietrzliny. Celem pracy było określenie przebiegu zmian warunków stateczności wybranych zboczy związanych ze warunkami meteorologicznymi występujących w latach 2008–2013 na obszarze Pogórza Wiśnickiego. Dla potrzeb pracy wykorzystano dane meteorologiczne, tj. temperatura powietrza, wilgotność gleby, prędkość wiatru, sumy opadów i liczba dni z deszczem, pochodzące ze Stacji Naukowej IGiGP

UJ w Łazach koło Bochni (Pogórze Wiśnickie). Przeprowadzono terenowe i laboratoryjne badania parametrów geotechnicznych gruntów stanowiących pokrywy stokowe wybranych zboczy osuwiskowych we wsiach Królówka i Łychówo. Wcześniej wspomiane dane meteorologiczne, a także dane dotyczące temperatury, wilgotności względnej powietrza wykorzystano w dalszej części pracy do określenia zmian stanu naprężeń dla dwóch zboczy osuwiskowych. W tym celu zastosowano moduły Slope/W, Vados/W oraz Seep/W stanowiące część pakietu GeoSlope. Wyniki analiz potwierdziły, że stabilność zbocza jest silnie związana z opadami atmosferycznymi, ale wykazały również jej istotną zależność od warunków termicznych. Przeprowadzone obliczenia z lat 2009–2013 wykazały, że najbardziej niekorzystne dla zachowania statyki zbocza warunki wystąpiły w maju 2010 roku, co jest potwierdzeniem obserwacji terenowych.

*Słowa kluczowe:* współczynnik bezpieczeństwa, osuwisko, Pogórze Wiśnickie

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