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Slope relaxation following landslides in the Łososina River Basin, Beskid Wyspowy Mts., Poland

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Abstract: The paper presents results from a study of the functioning of slopes in conditions where the dynamic equilibrium has been upset and sliding has been followed by slope relaxation. The research was an attempt to analyze large-scale changes in slope morphology in the Łososina River basin in the Beskid Wyspowy mountain range caused by an extreme rainfall event in 1997. The enormous scale of the sliding process that occurred on the slopes of the Łososina basin provided an opportunity to study the role of mass movements in landform development in mountains of medium height. The paper attempts to summarize the rate and course of slope relaxation processes using geomorphological mapping done from 1997 to 2000. The study tested the hypothesis that following the occurrence of an extreme event, slope relaxation processes will slow down mass movement processes to the point where they stop acting on the slope, and ultimately a new set of slope development processes will emerge.

Key words: landslides, slope relaxation, monitoring, Łososina basin, Beskid Wyspowy

Introduction

During the period 1997–2002, a series of extreme events triggered by torrential rainfall and rapid thawing caused a large-scale transformation of slopes and valleys in various parts of the Carpathian Mountains (Kirchner & Krejčí 1998, Kotarba 1998, Gorczyca 2000, Mrozek et al. 2000, Lach & Lewik 2002). Łososina River basin in the Beskid Wyspowy mountain range – a part of the Carpathian mountain chain – was one of the areas affected.

Between 1997 and 2000, three extreme weather events activated landslide processes in the Łososina River basin. During the first event (July of 1997), short but intense rainfall immediately followed earlier long-lasting rainfall causing the Łososina River to burst its banks, triggering large mass movements on the basin slopes (Gorczyca 2004). The rain totals (218.4 mm and 241.8 mm) recorded between July 4th and July 9th were measured by two local stations of the Polish Weather Service (IMGW).

In 1998, the annual rainfall total once again exceeded the long-term norm (Mrozek et al. 2000). On June 4th of 1998, a thunderstorm produced 83.1 mm of rain but the geomorphological effects were largely limited to intensified erosion in flooded streams.

In the spring of 2000, snow was thawing rapidly when (on April 5th) a rainfall event produced 51.8 mm of water and then quickly turned into heavy snowfall. The slopes were already saturated with water from the previous days of thawing and could not absorb any more water. This caused landslides to develop.

The most powerful of the three events – the rainfall of June of 1997 – produced 1,340 landslides, mudflows, and creeps on the slopes of the Łososina basin (Fig. 1). A research study conducted at the time produced a map featuring 1,193 new landslide forms covering a combined area of 254,391 m^2. The mapping process also covered 147 old landslides and creeps with a combined area of 7,774,121 m^2. This included 89 creeps that had become partially reacti-

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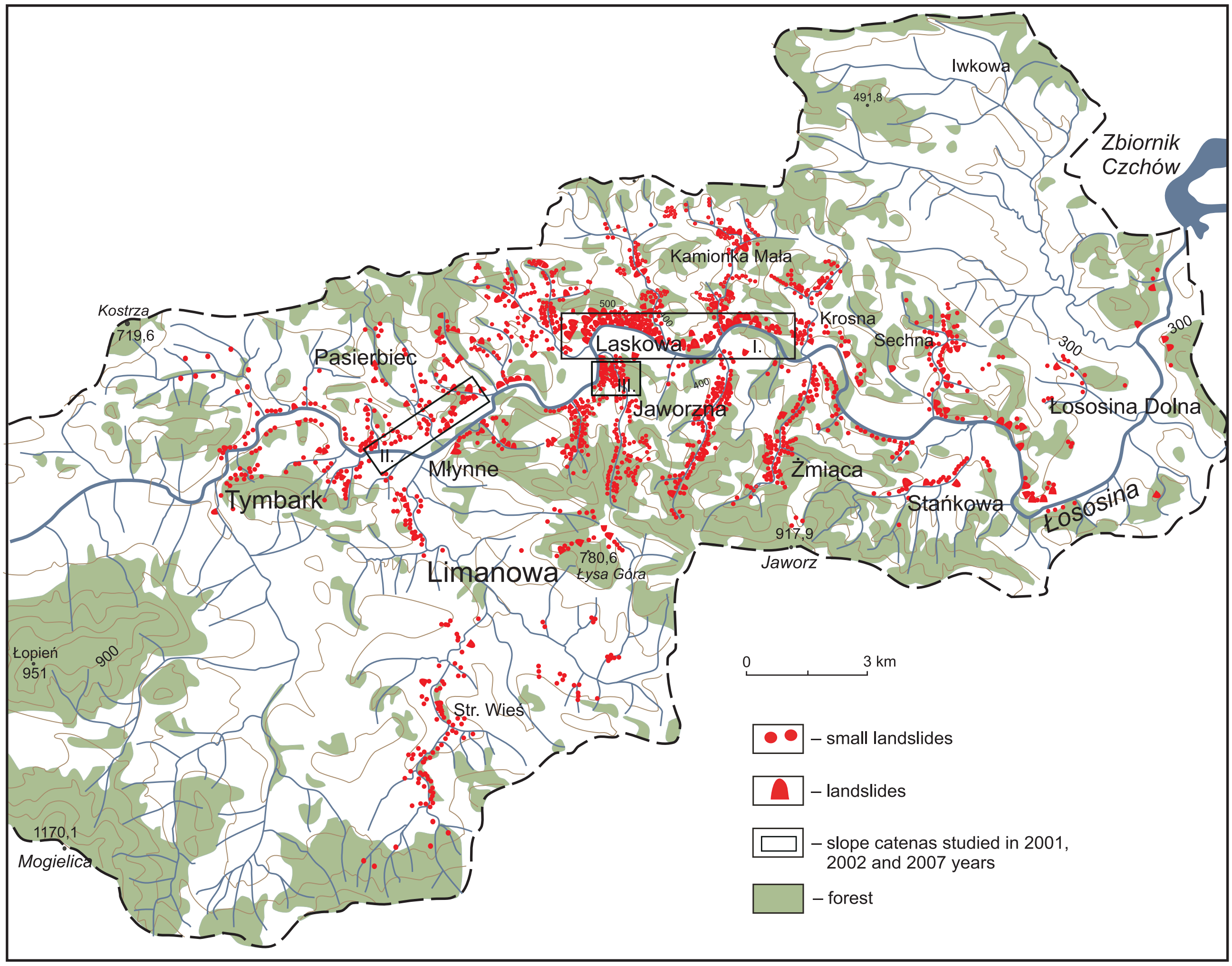

Fig. 1. Location of landslides developed or activated during 1997–2000 in Łososina basin

vated and 21 that had become reactivated during the study itself. A number of old landslides and creeps were also discovered to have reactivated (Gorczyca 2004). The vast majority of the new landslide forms that had developed in July of 1997 were shallow debris landslides. Many of the new landforms developed as a result of both sliding and flow mechanisms, thus combining features of a landslide at the top and a soil flow or debris flow at the bottom.

Purpose of the study

The enormous scale of the sliding processes that had occurred on the slopes of the Łososina basin provided an opportunity to study the role of mass movements in landform development in mountains of medium height. The study focused on trying to understand both the functioning of slopes in conditions where the dynamic equilibrium has been upset and slope relaxation after sliding processes have taken place. The paper discusses the course and pace of slope relaxation in the study area as well as the environmental and human factors that influence slope relaxation. The study advanced a working hypothesis that the relaxation of a landslide slope depends on sliding movement type, the morphology of the new landform, and its physical location on the slope. The evolution of slopes affected by sliding processes was studied using field data on landforms and their immediate vicinity for the period 1997–2000.

Study area

The Łososina River is a left-bank tributary of the Dunajec River. Its drainage basin is built predominantly of flysch formations of the Magura Nappe, dating for the most part from the Cretaceous and the Paleogenic (Cieszkowski 1992). The eastern section of the basin is part of what is known as the Michalczowa Zone, a geological structure that runs askew of main Carpathian structures (Cieszkowski 1992). The study area includes the middle and eastern sections of the basin, 241 km^2 in all, and accounts for approximately 60 percent of the entire basin. The area between the town of Tymbark and the point where the Łososina River flows into the Czchowski

Reservoir ranges in elevation between 905 and 230 m. Local morphology is linked to local lithology, whereby less resistant thin layers of shale and sandstone of the Sub-Magura Series dominate gentler lower slope sections, while more resistant thick-layered sandstones of the Magura Series proper are found primarily in the ridge sections of hills with gradients ranging up to 30°.

Sliding is a common process in the Beskid Wyspowy mountain range. Slides occupy approximately 3% of the total area of the mountain range (Bober 1984). The widespread occurrence of slides in the Beskid Wyspowy is caused by local geology, which is dominated by flysch-type formations consisting of alternating layers of shale and sandstone as well as by the presence of shale and debris cover that had evolved via weathering processes.

Methods

The main study method presented in this paper is the mapping of slide forms. Indeed, geomorphological mapping followed every mass movement that had occurred in the study area from 1997 to 2000. The landforms mapped in 1997 were observed again in 1998, 1999, and 2000. Photographs of the landslides were taken and drawings sketched. The condition and size of the mapped landforms were referenced to landmarks in their vicinity as well as other reference points including trees, poles, buildings, and roads. The fieldwork allowed for the observation of morphological changes over time. This phase of extensive research was followed by assessments in 2001, 2002, and 2007. The purpose of each assessment was to examine the degree of degradation of the landslide forms in the three selected slope zones by looking at the degree of overgrowth, the thickness of colluvia, the shape of the colluvial toe, and the "freshness" of the landslide scar. The three slope zones were selected for study purposes because of their degree of transformation by sliding processes and the diversity of types of landslides present (Fig. 1).

Geomorphological mapping data on landslides triggered by extreme rainfall in July of 1997 was used to identify seven principal types of slope development. The purpose of this was to study slope relaxation processes over the next three years. Slope development is defined herein as a set of processes that shape slope landforms resulting from landslides. In this case, the landslide triggering event was intense rainfall in July of 1997, which led to mass movements on slopes, which was followed by denudation and eventually loss of distinct form.

Seven types of slope development:

0 – No visible changes in the landforms and no secondary sliding movements.

1 – Overgrowth of slide landforms by predominantly herbaceous plants and trees. An undisturbed turf surface suggests seasonal stabilization of the landform and an absence of mass movement processes or erosion. The overgrowth possesses negligible stabilization value and cannot prevent sliding in the future.

2 – Degradation of landslide toes, debris/mud or torrential cones or fans as a result of sheet wash, subsidence and creep, all of which reduce toe thickness.

3 – Elimination of landslide form by humans. This happens wherever such landforms pose a risk to infrastructure such as buildings, roads, and agricultural land. In most cases, the infrastructure-friendly solution involves the removal of colluvia. In very rare cases, concave sections are also filled in.

4 – Degradation of slide scar edges; gravitational processes (sliding and subsidence) and erosion were observed to cause a retreat of the scar edge as well as subsidence of debris packets and a very slow smoothing-over of scar relief.

5 – Secondary movements; observable mass movements and erosion within the slide form. Subsequent sliding mainly involved the displacement of colluvia and the development of small scars within old ones. Washing processes lead to the linear dissection of the old form and the displacement of material out of the scar, toe, and colluvial bands.

6 – Additional development of slide forms; mass movements leading to a considerable expansion of the given form at the expense of a stable slope. This type of slope development also includes the emergence or activation of sliding forms after 1997.

Each of these slope development types was then assessed for the frequency with which it had occurred during the subsequent four years of research. The same type of assessment was performed for each of the four landform types analyzed: translational slides, rotational slides, small rotational slides, earth flows. The χ^2 test for independence (Gregory 1976) was used to assess the statistical significance of differences between the mean frequency of occurrence of a given trend in a given year (expected values) and the frequency of occurrence of a given trend for a given type of landform (observed values).

Results

The course of slope relaxation and the rate of slope relaxation in the parts of the Łososina basin affected by mass movements depend on a number of factors. These include the manner in which the shapes of the given landforms had developed such as the path the sliding masses had traveled, the nature of the displaced material, the given landform's morphology, and its physical location on the slope. Others included natural and human factors such as heavy rainfall, thawing effects, and highway repairs. Ultimately, each factor had had a different impact on the rate of relaxation.

The landslides that had developed or had become reactivated in 1997 were grouped into four types. The main criteria included the way the debris or rock masses had become displaced and the evolution of certain sets of features typical of each mass movement.

Movement under the influence of shearing stress was the most common type of mass movement in

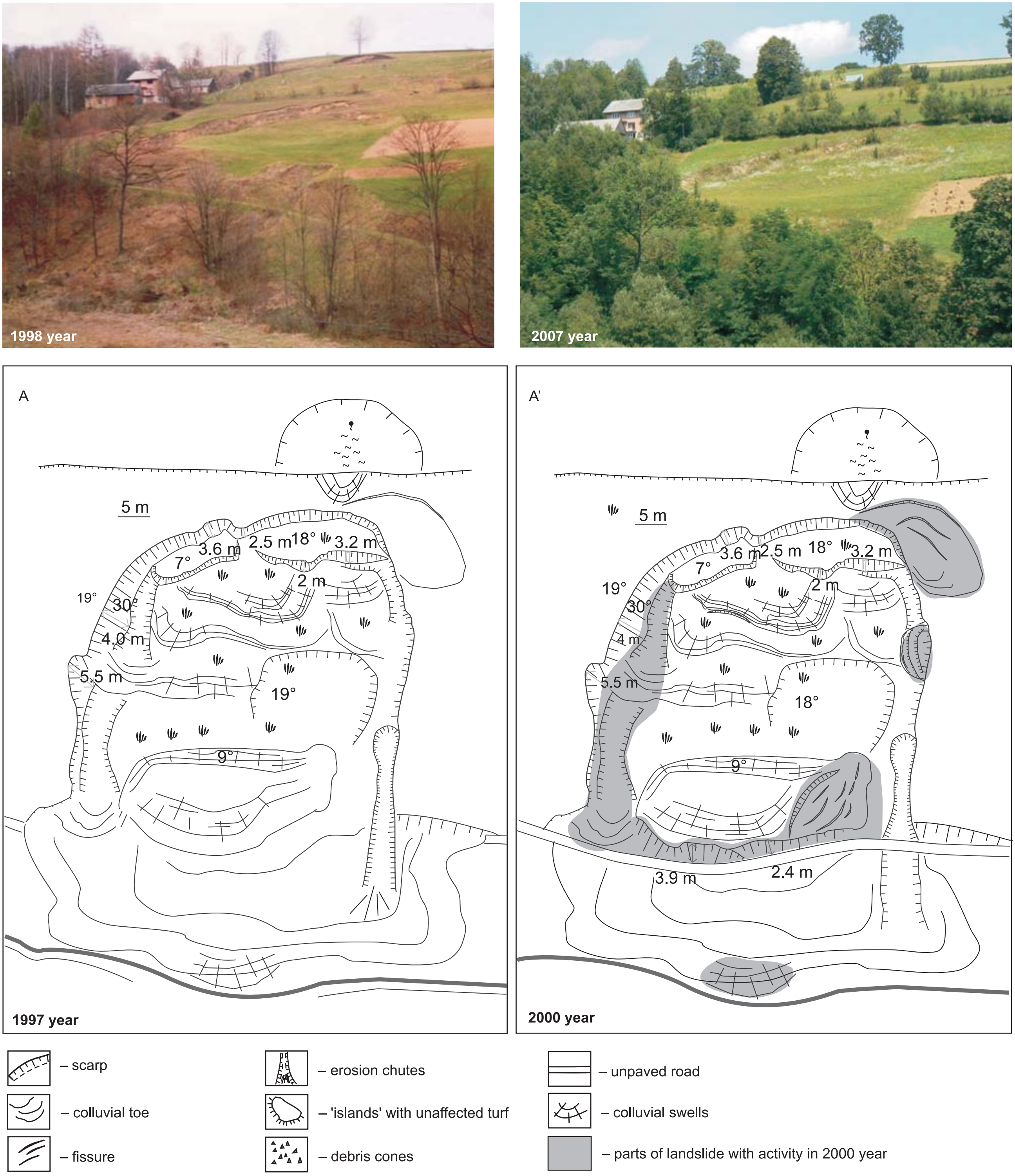

Fig. 2. A rotational slide on the slopes of the village of Młynne (form no. 966); A – map of the slide produced in 1997 immediately after it had occurred and before human intervention; A' – map of the same slide produced in 2000

1997. The landforms encountered most often were rotational slides. Most of the rotational slides were small – less than 100 m^2 of surface area. In the paper, they are called small rotational slides from this point on. The material displaced was mainly debris, which may be assumed to be an approximately uniform medium. The rotational landforms studied were mainly debris slides, normally up to 2–3 meters deep. According to Margielewski (2001), the curvature of the slip surface is small if the vertical depth of the landform is less than 10 meters. Indeed, the shallow rotational slides that had developed on the slopes of the Łososina basin had only minor curvature. The movement was accompanied by a rotation of the displaced masses, extrusion, and down-slope travel, in most cases preserving at least part of the original structural form of the material (Fig. 2). Compression forces occurred in the toe zone producing ground swells, which then moved onto the surface of the slope below.

Small rotational landforms produced as a result of subsidence were the most numerous landforms with a concave surface. They normally developed on steep slopes near cut banks, along the edges of roads cutting into the slopes or the edges of agricultural terraces and within old landslide scars. Small subsidence-type rotational landforms usually developed only a scar, not a toe. Displaced material is deposited at the outlet of the scar or pushed barely beyond the rotational landform's edge. A detailed analysis of small rotational landforms is provided in a later section, as their characteristic structure has a major impact on the relaxation process.

Much less numerous were landforms classified as translational slides defined as having straight-line slip surfaces and various degrees of breakdown of the displaced mass. The displaced material was predominantly unconsolidated and underwent further deterioration during the slippage process. The slip surface was found mostly on top of better consolidated debris or, less often, at the contact point between debris and bedrock. The sliding debris masses were normally no more than 0.5–2 meters thick. The slides had occurred on a wide range of slope gradients (18–50°).

Flows are a type of mass movement that does not fit into the main types described above. Debris flows and soil flows border on gravitational and erosional processes but are classified as mass movements by most researchers (e.g. Varnes 1978, Brunsden 1985). While clean landforms produced by such processes are very rare, there do exist abundant forms produced by a combination of flows and slides of both the rotational and translational type. These produce

Fig. 3. Flow-slides (village of Laskowa, form no. 597); photos show the course of degradation of the toe section; the red arrow points to a reference point, a power line pole

complex land features such as flow slides and slump-earth flows (Fig. 3). Water pressure in the waste-mantle is presumably so strong that ground-water bursts through, violently turning an initial slide into a more complex movement type. The resulting landforms are characterized by poorly defined slide surfaces, uneven scar surfaces, and very long distances covered by the displaced material.

A single sliding displacement of mass is very rarely the end of a sliding slope degradation process. Indeed, slope stability is very likely to be upset again within the new landform created, and a new displacement cycle begins (Jakubowski 1974). In order to assess the progress of slope relaxation, all the slopes of interest were observed during the period 1997–2000, followed by selective monitoring of slopes in 2001, 2002, and 2007.

Slope relaxation was measured by assessing the share that each type of slope development had contributed to total change (Fig. 4). The first type of slope development, “0” (no change), which provides an indirect indication of the permanence of the given landform in the slope system, declined from 70% in 1997 to 27% in 2000. Three years after their original development, 73% of landforms had undergone at least some change. A reverse pattern is apparent with regard to vegetation overgrowth (1), which had increased every year to affect approximately 50% of landforms in 2000 (Fig. 4). The most powerful set of processes responsible for the degradation of the toe sections of the slides (2) peaked at 28% of all landforms one year after their development. From that point on, the type of slope development subsided gradually (only 37 landforms in 2000). Human impact (3) reached a peak in 1997. Types of slope development 5 and 6 were found to have the greatest influence on the development of slide-affected slopes. Their percentage share was the result of initial slope instability following the major rainfall event of 1997 combined with the effects of subsequent rainfall events in 1998 and 2000. The rainfall event of 2000 may help explain the increase in the share of these two type of slope development. During the second phase of research, it was discovered that secondary mass movements had occurred mainly within large old slides that had become reactivated in 1997. Small and shallow slide forms started to overgrow rapidly and blended into the surrounding landscape via the masking effect produced by vegetation and the rapid degradation of their toe sections and scar edges (Fig. 3).

The four analyzed types of landslides differ in terms of the frequency of the types of landform development associated with them (from “0” to “6”).

Slides with a concave slip surface were the most numerous landform type in the study. Small rotational slides accounted for the vast majority of them at 612, while rotational slides were far less frequent at 57. The two landform types differ in terms of their predominant development types (Fig. 5).

Small rotational slides with their relatively small surface area and colluvia deposited in-situ were subject to intense degradation of scar edges (Fig. 5). The most characteristic feature of the slumps was how quickly they became overgrown with vegetation (55% in 2000). As a result of this rapid overgrowth and intense degradation of colluvial toes and scar edges, slumps were the least visible of landforms as early as four years after their initial development. Six

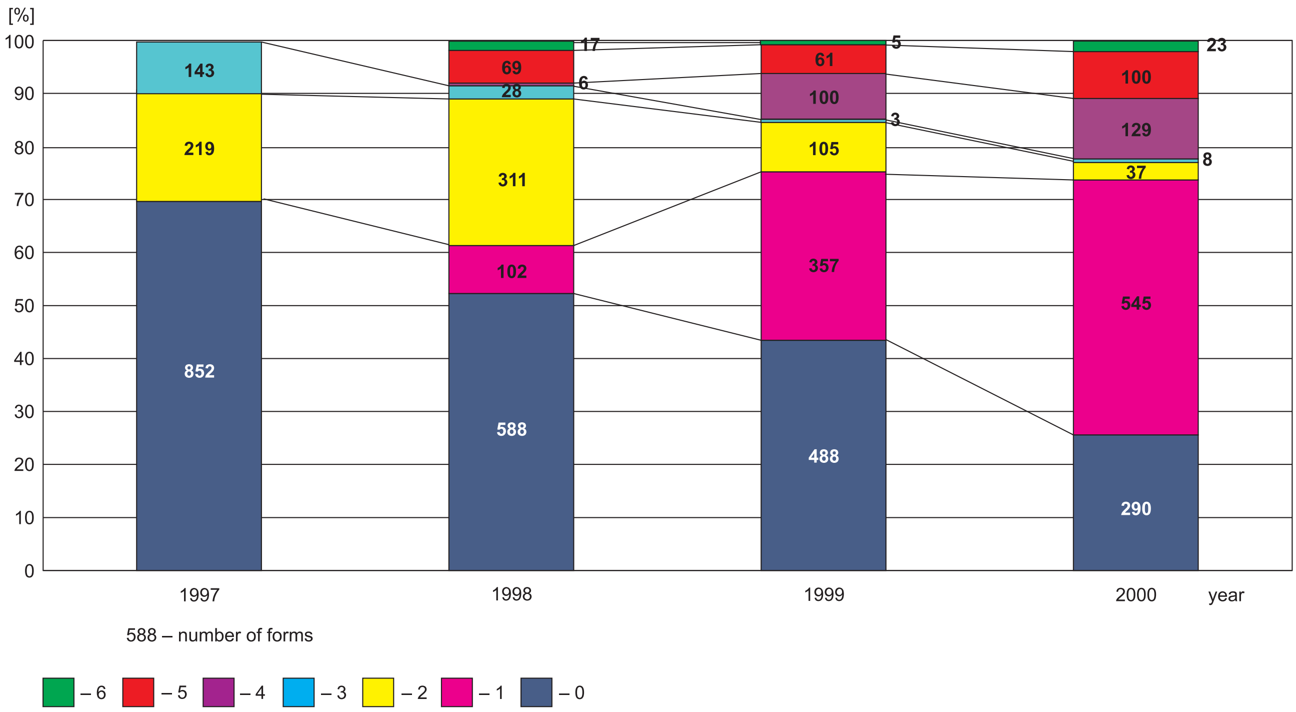

Fig. 4. Share of slope development types (“0” to “6”; see text for detailed legend) during the period 1997–2000

years later, many of them were hardly visible at all. While small rotational slides constituted over 50% of the forms studied, their course of development was not statistically different from averages observed in subsequent years. The only exception was overgrowth, which occurred more frequently than the annual average. The statistical significance of this, however, was only 0.1.

Large rotational slides, on the other hand, featured much more development (12% of forms in 2000) and accounted for the greatest share of secondary movements (16% of forms in 2000) of all the landforms studied (Fig. 2). This was largely the result of the lack of stability of the displaced colluvia, which led to their secondary displacement during the study period. The difference between the frequency of secondary mass movements of these types of landforms and the mean frequency of such movements in subsequent years was large enough that its statistical significance was at 0.05.

Translational slides (294 forms) were the most stable landform type investigated (Fig. 5). This landform type featured the largest share of forms that displayed no signs of significant change during the four-year study period (55% of forms in 2000). The difference between the percentage of unchanged translational landslides and the percentage of this type of slope development in the total number of investigated landforms is statistically significant at 0.05. This is a result of the fact that the displaced debris had undergone an enormous degree of disintegration including some liquefaction. The debris had been deposited with a certain level of stability and thus did not continue to move at a later date.

At the other end of the spectrum was found a very dynamic evolution of landforms combining slide features in the top sections and debris flows or earth flows in the middle and lower sections (119 forms). These forms feature the highest rate of colluvial toe degradation (50% in 1998), scar edge degradation, as well as overgrowth (61% in 2000) (Figs 3 and 5). The higher than average share of secondary movements of these landslides stems from their complexity as well as activity associated mostly with their top sections. The differences described herein relative to the mean frequency of the occurrence of each type of slope development in subsequent years are statistically significant at 0.05.

Landform evolution trend "3", although not natural, exerted a great deal of influence on the subsequent evolution of landforms. There exists a certain relationship between the number of landforms from which colluvia were removed by man and secondary movements of these landforms in the subsequent years of the study. This relationship can be observed in the group of rotational slides and complex forms

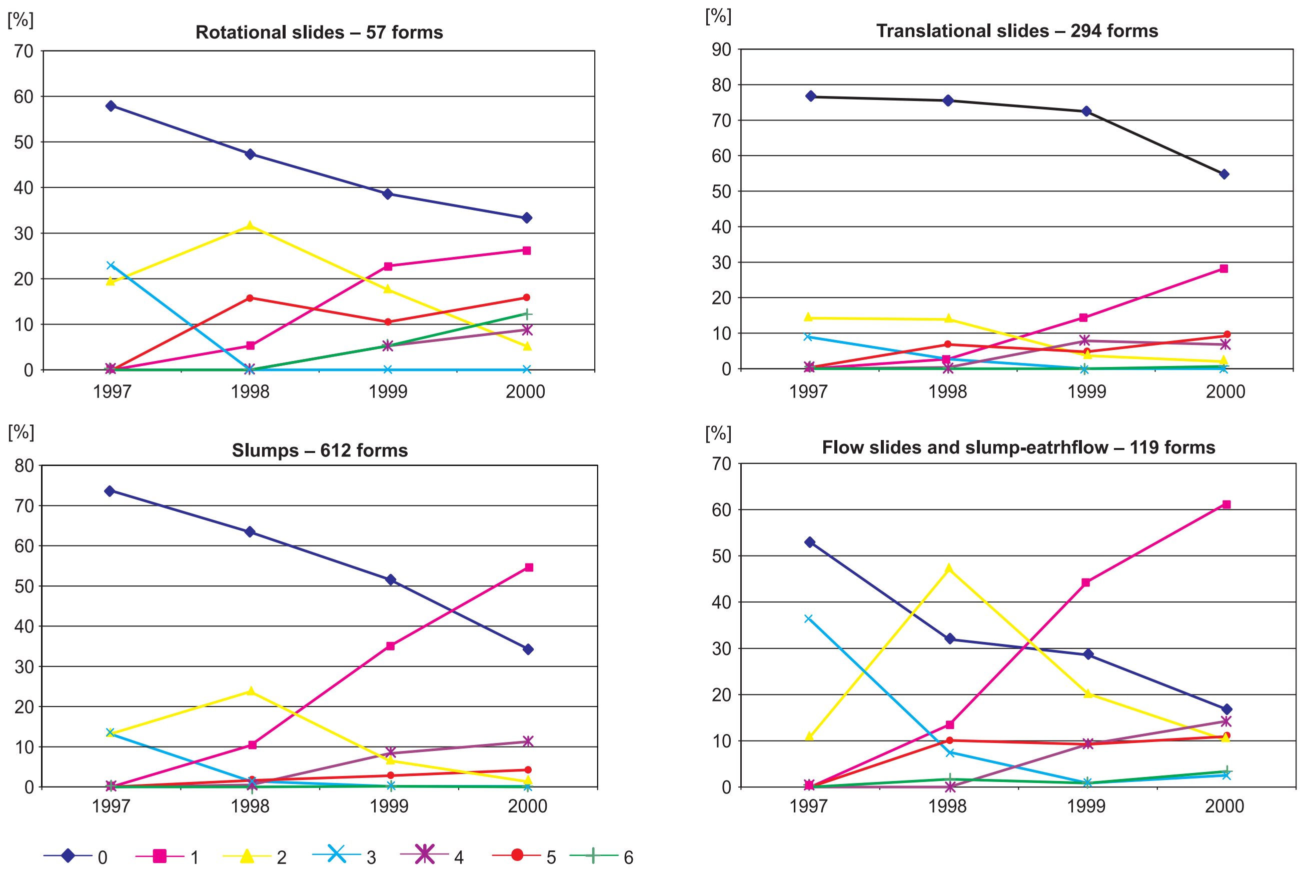

Fig. 5. Share of slope development types for the four landform types during the period 1997–2000 ("0" to "6"; see text for detailed legend)

with a very high rate of colluvia liquefaction (Fig. 5). The effect is either a result of cutting into colluvial swells or toes or the result of removing their support during remedial action such as the rebuilding of a damaged road (Fig. 2).

This confirms the initial assumption that the rate and course of slope relaxation depend on the type of landform developed, which in turn depends mainly on the type of movement involved.

At the beginning of the four-year research project, it was hypothesized that most of the landforms of interest would achieve a stable state rather quickly. This was dictated by the fact that most of the selected landforms were debris slips, which by definition are quick to stabilize. It was assumed that slide scars would be visible for the longest amount of time in the morphology of the slopes of interest, mostly as a result of frequent secondary movements that would refresh the landforms of interest. Tongue sections were to become denuded into the slope surface much more quickly as a result of secondary movements and downwash processes, and the slope surface would be become smooth.

In any study of the role that sliding movements play in the development of overall morphology, it is important to find a point in time when there is no more movement within a landform. According to Jakubowski (1974), the scar section of a slide where the sliding mass has been torn from its original location is the landform that remains visible on the slope surface for the longest period of time. The toe section, on the other hand, quickly blends into the slope surface. A stabilized slide is characterized by a "cessation of any slide-related deformation within the slide area" (Jakubowski, 1974) and any movement of the colluvia is primarily the result of erosion, linear flow, and slow creep.

A similar course of slide stabilization was observed during studies of shallow slide processes in the mountains of New Zealand (Crozier 1997). In this case, the disappearance of slide morphology began with wash and creep processes followed by vegetation masking and secondary movements. The final sign of the slide form was a modified slope profile. Crozier (1997) pointed to the significant role played by man in the speeding up of the disappearance of slide landforms. Similar patterns of disappearance were found on the slopes of the Lososina River basin during the 1997–2000 research project.

Towards the end of the research project, three years after the commencement of mass movements, most of the landforms of interest were still highly visible (Fig. 2). Scar edges were still clearly visible and scars were not filled with washed-in material. No systematic surface drainage was discovered within the landforms studied despite the presence of numerous erosion dissections. Three years, however, is too short a period of time to analyze the path to full stabilization of slide-affected slopes. Research conducted ten years after the initial development of the slides confirms the initially stated hypothesis of rapid stabilization of landforms. The slides have become difficult to identify in the surrounding landscape as a result of the masking role of the vegetation. In addition, their morphology has become partly effaced as the toe-sections and scars have been degraded. Colluvial toes were the first to attain stability, especially in detritus slides with a significant degree of liquefaction.

Conclusions

Differences in the course of relaxation between various slide forms depend on the types of sliding processes acting on a slope including rotational slides, translational slides, and flows. What turned out to be very important for the course of the subsequent evolution of the slide-affected slopes was whether the displaced material had been deposited as bands or packets (rotational slides) or whether it had been saturated with water and deposited far beneath the scar (complex forms and flows). In the former case, most of the landforms underwent frequent secondary movements, while in the latter case, the processes present were sheet flow and linear wash and landform surfaces became gradually covered with vegetation. The progress of the degradation of these landforms was readily apparent and they are the most likely to reach equilibrium first. Old slide landforms kept reactivating throughout the study period after subsequent rainfall stimuli.

Ten years after the original sliding event, landslide scars are the most visible of resulting landforms. The only key change in these landforms involved vegetation overgrowth. The most rapid change, on the other hand, was noted in the toe sections and colluvial swells. Colluvia rich in water have largely blended in with the surrounding morphology. Landslides with coherent colluvia were highly unstable throughout the study period as a result of secondary mass movements and remained clearly visible in the morphology of slide-affected slopes.

The final piece of evidence left behind by a landslide form is a modified slope profile. A formerly convex or convex-concave slope becomes transformed into a concave slope. Research has shown that shallow sliding contributes to an increase in the number of irregular sections in slope profiles.

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