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Landslides on river banks in the western part of Podhale (Central Carpathians, Poland)

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The authors studied landslides in alluvial sediments on undercut steep banks of the rivers flowing in the western part of the Podhale region. The landslides are of rotational type. Landsliding processes are complex and they differ from those on solid rock slopes because of the heterogeneous lithology of the alluvial sediments in the banks (muds, sandy gravels, clays) and because of uneven degree of their consolidation. Their course depends on the mode rate of water infiltration into the sediments. Multiannual observations of changing landslide surfaces and measurements of scarp surface with erosion pins indicate that each type of sediment behaves in a different way during the sliding. The layers of mud in the highest parts of the banks were sliding down in blocks and soon became fragmented, soaked and washed away. Sandy gravels were sliding as whole layers or separate fragments. The more compact the alluvium, the more compact was the resulting colluvium. The thick layers of massive claystones underlying the alluvial sediments at the bank bases were mobilized by landsliding only to the depth to which they became plastic. The claystones appeared the most resistant to landsliding among the bank materials. The surfaces of rupture were shallow and uneven where poorly consolidated layers of alluvium lied horizontally (landslides at Chochołów and Ludźmierz). In areas where alluvial sediments were more consolidated and inclined, and the layers of clay alternated with sands and gravels, the surface of rupture occurred deeper and was smooth (Stare Bystre landslide). Landslides in undercut river banks are an important source of debris in fluvial channels.

Key words: landslides, river banks, Podhale, Carpathians.

INTRODUCTION

Landslides are a common phenomenon in the Carpathians. Conditions favourable for their occurrence include steep slopes, permeable grounds, and fractured and favourably inclined bedrock strata. Triggers are provided by intense rainfalls or resulting floods in river channels (e.g., Dziuban, 1983; Kotarba, 1986; Ziętara, 1988; Wójcik and Zimnal, 1996; Gil, 1997; Margielewski, 1998; Zabuski et al., 1999; Rączkowski and Mrozek, 2002; Poprawa and Rączkowski, 2003; Starkel, 2006; Wójcik et al., 2006; Rączkowski, 2007; Gil et al., 2009). Widespread landslides originate on slopes of mountain ranges and valleys, but more numerous are small slumps in young V-shaped small valleys or on steep banks of larger rivers. Landslide studies are focused on those occurring on land areas used for agriculture, transport or dwelling, as most damage takes place there and the surface area involved is greatest (e.g., Rączkowski, 2004; Nescieruk and Rączkowski, 2007; Grabowski and Przybycin, 2010; Małecki et al., 2012). Less attention is given to slumps on river banks, especially those which do not represent immediate hazard for humans. Being so numerous these landslides are essential for stability of river banks and for the supply of rock and wood debris to river channels.

Landslides of this type occur in Poland mostly on the banks of highland and lowland rivers. They are mainly found on the high banks of the Vistula River near Nowe Brzesko, Sandomierz, Puławy, at the Warsaw escarpment, in Dobrzyń and Świecie (e.g., Banach, 1973, 1977, 1988, 1998; Bijak, 2007; Ilcewicz-Stefaniuk and Stefaniuk, 2007; Ilcewicz-Stefaniuk et al., 2007; Tyszkowski, 2008, 2012a, 2014). Landslides are especially frequent on banks of artificial dam reservoirs (Spanila, 1996), such as at Włocławek (Banach, 1985, 1994, 2004, 2006; Banach et al., 2013), Pakość (Grobelska, 2006) and Jeziorsko (Banach and Grobelska, 2003; Kaczmarek, 2010), or in Siberia (Shirokov, 1984; Kuskovskiy and Khabidov, 2002; Kozyrieva, 2001; Nazarov, 2006) and China (e.g., Wang et al., 2004; He et al., 2008) but also on the sea cliffs (Lefebre, 1986; Barret et al., 2011). The landslides originated in those places where water was or is now undercutting banks of rivers or lakes or where water soaked the banks (Szabó, 2003; Scesi and Gattioni, 2009). Many landslides on valley slopes in the Polish and Slovak Carpathians reach with their tongues to the river banks (e.g. Dauksza and Kotarba, 1973; Nemčok, 1982; Modlitba and Klukanova, 1996; Haczewski and Kukulak, 2004; Liščák et al., 2010; Baliak and Striček, 2012; Bednarik et al., 2014; Kopecký et al., 2014). Alluvial sediments in these landslides are rotated together with the slope sediments.

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Landslides on river banks are present along most of the world's rivers where their banks rise above the bankfull flow. They have been described, among others, from the Alps of Switzerland (Oppikofer et al., 2008) and Italy (Scesi and Gattioni, 2009), from the Carpathians of Romania (Boengiu et al., 2011), and from the banks of Scandinavian (Millet, 2011) and Canadian rivers (Béland, 1956; Williams et al., 1979). It has been noted that the course of landslide processes in river banks depends on the geological structure of the banks (Clifton et al., 1981). The banks cut in young, poorly consolidated sediments (morainic, lacustrine, aeolian, alluvial) are easily susceptible to landslides that result in significant modification of the channel relief and locally alter the course of channel processes (Lefebre, 1986; Pécsi et al., 1987; Miller and Sias, 1998; Harris, 2003; Kukemilks and Saks, 2013; Chen et al., 2015). Landslides of this type induce economic loss by destroying buildings and transport facilities. Nicolet and Saint Barnabé-Nord landslides (Jaboyedoff et al., 2009), those along the South Saskatchewan River Valley (Clifton et al., 1981) and those in Winnipeg (Baracos and Graham, 1981) may serve as examples of such problems in Canada.

A distinctive feature of most river-bank landslides is that they involve only or mainly alluvial sediments, often of variable grain-size and consolidation. Conditions for their origin and the mechanism of translation are somewhat different than in landslides involving flysch strata or regolith. Presented below are examples of landslides formed on river banks where mainly alluvial sediments are involved. The landslides were studied with the aim of finding how variations in grain-size and consolidation of alluvial sediments influence the course and intensity of sliding. We tried also to determine the stability of relief on such landslides.

STUDY AREA

The studied landslides are located in Podhale, in the boundary zone between Orava–Nowy Targ Depression, Gubałówka Foothills and Pieniny Klippen Belt (Klimaszewski, 1972). In geological terms the landslides formed at the contact of the sediments filling the Orava–Nowy Targ Depression with the Podhale Synclinorium (comprising Oligocene to Early Miocene sandstones and shales) and the rocks of the Pieniny Klippen Belt (Watycha, 1959, 1976; Mastella, 1975; Mastella and Rybak-Ostrowska, 2012; Łoziński et al., 2015). In Neogene and Quaternary times the Orava Depression was the main site of sediment deposition by the rivers draining the Western Tatra Mountains (Czarny Dunajec River) and the Gubałówka Foothills (Cichy, Bystry and Czerwony streams). These sediments are now partly exposed along the channels incised in these sediments. Neogene sediments in the western part of the depression consist mainly of claystones; intercalations of flysch gravels appear in the south-east (Plewa, 1969; Watycha, 1976; Birkenmajer, 1979). The Quaternary sediments along the Czarny Dunajec are mostly gravels composed of material from the Tatra Mountains (mostly crystalline rocks), while along the other rivers the gravels are composed of flysch rocks with admixture of clasts derived from the Pieniny Klippen Belt. Gravels in all Pleistocene fluvial terraces are overlain with clays 1–2 m thick. In the marginal zone of the Orava Depression, the banks of the mentioned rivers over long distances (up to 1.5 km) are built of Neogene claystones or gravels discordantly overlain with Pleistocene or Holocene gravels and clays. Many landslides have formed in these sections of the river channels where the rivers were undercutting the banks. A common feature of these landslides is not only the type of substrate but also their position in the relief. The gravity mass movements involved scarps of high fluvial terraces (Czarny Dunajec River and Wielki Rogoźnik Stream) and also undercut alluvial fans (Cichy and Bystry streams). The terraces are of composite nature, with bedrock of Neogene claystones and alluvial cover of loose Quaternary gravels and clays. Active sliding processes are best pronounced on the banks which are now being undercut by the rivers, but they also persist in the landslides which now lie beyond the reach of flood waters.

For this study we have chosen three landslides situated on the banks of the Czarny Dunajec River at Chochołów, Bystry Stream at Stare Bystre, and Wielki Rogoźnik Stream at Ludźmierz (Fig. 1). The landslide at Chochołów involved a fragment of the 12 m high left-bank Pleistocene terrace. It is situated

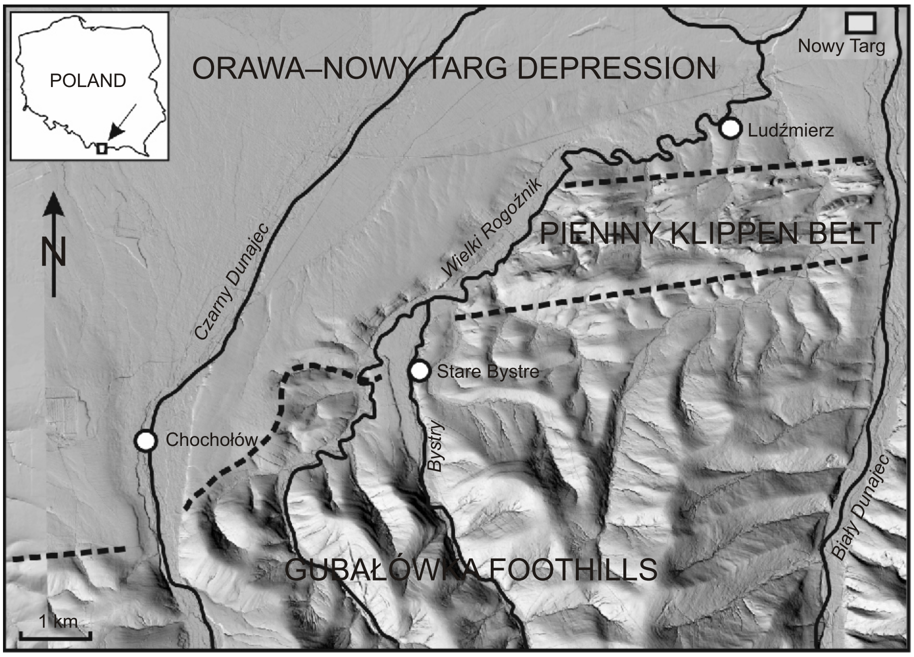

Fig. 1. Location of the landslides studied in Podhale

2.2 km downstream of the bridge over the Czarny Dunajec River on the road to Sucha Hora in Slovakia and its surface area is ca. 10 ares. On the Bystry Stream, the landslides form a linear front that rejuvenates the relief on the west side of the Czerwona Góra (696 m a.s.l.) ridge – an erosional remnant at the apex of a Neogene alluvial fan. Seven landslides with surface areas about 0.3–0.5 ha each are situated along an erosional scarp 1.5 km long and 16–22 m high. The landslide selected for this study lies in the southern part of this scarp. The landslide at Ludźmierz occurs in the right bank of the Wielki Rogoźnik Stream on a sharp bend of the river, and it involved sediments of the 6–7 m high Pleistocene terrace. All the studied landslides lie on active banks of the rivers and their tongues lie within the rich of the medium water level in the rivers.

METHODS

Our study focused on morphological, geological and hydrological features of the three landslides. Surface relief of the landslides was surveyed during four successive years (2012–2015). The survey registered the distribution of scarps, cracks in the ground, as well as risers and depressions within the landslide mass. All evidence of rejuvenation of the crown and fractures along it were also registered during the four years. The geological observations included investigation of complete lithological sections of the landslide slopes, attitude of strata, density and attitude of joints in the rocks exposed in the head scarps, and location of the contact between the claystone bedrock and alluvial gravels. Mesoscopic characteristics of the rocks (grain-size, coherence, plasticity) were described at the exposed fragments of detachment surfaces. Location of groundwater outflows, marshes, water seeps, ephemeral water courses and ponds was registered (Grabowski et al., 2008).

Persistence of the slip surface of the Chochołów landslide (Fig. 1) was evaluated by measuring erosion of this surface after multigelation events during winter semesters using gauge rods (Augustowski and Kukulak, 2013). Volume of sediment transferred toward the base of the landslide was also calculated. Modification of the landslide tongue was observed after successive floods of the Czarny Dunajec.

Observations on the landslide on the Bystry Stream (Fig. 1) concerned permanence of the landslide ponds; registration of the location and type of alterations of the landslide surface after heavy rains and after winters 2012 to 2014, and the progress in erosion of the tongue that was being undercut by the river. Orientation of landslide elements was compared with orientation of joints in the main scarp.

Observations on the landslide at Ludźmierz (Fig. 1) consisted in measuring retrogressive dissection of the crown by water flowing from the peat bog situated above, and in evaluating the age of plants overgrowing the colluvial masses. Degree of weathering of the gravel layer exposed in the main scarp was determined, and the depth to the claystone base of the terrace was established using probes. Hydrological data were used to determine the extent of flood waters on the tongue of each landslide.

Progressive changes in the relief of the landslide at Chochołów were also registered by comparing its photographs taken in years 2012–2015. The photographs taken at various seasons allowed delineating permanently active, intermittently active and inactive zones on the landslide surface. The photographs also allowed determination of the directions and amounts of translations of separate fragments of the landslide in the studied period. A GIS software was used for comparison of the photographs.

RESULTS

The landslide at Chochołów is situated on the slope of a terrace undercut by the Czarny Dunajec. The landslide is 20 m long and 50 m wide (Fig. 2A). The vertical drop height of the landslide is 10–12 m, while the inclination of its slope varies from vertical at the main scarp to 10–15° in the lower part. The crown is on a flat surface of the terrace and the tongue reaches the river channel. The tongue is now actively undercut by the

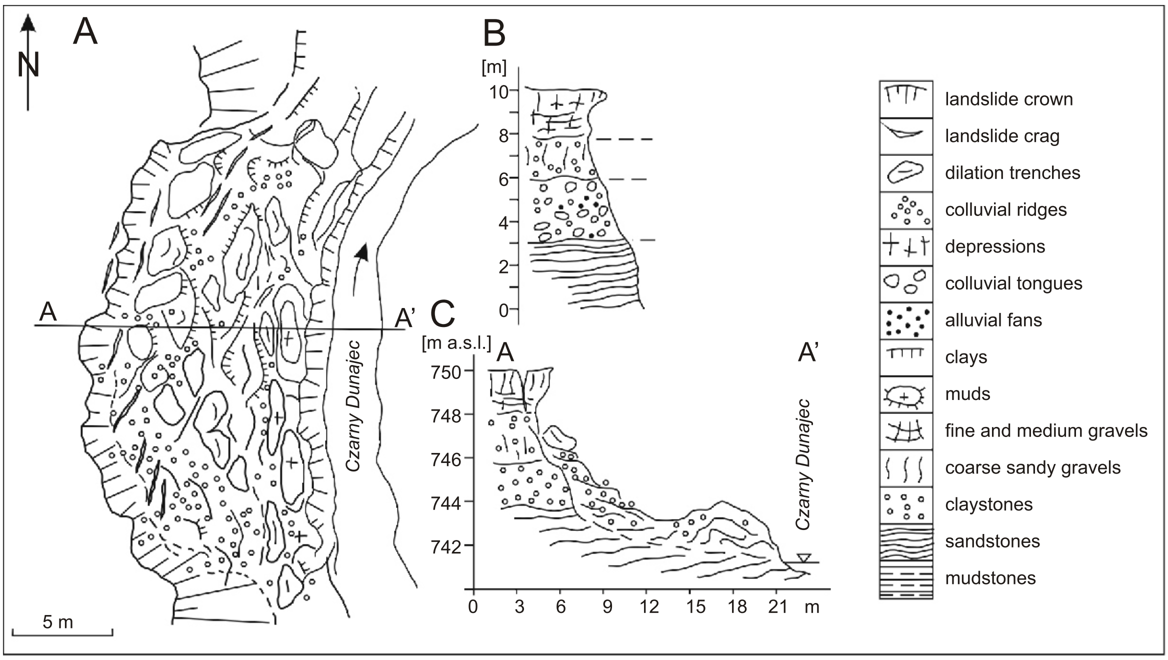

Fig. 2. Landslide in the bank of the Czarny Dunajec River at Chochołów

A – map of landslide; **B** – geological structure of affected slope; **C** – cross-section (A–A') through landslide

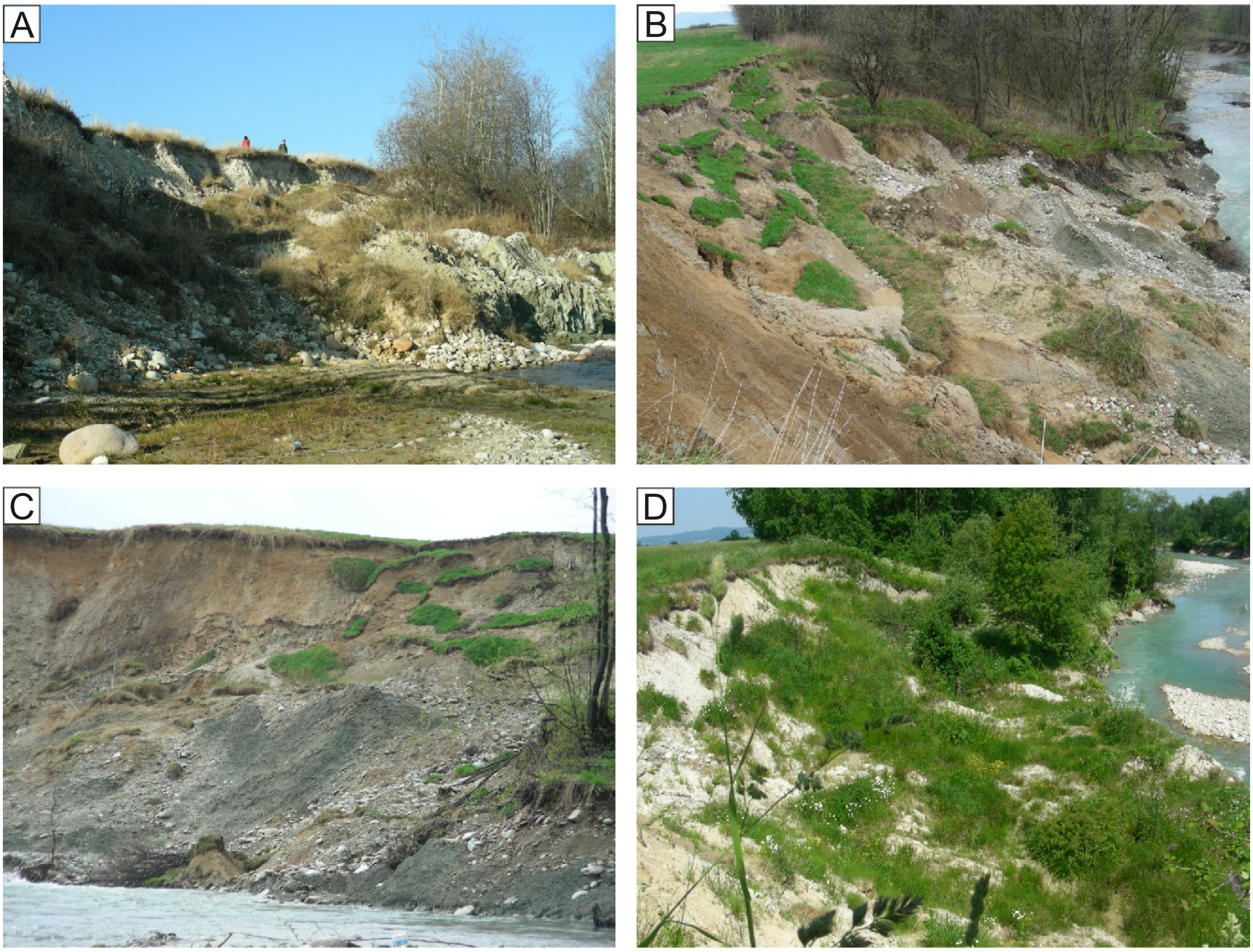

Fig. 3. Changes in relief of the landslide at Chochołów during the period 2012–2015

A – September 2012; **B** – April 2013; **C** – September 2014; **D** – May 2015

river. The terrace surface is occupied by narrow cultivated plots, delimited by ploughing rills that drain rainfall and thaw waters to the landslide.

The slope of the cut-in-fill terrace is cut in terrace sediments (5.5–6 m thick) and the bedrock (strath terrace) of Pliocene clayey-muddy shales (5.5–6 m). The upper part of the alluvium consists of clay (1.7 m), and the lower part of gravel and sand (4-4.5 m; Fig. 2B). The clay does not display sedimentary structures. It is cut by vertical contraction fractures and by a dense set of horizontal joints. Laboratory analyses of the clay samples indicated that silt fraction predominates in the whole section (2/3 of the total), the content of sandy fraction is 21%, clay fraction 7% and gravel fraction 6%. The sediment is mainly mud; this is mainly gravelly mud to a depth of 0.7 m, and gravelly-sandy mud below that depth (Chmielowska, 2013). The underlying gravels are rich (up to 45%) in mud and sand in their upper part (1.7 to 2.8 m), are poorly sorted and chaotically arranged. The pebble size (*b*-axis) varies from a couple of centimetres up to 30 cm, 3–8 cm on average. Only the lowest part of the gravels (2.8–4.5 m) consists mainly of coarse clasts embedded in coarse-grained sand. The whole series of gravels is composed of crystalline rocks from the Tatra Mountains and is feebly cemented. At the base of the terrace sediments lies a series of slightly fissile clayey muds. The muds are compact, slightly plastic, irregularly fractured on the dry surface, and waterlogged within the range of capillary draw and at the contact with the river water.

The surface of the landslide is uneven and varies from part to part. The surface is concave in the southern part and rather uniformly inclined in the north (Fig. 2C). The northern part of the landslide consists of large and thick packages of clayey-gravelly sediments with undisturbed internal structure, reaching down to the river channel. The slip surface of the landslide is steeper there and lies at a greater depth (5–7 m). Displacement of the landslide masses occurred as one-time rotational translation. In the southern part the slip surface is shallower, the colluvial mass is more fragmented and its surface is covered with chaotically crowded gravelly-clayey elevations separated by depressions filled with clay. They are present in the lower, less inclined, part of the landslide.

The relief of the landslide varies also along its length. Numerous sheets of clay with turf are present in the upper part (Fig. 3). One of them has preserved its continuity along the width of the landslide, and lies on the inclined surface. The other sheets are detached from the crown along fractures and slid down over a distance dependent on the slope angle: the steeper the slope, the longer the distance of translation. There are also small secondary crowns 1–1.5 m high. The arcuate crown of the landslide is incised and recessed by 1–1.5 m at the outlets of the ploughing rills. Erosional rills are cut in the landslide surface below these outlets. Cones of washed-out gravels lie within these rills. A distinctive feature of the lower part of this landslide is debris ridges with clay cores coated with gravel. Some ridges are entirely built of clay (Fig. 4) and have a form of

Fig. 4. Compressional fold in clays in the landslide at Chochołów

Fig. 5. Fractures and cracks in colluvium of the landslide at Chochołów

a series of imbricated folds. This part of the landslide is boggy and the clays are soft and plastic. The landslide is wet up to the boundary between the gravels and Neogene claystones. Two groundwater outflows are present along the boundary.

The landslide surface is disrupted by sets of cracks diagonal or parallel to the landslide crown or the toe (Fig. 5). Cracks along the toe, where it is being undercut by the river, are oriented 5–55° and parallel to the erosional scarp, which means that they formed by gravity. Cracks on the sandy-gravelly colluvium in the central and upper parts of the landslide, oriented 155–170°, are locally diagonal to the crown.

The crown of this landslide is receding by mass movements not only in the summer semester, during heavy rains and during floods of the Czarny Dunajec, but also in the winter semester, during repeated periods of multigelation. The averaged recession of the crown during the winter semesters 2011/12 and 2012/13 was 5–55 cm in clay and 5–30 cm in gravel, with a stable position of the toe in the same period (Augustowski and Kukulak, 2013).

The landslide on Czerwona Góra has a shape of an elongated trough, ca. 100 m long, 15–20 m wide and ca. 0.2 ha in surface area. It cuts across the whole length of the steep slope and its tongue enters the channel of the Bystry Stream (Fig. 6). The vertical drop height of the landslide is 25 m (688–663 m a.s.l.), and the average slope is 25°. This is a quite deep landslide, the height of the slip surface exposed at the crown is 4–6 m, but in the middle part the trough is probably even 7–9 m deep, including the thickness of the colluvium within it. The

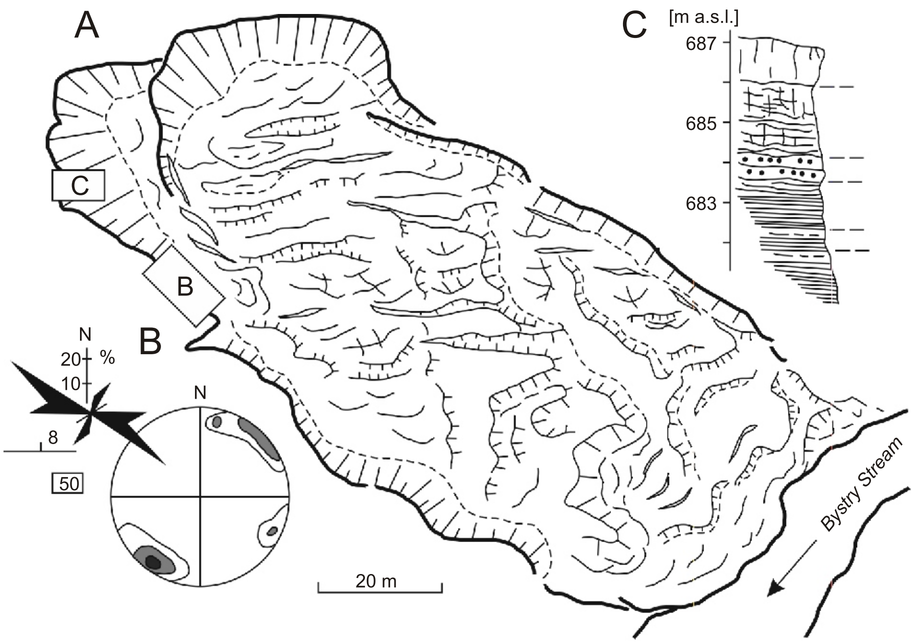

Fig. 6. Landslide at Czerwona Góra

A – sketch of landslide; **B** – joints: on a directional diagram (with the number of measurements) and on a contour diagram (equal area plot, projection of normal on under hemisphere, contour intervals: 5.0–10.0–15%); **C** - geological cross-section at head scarp; other explanations as in Figure 2

Fig. 7. Bedrock crown of the landslide at Czerwona Góra

whole trough is surrounded by a rocky scarp, much higher on the right, northern side (4–5 m) than on the south (1–3 m; Fig. 7). The crown is arcuate in the highest part of the landslide, but its line is broken with two kinks at the transition to the lateral scarp on the right side. The lateral scarps are straight and parallel to one another.

The landslide was formed in sediments of the Neogene alluvial fan. The Czerwona Góra hill is an erosional remnant of the apical part of the Domański Wierch alluvial fan, built of flysch gravels interlayered with claystones and tuffites (Plewa, 1969; Birkenmajer, 1979). A section of the detached part of the Czerwona Góra slope is well-exposed in the upper right scarp of the landslide (Figs. 6A and 7). A layer of clay with fine and medium gravel, 1.0–1.2 m thick, is underlain by deeply weathered and fractured light claystones with discernible layering, 1.0 m thick. The deeper-lying claystones (0.8 m) are less weathered and more sandy. They are underlain by two layers of fine-grained sandstones (0.2 m each), feebly cemented, with rusty stains, underlain by hardpan. Blue claystones, 0.3 m thick, with admixture of sand, lie below a depth of 3.5 m. They pass downward into claystones with fine mud (1.5 m). The still lower part of the landslide slope is exposed on the slip surface of the next landslide to the south. Five inclined layers of blue claystones (0.3–0.6 m thick) alternate with slightly sandy light claystones (1.0–1.6 m). The whole Neogene series dips gently (8–18°) to the north (88–95°), nearly perpendicular to the course of the Bystry Stream and to the landslide-affected slope of Czerwona Góra (170–180°). The claystones are densely cut by joints in the lateral scarp of the landslide. Two sets of joints and slickensides predominate – 100–110° and 120–130° (subordinately 20°), steeply dipping (80–88°) mostly to the north (Fig. 6B). Both lateral scarps of the landslide have similar azimuths (110–120°).

The landslide tongue is overgrown with young forest. The tongue is 3–4 m high at its front. Upon reaching the river the tongue becomes soaked and plastic; by fracturing it disintegrates into blocks. The tongue's surface is uneven, covered over its whole length with many ridges and hollows, and it has four active steps in the frontal part. The most rotated part of the landslide is its lower portion represented by claystones. The ridges and steps are arranged diagonally to the long axis of the landslide, at the azimuths of ca. 140–160°, similarly as the cracks in the axial part. The cracks along the lateral scarps, especially on the northern side, are longer, deeper and parallel to the scarps. The tongue is waterlogged in its lower part, and the water outflows from it at two places. Ephemeral ponds are present on the upper ridges, on the crown side.

The landslide at Ludźmierz was formed at the sharp bend of the Wielki Rogoźnik Stream. It is the smallest of the three landslides, more than 100 m wide, up to 20 m long, and has 5–6 m of vertical drop height.

The front of its colluvial ridge reaches the river. The crown is semicircular, composed of three smaller arcs formed by gradual expansion of the landslide along the river bank (Fig. 8A). The whole landslide consists of three parts, and every successive part has younger forms of the surface. Its steep crown with the exposed slip surface is well expressed in its longitudinal section and compressed colluvial ridges on the nearly horizontal base in the lower part (Fig. 8B). The ridges are higher (up to 2 m) and wider (up to 9 m) in the upper part of the landslide. Currently, the river is eroding intensively the lower ridges, weakening the natural support of the landslide. The area above the crown is overgrown with young coniferous forest, and an extensive blanket-bog lies nearby. The bog feeds acidic water draining to the crown of the landslide as surface water courses along plough rills or by as flows through the piping systems in clay.

The sliding mass consists of an alluvial cover of the Pleistocene fluvial terrace composed of gravel and clay (Fig. 8C). The upper part of terrace alluvium consists of a clay layer up to 2 m thick, composed mainly of silt with admixture of clay and sand and with dispersed coarse and medium-sized pebbles of granite and quartzite. The clay is compact, slightly plastic and structureless. Its non-uniform composition is indicated by water seeps and outflows from piping channels irregularly distributed on the exposed slip surface. A series of gravels of the Tatra granite that underlies the clay consists of three layers varying in size and arrangement of pebbles. They differ also in the degree of weathering, presence of intercalations of sand, and concentrations of ochre in wet parts. The lower levels of the gravel series are strongly weathered and decomposed into a groat-like clay. The gravels along the contact with clays are water-soaked. The claystone bedrock of the terrace is exposed at the very base of the terrace, almost at the river level. Five probes in the colluvial ridges have shown that the claystone base of the terrace lies above the river level, but its top is uneven with differences in elevation up to 1.3 m. The water-soaked claystones are soft and plastic but still quite coherent. The surface of landslide slip runs along their uneven contact with gravels. Lateral displacement of colluvial masses toward the river channel over the top of the clays attains 10–20 m.

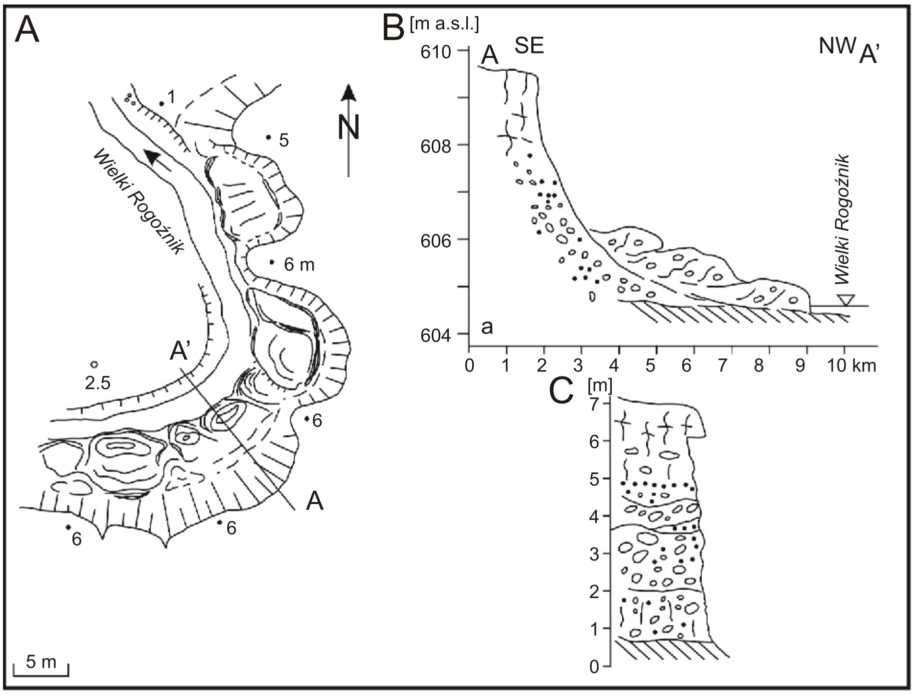

Fig. 8. Landslide at Ludźmierz in the bank of the Wielki Rogoźnik

A – map of landslide; **B** – cross-section through landslide; **C** – geological cross-section of landslide scarp; other explanations as in Figure 2

INTERPRETATION AND DISCUSSION

All the studied landslides are situated at river bends where intensity of lateral erosion of concave banks increases during floods. The loss of bank stability by undercutting naturally favoured initiation of the landslides. Lateral erosion of river banks is widely accepted as the factor accelerating the rate of landsliding (e.g., Zieliński, 2001; Tyszkowski, 2012b, 2014). Even the changes in water level alone may stimulate mass movements on the undercut river banks (Małecki et al., 2012). The tongues of the studied landslides are still being undercut, hence all the landslides are intensely reactivated during every flood of the Wielki Rogoźnik, Bystry streams and Czarny Dunajec River.

Nevertheless, the main factor leading to the triggering of the landslides was the abundance of water in alluvial sediments above the river channels. Variable lithology of these sediments and the resulting differences in the rate and modes of water circulation within them controlled the course and type of landslide processes on the river banks. The most important feature of the river bank structure, as compared with the banks built of flysch rocks, is the presence of a thick cover of loose or weekly compacted alluvial sediments on a bedrock of compact claystones. The Neogene claystones in Orawa are generally compact and have low permeability (Watycha, 1976, 1977; Wiewióra and Wyrwicki 1980). Such system, with permeable layers lying on impermeable rocks, favours infiltration of rainwater and meltwater above the clayey base of the terrace sediments (Zabuski et al., 1999). Water penetrates quite easily into the alluvial clays and gravels to the top of the Neogene claystones. The much slower infiltration into the Neogene claystones results in accumulation of water in the zone of contact between the claystones and gravels; this in turn favours detachment and translation of the overlying sediments.

A classical example of this is provided by the mechanism of the formation and evolution of the Chochołów landslide. The thick topmost low permeability clay retards infiltration of water, hence most of it drains by plough rills to the upper edge of the landslide crown. Near the crown, the joints in the surficial clays are more dense and vertical, facilitating infiltration of water into underlying gravels (Fig. 9). Poor consolidation of the gravels allows for deep penetration. Increased water content in gravel lowers their shear strength, mainly by reduction of the angle of internal friction (Schuster, 1979). The gravel becomes still less coherent and slides in layers toward the river. The distance of translation does not exceed the front of the clayey base of the terrace. The slowly wetting Neogene clays swell, and deep slip surfaces do not develop within them. Changes in compressibility and shear strength occur only to the depth of wetting (Thiel, 1980; Choma-Moryl, 2001). The clays may, however, provide a slip surface for the waterlogged gravels and surficial clays (Rączkowski and Mrozek, 2002). Only their softened part, adjacent to gravels, is subject to translation. It was ca. 1.2–1.5 m thick in the landslide at Chochołów, up to 2–3.5 m on Czerwona Góra, and 0.5–0.8 m at Ludźmierz. It is in the layer of the most frequent formation of folds under the stresses induced by the weight and movement of the overlying colluvium (Nescieruk and Rączkowski, 2007). This process may explain the folds in clayey-gravelly sediments at the base of the Chochołów landslide. For the same reason the longitudinal section of this landslide shows marked loss of sediments in the clayey-gravelly part and a small one in the base clays (Fig. 10).

Gravity translations in the individual layers of alluvium do not proceed in a uniform way. In the surficial clay layer this process runs in two ways. Near the edge of the main scarp, where the clay is cracked by contraction, coarse lumps of clay slide down kept together by the turf on the upper side. They disintegrate with time by desiccation or waterlogging. The clay which is more sandy slides down in a less coherent way. They fall down

Fig. 9. Fractures and cracks in silts in the upper part of the main scarp of the landslide at Chochołów

Fig. 10. Neogene claystones eroded by the Czarny Dunajec within the landslide at Chochołów

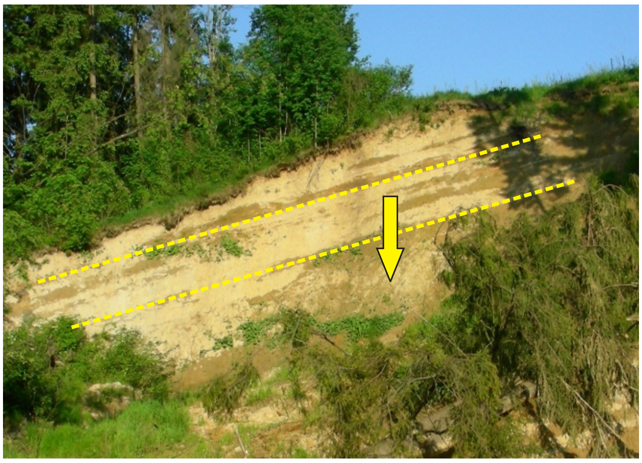

Fig. 11. Discordant directions of the slip surface and attitude of strata at Czerwona Góra

into smaller fragments at start and, when later soaked, they easily flow down toward the base of the scarp. This process is usually slowed down by long-lasting soaking of clay with water and it lasts longer than in gravels. This is why these sediments cover gravelly colluvia with a clayey blanket. Clay is creeping down immediately after showers only directly from the main scarp. Infiltration of water is easy in the layer of feebly consolidated gravel, and water flowing over their surface still lowers their cohesiveness. Shallow sheet-like slides or slow creep of gravel occur subsequently. These movements are active mostly in winter, when gravel slides slowly down in a layer of various thickness over the surface of frozen deeper ground (Skarżyńska, 1969).

Taking into account the distribution, structure and surface forms of the landslide at Chochołów it may be described as rotational at its start, later reactivated in the clayey part by falls and in the gravel – by sliding of loose sediments, and in the part being undercut by the river – by falls of the claystone bedrock of the terrace. The deeper extent and more sheet-like mode of translation in the northern part of the landslide are probably caused by the deeper position of the slip surface and its later origin. The faster and more clockwise rotation of individual clay-and-turf rafts in the southern part of the landslide is the result of increasing steepness of the main scarp in this direction. The presence of cracks over the whole surface of the landslide points to continuation of the gravity movements within it.

The landslide at Czerwona Góra is also rotational, though many of its features are related to the structure of the bedrock. Orientation of its lateral scarps, step-like outline of the crown, and orientation of most cracks in the upper part of the tongue, all correspond to the orientations of cracks and fractures visible in the side walls of the landslide. This landslide is much deeper than that at Chochołów. This may be caused by stronger cementation of the rocks involved. Deeper along the northern margin, the slip surface is asymmetrical in cross-section. This may be caused by detachment along the surface of one of the layers of blue claystones dipping to the north like all layers in the landslide (Fig. 11). The slip surface is inclined steeper that the dip of the layers, so the slip surface must cut through successive deeper layers toward the base of the landslide. This explains the predominantly argillaceous composition of the landslide's toe, its higher rotation and wetness, and its permanent tendency to reactivation.

The landslide at Ludźmierz is of rotational type and is polygenetic. It was caused by joint action of erosional undercutting of the terrace at the river bend, oscillations of the water level in the river, and ground water action in the area of its head. Near-surface acidic ground water inflowing from the nearby bog intensifies chemical weathering of clay and gravel and soaks the scarp beneath the sites of its outflow. The deeply weathered water-soaked gravel becomes an active layer susceptible to displacement by gravity. Activity of the landslide increases after heavy rainfalls and during high water levels of the river. Water penetrates subsequently into the landslide mass from the river, favouring mobilization of the whole landslide (Małecki et al., 2012).

The contribution of tectonic processes to the origin of the landslides should be also taken into account. All the landslides formed within the zone of marginal faults of the Orawa Depression. Faults in Neogene mudstones and claystones and boundary faults between the Podhale Flysch and Neogene rocks are exposed near the Chochołów landslide (Kukulak, 1998; Fig. 12). It is noteworthy that the landslide activated only a fragment of the undercut terrace of the Czarny Dunajec. The structure of the valley slope is identical above it, but mass movement does not disturb it; the slope is stable despite groundwater outflows on its surface. Large faults belonging to the Krowiarki

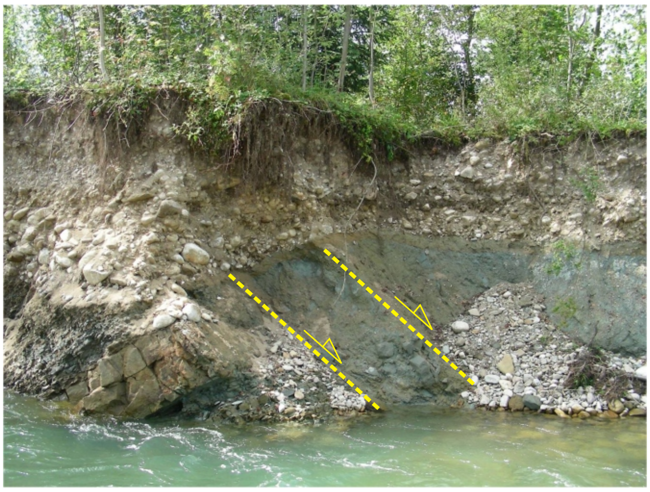

Fig. 12. Fault in Neogene claystones at Chochołów

Fault Zone and the western termination of the Tatra Mountains (Bac-Moszaszwilli, 1993; Baumgart-Kotarba, 1996, 2001) are exposed at Czerwona Góra near the studied landslide. They dissect Czerwona Góra into horsts and grabens below the landslide. The unusual shape of this landslide and the neighbouring ones – narrow, long troughs, attitude of joints in sandstones and claystones. and the orientation of the lateral scarps seem to follow the directions of these faults.

CONCLUSIONS

Landsliding on scarps of fluvial terraces is more complex than on slopes built of flysch. The landslides are usually initiated as rotational ones, but their further evolution is polygenetic. This is due to a difference in lithology of the involved sediments, variations in the properties of alluvial sediments with respect to their cohesiveness, permeability and plasticity, and also to their usually horizontal attitude (Oppikofer et al., 2008). The landslides formed in those places where feebly consolidated or loose sediments (sandy gravels) were lying on cohesive impermeable rocks (Neogene claystones). Such structure of sediments facilitated infiltration of water into the alluvium and a soft plastic zone could form at the contact with the Neogene claystones serving as the site of the slip surface. The depth of the slip surface increased with the increasing depth of the claystone base of the terrace and increasing consolidation of the alluvium. The claystone base of alluvia at Chochołów and Ludźmierz was involved in sliding only to the depth to which it became plastic. In the thick basements of the terraces with an alluvial cover, landslide movements tend to be shallow, because the clays loose strength and become plastic at a very slow rate. These movements normally do not reach down to the channel bed (Harris, 2003; Schwert, 2003). Landslide movements in the Quaternary alluvium were more dynamic than in the Neogene claystones, though they were not uniform within each layer. They were slower and lasted longer in the layers of topmost clays and were faster in gravels. Local factors that influenced the initiation and course of the landslide movements included: the position of the alluvial strata; the presence and orientation of tectonic structures; ground water outflows on the scarps; and the variable degree of weathering of the sediments involved.

Landslides on river banks are permanently reactivated because their fronts are eroded by stream currents during every flood. This is in contrast with the landslides on slopes. Although tongues of some slope landslides reach river channels and are eroded by the rivers, this does not result in reactivation of the whole landslides (e.g., Dauksza and Kotarba, 1973; Baliak and Striček, 2012). The eroded colluvium contributes to the sediment load of the river (e.g., Béland, 1956; Van Asch et al., 1999; Scesi and Gattioni, 2009; Kukemilks and Saks, 2013), so that the relation between the river and the landslide is dynamic and vital for the activity of the landslide.

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