VARIED RIVERBANK STABILITY IN THE FORELAND OF THE TATRA MOUNTAINS

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The northern foreland of the Tatra Mountains is drained by local streams (e.g. the Cichy Stream, the Bystry Stream, the Czerwony Stream) and transit rivers flowing from the Tatra Mountains (the Czarny Dunajec River, the Biały Dunajec River, the Białka Tatrzańska River). Riverbanks of smaller channels are cut in the Podhale Flysch or in alluvia of these rivers. In the downstream river reaches, the banks are typically composed of undercut rock (sandstone-shale or loam) topped with sandy-silty or gravelly overbank deposits. The rocks were examined in terms of their resistance to frost weathering and gravitational processes at several study sites on the banks of the Czarny Dunajec River and the Cichy Stream. Erosion pins method was used to determine the rate of frost processes. Measurements of bank retreat were carried out several times during the freezing and thawing periods. Grain-size distribution and cohesion of the fine-grained alluvium were determined. Density and pattern of the cracks as well as textural and structural properties of rocks were measured on the sandstone and shale undercut riverbanks.

Frost action first blasts the banks built of silty-sandy material, then gravelly, poorly cemented ones (young terraces), and finally sandstone and shale outcrops. There are also significant differences in the dynamics of bank retreat depending on its lithology. High riverbanks are also subject to mass movements. Landslides occur mainly in places where the terrace bedrock consists of clay material and the accumulation cover is gravelly and sandy-silty. Groundwater seepage from the surface of the slope increases the plasticity of clay thus inducing landsliding processes. Others mass movements occur when the banks are undercut during flood events and during the spring thawing of the soil. Stability of the banks is minimal in areas with no vegetation cover as geological structure is exposed directly to the activity of weathering and gravitational processes.

Keywords: riverbanks, frost weathering, landslides, the Nowy Targ – Orava Basin

INTRODUCTION

Riverbank erosion depends not only on river discharge and water stage but also on the activity of weathering, slope processes and river icing (e. g. WOLMAN 1959, KLIMEK 1974, RACHOCKI 1978, TEISSEYRE 1979). All these processes are additionally controlled by precipitation and temperature variability throughout the year (TEISSEYRE 1984, STARKEL 2006). Riverbank stability is thus dependent on a range of morpohogenetic processes operating in a given set of environmental conditions (ZIĘTARA 1968, KLIMASZEWSKI 1978, KRZEMIEŃ 1984, KLIMEK 1991). Some authors emphasised that frost processes are the dominant factor in the development of the riverbanks (TEISSEYRE 1984, LAWLER et al. 1997) but the majority of studies were carried out in areas with permafrost (e. g. HOOKE 1979, HOOKE 1980, WALKER et al. 1987, WYNN and MOSTAGHIMI 2006) where bank forming conditions are significantly different. Only a few works present results of similar studies from temperate climate (e.g. GARDINER 1983, LAWLER 1986, ABERNETHY and RUTHERFURD 1998, COUPER and MADDOCK 2001, SAYNOR et al. 2003, LUPPI et al. 2009, KRONVANG et al. 2012) and the authors usually do not differentiate the retreat rates between seasons. For instance, LAWLER et al. (1999) estimated the rate of riverbank retreat at 6.5 cm/yr, which represents 32 – 43% of the total erosion observed annually. The results obtained from the hydrological year of retreat of the riverbanks range from 2.7 cm to 60 cm/yr (COFFMAN 2009). Most studies on frost processes have focused on banks formed of non-cohesive material and there is little data on retreat on rocky or highly cemented riverbanks.

As riverbank material strength is one of the factors influencing riverbank susceptibility to erosion (NIEMIROWSKI 1970, KLIMEK

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1974, RACHOCKI 1974, BIEROŃSKI and TOMASZEWSKI 1979, KRZEMIEŃ 1981, KRZAKLEWSKI 2008), bedrock, alluvium or composite banks may markedly differ in resistance. In bedrock banks, resistance depends on structural characteristics of the rock (bed thickness, bedding or lamination), texture (mineral composition, grain size and packing, presence of fractures) and bed orientation. In turn, retreat of alluvial or composite riverbanks depends on material grain-size distribution, cohesion, density of cracks, resistance etc. This paper examines the influence of lithology and moisture of riverbank material on bank stability in some rivers and streams in the Tatra Mountains foreland (the Nowy Targ – Orava Basin and the Gubałówka Hills).

Current development of riverbanks proceeds under the conditions of their direct contact with rivers, lack of turf cornice on the surface and without human intervention. Bank retreat is affected by fluctuations in water level due to floods. The studied rivers flow either directly from the Tatra Mountains (the Czarny Dunajec River) or originate in the Tatra Mts. foreland (tributaries of the Czarny Dunajec River), where annual rainfall is relatively high (about 800 - 1100 mm/year) but fairly variable between years and seasons. The Nowy Targ - Orava Basin, an intramountain depression, is characterized by cool temperate climate. The mean annual air temperature ranges from 4^0C to 6^0C. During the winter months the average temperature decreases to – 6^0C with minimum

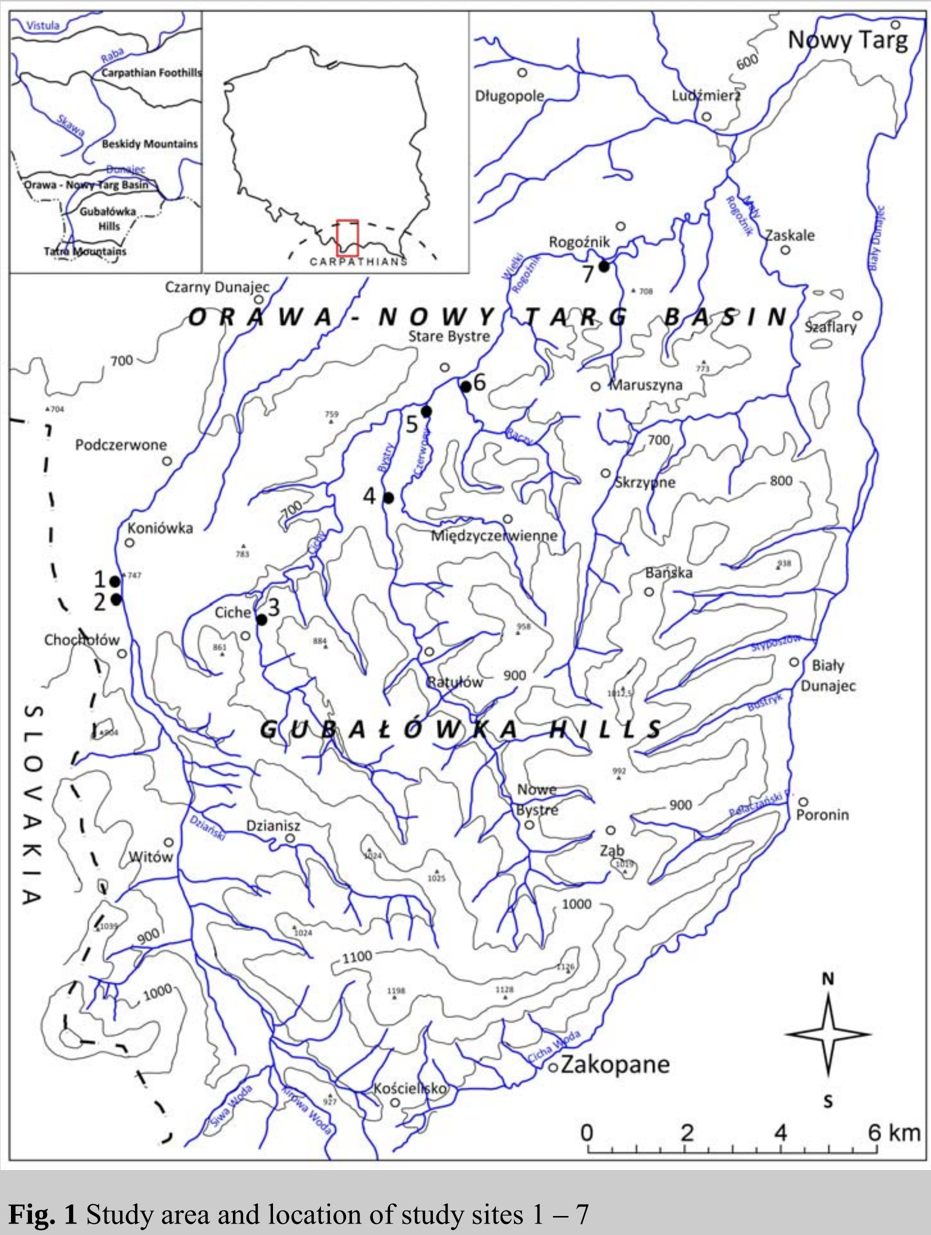

Fig. 1 Study area and location of study sites 1 – 7

daily temperatures often below -30^0 C (KUKULAK 1999) which is related to the frequent thermal inversions within the basin. For weathering and slope processes, frequent daily oscillations of air and soil temperatures around 0° C are also important. However, the ground thermal conditions are of primary importance and are often significantly different from the recorded air temperature. Soil temperature fluctuations directly affect the rate of bank retreat, although the depth at which temperature oscillations around 0˚ C have the most impact of the intensity of frost erosion has not been determined yet. A significant role is also played by low temperatures sustained for a long period of time, when the soil freezes to a considerable depth. In the thaw periods the rate of riverbank retreat increases. The lack of thick snow cover on the steep banks enhances freezing to a larger depth (KUKULAK 1999)

AIM, STUDY AREA AND METHODS

This paper examines the differences in the manner and rate of change of riverbanks with distinct lithology. Riverbank retreat was investigated on riverbanks cut in flysch sandstones and shales, gravelly alluvium and alluvial and residual loams.

The influence of contrasting mechanical characteristics of these rocks on bank susceptibility to weathering, fluvial erosion and slope processes was investigated. Riverbank forming processes and their effects were studied in relation to air temperature and river water stage variability in 2011 and 2012; observations made in the preceding years were also taken into account. Particular attention was paid to frost action and its effect on the riverbanks. Study sites were located on the active riverbank undercuts of the Czarny Dunajec River and its tributaries: the Cichy Stream, the Bystry Stream, the Czerwony Stream, the Molczy Stream and the Wielki Rogoźnik Stream in the western part of the Tatra Mountains (**Fig. 1**).

Rate and pattern of bank erosion were investigated by repeated surveys and measurements at the study sites. Steel pins installed in riverbanks were used to monitor the occurrence of bank retreat events and the volume of removed material (**Fig. 2A**). Erosion pins were placed in a horizontal line along the bank slope, in flysch shales, cemented gravels and sands as well as in thick loam cover below the crest of river terraces. The rates of frostaction and massmovement on the banks were measured with the installed pins repeatedly duringthe cold half-year. The measurement results were then compared with ground temperature record from a temperature logger mounted near the pins.

The volume of the material evacuated from riverbanks was estimated with traps installed at the study sites. At each site, horizontal ledges

Fig. 2 Erosion pins at site 1 (A) and bank sediment traps at site 3 (B)

were mounted at the bank slope or bank toe to trap material falling from the bank face during freeze-thaw periods (**Fig. 2B**). During the winter, the occurrence of ice lenses and horizontal cracks within the loam cover were recorded, and in the summer the orientation and density of drying cracks were measured. The degree of compaction and general variation in grain-size were determined for gravel covers. On flysch outcrops in the bank of the Cichy Stream, joint orientation and spacing as well as bed orientation in sandstones and shales were measured. Pre-sence and length of tension cracks along bank crest as well as turf cantilevers were recorded.

GEOLOGY AND STRUCTURE OF THE ANALYSED BANK UNDERCUTS

A. The Czarny Dunajec River - site Chochołów (1 in Fig. 1)

Between Chochołów and Koniówka, the Czarny Dunajec River undercuts the terraces of various height. Active undercuts of 6 – 7 m and 9 – 10 m high terraces were analysed (site 1 and 2). At these sites, clay bank toe is overlain with gravel and loam (**Fig. 3** – sites 1 & 2). The Neogene clays, representing the fill of the tectonic Orava Basin, are covered with poorly sorted, loosely-packed gravelly alluvium derived from the Tatra crystalline rocks. The matrix consists of coarse quartzite sands. Occasionally, lenses of sands are present within the gravels. The deposits are weakly cemented and susceptible to water seepage or ice accretion. The origin of the 2.5 m thick topmost loam layer, with clayey, muddy or sandy layers and fine gravels, is most likely related to weathering and fluvial deposition (lower part) and slope wash (the upper part).

B. The Cichy Stream – site Ciche (3 in Fig. 1)

The Cichy Stream bank undercut is 9 m high and 20 m long, and exposes the upper section of the Zakopane beds. The flysch beds are dipping upstream at 30 – 32°, with the strike of 80 – 85° slightly oblique to the stream. The lower part of the profile is mostly shaly. The shale complexes are intercalated with single, 10 – 40 cm thick sandstone beds. The upper part of the profile is dominated by sandstones without shaly intercalations. All the outcropping flysch beds are densely fractured and the density of the fractures increases with the decreasing thickness of the beds.

C. The Bystry Stream – site Ratułów (4 in Fig. 1)

Site Ratułów is located on the right bank of the Bystry Stream that undercuts the Czerwona Góra Hill in its highest section. The 12 – 15 m high streambank undercut is composed of thick (5-15 m), alternating gravel and clay complexes which represent the Neogene sediments of the apex of the Domanski Wierch alluvial fan (BIRKENMAJER 1958, PLEWA 1969). The high streambank is cut almost entirely in the gravel complex, only its lowermost toe part is clayey (**Fig. 4D**). Strong cementation of the gravels inhibits erosion, however, a high degree of weathering and a dense network of fractures of the entire complex and single particles may enhance bank retreat.

D. The Czerwony Stream – site Stare Bystre (5 in Fig. 1)

Site Stare Bystre is located on the right bank of the Czerwony Stream, approximately 1.3 km upstream of the confluence with the Wielki Rogoźnik Stream. The 1.6 – 1.7 m high streambank undercut is composed of grey clayey-muds rich in organic material (at bank toe), overlain with a 45 cm thick complex of layers of fine gravels intercalated with mud and sand. The upper part of the profile consists of 40 cm thick layer of fine deposit (layered muds with clay or sand). Both complexes are separated by an erosional surface.

E. The Molczy Stream – site Stare Bystre (6 in Fig. 1)

Site Stare Bystre, on the right bank of the Molczy Stream, is situated 350 m upstream of the confluence with the Wielki Rogoźnik Stream. The lower part of the streambank (1 – 1.2 m) consists of fine, highly cemented sandstone gravels with sandy lenses separated by an erosional surface from the overlying 0.5 – 0.6 m thick layer of poorly cemented sandstone pebbles and cobbles. The topmost layer consists of 0.3 – 0.5 m of sandy alluvial loam. The high cementation of the lowermost layer of older gravels results in its high resistance to fluvial erosion, while the younger upper deposits are prone to degradation.

F. The Wielki Rogoźnik Stream– site Rogoźnik (7 in Fig. 1)

The site Rogoźnik is located on the right bank of the Wielki Rogoźnik Stream, about

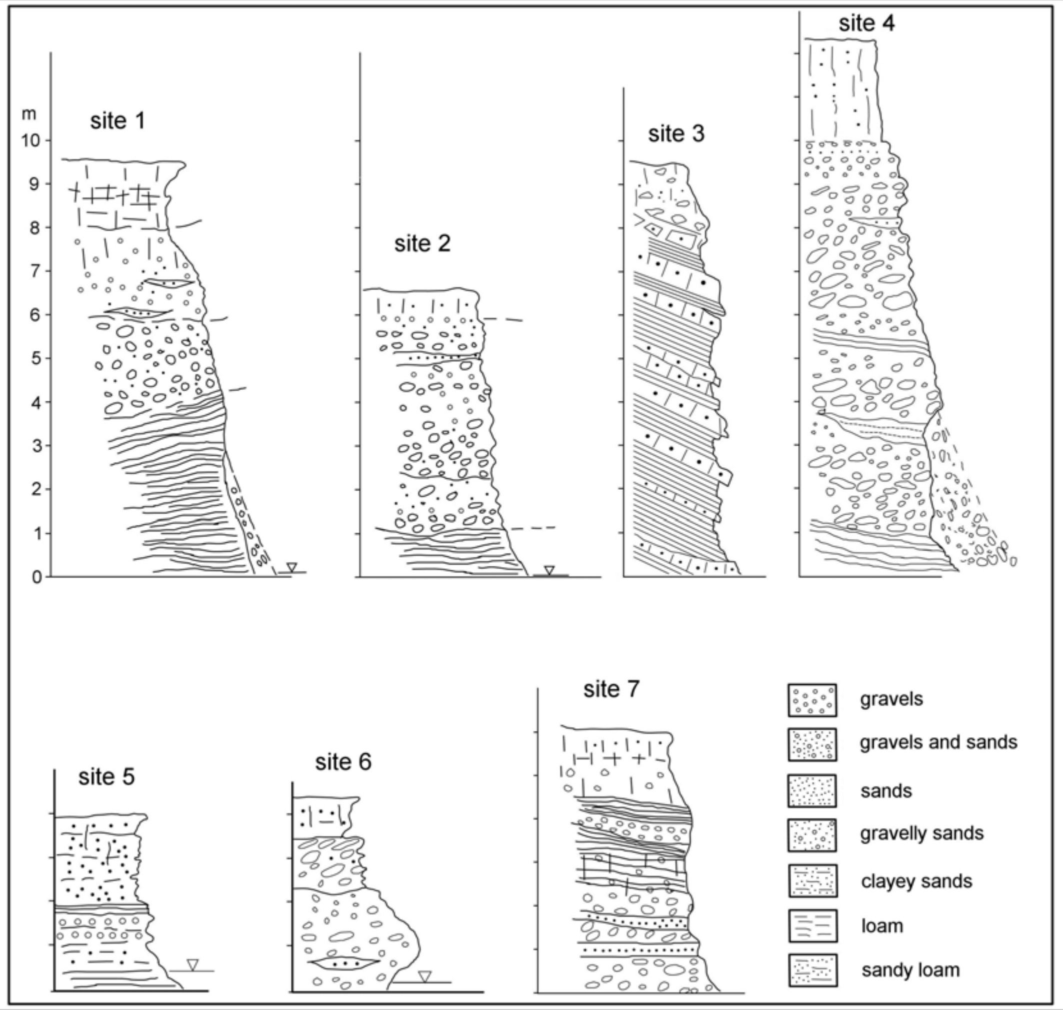

Fig. 3 Geological profiles of the surveyed banks (sites 1 – 7)

200 m upstream of the confluence with the Trawny Stream. The undercut of a 6 m high terrace exposes highly cemented gravels with sandstone, limestone and flint framework. The gravels are covered with 1.2 – 2 m of loam of alluvial or colluvial origin. The structureless gravels (2 – 5 cm, occasionally up to 20 cm in diameter) differ in roundness, and in comparison to the 6 m high terrace of the Czarny Dunajec River at site 2, are highly cemented, similar to Neogene gravels at site 5 on the Bystry Stream. The upper, loamy cover is unusually thick and its structure resembles that of the loam layer at site 1. Its uppermost section (0.5 – 0.8 m) consists of sandy loam, while the lower one is largely clayey with tension cracks.

RIVERBANK-FORMING PROCESSES ON LOAMY BANKS

The loams constitute the top layer in all investigated riverbank profiles that do not usually become inundated by floodwaters. Regardless of their origin, age or grain-size distribution, the loam is the least resistant material in these bank undercuts. Although cohesive, it is prone to weathering and mass failure. These processes alternate between seasons: weathering dominates in the winter and mass wasting is more common in the summer. However, their effects are most noticeable in the autumn (with ground-frost and dry conditions) and spring (during thaw or recurring freezing conditions). Summer downpours induce slope wash, rock fall and linear erosion on the loamy parts of the bank undercuts, however, their overall effects are less pronounced than those of ground ice activity.

During the winter season of 2011/2012, despite the insulating effect of snow cover, the riverbanks froze to the depth of 0.3 – 0.4 m. In January 2012, ground temperature at 0.25 m below the surface on the bank of the Czarny Dunajec River (site 2) was only slightly lower than 0° C, even during the periods of severe frost with markedly lower air temperatures.

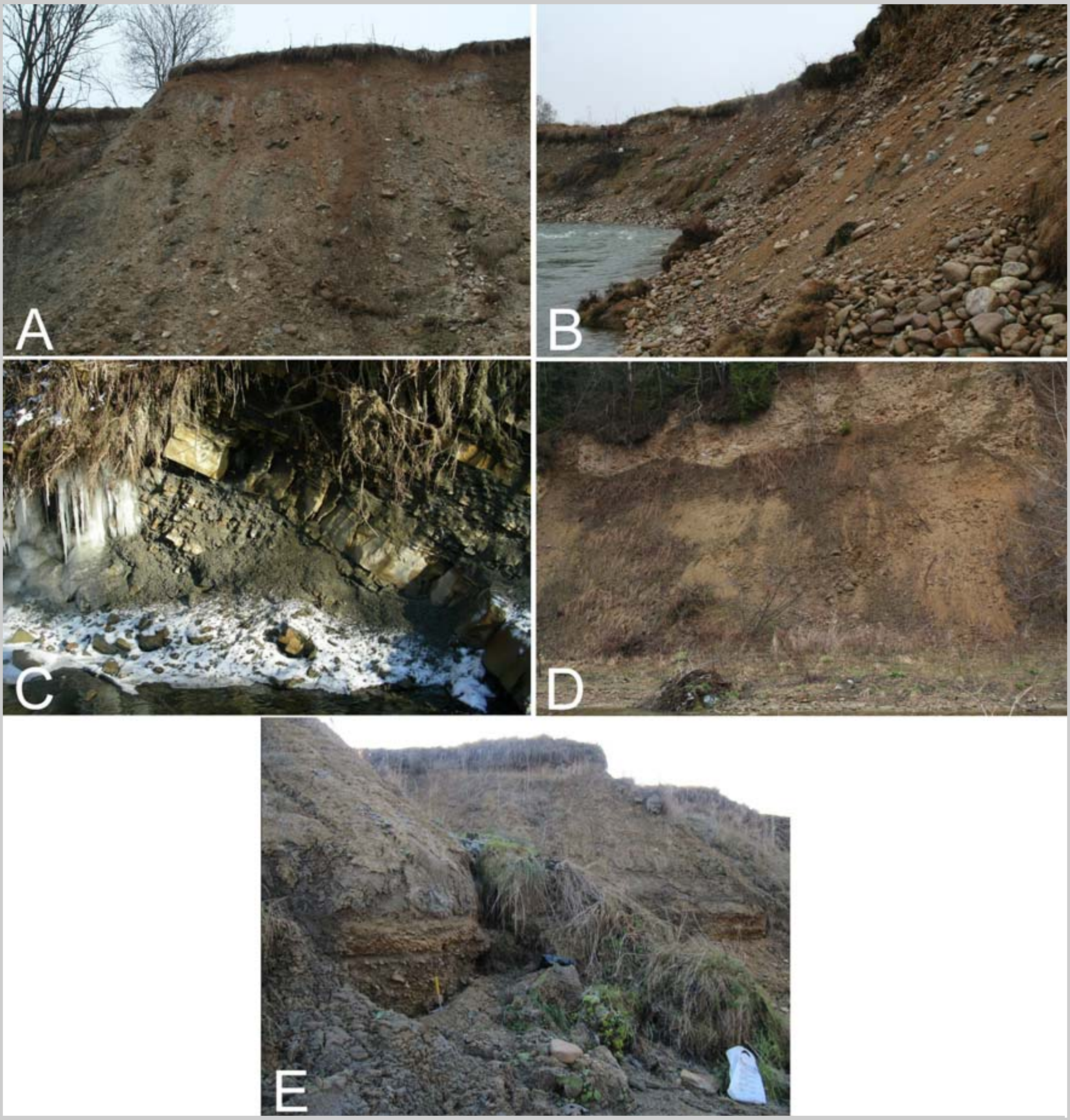

Fig. 4 Structure of the surveyed banks (A – E):
A – site 1; B – site 2; C – site 3; D – site 4; E – site 7

Needle ice and ice lenses formed on the loam bank undercuts, the upper parts of the loam profiles became ice-coalesced. Frost-heaving caused the erosion pins to 'sink' 2 – 3 cm within the bank material. Differential frost heaving opened vertical and horizontal cracks within the loam, parallel to the freezing front. The highest density of the cracks was recorded 0.2 – 0.4 m below the soil surface. The cracks at that depth were especially pronounced during spring thaw and during periods of gradual drying of the soil. This is due to the melting of ground ice, breaking off and failure of blocks of dried loam. Removal of large blocks of loam from the upper part of the riverbank profile led to the formation of post-frost turf cantilevers at riverbank crest and caused fracturing on the surface of the adjacent terrace. Cantilevers that were mostly formed during thaw usually collapsed in the spring or summer. In the summer, loam bank undercuts were degraded by falling and sliding of cantilevers and lower layers of fractured loam. This was particularly evident in loams with higher clay content and deeper tension cracks (sites 1, 2, 4, 6 and 7). Non-vegetated riverbanks were susceptible to sheet-wash during summer downpours. In the summer, high air temperatures caused gradual drying of the loam and formation of tension cracks.

The pattern and density of the cracks were related to grain-size distribution of the loam deposit, aspect and bank slope. Steep riverbanks with southern exposure and cut in more clayey loams exhibited deeper and more numerous vertical cracks with 15 – 30 cm spacing, whereas less deep, polygonal cracks developed on gentle riverbanks. The presence of tension cracks substantially decreased riverbank resistance to fluvial erosion.

RIVERBANK FORMING PROCESSES IN GRAVELLY ALLUVIUM

The gravels in the studied riverbanks vary in terms of lithology, grain-size and, more importantly, degree of cementation. In general, the earlier the loam was deposited (site 3), the stronger its cementation. Cementation of the material inhibits the efficiency of frost-weathering and mass wasting. During the winter of 2011/2012, the gravely banks froze to the depth of 0.4 – 0.6 m and this depth was greater in loose gravels. Ice lenses formed within loosely packed pebbles and sands and induced formation of horizontal cracks No needle ice was recorded as it does not form in gravels (TEISSEYRE 1984).

Retreat of gravely banks was usually recorded during freeze-thaw cycles, both in winter and spring. During short thaw periods, single particles broke off the thawing riverbank surface and fell or slid to the bank toe, forming gravely belts. This process was particularly dynamic during spring thaw when bank thawing was faster and deeper thus increasing the thickness of the layer loosened by frost-heaving and saturated due to the melting of ground ice. For instance, bank retreat during spring thaw at sites 1 and 2 ranged from 7 to 70 cm. High mobility was also typical of loose gravels accumulated at the toe of vertical riverbanks (site 1and 2) with either single particles or layers of thawing gravel sliding down. Some of these particles were trapped on the patches of older, collapsed turf cantilevers. The volume of bank material that accumulated along 20 m of riverbank toe after the winter of 2011/2012 (site 1) amounted to 12 m³. In the summer, the banks retreated mostly due to the failure of blocks of material from bank undercuts destabilized by flood waters (sites 2, 5, 6 and 7). Large proportion of the collapsed material was then transported downstream.

RIVERBANK - FORMING PROCESSES ON ROCKY BANKS

Flysch outcrops on the undercut riverbanks are, relatively, most resistant to degradation. However, both the flysch (sandstones and shales) and the Neogene claystones of the Orava Basin (site 1, 2 and 4) are fairly susceptible to weathering and mass wasting; this susceptibility is increased by the presence of dense tectonic and weathering-related fracturing of these rocks. Freezing water widens the joints within shales and the fractures within sandstones. As shales break into thin layers and sandstones into blocks, with the melting of ground ice on the bank of the Cichy Stream (site 3) particles of varied size fell off the streambank face. The disintegration and breaking off of shales was more intensive, shale banks also retreated faster. The sandstone beds, protruding from the bank face broke off along the existing fractures. The debris accumulated on the protruding sandstone beds or at riverbank toe. The shale debris was imbricated and the increased cohesion in wet material caused the debris accumulation to form convex profiles, steeper than those formed of dry shale debris.

At site 3, the volume of the material accumulated during the winter of 2011/2012 amounted to 3.5 m³, and the exposure of the steel pins installed within the bedrock bank undercuts ranged from 10 to 52 cm. The debris was then entrained by flood waters which removed all ine particles, leaving only boulders with the weight exceeding the river’s transport capacity.

EVALUATION OF RIVERBANK STABILITY

The study confirmed that bank lithology may strongly influence the rate of riverbank retreat. In the years 2011-2012 the fastest retreat was recorded on loamy banks (70 – 100 cm/year). The process was slower on loose gravels (7 – 70 cm/year), strongly compacted gravels (0.5 cm/year) and outcrops of solid rocks (10 – 52 cm/year). The material collapsed from retreating riverbanks was partially or temporarily accumulated as debris talus at bank toe. Most of that material will be entrained by the river during floods greater than that of 2012.

Bank stability was disturbed several times during all seasons, however, bank retreat related to freeze-thaw cycles during winter season was found to be the most effective and entailed material evacuation from entire riverbank face, irrespective of its lithology. The number of freeze-thaw cycles seems essential. Bank undercut forming processes were most active during thaw periods and resulted in largest bank retreat. Moreover, the frost processes enhanced the efficacy of mass wasting processes active in the warmer half-year. The loam fractured by ground ice in the winter and by drying in the summer changed its structure and became more susceptible to breaking off and fluvial erosion. Opening of fractures and widening of the joints in solid rocks facilitated mass wasting due to fluvial erosion on the riverbank undercuts.

CONCLUSIONS

Erosion of the riverbanks of the rivers in the Tatra Mountains foreland is enhanced by frost weathering and mass wasting controlled by climate conditions. In the hydrological year of 2011/2012 these processes affected bank face surfaces irrespective of flow discharge and water level. The rate of fluvial erosion on active riverbanks was mostly controlled by the resistance of flysch bedrock and the degree of compaction of the alluvium. A striking contrast in resistance to erosion was found between loamy, gravely and flysch riverbanks. The effects and course of frost processes were also different on the riverbanks cut in the three types of material: from frost heaving and fracturing of the uppermost, loamy cover to the sliding of gravel particles and collapse of flysch blocks. The most uneven rate of erosion was recorded on the gravely parts of the bank undercuts, where stronger compaction of older, Neogene gravels significantly slowed the rate of riverbank retreat in comparison with the younger, more weakly cemented Holocene gravels. Neither the petrographic composition of the gravels nor the grain-size of the gravel particles was found to affect the rate of bank retreat.

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