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ORIGINAL ARTICLE

Morphology and environmental impact of the Colţi–Aluniş landslide (Curvature Carpathians), Romania

Mihaela Constantin · Aurelian C. Trandafir · Marta C. Jurchescu · Daniel Ciupitu

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Abstract The May–August 2005 heavy rainstorm events in Romania triggered a large number of geomorphic hazards of great magnitude, consisting of primarily floods and landslides. Some of the most affected regions were the Curvature Carpathians and Subcarpathians. This paper addresses the effects of rainfall on slopes, especially in the middle sector of the Sibiciu basin (the Buzău Carpathians) outlining the significant landslide damage along the road connecting the Colţi and Aluniş villages. The landslides are analyzed in terms of geologic, geomorphic and engineering geologic features, focusing on the Colţi–Aluniş landslide which had the greatest impact on the road displacement. The related environmental and social impacts are also discussed.

Keywords Curvature Carpathians · Sibiciu basin · Landslide morphology · Subsurface stratigraphy · Engineering geologic analysis · Environmental impact

Introduction

The hills and mountains of Romania are affected by many landslides of various types and magnitudes depending on the geology of the landforms involved and on triggering factors (Cioacã et al. 1993; Bălteanu 1997; Ielenicz et al. 1999; Constantin 2006). The Curvature Carpathian and Subcarpathian regions undergo severe geomorphological processes (Constantin and Chendes 2003). Some of the most frequent types of mass movement processes involved in present-day terrain features modeling are landslides (Sandu and Bălteanu 2005; Constantin et al. 2005; Constantin 2006). The summer 2005 heavy rainfalls triggered numerous landslides associated with a serious environmental impact including damage to households and roads in the region. This paper addresses some conspicuous landslides that affected the road linking Colţi and Aluniş settlements (Fig. 1). The road had just been constructed with SAPARD funds in 2004. However, it was severely damaged by landslides only 1 year later and the absence of landslide treatment measures along the road suggests that the landslide hazard in the region has not been considered during the initial design process of the road. Because the landslide hazard was not a concern at that time, there is also no information available regarding the state of the landslide during the road construction. The geology of the roadside consists of Paleogene deposits in Kliwa facies (i.e. alternations of sandstone, clays, marls and disodile schists—folded and faulted) (Andreescu and Ţicleanu 1992; Dumitrescu and Săndulescu 1970). The road was affected only along the segment where the Kliwa Sandstone Formation occurs. Associated with the presence of clayey strata in Kliwa Formation, the landslide occurrences end at the limit between the Kliwa Sandstones and massive sandstone cropping out to the surface (Fig. 2).

The road is connecting the Colti and Alunis villages, and has a touristic importance, facilitating the access to the Aluniş Monastery which is well known for its rupestrian monuments of great historical importance for Romania. Figure 1 shows the major landslide complexes associated with the most significant damage to the Colţi–Aluniş road.

M. Constantin (✉) · M. C. Jurchescu · D. Ciupitu
Institute of Geography, Romanian Academy,
Str. D. Racovita 12, 023993 Bucharest 20, Romania
e-mail: mihaela.constantin@gmail.com

A. C. Trandafir
Department of Geology and Geophysics,
University of Utah, 135 South 1460 East Rm 717,
Salt Lake City, UT 84112-0111, USA

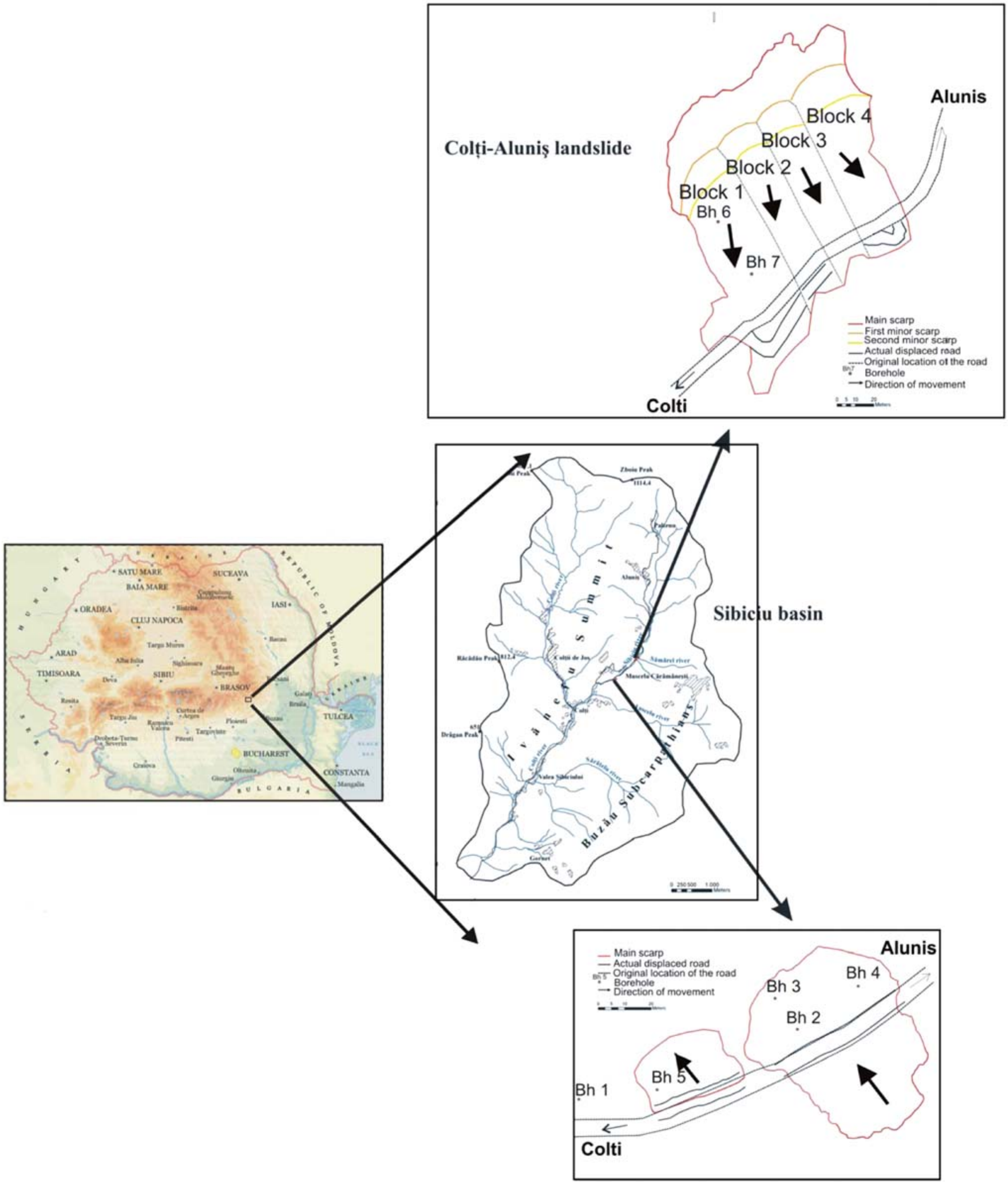

Fig. 1 Location of the study area in the Sibiciu basin, Curvature Carpathians, Romania

The Colţi–Aluniş landslide (Fig. 1) damaged the road by displacing it about 14 m horizontal distance from its original location causing therefore a major traffic disruption in the area.

The aim of this paper is to discuss the geologic and geomorphic settings in the context of landslide occurrences throughout the Sibiciu Basin located at the contact between the Curvature Carpathians and Curvature Subcarpathians,

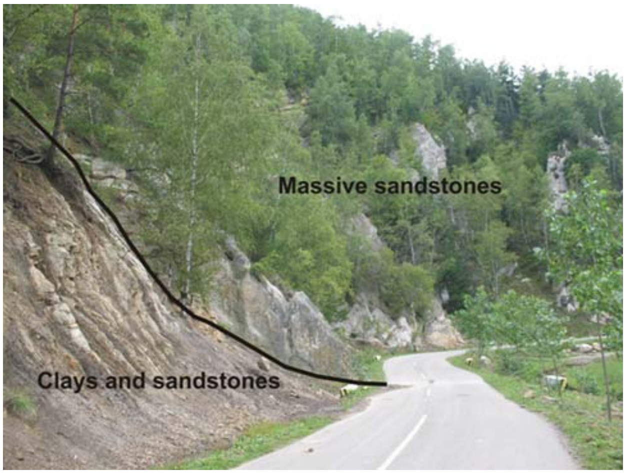

Fig. 2 Contact between the Kliwa sandstone formation and massive sandstone

with special emphasis on the morphologic, morphodynamic and engineering geologic characteristics of the Colţi–Aluniş landslide, i.e., the largest landslide that affected the Colţi–Aluniş road in the basin (Fig. 1).

Terrain features of the Sibiciu Basin

The Sibiciu basin (47.11 km^2) extends on two terrain units, with one of the units belonging to the Curvature Carpathians (i.e., the Buzau Mountains represented by Ivanetu Summit) and the other unit belonging to the Curvature Subcarpathians (i.e., the Buzau Subcarpathians). The Ivăneţu Summit, built on Paleogene flysh deposits consisting of an alternation of sandstone, clays, marls and disodile schists, is NE–SW oriented and is located in southeastern part of the Buzau Mountains. The Buzau Mountains (2,156 km^2) are located in the central part of Curvature Carpathians, and their general features are typical for small and medium mountains with round summits dissected by transversal valleys (Sandu and Bălteanu 2005).

The Buzau Subcarpathians (2,760 km^2) include a succession of hills and depressions, corresponding to various anticlines and synclines in the region. The relief has altitudes of 300–800 m, and the hills are underlain by Neogene molasse deposits, consisting of marls, clays and sands (Sandu and Bălteanu 2005). The drainage densities of the Buzau Subcarpathians are of the order of 3–4 km/km^2.

The Sibiciu basin is located at the contact between the Paleogene flysh of the Ivanetu Summit and the Mio-Pliocene molasse formation of the Buzau Subcarpathians. The highest altitudes occur in the north of the basin (Zboiu Peak—1,114 m) and are grafted on Kliwa sandstone. Its western perimeter is delimited by a few peaks (i.e., Oii Peak—1,037.1 m; Răcădău Peak—812.4 m and Drăgan Peak—651 m) with altitudes decreasing from north to south and towards the junction with the Buzau River (Fig. 2). The southeastern part of the basin features gentler slopes at the contact with the Subcarpathians hills. The relief energy is characteristic of the mountain region (i.e., 200–250 m). The drainage density in the basin is generally of the order of 3–4 km/km^2, typical for a moderately dissected terrain (Ielenicz 1984).

Landslides are associated mainly with the 12°–24°, 24°–36° slope classes, representing 52 and 4%, respectively, of the whole basin area (Fig. 3). The Sibiciu Basin is richly forested, pasturelands being scarce. West of Colţi village, bushland is the predominant physiognomic type, whereas only a few arable terrains can be found around the Colţi and Aluniş settlements.

Main geologic features of the Sibiciu basin

The Sibiciu basin is oriented NNE–SSW having a length of approximately 11 km and an average width of 3.5 km. Its surface area is marked by outcrops of the Tarcau Nappe, deposited during the Paleocene–Eocene (Pg_{1-2}) and Upper Eocene-Oligocene (lt-ch) (Andreescu and Ţicleanu 1992; Dumitrescu and Săndulescu 1970) (Fig. 4). The Paleocene–Eocene deposits are developed in the schistose and sandstone monotonous facies of Colţi, with tight alternations of sandstones, clays and marls. These flysch strata outcrop in the Upper basin of the Sibiciu, close to the Zboiu Peak.

The Upper Eocene–Oligocene (Latorfian–Chattian) has evolved in the bituminous facies with Kliwa strata; here, one sees three distinct horizons: (1) cca 80 m thick lower menilites alternating with bituminous brown marls; (2) 50–60 m thick lower disodilum shists progressively grading into (3) lower Kliwa sandstone (650 m thick). The Helvetian, Badenian and Sarmatian deposits occur in the southeastern part of the basin (Fig. 4). Helvetian deposits are represented by marls, clays and sands alternating with gypsum strata. Badenian (Bn) is represented by marls and sandstones while Sarmatian (Sm) deposits are represented by an alternation of clays and sandstones. Holocene (qh1–qh2) deposits are represented by sands, clays and loess deposits.

The geologic formations of the Sibiciu Basin are embedded in folds-faults, striking NNE–SSW. Faulting and over thrusting dates to the Tertiary's Savian, old Stirian (intra-Burdigalian) and New Stirian (intra-Badennian), and Attic (intra-Middle Sarmatian) orogenesis phases. The main characteristic of the Tarcau Nappe and the

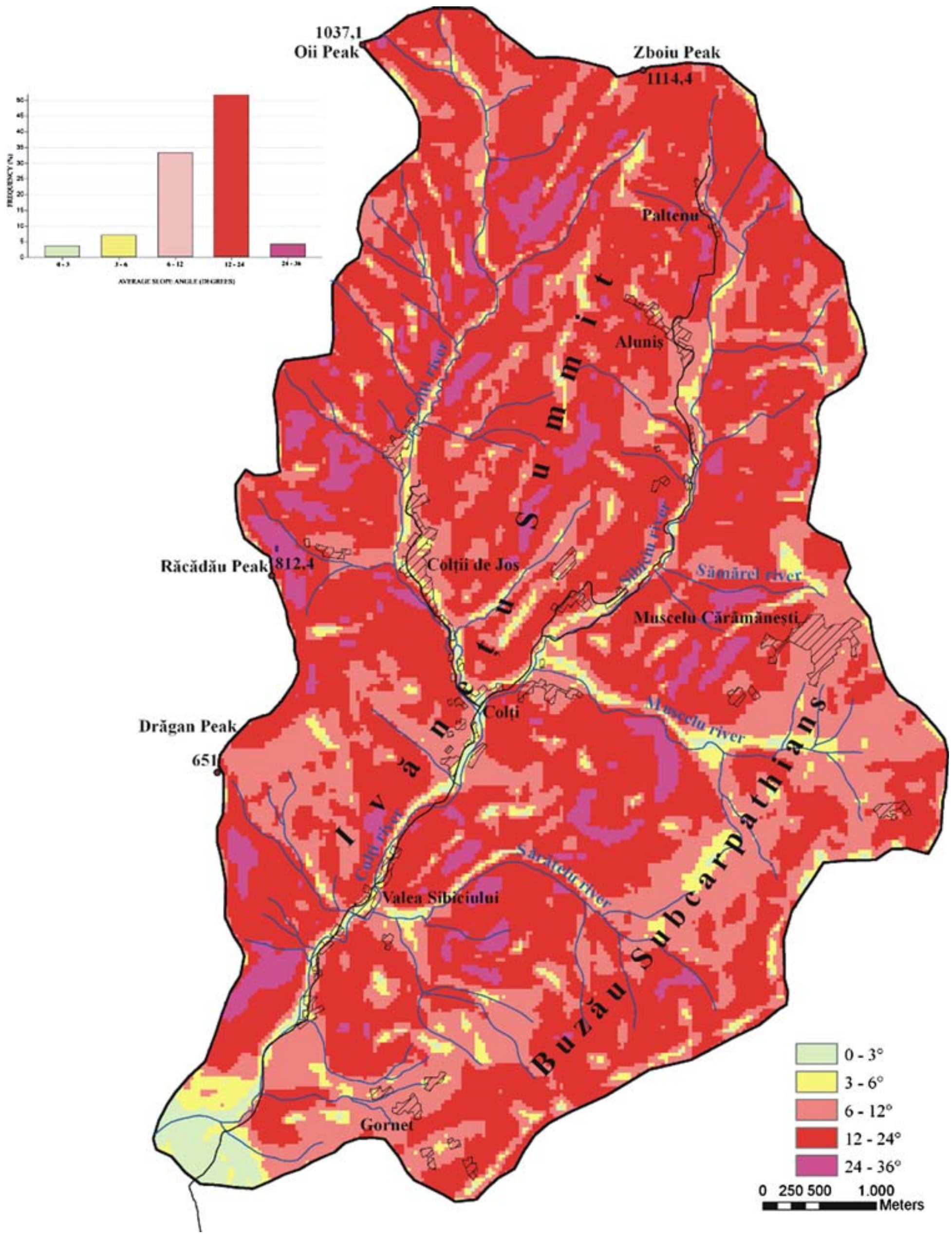

Fig. 3 Slope angle map of the Sibiciu basin

Subcarpathian Nappe formations is their deepening from NE to SW (Dumitrescu and Săndulescu 1970).

An analysis of the relationships between litostratigraphy, structure and the onset of mass movements revealed that landslides are prevalent in the lower and middle sectors of the Sibiciu basin featuring Paleocene–Eocene formations within a binary facies (brittle rocks and plastic soft and friable rocks, highly fractured and fissured and highly weathered). The landslide distribution correlates well with the location of the Kliwa Sandstone Formation involving white orthoquartzitic sandstones interbeded with bituminous shales and clays. The presence of clays in Kliwa Formation appears to be the main reason for landslide occurrences in this formation.

Landslides features

Types of landslides in the Sibiciu basin

The Sibiciu basin is affected by numerous types of landslides ranging from shallow translational landslides (<2 m depth) to deep-seated rotational landslides (>10 m depth) with different sizes and magnitudes (Ielenicz 1984; Sandu

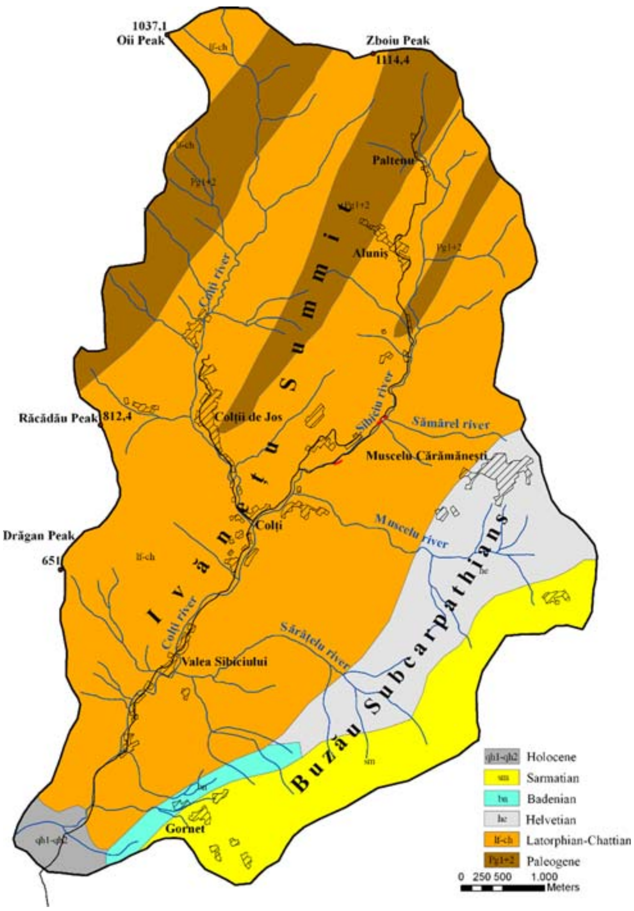

Fig. 4 Geologic map of the Sibiciu basin

and Bălteanu 2005), as seen in Fig. 5. Most of them occur after torrential or long-lasting precipitation (Bălteanu 1983; Ielenicz 1984; Constantin 2006).

The shallow landslides are encountered at various locations throughout the basin, taking place in the soil cover overlying the bedrock. On the other hand, the location of the deep-seated landslides is closely related to the presence of the Kliwa Formation throughout the basin.

Subsurface conditions of landslides along the Colţi–Aluniş road

Figures 1 and 6 show a series of boreholes drilled at various landslide locations along the Colţi–Aluniş road, which are used in the interpretation of stratigraphic conditions. The boreholes were drilled during a geotechnical study associated with a rehabilitation of the road in summer of 2006, i.e., 1 year later after the occurrence of the landslides. For the first half of the investigated road segment, the subsurface conditions encountered in boreholes Bh 9, 1, 5 in Figs. 1 and 6, include a medium-stiff to stiff brownish-gray sandy-clay layer (4–6.5 m thick) overlying a soft to firm gray clay layer (2–3.5 m thick) which is underlain by

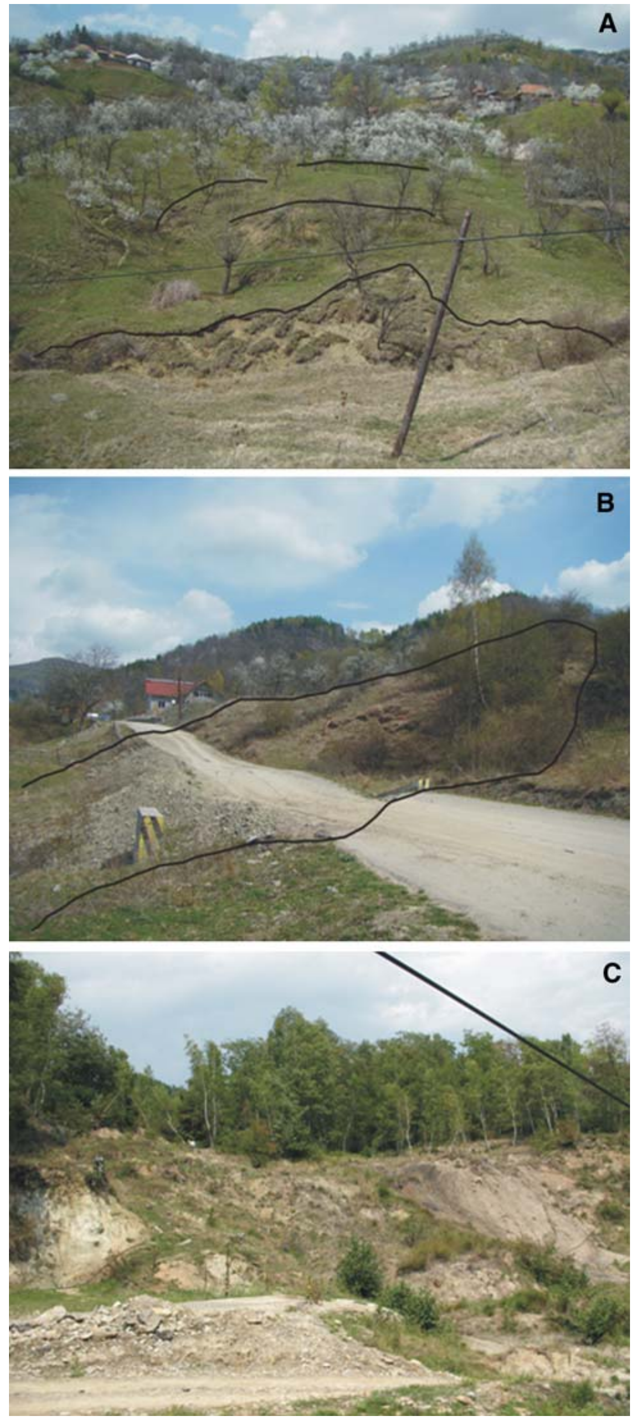

Fig. 5 Types of landslides in the Sibiciu basin **a** shallow landslide (depth < 2 m), **b** moderate-depth landslide (depth 2–10 m), **c** deep-seated landslide (depth >10 m)

a weathered sandstone layer at depths of 8–12 m from the ground surface. The weathered sandstone is either grading into massive sandstone at depths of 10–15 m or is underlain by hard claystone with inclusions of sandstone and slates (at depths greater than 12 m). The sliding surface of the landslides along this road segment was encountered in

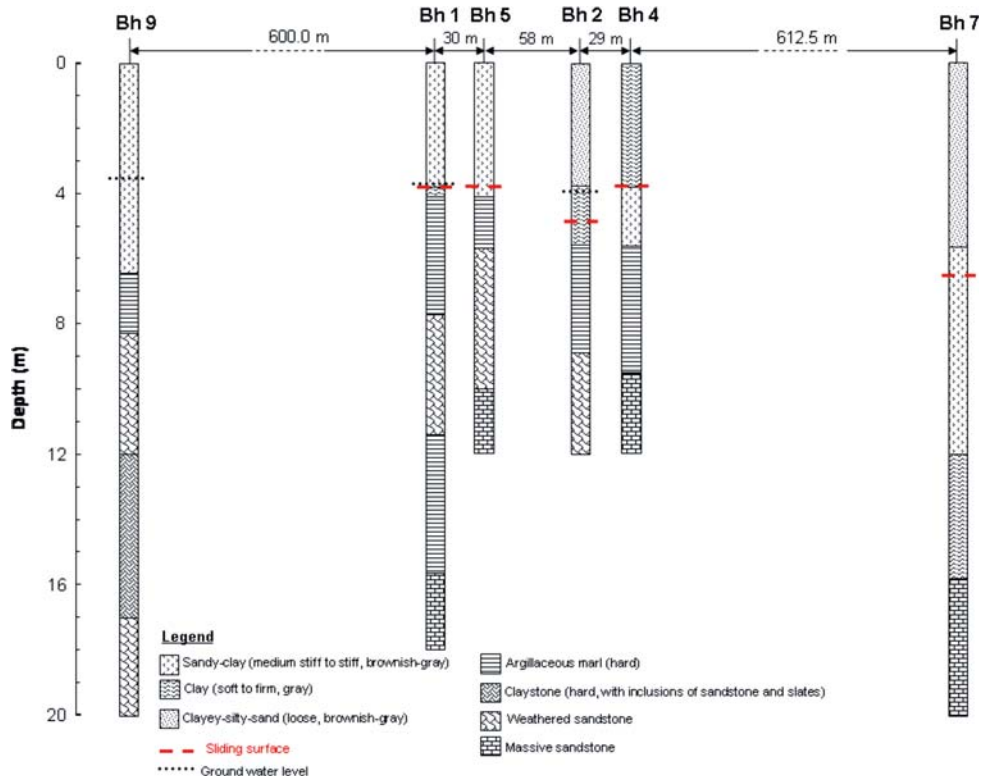

Fig. 6 Subsurface stratigraphy in boreholes drilled along the Colţi–Aluniş road

the sandy-clay layer at the borehole locations, as shown in Fig. 6.

A generalized subsurface profile for the second half of the investigated road segment that includes the Colţi–Aluniş landslide addressed in this study is based on the information from boreholes Bh 2, 4, 6, 7 (Figs. 1, 6). The profile would consist of a 4–6 m thick loose brownish-gray clayey-silty-sand layer (Fig. 6) underlain by a medium-stiff to stiff brownish sandy clay (2–6 m thick) which overlies a soft to firm gray clay (approximately 2–4 m thick). The bedrock in this area consists of massive sandstones encountered at depths of 10–15 m below the ground surface. The sliding surface of various landslides along the road occurs at depths of 4–11.5 m in the gray clay or sandy-clay layer.

Groundwater table location was observed in boreholes Bh 1, 2 and 9, all of these measurements pointing towards a depth of the ground water table at the time of investigation at about 3.80 m from the ground surface (Fig. 6). The available data from borehole Bh 6 does not include any information on the position of the groundwater table in this borehole. Therefore, the level of groundwater table at Bh 6 (Fig. 8) has been inferred based on geomorphic observations of water ponding at the ground surface throughout the investigated landslide block. An approximate groundwater table was obtained by linking pond 2 with the next water ponding location occuring 10 m uphill from Bh 7. Furthermore, as no information on the water level in Bh 7 was available, the presence of water ponding observed around Bh 7 during field reconnaissance surveys was used as an indicator for a groundwater level near the ground surface at the toe of the landslide (Fig. 8).

Geomorphic and engineering geologic characteristics of the Colţi–Aluniş landslide

The Colţi–Aluniş landslide occurred due to prolonged rainfall during May–August, 2005 when a total cumulative rainfall of 528.2 mm was recorded. The slide occurred on the right hand side slope of the Sibiciu Valley, at approximately half way between the Colţi and Aluniş villages (Fig. 1). Morphodynamically speaking, the slide was divided into four blocks, as seen in Fig. 7.

Block 1 shows in its upper part a 64 m-long scarp, and has an average slide width of 38 m, and a length of 133 m. The slide is of consequent rotational type. Measured horizontal and vertical displacements of the road are 14 and 2.18 m, respectively (DGPS measurements were made on 2 November 2007). Two small ponds (i.e., pond 1–20 m length, 12 m width, and pond 3–21 m length, 6 m width) were located above the main scarp contributing to high moisture inside the slide mass. Pond 3 is drained through a small channel extending down to the second minor scarp. Water ponding at the ground surface has also been observed on the second minor scarp of the landslide

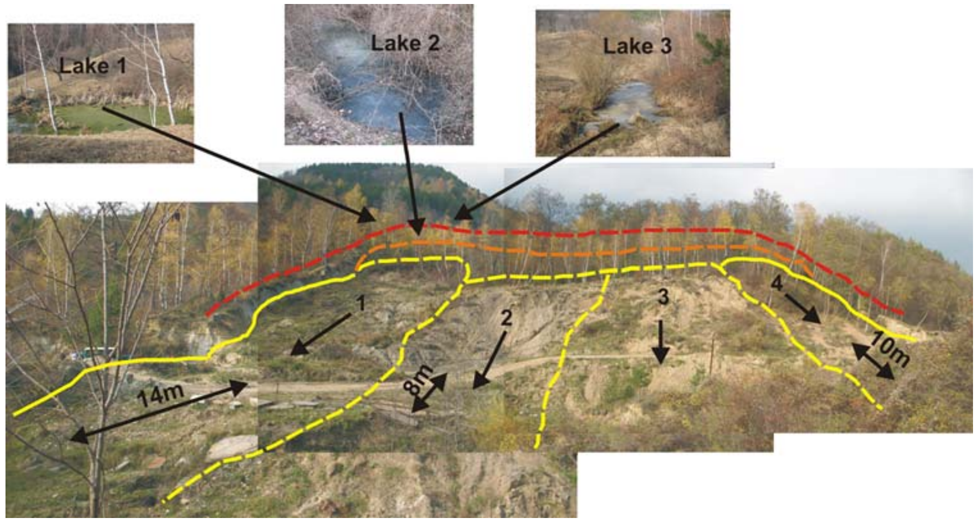

Fig. 7 The Colţi–Aluniş landslide. Delimitation of blocks and main slide directions

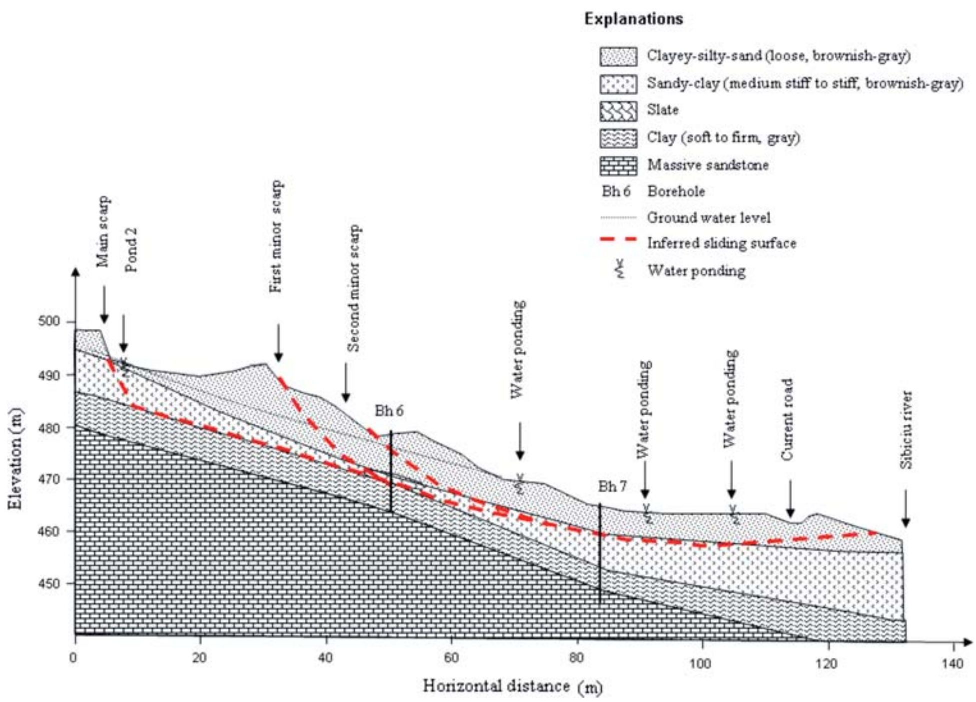

Fig. 8 Engineering geologic cross-section for Block 1 of the Colţi–Aluniş landslide

(Fig. 8). Another pond (pond 2–18 m length, 5 m width) was localized on the landslide head. *Block 2* is also of rotational type (Fig. 7). The length of the main scarp is 28 m, average slide width is 21 m and slide length 122 m. The measured road displacement was 8 m on the horizontal and 3.18 m on the vertical. The slide mass was covered with delluvial materials generated by ravel erosion processes occurring upslope. *Block 3* has a main scarp of 29 m length, average width of 23 m, and a length of 116 m. This block shows the most recent (second minor) scarp at about the same level as the recent second minor scarp of block 2 (Figs. 1, 7). The different movement direction and the presence of shallow failures (Fig. 7) on this block indicate a different behavior compared with block 2. Movement of this block did not affect the road location (Fig. 7). *Block 3* is in a stage of incipient failure. *Block 4* shows a main scarp length of 68 m, average width of 29 m, length of 118 m, and is of rotational type. The horizontal and vertical displacements of the road are 10.93 and 2.75 m, respectively.

Figure 8 represents an engineering geologic cross-section of the Block 1 of the Colţi–Aluniş landslide. The slide mass consists predominantly of fine silty-sands with inclusions of schists and sandstone lenses. The sliding surface comprises three geologic materials (i.e., sands, sandy-clays and gray clays). The sliding surface intercepts the sandy-clay layer at a depth of 6.5 m in borehole Bh 6, and the grey clays at a depth of 11.5 m in borehole Bh 7. The major drainage feature of Block 1 (i.e., the most active block that affected significantly the road) is the Sibiciu River located at the toe of the slide. Rain and snow-melt water infiltrates through the sandy layer (comprising most of the slide mass) down to the sandy-clay and grey clay layers in which the sliding surface resides. The groundwater migrates downslope, and water ponding on the ground surface stands as evidence for the location where the groundwater is near the ground surface (Fig. 8). Throughout Block 1, the slide elevation ranges from 500 to 465 m, resulting in a difference in elevation of 35 m. The slope angle ranges from 0° to 33° with an average slope angle of the displaced slide mass of 16.7°. The direction of the movement of the block ranges from NNW–SSW to NW–SE.

The main scarp and other two minor scarps, as well as the depletion zone can be easily noticed on the engineering geologic cross-section (Fig. 8). The toe of the landslide is slightly above the Sibiciu River. The groundwater table in Fig. 8 was inferred from the information available in boreholes together with the evidence of water ponding identified during field surveys. The inferred sliding surface based on the information from boreholes and examination of the main scarps is shown in Fig. 8.

The physico-mechanical properties of the clayey-silty-sand and gray clay layers in Fig. 8 were obtained from unpublished geotechnical reports in the study area. The clayey-silty-sand has the following properties: saturated unit weight $\gamma = 18.7$ kN/m^3, effective cohesion $c' = 10$ kPa, effective friction angle $\phi' = 22°$. The physico-mechanical properties of the clay layer are saturated unit weight $\gamma = 20$ kN/m^3, effective cohesion $c' = 9$ kPa and effective friction angle $\phi' = 14°$. As seen in Fig. 8, most of the sliding surface of the Colţi–Aluniş landslide is located in the sandy-clay layer bounded above and below by the silty-sand and the gray clay layers. Therefore, an extensive experimental investigation on disturbed and undisturbed sandy-clay specimens has been undertaken to determine the physical and mechanical properties of this material since it is the most important in the stability of the analyzed landslide. Index properties test results qualify the sandy-clay as a low plasticity (CL) material with a plasticity index of 21% and a liquid limit of 49%. The average specific gravity (G_s) is 2.6. The following in situ index properties were determined for undisturbed sandy-clay specimens: void ratio $e = 0.858$, porosity $n = 46.18\%$, saturated unit weight $\gamma = 18.3$ kN/m^3, and dry unit weight $\gamma_d = 13.7$ kN/m^3.

To understand the shear behavior of the sandy-clay material from the Colţi–Aluniş landslide, undrained (CIU) and drained (CID) triaxial compression tests were conducted on undisturbed specimens saturated by back-pressure. The triaxial tests results are depicted in Fig. 9 in terms of deviator stress–axial strain relationships and effective stress paths. The CID tests were performed under isotropic effective consolidation stresses of 150 and 350 kPa (i.e., tests CID150 and CID350 in Fig. 9), whereas the isotropic effective consolidation stresses for the CIU tests were 150 and 400 kPa (i.e., tests CIU150 and CIU400 in Fig. 9). In the CIU tests, the specimen demonstrated a contractive response associated with excess pore pressure generation during the initial stages of deformation at very small strains. Subsequently, the behavior becomes dilative before failure and after failure (Fig. 9b). Observations of the volumetric strains in relation to axial strain in CID tests also indicate a dilative response as the material approaches failure and also after failure. The post-failure behavior of the investigated sandy-clay is characterized by strain-softening in all CID and CIU tests, associated with reduction in strength towards a residual value (Fig. 9a). The peak failure envelope in Fig. 9b was constructed using the peak shear stress, $(\sigma'_1 - \sigma'_3)_{max}/2$, as the failure criterion (σ'_1—major effective principal stress, σ'_3—minor effective principal stress), and is characterized by a peak effective cohesion $c'_p = 2$ kPa and a peak effective

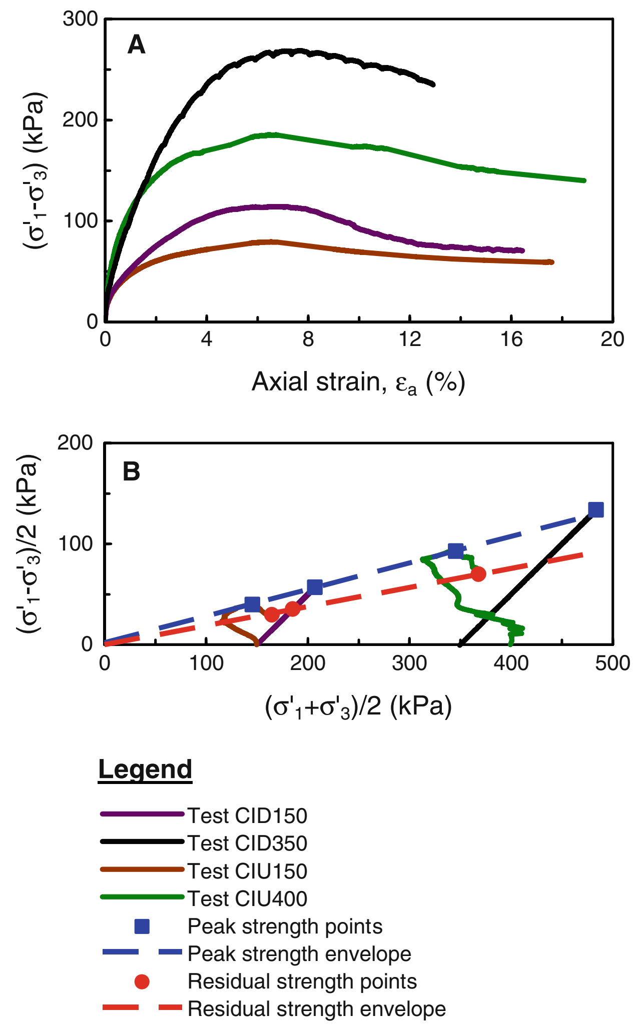

Fig. 9 **a** Deviator stress-axial strain relationships and **b** effective stress paths from consolidated-drained (CID) and consolidated-undrained (CIU) triaxial tests on saturated sandy-clay specimens from the Colţi–Aluniş landslide

friction angle $\phi'_p = 15.3°$. The residual strength parameters have been obtained using the ultimate strength values recorded at the end of tests CID150, CIU150 and CIU400, in which the specimen attained a residual or nearly residual state (Fig. 9a). The strength parameters describing the residual strength envelope for the investigated sandy-clay are $c'_r = 0$ and $\phi'_r = 11°$.

Figure 10 shows the results of a stability analysis addressing the critical location of the groundwater table that would trigger a reactivation of the Colţi–Aluniş landslide. The analysis was conducted using the standard license of the Slope/W module of the GeoStudio software package (GEO-SLOPE International Ltd 2008), and employed the physico-mechanical properties of the geologic layers discussed previously. Since the landslide is in an advanced stage of deformation, the residual strength parameters from triaxial testing were adopted for the sandy-clay material along the sliding surface. The calculated safety factors are representative for the Bishop's simplified method of slices. The analysis involved the potential sliding surfaces AD, BD and CD inferred from engineering geologic investigations (Fig. 10). The safety factor associated with the groundwater conditions shown in Fig. 10 is nearly 1.0 along the sliding surfaces AD and BD, and 1.23 along the sliding surface CD. This result indicates that for the considered location of the groundwater table, the slide mass is in limit equilibrium along the sliding surfaces AD and BD, suggesting that groundwater tables above this level may reactivate the landslide movements. The outcome of slope stability analysis demonstrates in fact that the landslide is currently active since field observations suggest groundwater tables higher than the estimated critical location (Fig. 8). Furthermore, recent field surveys indicate that the landslide is experiencing recurrent movements after snow-melt and rainfall events.

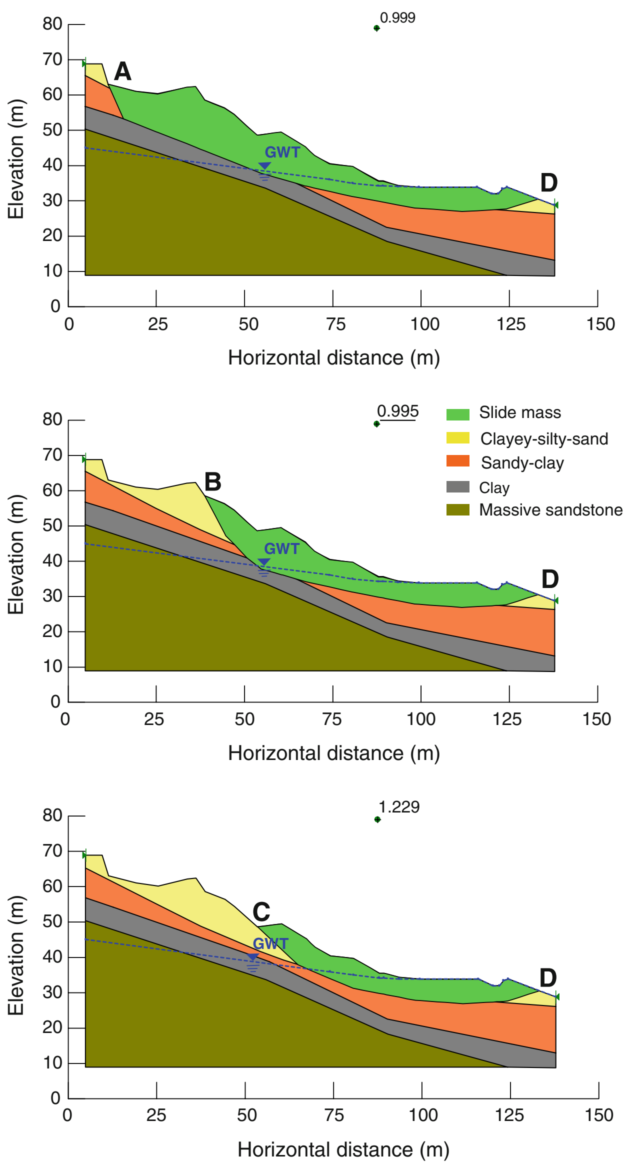

Fig. 10 Estimated critical groundwater level (GWT) for the reactivation of Colţi–Aluniş landslide based on limit equilibrium slope stability analysis

Environmental and social impact

The landslides along the road between the Colţi and Aluniş villages occurred as a result of long-lasting precipitation during May–August 2005 and affected the adjacent slopes on a surface area of 3,619 m^2. The total length of the affected road is approximately 300 m, representing 6 % of the total road length. As the road was closed in 2005, the access to the rupestrian monuments has been barred. The road is also of significant social importance, since it facilitates the access of children from the neighboring villages to the school in Aluniş Village. Owing to the present traffic disruption, they must currently cover the distance of 5 km on foot.

In the context of a sustainable development in the region, the local government requested in 2004 from the European Union SAPARD funds in amount of 634, 000 Euro in order to rebuild the road. However after the landslide damage in 2005 the total reconstruction cost of the road increased by 58% to a total of about 1,000,000 Euro. These estimates illustrate the crucial role of a rigorous assessment of the landslide hazard before planning various land development activities in this area.

Conclusions

The Sibiciu Basin represents a region with a long history of landslides in Romania. The most recent landslides have been documented during summer 2005 as a result of long-lasting precipitation. The geologic setting plays an important role in the location of landslide occurrences which are associated with the distribution of Kliwa Sandstone Formation consisting of interbeded shales, clays and sandstones. Our field surveys along the Colţi–Aluniş road in the Sibiciu basin also revealed the correlation between landslides and Kliwa facies.

The length of the landslides varies from a few meters to more than 100 m. The depth and magnitude of the landslides along the road is controlled by the position of the clayey layers in the subsurface ranging from 3 to about 12 m depth. Consequently, the landslide impact on the Colţi–Aluniş road was different according to the magnitude of the landslides, resulting in very small or very large disruptions of the road. The displacements ranged from a few centimeters in the case of moderate-depth landslides (2–10 m) to more than 10 m in the case of the deep-seated Colţi–Aluniş landslide.

Detailed field surveys combined with subsurface investigations have been conducted for the Colţi–Aluniş landslide, the largest landslide associated with the most significant damage along the Colţi–Aluniş road. The landslide was divided into four blocks based on the geomorphic features and direction of movement. An engineering geologic profile has been developed for Block 1 of the landslide complex based on the information from boreholes and field surveys. It was found that the sliding surface intercepts three geologic materials (sands, sandy-clays and grey clays), whereas the slide mass consists mainly of sandy soils. The results of stability analyses for the Colţi–Aluniş landslide demonstrated that the groundwater levels recorded in boreholes are higher than the critical location of the groundwater table necessary to reactivate the landslide. Furthermore, recent field monitoring indicates that the landslide is still active and continues to deform after snowmelt and rainfall events. Currently, there are some proposed landslide treatment measures to be applied before reconstruction of the Colţi–Aluniş road. The proposed measures include, plantation of trees on the slope, drainage of water flowing on the slope surface, and construction of a retaining wall along the road segment affected by landslides. The effectiveness of the proposed measures in stabilizing the Colţi–Aluniş landslide is questionable though since they do not include a rigorous drainage system for lowering the groundwater table within the slope.

Owing to its social and touristic importance, the Colţi–Aluniş road was modernized in 2004 with EU funds. However, after the landslide damage along the road in 2005, the road must be reconstructed with an estimated budget significantly greater than in 2004. This case history highlights the importance of an interdisciplinary approach, including detailed engineering geologic and geomorphic studies addressing the landslide hazard that must be considered by investigators involved with the road rehabilitation in the near future.

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