ORIGINAL PAPER

Assessment of vulnerability for rockfalls in Cozia Gorge (Southern Carpathians, Romania)

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Abstract

Rockfalls represents a sudden, extremely important geomorphological hazard and may become a threat for people's life, as well as goods and transport. The present study aims to assess the rock surfaces stability in relation to a series of variables: resistance of intact rock determined in the field by geotechnical test—the SCS value obtained with Schmidt hammer; weathering degree, as visually assessed; characteristics of fissures—density, width, orientation, continuity; lithological and tectonic conditions—characteristics of rocks and the distance in relation with the faults; angle and exposure of slopes, their cover with vegetation, dimension of blocks identified close to the roadside and the volume of material accumulated in the protection mesh. In order to achieve the objective and determine the susceptibility of slopes to rockfalls, we run two campaigns of field measurement using a Schmidt hammer and microtectonic mapping based on GPS and feller gauge. The data integration was accomplished in the GIS environment, by applying the multi-criteria techniques. The results highlight the susceptible areas which allow us to map it and analyze the efficiency of the slope arrangement work made for rockfall prevention and identify new areas that require prevention measures. Finally, all the data were reported to a segment of the E81 highway and mapped the vulnerability to rockfall. The Olt Valley in the Cozia Gorge is one of the most important transversal valleys in Romania and a linking road between regions of both side of Carpathian range. The results of the study emphasize the anthropic pressure exercised in the analyzed Gorge section which created imbalances in terms of cut slopes.

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1 Introduction

Rockfalls are geomorphological processes of mass movement, specific to mountain regions with hard, cohesive and strong cracked and fault rocks. Although they appear in an isolated manner and involve a reduced volume of material, the energy and fastness of these processes lead to many negative effects at socio-economical level (Guzzetti 2004). The damages that they cause determined the introduction of rockfall into the geomorphological hazards category (Glade et al. 2001).

In time, there have been numerous contributions regarding the definition and study of the mechanism by which these slope-related processes take place. Rapp 1960 considers that "by rockfalls, we understand more or less the free falling of rock fragments of any size whatsoever from an abrupt rock wall or block." According to Varnes 1984, rockfall stands for "a fragment of rock detached by sliding, toppling or falling from a vertical or subvertical cliff, before proceeding downslope by bouncing and flying along parabolic trajectories or by rolling on talus or debris slopes." In Evans and Hungr (1993), rockfall is defined as being "a detachment of a fragment or several pieces with an episode of free falling during the movement." There is a vast specialized literature that is focused on the elaboration of methods to predict and to quantify the rockfall hazard (Dorren 2003; Berger and Dorren Luuk 2007). In this respect, one has to develop a number of empirical models (Tianchi 1983; Moriwaki 1987; Toppe 1987; Keylock and Domaas 1999), experimental models (Azzoni et al. 1995; Bozzolo and Pamini 1986; Kobayashi et al. 1990; Gascuel et al. 1998) and G.I.S.-based models (Van Dijke and Van Westen 1990; Meissl 1998; Tarboton 1997). Also, this geomorphological process was treated by the Romanian geomorphology, where the terms "failure" or "crumbling" are also used, as the latter designate the sudden falls of some huge quantities of material (Posea et al. 1970; Grecu 2006; Radoane and Radoane 2007; Ilinca 2009; Ielenicz 2010; Onaca et al. 2017).

The rockfalls occur at a much higher frequency and intensity on the slopes of mountain spaces that were anthropically cut in order to build transport infrastructure (Uribe-Etxebarria et al. 2005), determining much more important material damages and human life losses than in regions being under natural conditions. In this context, in the international literature are numerous assessments of this hazard along the transport ways (Ritchie 1963; Pierson et al. 1990; Pierson and Van Vickle 1993; Baillifard et al. 2003; Hantz et al. 2003; Budetta 2004; Guzzetti et al. 2004; Uribe-Etxebarria et al. 2005; Mölk et al. 2008; Saroglou et al. 2012; Ferrari et al. 2017).

The present study proposes to approach this issue, having as its main objective to establish the stability degree of slopes based on geotechnical properties of the rocks by assessing the rock resistance and GIS modeling of susceptibility. Also has been analyzed the stability of anthropic cut slopes, in order to make possible the delimitation of susceptible areas to rockfalls. In this respect, the entire surface affected by this process was mapped and inventory of all the protection measures. Within this work were revealed the engineering works that need improvements and slopes that do not have yet adequate prevention measures. Another objective was to assess the vulnerability for E 81 and Călimănesti ring road. The road E 81 is one of the most important and circulated corridors of Southern Carpathians including heavy lorries which imposed the assessment of slopes susceptible to rockfall as a necessity.

2 Study area

The sector between Brezoi and Călimăneşti within Olt Valley in Cozia Gorge is situated in the Southern Carpathians, between Cozia Massive to the East and Căpăţânii Mountains to the West, having a length of 14 km. The center of the study area is marked by the crossing of 45°17′30″N parallel with the 24°18′0″ E meridian, a fact that locates it in the full temperate area. This type of climate is favorable to rockfall by the presence of transition seasons (spring and autumn) with temperatures that oscillate around the value of 0 °C. In this period of the year, the thermal processes that contribute to the physical weathering of rock surfaces are the most intense, thermoclasty and crioclasty having a synergic action. To the aforementioned, we shall hereby add the action of liquid and solid precipitations, their distribution being relatively homogenous during the year (Fig. 1).

The valuable landscape of this part of Carpathian Mountains is imposed by particularity the relief and geo-historical evolution since the ancient times, as well as from its economic and touristic importance. The building of the transport infrastructure along the Olt Gorge began in the Romans times, when, after conquering Dacia, they built the first trans-Carpathian pass—Traian's Road, being one of the most important roads with strategic and commercial functions. Another important stage in the development of infrastructure along Olt Valley was represented by the beginning of the eighteenth century, when between 1717 and 1719 the Austrian Empire built the road on the right side of the Olt River. In the same period, the river became partially navigable for transport of materials such as timber and salt. The railroad infrastructure was made beginning with the year 1888, but it grew more
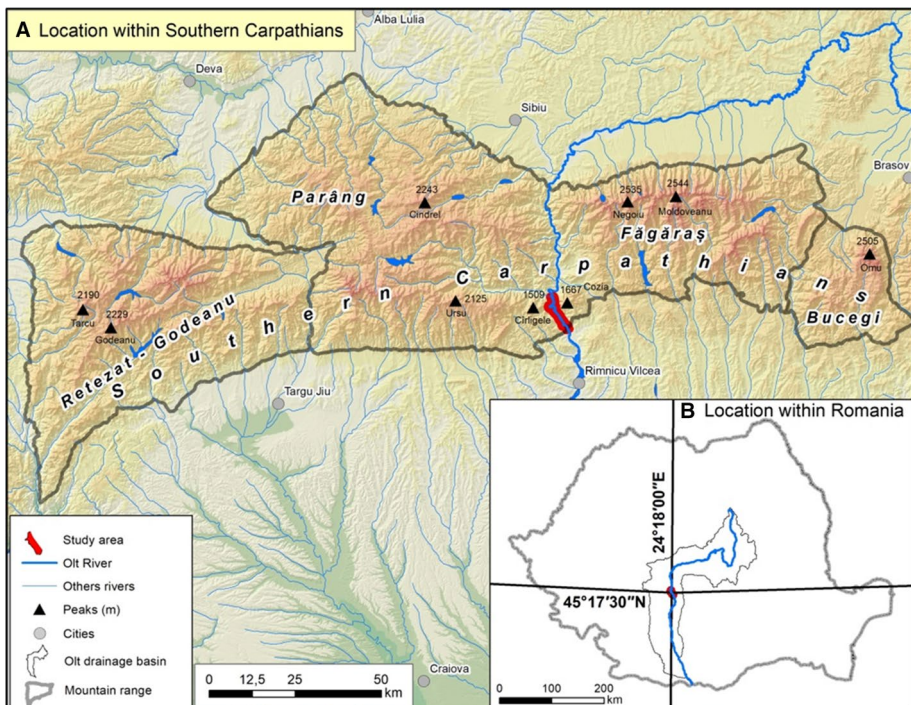

Fig. 1 Localization of the study area

after 1918. Besides the importance for the transport, Olt River also has a special role from the hydroelectric point of view, in this sector building five hydroelectric power plants (Badea et al. 1987).

The anthropic interventions also continued with the development of modern transport infrastructure: E81 road, railway 201 to Sibiu and Turnu—Cârligul Mare forest road. The extraction of Cozia gneiss and the hydrotechnical works for water storage reservoir had a negative impact upon the environment generally, and upon the relief, especially. The improvements in transport ways led to the increase in merchandise and passenger traffic, but also the increase in touristic flows. Under these conditions, the increase in rockfalling from the upper part of steep slope represents a real risk and embarrasses the road and rail transports (Ilinca 2009).

The recent work for improvement in E81 highway for speed increase required the cut of slopes on a wide area with a feedback in slope destabilization. Due to the importance of these road and rail ways for rockfall protection and prevention of incidents, a lot of engineering works for slope stabilization which consist in placement of high-tensile rockfall steelgrid mesh, stone and concrete slabs wall and gabions were done.

The Cozia Gorge morphology is strongly influenced by petrography with an alternation of narrow sectors in metamorphic rocks such as gneiss, paragneiss and orthoamphiboles and small depression in sedimentary formation made up by sandstone, marls and conglomerates (Popescu et al. 1977; Badea 1983) (Fig. 2). The characteristics of rocks are very important for the analysis of this type of hazard, but, especially, the presence and density of discontinuities in the rock mass (fault, breaks). Although the rock is cohesive and hard, these "natural weak points" of rock mass (faults, foliation, bedding plane) (Hencher 1987) reduce the shearing compressive strength and fragment them in individual blocks. Brezoi Fault Line (situated on the North of Cozia Massive) is the main discontinuity plan in this region. The fault spreads from Vâlsan valley up to Malaia valley, for a length of 80 km and an uplift of about 1000 m along the discontinuity plane (Ghika 1958). The studies performed on a local scale need to take into calculation all the cracks in the rock mass, as the surfaces that are the most prone to rockfall are the tectonized and intensely cracked slopes (Ilinca 2009). The more the cracks are placed in an uneven, random manner, the lower the rock compressive strength is, and the possibility for the hazard to occur is higher (Ilinca 2009). Another factor that contributes to the reduction of slope stability is the physical and chemical weathering of rocks. The rock degradation may be reached both by thermoclastism processes (insolation) and by crioclasty processes (freeze–thaw), the latter being caused by water circulation through the crack network of the slopes (Fig. 3).

Cozia Gorge corresponds to the leveling surface of 800–850 m above sea level (m.a.s.l), and 400–450 m above the thalweg. Under this level can also be identified other two steps being at 570–600 m.a.s.l, respectively, 270–300 m.a.s.l. Under this level is developed the system of 7–8 terraces that are imposed in the Gorge as shoulder levels (Popescu 1972; Badea 1987). The terraces steps are developed at relative altitudes from 1 to 3 m and up to 210 to 240 m. Therefore, the Gorge is developed under the threshold of 570–600 m and corresponds to the periods of strong deepening of Olt, when quaternary terraces also appeared (Fig. 4) (Popescu 1972).

The Gorge slopes can be grouped into two categories: lower part, cut for the engineering works of communication and exploitation ways, very steep, mostly 90°, with sparse or absent vegetation; and the upper part, unaffected by the anthropic activities, with slopes of over 40 degrees (Ilinca 2009). The inferior part of the slope has heights of approximately 30 m, whereas the superior one may exceed 200 m (Ilinca 2009). On the left side of Olt, the slopes have a predominantly Western, South-Western and Southern exposure, and on
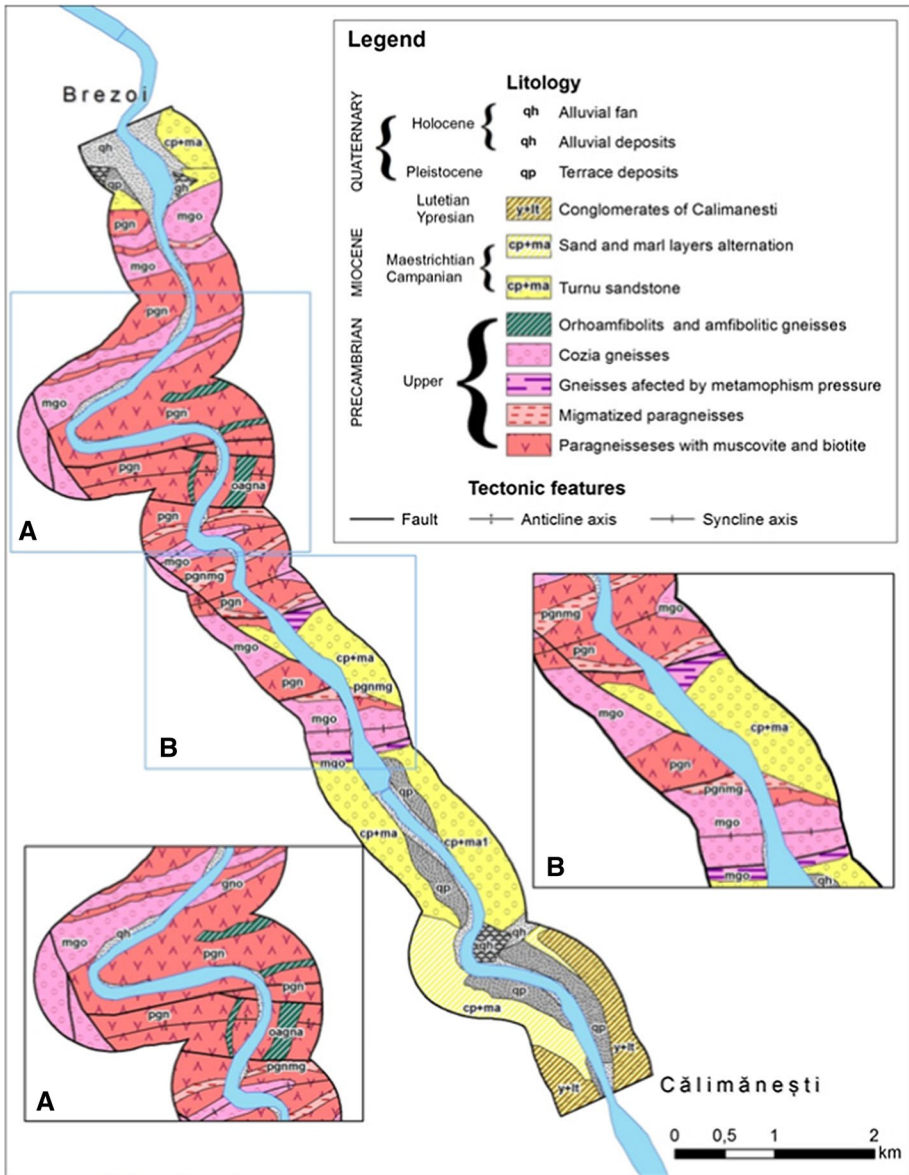
Fig. 2 Geologic map (Brezoi–Călimănești) (Popescu et al. 1977)

Fig. 3 Circulation of water through the crack network of rock mass

the right side, an Eastern, North-Eastern and Northern one. This aspect plays an important role in the way the thermal processes (thermoclastism and gelival) happen that contribute to the physical weathering of rock surfaces.

3 Methodology

The assessment of rockfall susceptibility needed, first, a thorough research developed in the field that consisted in establishing the compressive strength of rock surfaces, by using geo-mechanical assessment methods. In this respect, a mechanical Schmidt hammer of N type was used, manufactured by Proceq, Zurich (Fig. 5) (Vasile 2014). The values recorded by this instrument represent the reaction force of the rock that indicates the degradation degree of the respective surface. Over 80 slope surfaces with uncovered rock, being under different degrees of degradation were investigated and mapped. In order to eliminate, as much as possible, errors, each assessed rock surface was manually polished with an abrasive stone, after which ten measurements were taken, which were averaged in order to obtain the final value. Besides the compressive strength measured with this device, one has visually assessed the weathering degree, as well as the characteristics of the cracks and counted the density, width, orientation and continuity (Selby 1980). Each parameter got a score, and by addition, the final score resulted for each rock surface taken into consideration and, subsequently, its classification (Table 1). The density of cracks was established by comparison to horizontal profiles of 2 m, and the thickness was measured with the help of a feeler gauge with ten divisions (0.05–1 mm) (Fig. 6). For each of the SCS (Schmidt compressive strength) and TCS values (total compressive strength or the final score), the mathematical coordinates using GPS were also recorded, for the subsequent location of the data. The dimensions of the blocks fallen at the base of the slopes and the volume of weathering blocks accumulated behind the dynamic rockfall barriers were measured. The analyzed parameters for each slope were included in worksheets according to the following table (Table 1). The values obtained from the measurements made in the field were transposed in a GIS environment and represented in Romanian National Projection System—Stereographic 1970

Fig. 4 Geomorphological map (according to Badea 1987, with modifications)

Fig. 5 Determining the strength of the rock using the Schmidt hammer

with an EPSG code 3844. The process continued with interpolation of vector data to raster models more suitable for statistical analysis. The interpolation of SCS and TCS points was done using the Thiessen polygon method, which followed two synthesis maps: SCS map of the compressive strength degree of rock surfaces and the map of total compressive strength, obtained following the addition of the scores of all the analyzed parameters (TCS). In order to highlight the quantitative relationship that exists between the variables presented in the worksheet, these data were reported in scatter plot charts. A first correlation was done between the *distance between cracks (cm)* and its resistance measured with the Schmidt hammer entitled—*the Schmidt compressive strength (SCS)*, followed by the correlation between the material gathered at the base of the slopes—*displaced blocks volume (cubic m)* and their resistance measured with the Schmidt hammer entitled *the Schmidt compressive strength (SCS)*, and finally the last correlation was made between the overall *total compressive strength (TCS)* and *the Schmidt compressive strength (SCS)*.The calculation of R help us to identify the parameters that determine differences in resistance degree for surfaces with the same lithology.

It must be mentioned that the values of SCS and TCS parameters were classified according to the maximum recorded value (having at its basis the classification of Selby 1980), as follows: SCS—under 2: very low compressive strength, 2–3: low compressive strength, 3.1–3.5: moderate compressive strength, 3.51–4.5: high compressive strength, over 4.5: very high compressive strength; TCS—under 40: very low compressive strength; 40.1–50: low compressive strength; 50.1–60: moderate compressive strength; 60.1–70: high compressive strength; over 70: very high compressive strength. This was necessary taking into account the relatively reduced space development of the study area, as well as its specificity (scope of the activities for the arrangement of transport infrastructure and of the geotechnical protection measures related to the instability of the slopes).

The field activity also envisaged the mapping of all the engineering works of the communication ways (railways and roads) such as: railway tunnels, false railway tunnel, rail embankments, road tunnels, viaducts; of river beds, as an example: dams, levees, spillway tunnels and of the slopes for the reduction in rockfall effects: high—tensile rockfall steelgrid mesh, gabions, retaining walls, concrete cloths, dynamic rockfall barriers, cement ditches.

During the field campaigns were identified and mapped the slope areas that need a series of protection systems in order to prevent the rockfall on the highway. Following this approach, the geomorphotechnical map was obtained (Dobre et al. 2011) of the

Table 1 Worksheet for the classification of rock compressive strength degree based on mechanical parameters (according to Selby 1980, with modifications)

Parameter						
R. Schmidt	Value	10–6	6–5	5–4	4–3.5	3.5–1
	Score	20	18	14	10	5
Weathering degree	Value	Not weathering	Little weathering	Moderate weathering	Highly weathering	Completely weathering
	Score	10	9	7	5	3
Distance between cracks	Value (mm)	>3000	3000–1000	1000–500	500–300	<50
	Score	30	28	21	15	8
Orientation of cracks	Value	Very favorable	Favorable	Optimal	Unfavorable	Very unfavorable
	Score	20	18	14	9	5
Width of cracks	Value (mm)	<0.1	0.1–1	1–5	5–20	>20
	Score	7	6	5	4	2
Continuity of cracks	Value	None continuous	A few continuous	Continuous without deposit	Continuous with reduced deposit	Continuous with consistent deposit
	Score	7	6	5	4	1
Dimension of displaced blocks (cubic m)	Value	>0.1	0.001–0.1	<0.001		
	Score	3	2	1		
Total	Score	100–91	90–71	70–51	50–26	<26
Classification of resistance		Very High	High	Medium	Low	Very Low

Fig. 6 Feeler gauge to determine
the thickness cracks

studied area, that comprises, along with the previously mentioned engineering works, also the microrelief morphology given by different processes: rockfalls, collapses in some quarries for rock extraction, debris flows, intense weathering area sheet erosions, gullies, torrents, lake abrasion, scarps.

The next stage consisted in the assessment of susceptibility for rockfall based on GIS tools. The method supposes the creation of a database that includes information about lithology, tectonics, declivity, slope aspect and the land use. The relief-related aspects were derived from the digital elevation model (DEM) at a resolution of 10 m/pixel, based on the topographic plans 1:5000, of the year 1975. The information about geology was classified into two distinctive categories—lithology and fault system—and were obtained from the geological maps at scale 1:50,000, of the year 1977. For the accomplishment of the map with the distance between the slopes and the faults, cracks, anticline and syncline axes the path Euclidean distance were calculated in GIS. The data concerning the land use was extracted from the orthophoto of the year 2012 provided by National Agency for Cadaster and Land Registration (ANCPI). The analyzed parameters were classified into five classes, each interval being given a score directly proportional to the contribution that it has in causing the rockfall. Thus, value 1 was given to the elements that are not favorable to produce rockfall and 5 to those parameters that contribute in a high extent to their occurrence. After the analytical maps were made for each factor in part and scores were established, their multiplication by a formula was made:

(3 Geodeclivity + 3 (distance between 2 faults)+2 lithology + aspect + land cover)/10.

Since the factors do not have an equal influence in establishing susceptibility, a different weight was given to the elements included in the equation. The final map of slope susceptibility to rockfall was reclassified into five susceptibility classes: very low, low, moderate, high and very high.

Subsequently, a qualitative relationship of values SCS and TCS with the (geological, geomorphological and land cover) variables was established that laid at the basis of accomplishing the susceptibility of rockfall. For the same purpose, a transversal profile of the Gorge through a sector with the same lithology, but different compressive strength and stability was also made.

Vulnerability for the road sectors included into the Gorge needed the transformation of roads from vectorial format in raster format, after it was multiplied by the total compressive strength of the slopes and with their susceptibility to rockfall. Also, for calculating vulnerability the engineering works indicated on the geomorphotechnical map were also taken into account. The resulted raster was again transformed into vectorial
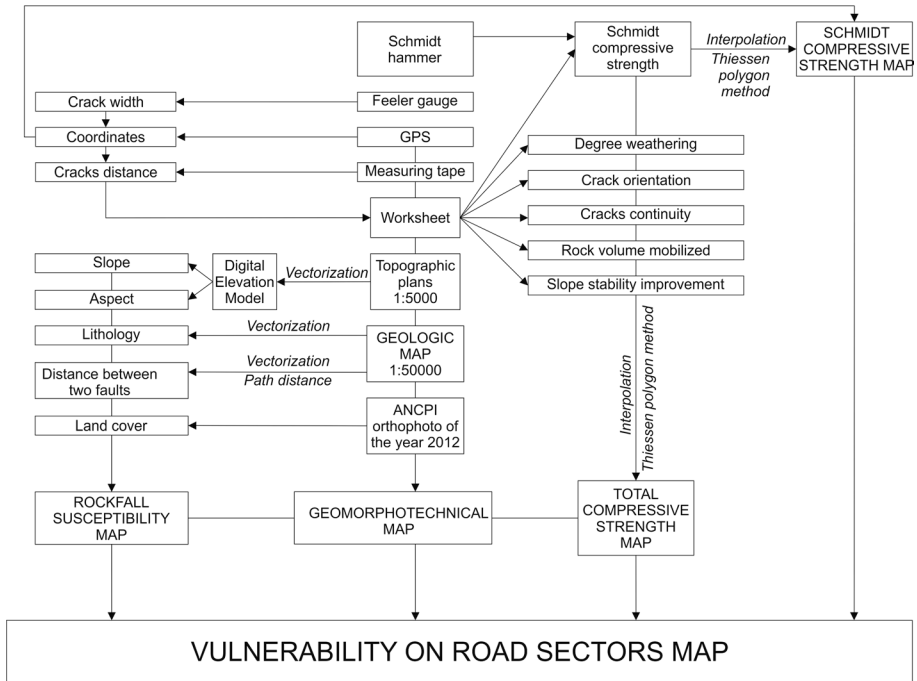
Fig. 7 The synthesis of the methodological approach

format and classified into five vulnerability classes (very low, low, medium, high, very high). Finally, the lengths of the road segments corresponding to each vulnerability class were calculated.

The synthesis of the methodological approach comprises information about the instruments used in the field for making the measurements, exemplifies the necessary data sources and presents the main data processing functions (Fig. 7).

4 Results

The construction of road and transport infrastructure caused imbalances due to cut slopes, demonstrated by the geotechnical measurements performed in situ. The Schmidt compressive strength of rock surfaces records values from under 2 (very strong resistance) up to over 4.5 (very high resistance), in the Brezoi–Călimăneşti area (Fig. 8).

Slopes with a much reduced compressive strength (<2) comprise 8.955% of the study area and represent, on one side, the rock surfaces intensely cracked and altered, and on the other side, the friable rocks (sandstones or marls). These situations can be found: to the South of Brezoi on the slopes from the base of Muchia Foarfecii, on the concave slopes of Cârligul Mic and of Olt in Muchia Roşie Area, on the anthropically cut slopes of Plaiul Lotrişorului, in the proximity of Turnu Monastery and on the slopes of Păuşa Hill, cut by Călimăneşti ring road (Fig. 9).
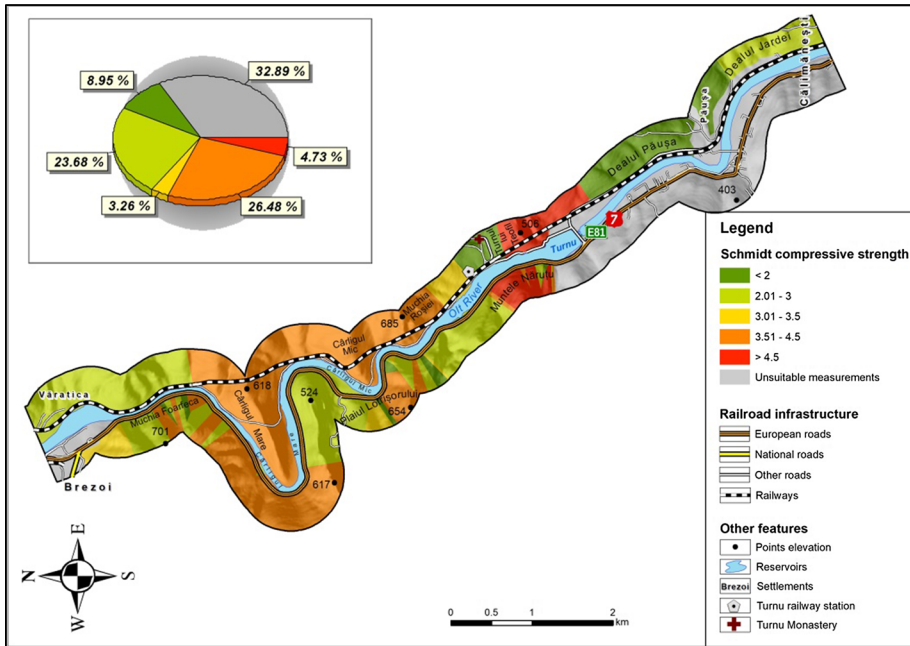
Fig. 8 Schmidt compressive strength map

Fig. 9 Sandstones alternating with marls (SCS < 2.00) (20.XII.2016)

Slopes with low compressive strength (2.00–3.00) comprise 23.685% of the Gorge surface. These values were recorded on the North of the area, on the South of localities Brezoi and Văratica, on the convex slope of Olt on the South of Cârligul Mare, on the slopes comprised between Plaiul Lotrișorului and Muchia Basarab, and on the South of the Gorge, on the left slope of Olt, next to locality Călimănești (Fig. 10).

Medium values of Schmidt compressive strength (3.01–3.50) are present on about 3.26% of the analyzed surface and characterize the slopes situated at the entry of Brezoi

Fig. 10 Low-strength slope near Năruţu (left) and Brezoi (right), (SCS 2.00–3.00) (05.VII.2017)

Fig. 11 Medium-strength slope near Turnu (RS 3.01–3.50) (20.XII.2016)

Fig. 12 High-strength slope (SCS 3.51–4.50) and huge fragments of rock detached by sliding (volume = 48 m^3) to quarry excavation from Muntele Cârligul Mic (06.VII. 2017)

locality, a part of the concave slope of Cârligul Mic and the slopes close to the Railway Station Turnu (Fig. 11).

Fig. 13 Very-high-strength slope (> 4.5). Muchia Basarab or Muntele Năruțu—left and Teofil Tower—right (19.XII.2016)

Rock surfaces with *high compressive strength* (3.51–4.50) are developed on 26.48% of the studied area and present a wide spread on the left side of Olt (on the slope of Cozia Massive). Here, one can also include: Cârligul Mare Mountain, Cârligul Mic Mountain and Muchia Roșiei. Also, these values were obtained on the right side of the Olt River, on the concave slope of Cârligul Mare and Cârligul Mic (Fig. 12).

Surfaces with a *very high compressive strength*, of over 4.5, have a reduced weight (4.74%). These values were recorded close to Turnu Lake, both on the right bank of Olt River (in Năruțu Mountain), and on the left side of Olt (on the slopes of Teofil Tower) (Fig. 13).

The space distribution of the values of *total compressive strength (TCS)* generally corresponds to the Schmidt compressive strength, this correlation being a consequence of the big number of variables taken into account.

Slopes with the lowest total compressive strength (< 40) have only 0.68% of the studied area. These surfaces are situated on the concave slopes of Cârligul Mic.

The reduced TCS values (40.01–50) characterize 18.75% of the Gorge and appear predominantly on the right bank of Olt (on the South of Brezoi and on the South of Cârligul Mare, up to close to Năruțu), but also in the proximity of Turnu Monastery and of the Călimănești town.

The medium compressive strength of rock surfaces varies between 50.01 and 60, occupying 26.055% of the analyzed area and characterizing Cârligul Mare Mountain, Muchia Roșiei, Păușa Hill, on the left side of the Olt River, but also areas from Muchia Foarfeca, Plaiul Lotrișorului and reduced areas from Muchia Basarab, on the right side of the Olt River.

Slopes with high total compressive strength (60.01–70) have a weight of 16.475% and are located on the North of the Gorge, on the South of the locality Văratica, on the concave surface of Cârligul Mare, on reduced areas of Muchia Basarab and in the proximity of Teofil Tower.

The highest values of total compressive strength (> 70) appear isolated on the right slope of the Olt River, occupying a more extended surface on the left side of Olt, in Cârligul Mic Mountain. The total surface occupied by maximum TCS is of 5.14% (Fig. 14).
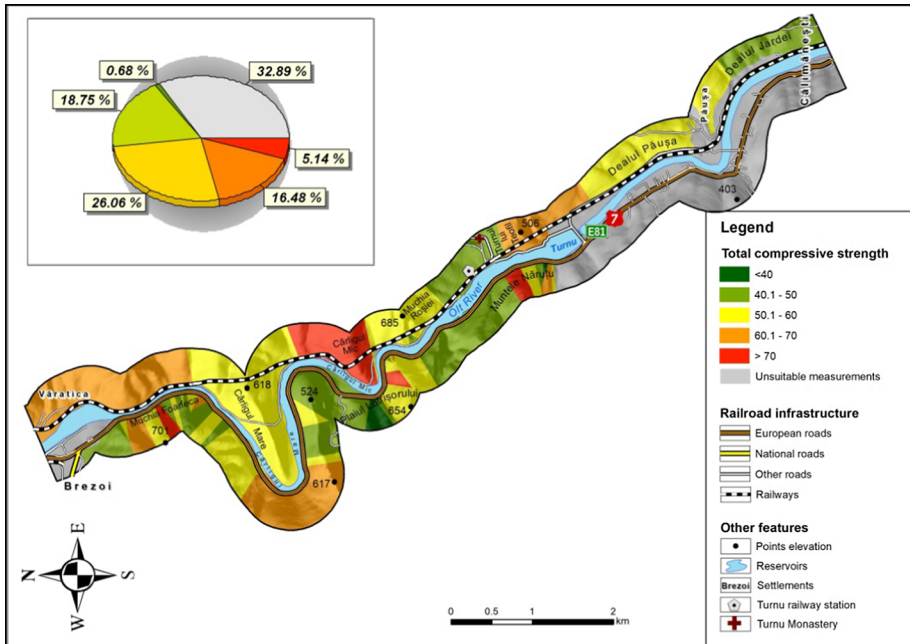
Fig. 14 Total compressive strength map

For Figs. 8 and 14, the presence can be noticed, on the South of the study area, on the right slope of the Olt River, of an area that was not fit for measuring (32.89%). This can also be identified, with a small extension, also in the vicinity of localities Brezoi and Păușa. The areas where compressive strength measurements were not conducted are characterized by the presence of a thick layer of alteration cover and soil that cover the base rock or of proluvial deposits (alluvial fan close to the previously mentioned localities).

The compressive strength measurements justify the need of some large-scale engineering works for stabilizing the slopes and for stopping the materials, reducing the damages and even human life losses. Thus, within the perimeter of Cozia Gorge, with a length of 14 km, there is a number of 133 special engineering works (frequency of 723,785 engineering works/km), totaling 28,773 km in length (2.05 km engineering works length/km) (Table 2, Fig. 15a, b, c). Also, the hydroelectric dam Turnu situated on the Olt River can be mentioned. Because of the reduced compressive strength of the slopes and of the high weathering degree, it was necessary to propose two structural works on the right slope of Olt. These have a total length of 107 m (34.3 m high—tensile rockfall steelgrid mesh and 72.7 m dynamic rockfall barrier) and are situated on the North of the Gorge, on the South of the locality Brezoi.

From the analysis of the map with susceptibility to rockfall (Fig. 16), it results that almost a half (44.09%) of Cozia Gorge presents high and very high values of susceptibility. These values are concentrated in the space of maximum narrowing of the Gorge (between Văratica and Turnu Lake). On the section: Năruțu–Teofil Tower straightway, there is a tectonic break that marks the exit from the proper Gorge, making the pass to the Subcarpathian region. On the South of this straightway, the values of rockfall susceptibility are

Table 2 Engineering works in Cozia Gorge (own observations and measurements)

Type	Total number	Total length (m)	Left bank		Right bank	
			L	No.	L	No.
False railway tunnel	2	128.5	128.5	2.0	0.0	0.0
Levees	11	11,749.1	4049.6	5.0	7699.5	6.0
Gabions	26	2633.2	0.0	0.0	2633.2	26.0
Spillway tunnel	1	410.7	0.0	0.0	410.7	1.0
Dynamic rockfall barriers	5	274.2	0.0	0.0	363.3	6.0
High—tensile rockfall steelgrid mesh	29	2047.8	0.0	0.0	2047.8	29.0
Railroad bridge over Olt	2	201.4	0.0	0.0	201.4	2.0
Road bridge	5	660.2	0.0	0.0	0	0
Rail embankment	1	330.8	330.8	1.0	0.0	0.0
Cement ditch	1	258.6	258.6	1.0	0.0	0.0
Railway tunnel	5	4209.1	4209.1	5.0	0.0	0.0
Road tunnel	2	102.9	102.9	2.0	0.0	0.0
Concrete cloth	3	121.8	0.0	0.0	121.8	3.0
Viaduct	2	648.1	0.0	0.0	648.1	2.0
Cemented wall	2	105.6	0.0	0.0	105.6	2.0
Concrete wall	9	2083.6	2051.2	8.0	32.4	1.0
Stone wall	18	1396.1	0.0	0.0	1396.1	18.0
Stone and concrete slabs wall	1	121.2	0.0	0.0	121.2	1.0
Slab wall	8	1290.6	0.0	0.0	1290.6	8.0

reduced, existing just on the right side of Olt, in Păușa Hill and close to Călimănești, slope surfaces with medium susceptibility.

Vulnerability on road sectors (Fig. 17) was calculated both for the European E 81 Road (14 km) and for the ring road Călimănești (4.9 km) that is located along the left slope of Cozia Gorge, between Călimănești and the Turnu hydroelectric dam.

The Brezoi–Călimănești sector, on a length of 5.4 km (29%), presents a high and very high vulnerability to rockfall. These are followed by the sectors with medium vulnerability that sum up 4.4 km (23%). Low and very low vulnerability were recorded on a length of 9.1 km which means the 48% of the road ways that cross the study area. This high percentage—48%—is also explained by the fact that in calculating vulnerability by road sectors, the Southern segment of the European E 81 Road was taken into consideration as well, that is not fit for geo-mechanical compressive strength measurements.

If we refer strictly to the area of maximum narrowing comprised between the North of the Turnu water storage and the South of the Văratica water storage (9 km), the results show a significant increase in the sectors with high and very high vulnerability. The aforementioned presents a weight of 56.5%, that is 5.1 km.

The medium vulnerability characterizes 32.2% of the proper Gorge, meaning 2.9 km. In the maximum narrowing space of the Gorge, we can notice that the surfaces with low and very low vulnerability are much reduced (1.03 km, that is, 11.4%).
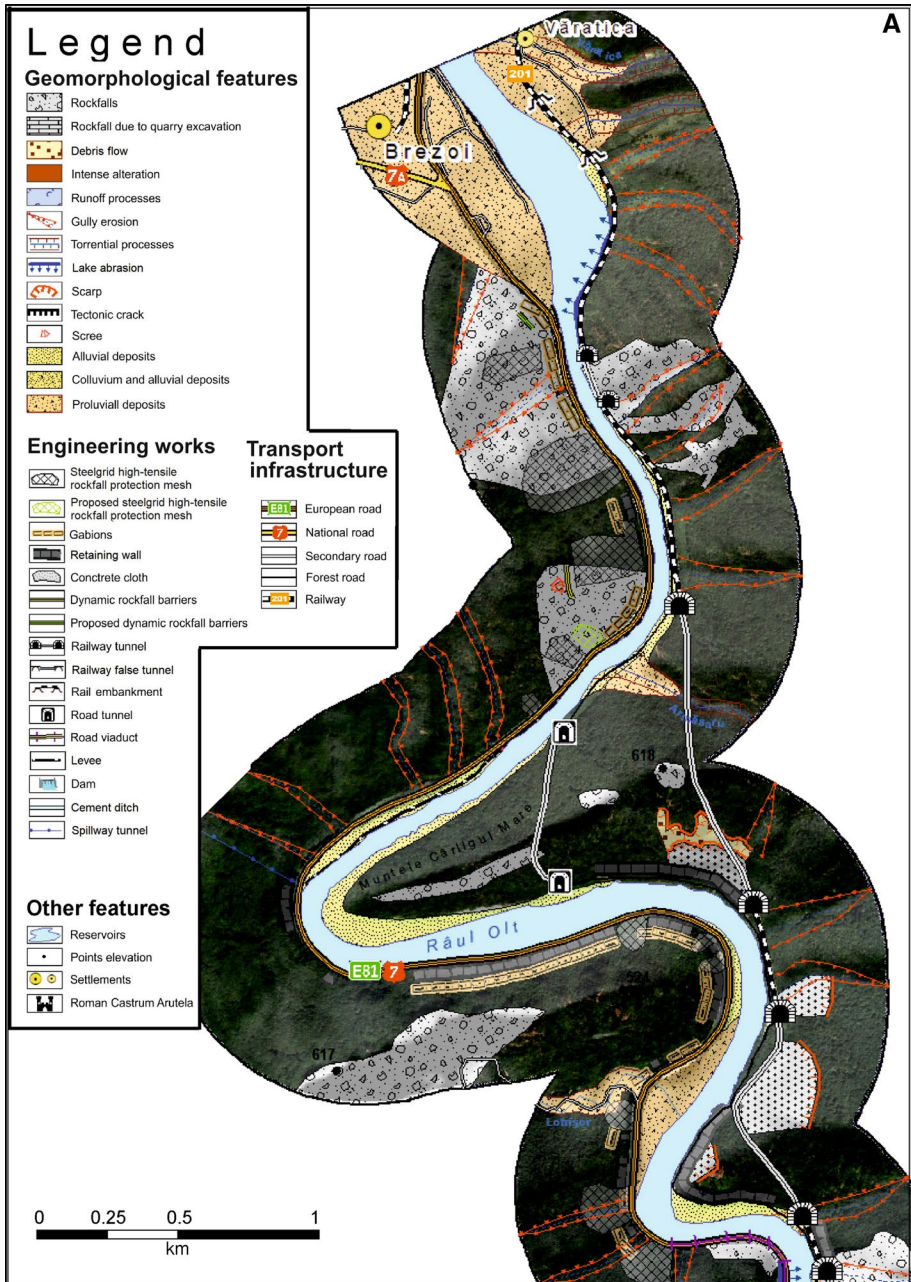
Legend

Geomorphological features

- Rockfalls
- Rockfall due to quarry excavation
- Debris flow
- Intense alteration
- Runoff processes
- Gully erosion
- Torrential processes
- Lake abrasion
- Scarp
- Tectonic crack
- Scree
- Alluvial deposits
- Colluvium and alluvial deposits
- Proluviall deposits

Engineering works

- Steelgrid high-tensile rockfall protection mesh
- Proposed steelgrid high-tensile rockfall protection mesh
- Gabions
- Retaining wall
- Conctrete cloth
- Dynamic rockfall barriers
- Proposed dynamic rockfall barriers
- Railway tunnel
- Railway false tunnel
- Rail embankment
- Road tunnel
- Road viaduct
- Levee
- Dam
- Cement ditch
- Spillway tunnel

Transport infrastructure

- E81 European road
- 7 National road
- Secondary road
- Forest road
- 201 Railway

Other features

- Reservoirs
- Points elevation
- Settlements
- Roman Castrum Arutela

0   0.25   0.5   1
km

Fig. 15 a Geomorphotechnical Map—northern sector. **b, c** Geomorphotechnical Map—central and southern sectors

The separate analysis of the proper Gorge highlights the fact that out of the total of 5.4 km with high and very high vulnerability, 5.1 km can be identified in this area, meaning 94.4% (Fig. 17).
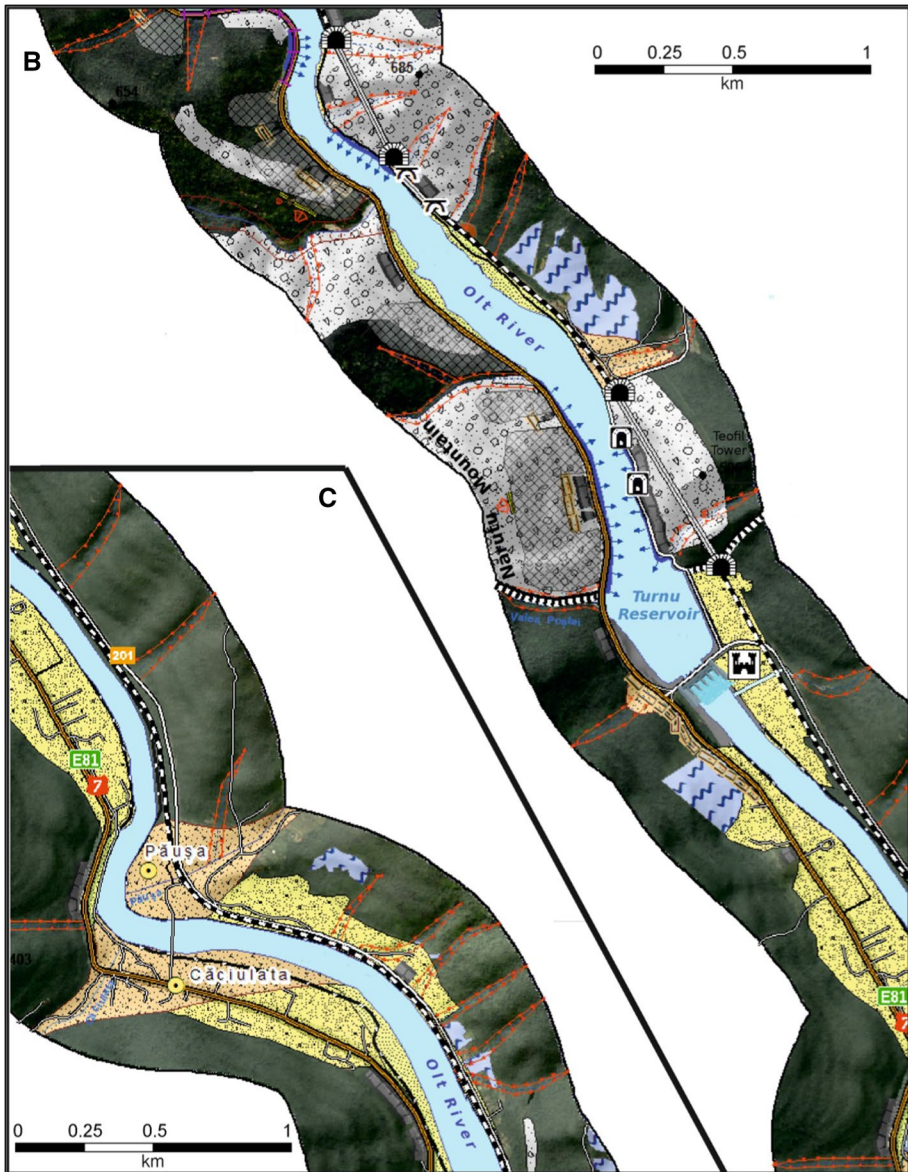
Fig. 15 (continued)

5 Discussions

The Cozia Gorge presents a high susceptibility to rockfall, the main cause being the anthropic cut of the slopes. The area is developed on a geological, geomorphological and land-cover background that is favorable for rockfall, but the anthropic intervention minimizes their importance, being a key factor in the trigger of the process.
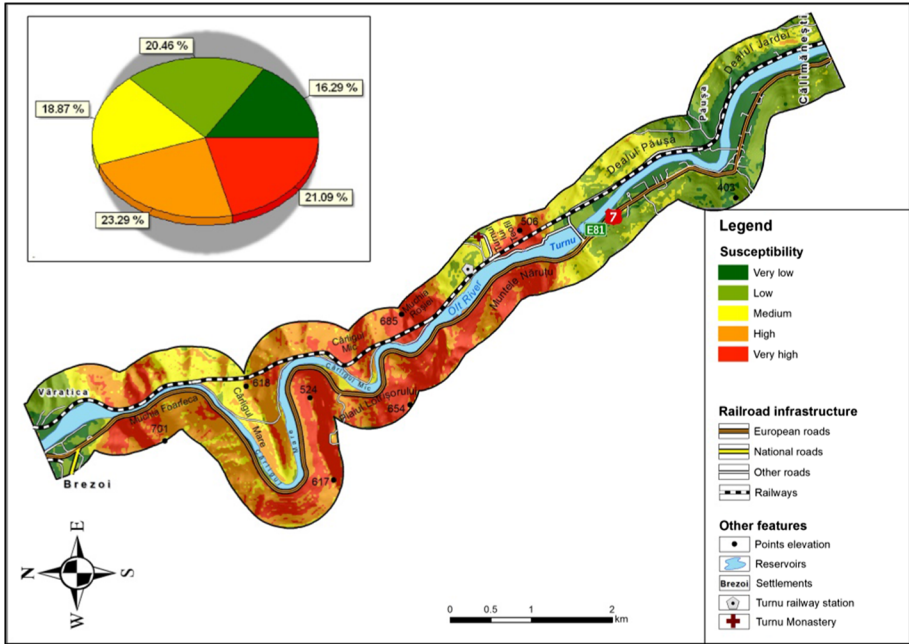
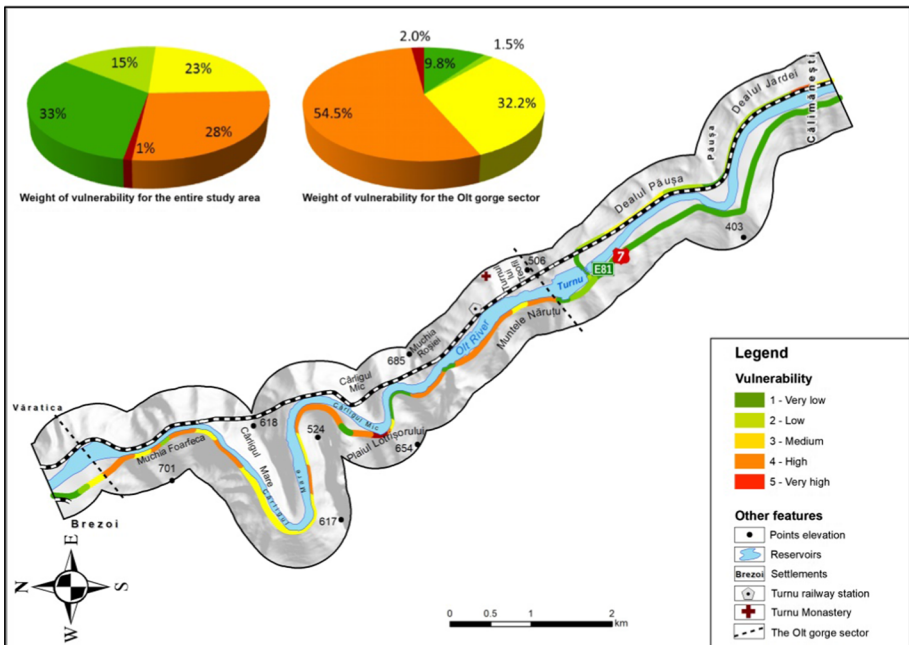**Fig. 16** Map for susceptibility to rockfall
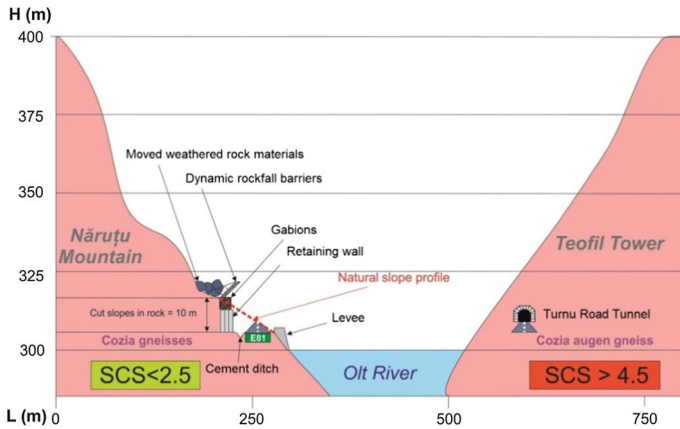

Fig. 17 Map for vulnerability on road sectors

Fig. 18 Cross-sectional profile between Nărufu Mountain and Teofil Tower

This importance of the anthropic factor is duly highlighted by the presence of some areas with the same lithology, but with very different values of the Schmidt compressive strength. For example, Nărufu Mountain (Muchia Basarab) and Teofil Tower, although they are both composed of Cozia augen gneiss, present SCS values of < 2.5 (reduced compressive strength), respectively, > 4.5 (very high compressive strength). This difference is given by the extent of the activities to arrange the communication ways, different from one slope to another (Fig. 18). The cut slopes of Nărufu Mountain were followed by different engineering works for slope stability, such as collection ditch, retaining walls, gabions, dynamic rockfall barriers in comparison with those of the Teofil tower crossed underground by a road tunnel.

The Schmidt compressive strength of the analyzed slopes depends also on their cracking degree. The crack system identified at the level of rock surfaces that were investigated is the result of a plurality of natural factors such as tectonics pressure, thermal stress, gelivity and anthropic by cutting, dynamiting the slopes and traffic. The very good correlation of the R values with the distance between the cracks, highlighted by the correlation coefficient R of 0.89, demonstrates the weight of discontinuities in the rock mass in the calculation of slope stability (Fig. 19).

Also, there is a strong correlation ($R = 0.85$) between the Schmidt compressive strength of the slopes and the dimension of the blocks that are at their base (Fig. 20).
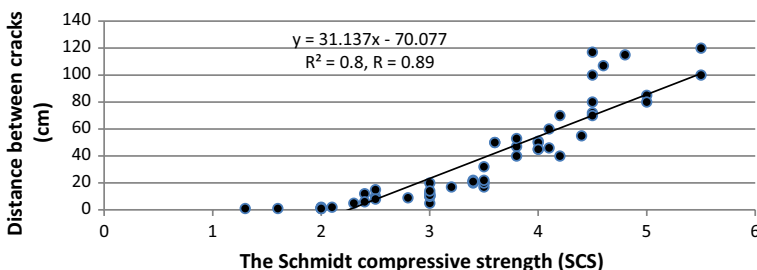

Fig. 19 Correlation between cracks distance and Schmidt compressive strength
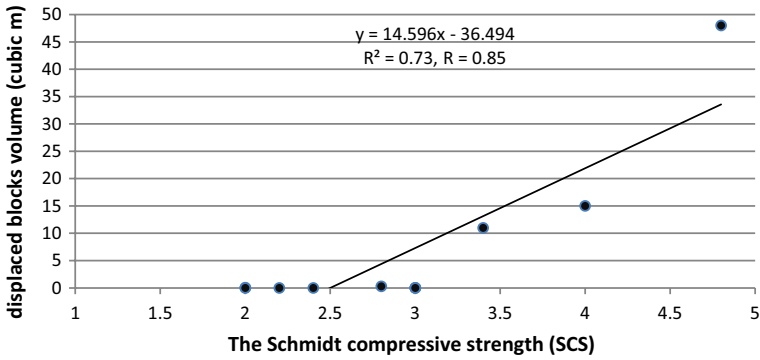
Fig. 20 Correlation between displaced blocks volume and Schmidt compressive strength
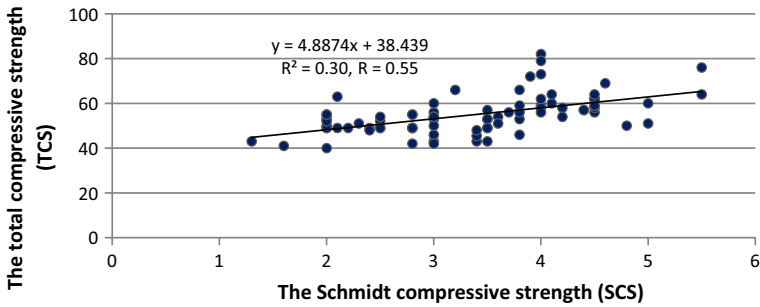

Fig. 21 Correlation between total compressive strength and Schmidt compressive strength

Fig. 22 Huge displaced blocks to quarry excavation, the location of the explosive and the crash left by it

The total compressive strength of the rock surfaces presents a relative correlation with the recorded values of the Schmidt compressive strength, these variables having a correlation coefficient of 0.55. The high value of the R coefficient shows the importance of rock

Fig. 23 Slope engineering works (high–tensile rockfall steelgrid mesh, dynamic rockfall berries, gabions, stone and concrete slabs walls)

characteristics in the calculation of slope stability. Thus, besides the anthropic activities and the slope cracking degree, the type of rock is another factor that influences the occurrence of rockfall in Cozia Gorge (Fig. 21). These correlated data are representative both for the dynamic of the studied process as well as for the statistical analysis and their distribution that is normal.

Therefore, hard, compact rocks, with a highly measured SCS (Schmidt compressive strength) have a reduced alteration degree, less cracks and reduced thicknesses. The weathering blocks have big dimensions, but reduced frequency. These characterize the stable slopes, with reduced rockfall susceptibility, the road sectors that cross them being the least vulnerable. The biggest rock blocks noticed at the base of the slopes appear in the areas of quarry exploitation of augen gneiss. The penetration holes for dynamite are visible, as well as the trace left by the explosive. Nevertheless, they are the most stable areas, the distance between cracks being very long (Fig. 22). The rocks with a lower compressive strength (low SCS value) are strongly altered, have a higher cracking degree. These give abundant weathering, but the dimension of clasts is smaller. In this context, the slopes have reduced stability and are the most susceptible to rockfall, and the road sectors that are along these areas present a very high vulnerability. This result is reflecting in the performance of structural engineering works for the support of the slopes and for the protection of the roads. The right slope is more affected by the anthropic intervention by the making of the European E 81 Road and presents the most special engineering works (high–tensile rockfall steelgrid mesh, gabions, cementations, concrete walls) (Fig. 23).

6 Conclusions

The results of the present study demonstrate that a very high anthropic pressure upon the relief of the analyzed Gorge sector with a concentrated network of transport and chain of reservoirs for hydropower plant along the Olt River induce a high susceptibility of the slopes for rockfall. Due to the importance of this communication corridor, it was necessary

to analyze the susceptibility of slopes and quantify the improvement in slope engineering works, and finally assess the vulnerability for E 81 and Călimănești ring road.

Thus, almost half of the Cozia Gorge 44.09% shows some high values of rockfall susceptibility, and 56.5% of the E 81 road is highly vulnerable. The engineering works for slope stabilization and rockfall prevention include 133 different structural works deployed on a length of 28,773 km.

All of these have as their finality the creation of a complex and complete database that would contribute to the superior management of the study area, to inform and prevent the traffic drivers and to update the road signs. Also, we propose, in a future approach, the assessment of the state of the different existing arrangements within the analyzed area, the optimal protection being ensured just by the undamaged and periodically cleaned arrangements, and also the inventory of the events when rockfall occurred, their impact on the material/human damages that were produced.

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