Rockfall Hazard Assessment
Case study: Lotru Valley and Olt Gorge*

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Key words: rockfalls, hazard assessment, roads, heavy rainfall

Abstract. Rockfalls - a natural hazard – can occur isolated in our country but they produce serious damage, hurting and even killing peoples. Despite all financial losses, rockfalls were not studied in Romania by the geomorphologists and engineering geologists. Those events are strictly linked with those climatic one and also with human activities which created slope instability. In this paper we tried to assess this kind of relations and also magnitude – cumulative frequency relationships and return periods. We tried also to estimate the probability of rock falling onto a moving vehicle using one simple formula made by the Australian Geomechanics Society. The two major events, the damages and people injuries caused by rockfalls in the last 8 years (after 2001) are described in detail.

Introduction

Rockfalls are present-day geomorphic processes spread in all mountain areas (Rapp, 1960; Whalley, 1984). They may occur both in natural (untouched slopes by human activities) and cut slopes (where a linear infrastructure exists). In this paper we will try to assess only the cut slopes along two major transport corridors.

Rockfall is defined as „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" (Varnes, 1978) or „the displacement of a single fragment or several pieces" (Evans & Hungr, 1993).

In Romania studies on rockfalls were not done neither by geomorphologists nor by engineering geologists as there were on landslides (soil slips, mudflows and snow avalanches), perhaps because the first occur on small and isolated areas.

When rockfalls may produce victims or even cause damage, destroying roads, railways, electricity lines, water and pipelines etc. they are considered natural hazards. Although on the rockfall hazard many kind of rockfall hazard assessments along transportation corridors can be found in the foreign literature (Ritchie, 1963; Pierson et al., 1990; Pierson & Van Vickle, 1993; Baillifard et al., 2003; Hantz et al., 2003; Budetta, 2004; Guzzetti et al., 2004; Uribe-Etxebarria et al., 2005), the assessment is still very difficult to achieve.

In most cases the greatest problem is represented by the lack of any data because only the most important and destructive rockfall events are noted in the institution files.

Study area

For analysis we selected two important transportation corridors affected every year by many rockfalls. The first site is the Lotru Valley (the sector between the Voineasa and Brezoi localities) crossed by the national road 7A and the second one is the Olt Gorge crossed by the European road E 81 (Fig. 1), which is also the road the most affected by this kind of geomorphic hazard from the whole country. We selected these two corridors because the rockfall frequency and also the traffic intensity are high. The length of the corridors is almost 100 km (39 km has the first and 50 km the second).

From an administrative point of view the two corridors are part of the Vâlcea County and only a few kilometers from the northern sector of the Olt Gorge is part of the Sibiu County.

* Paper presented at the "IAG Regional Conference on Geomorphology: Landslides, Floods and Global Environmental Change in Mountain Regions", September 15-25, 2008, Brasov, Romania

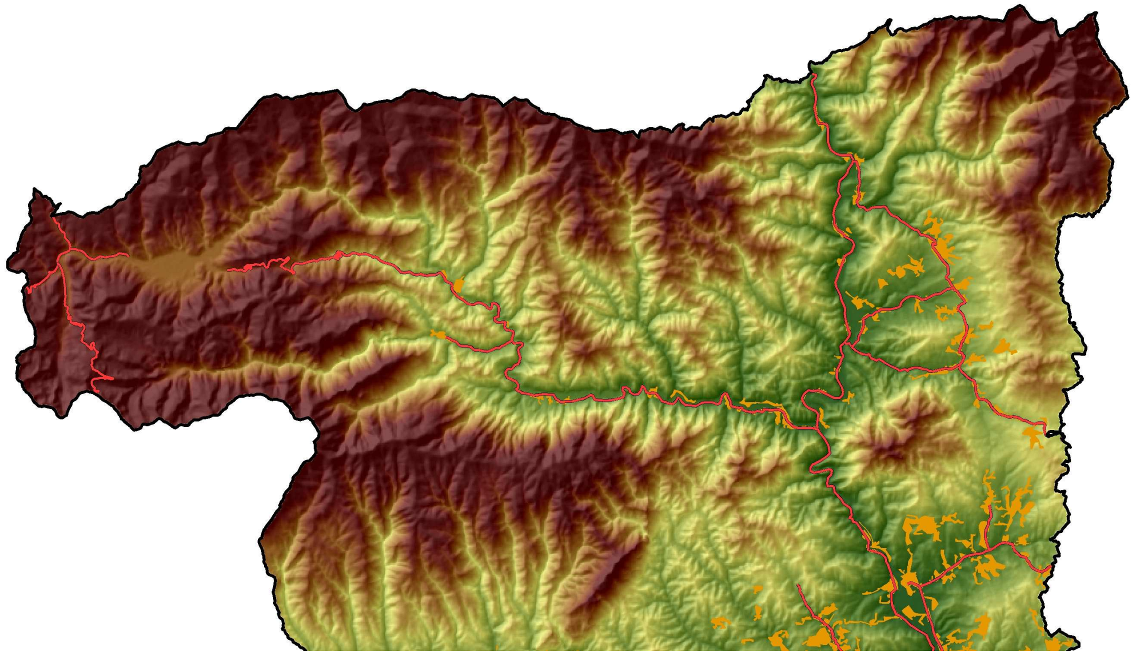

Fig. 1. **The position of the two main transport corridors.**
The W – E axis is the National Road 7A and the N – S red line represents the European Road 81

Geological settings

The geology is very important when we try to assess any hazard, because it influences the magnitude of events through the complexity of lithology and the presence of joint sets.

Both sectors are cut into metamorphic rocks (schists, augen gneiss, paragneiss) and less into sedimentary rocks (the sector between the Valea lui Stan and Brezoi localities as well as between the Câineni and Golotreni localities), which are made of conglomerates, breccias and sandstones and are part of the Brezoi – Titeşti sedimentary basin (Savu & Schuster, 1975; Savu et al., 1977; Popescu et al., 1977; Ştefănescu et al., 1982). The metamorphic rocks are included in the Getic Nappe and the Supragetic Nappe.

Although the hardness of these rocks is higher, the joints set (faults, foliation, bedding plane) have a major role in the detachment of rock blocks or fragments (Hencher, 1987). The most important fault of the entire region is the Brezoi Fault which has 80 km in length and an uplift of about 1000 m along the discontinuity plane (Ghika – Budeşti, 1958). It can be observed from the northern slope of the Cozia Massif and then at the bottom of Căpăţânii Mountains up to the Malaia Valley.

The joint sets are very important when researchers want to assess rockfalls to a local scale (microslope level for example). Generally large rockfalls are triggered under planar, wedge and overhang failures (Fig. 2). When joints have random orientation, the rock mass strength is lower and rockfalls occur.

Rock weathering is another geological factor which contributes at the failure mechanism. Although most part of the region is made of metamorphic rocks, the failure mechanism is possible due to physical and chemical weathering and also to the differential erosion. Many slopes are affected by these three processes especially in the sector between the Brădişor Dam and Voineasa locality (Lotru Valley) and between the Brezoi and Cozia localities (Olt Gorge).

Geomorphological settings

Both valleys are limited by steep slopes. In the cross sections along these valleys, slopes can be separated into two sections: the bottom part which is generally cut for road and railway bed, very steep (often vertically) without natural vegetation or with sparse vegetation and the upper part which is not affected by human activities but generally also very steep. Usually the cut slopes are 10-30 m high but the natural slopes can reach more than 100-150 m in height. The slopes aspects are N and S for the Lotru Valley and E and W for the Olt Gorge.

Fig. 2. **Types of failure mechanism: overhanging block in sandstone (left) and topple in paragneiss**

Climate settings

Hoek (2007) concludes that „rockfalls are generally initiated by some climatic or biological event that causes a change in the forces acting on a rock". Here can be included: „pore pressure increases due to rainfall infiltration, erosion of surrounding material during heavy rain storms, freeze-thaw processes in cold climates, chemical degradation or weathering of the rock, root growth or leverage by roots moving in high winds".

As in the case of the landslides from our study area (debris flow), there are few examples of rockfalls generated by heavy rainfall. Firstly, we can note many events which occurred during the August 10-11, 2007, then October 22-24, 2007 and March 08, 2009. The rockfall deposits were observed between the Brădişor Dam and the Voineasa Spa on the carriage way. In these regions, rockfalls occurred under heavy daily rainfall usually higher than 35-40 mm (Fig. 3).

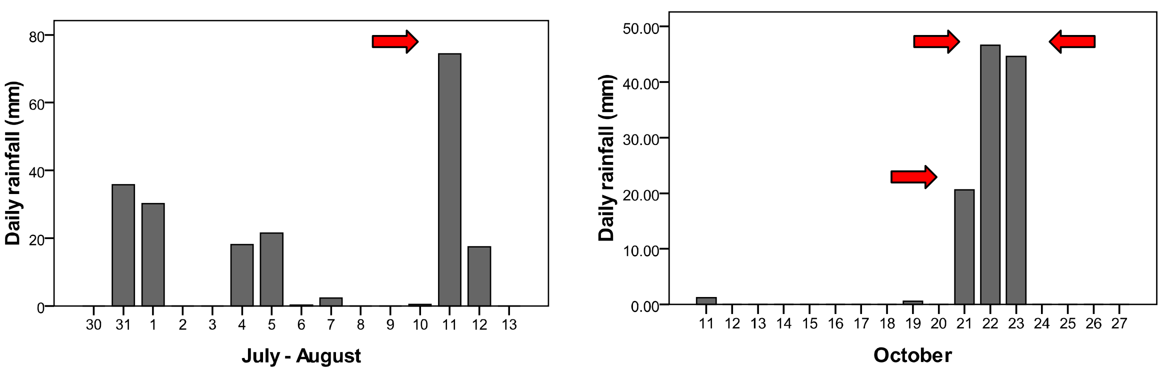

Fig. 3. **The daily rainfall for two periods with multiple rockfall occurrences. Red arrows indicate days with rockfalls**

Another example includes also the antecedent moisture from regolith. A big debris/rock fall was triggered in March 26, 2006 and destroyed an old motel in the Gura Latoriţei point. The moisture from the regolith triggered an initial slide and then a huge debris/rock avalanche (Fig. 7).

For the period 2003 - 2007 we found a good relation between monthly rainfall and rockfall events (Fig. 4). The relation is not valid for all months with high rainfall; few explanations are credible here:: (1) the deficiency of inventory (it is possible that rockfalls occurred in the months with the highest monthly rainfall but they were not registered in the official files); (2) large rockfalls did not occur, because before the month with a high monthly rainfall amount, only small events (fragments by fragments) occurred; (3) rainfall was distributed uniformly during the month that induced a low daily rainfall and made data difficult to analyze. It is known in practice that rockfalls are very often caused by rainfall and their relationship is weak (Corominas, 2000).

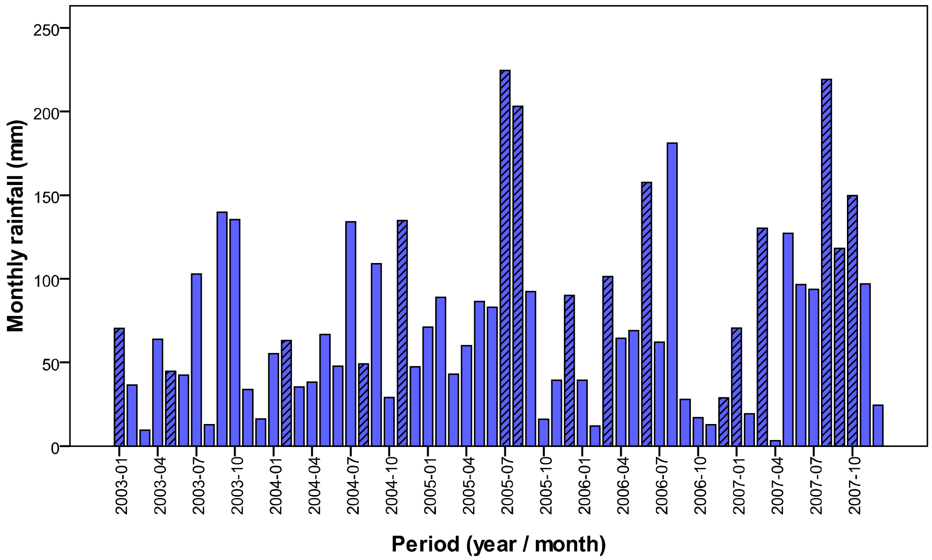

Fig. 4. **Monthly rainfall and rockfall events between 2003 and 2007. The dashed columns refer to months with rockfalls**

Regarding the rockfall distribution over a year (monthly frequency) it is clear that we have high frequencies in two periods. Firstly, during the months which had high daily rainfall in the last years (after 2003) especially July and August (Fig. 5). Although the rainiest months are May and June, our data base does not indicate a high frequency for these months, perhaps because of data lacking and the short period of inventory.

Secondly, it is the case of the transition seasons with freeze-thaw cycles, especially November, February and most of all March (Fig. 5). The last month has a high frequency of rockfalls due to the events that occurred on March 8, 2009, when we found 17 points with blocks on the road (Fig. 8). In our data base there are many multiple-occurrence events in both valleys.

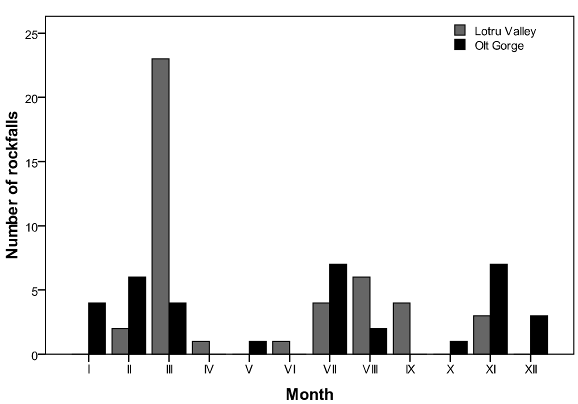

Fig. 5. **Monthly rockfall frequency in both valleys**

Hazard assessment – methods and data base

Because of the lacking information, we tried to create our own data base. In order for this to be more complete, we used the data from a few sources: the National Roads Administration from Râmnicu Vâlcea, online newspapers and our field observation and measurements. The period covered only 6 years (2003-2009) for the Olt Gorge and 5 years for the Lotru Valley (2004-2009). The total number of rockfall events is 79 (only 63 of them with registered volume) but the real number is much higher than this (it is very possible rockfall events were more than 300). The rockfalls volume ranges between 0.1 to 10.000 m³ with a mean of about 415 and a standard deviation of 1558.

Magnitude and frequency

In rockfall studies, like in others natural hazard, one of the most important aspects is magnitude – cumulative frequency relationships (Hungr et al., 2008). Magnitude is defined here as the volume of rock and debris displaced by a landslide (Hungr, 2005; Hungr et al., 2008) and the frequency can be expressed as the number of events of a given magnitude in a given unit of time (Alexander, 1993).

Magnitude – cumulative frequency relationships were adopted from seismology (Gutenberg and Richter, 1949) and applied in rockfalls and debris flows assessment by geomorphologists and engineering geologists (Wieczorek et al., 1995;

Hungr et al., 1999, 2008; Dussauge-Peisser et al., 2002; Chau et al., 2003).

We applied this relationship for events which occurred in both valleys – Lotru and Olt – which are also two transport corridors. The annual frequency for a rockfall of a certain magnitude can s

be read from the graphic curve (Hungr et al., 2008). As can be seen in the graphs (Fig. 6 a, c) the curves in both cases are similar and the low magnitudes have a high frequency and, vice versa, high magnitudes have low frequencie.

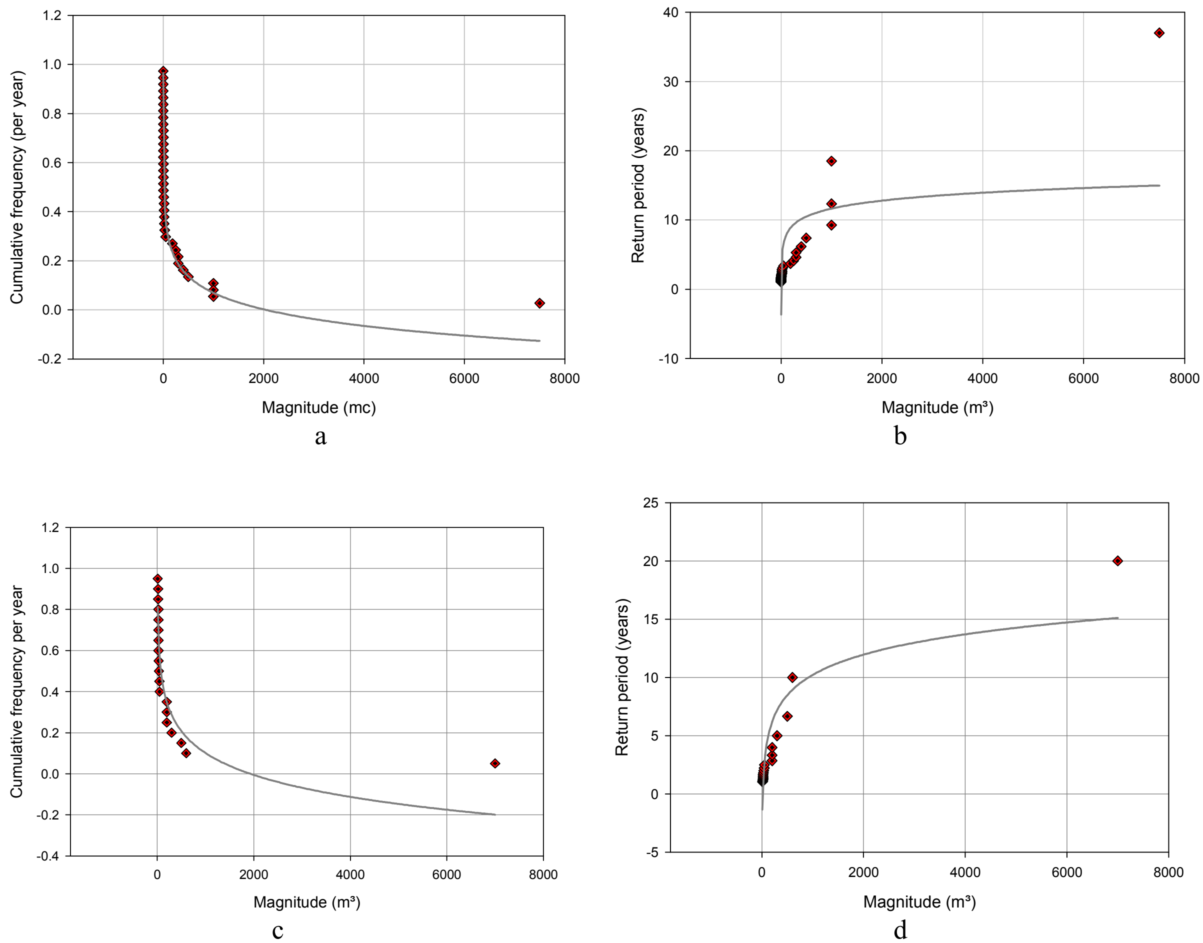

Fig. 6. **Magnitude – cumulative frequency relationships and return period for the Lotru Valley (a, b) and the Olt Gorge (c, d)**

After obtaining these relations, it is very easy to estimate the return period, as can be seen from Fig. 6 b and d. Because the high frequency events are insignificant and usually they do not damage the infrastructure we are interested especially in large events return periods because, generally, the latter events destroy roads, railways and buildings. The return period for the event with a high magnitude (>7000 m³) is higher and is approximately 15 years (Fig. 6 b, d).

But this data inventory is not complete and therefore the graphs above may be regarded with skepticism. Anyway, the magnitude – frequency relationships remain an important tool when geomorphologists and engineering geologists try to assess the hazard of rockfalls, especially along linear infrastructure.

Câineni and Gura Latoriţei – two major events in the last years

In the last years many events occurred which produced serious damage to roads and railways and also hurt a few people inside the cars that crossed the valleys. Two of these were large rockfalls that detached thousand of square meters of rock downslope.

One of these events occurred in December 28, 2005 in the Northern sector of the Olt Gorge, along the European Road 81. Here, more than 7000 m³ (10000 m³ from another source) were detached from a 40-50 m high cliff and covered the railway and the road on a more than 30 m distance (Fig. 7 a). This was a typical rock avalanche. The European Road was turned-off between December 28, 2005 and 11 January, 2006 and the financial loss was also very high. At the time when the rock avalanche was triggered, a train was in the proximity of this point.

After this event the Ministry of Transport invested a lot of money for rockfalls remedial measures and also for continuing with extending the existent railway tunnel at both ends. After many years of investments the people still work in this sector and the financial loss scaled up and exceeded millions of Euros.

In the case of the European Road it was very easy, because in this sector the valley is relatively large and the workers could deviate the river towards its left bank by 4-5 m. After that, they constructed from beginning a new road bed on the right bank which is a few meters away from the bottom of the slope.

Another large event occurred in the Lotru Valley along the National Road 7A in March 26, 2006 at the Gura Latoriţei point. Here, the debris/rock avalanche included more than 7500 m³ (Fig. 7 b). The material included rock blocks (generally smaller than 50 cm in diameter), soil, deluvial deposits and many trees, and covered two roads: the National Road 7A and the Local Road 175 which stopped the traffic. An old motel was also completely destroyed and a few people nearly died because at that moment they were inside.

a b

Fig. 7. **Two major landslides: (a) the Câineni rock avalanche** (Photo: Mediafax) **and (b) the Latoriţa debris/rock avalanche**

Fig. 8. **The rockfall event, from March 8, 2009, along the National Road 7A** (Lotru Valley). **The blocks in the left photo have about 20 m³ and covered part of the road** (the photo was taken after the authorities unblocked the road)**; the boulder from the right photo has a 1.5 m diameter**

Probability of rock falling onto a moving vehicle

To calculate the probability of rock falling onto a moving vehicle we adopted the formula from the Australian Geomechanics Society (2000):

$$P(s) = 1-\left(1-\left(P_{(S:H)}\right)\right)^{N_R} \qquad 1)$$

where:

P(s) = probability of one or more vehicles being hit;
$P_{(S:H)}$ = probability of a vehicle occupying the portion of the road onto rock falls;
NR = number of rockfalls/day,

and

$$P_{(S:H)} = \frac{N_v}{24}\cdot\frac{L}{1000}/V_v \qquad 2)$$

where:
N_v = number of vehicles/day;
L = length of the vehicles (m);
V_v = velocity of vehicles/hour (km/hour).

We selected the National Road 7A to apply this ecuation. As can be seen, the results depend on the number of vehicles per day, the length of vehicles, the velocity of vehicles and the number of rockfalls per day. For this reason we applied the formula for a velocity between 50 and 100 km/h and a length of cars of 5, 7.5, 10 and 12.5 m. The daily traffic is about 1350 vehicles/days and the number of rockfalls is 1/month. The daily traffic information was obtained from the National Road Administration in Râmnicu Vâlcea which has installed a monitoring video camera in the Malaia village and the number of rockfalls was estimated from the data base inventory.

From the graphics it can be observed how the probability of one or more vehicles being hit and the probability of a vehicle occupying the portion of the road onto rockfalls decrease proportionally with the decreasing of velocity. For a velocity of 50 km/h P(S:H) is 0.0056 and P(s) is 0.000079 and for 100 km/h P(S:H) is 0.0028 and P(s) is 0.000039 (Fig. 9). For this estimation we assumed that the daily traffic is constant and the distance between vehicles remains equal and no changes appear in this time (this is impossible in practice). Therefore this estimation is partial.

Roads are very frequently damaged due to rockfall events. People or cars are rarely hit by blocks when they cross the corridors transport. In the last years (after 2000) we can note two special events which seriously hurt people. The first event occurred in the second sector of the Olt Gorge (between the Brezoi and Cozia localities) and hit a police agent who drove onto Râmnicu Vâlcea. One block fall onto his car and hurt him very seriously. After that event the man's recovery was difficult and he remained with some physical lesions (and of course psychic damage) for the whole life. In 2002 a car with 3 people on board was also hit by a rockfall event, 2 of then being seriously hurt and another very easily. In 2008 two cars were hit very easily and nobody was hurt. From our information nobody died due to rockfalls events.

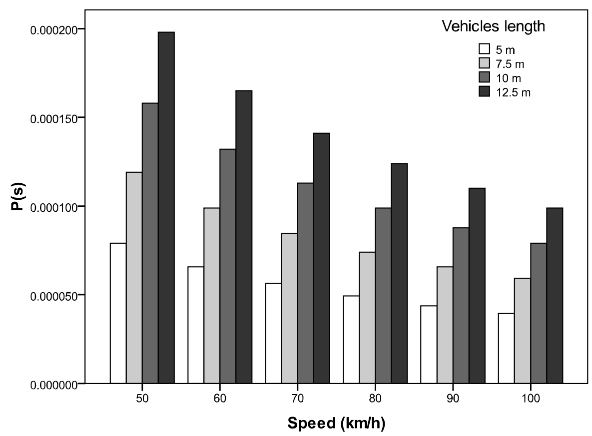

Fig. 9. **The probability of one or more vehicles being hit P(s) taken in account different vehicle lengths and different speeds** (National Road 7A)

Damage, hurt and killed people due to rockfalls

Rockfalls destroy very frequently the roads and railway and produce huge financial losses. Even when they occur without destroying the roads, they still produce financial losses because they may interrupt periodically the traffic and money are spent to release the way.

Conclusions

Quantitative estimations for rockfalls which occur in transport corridors are very important. One of the most important aspects is the lack of a data inventory because it is impossible to make the hazard map without this step. A problem is the heavy access to authority archives. If in the future those institutions which are involved in the administration of national and European roads will create a landslide data base inventory, the geomorphologists and engineering geologists will have a start point when trying to assess the landslide hazard.

Most of the rockfall events occurred in two distinct periods: in summer, when heavy daily rainfall occurred and at beginning and ending of winter as a consequence of freeze-thaw cycles, therefore more accurate meteorological data are needed.

Acknowledgments
The studies were financed by CNCSIS, grant TD no. 321/2007. I would like to thank the National Road Administration of Râmnicu Vâlcea and to Ms. Maria Moise who provided some useful meteorological data. I would also like to thank my friends who assisted me in the field during the observations and measurements.

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