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Discussions

Rockfall hazard assessment along a road on Peloritani Mounts (northeastern Sicily, Italy)

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Abstract

A hazard assessment has been performed on rock slopes impending over a segment of the Taorminese Road, which connects two popular tourist destinations in northeastern Sicily: the urban centers of Taormina and Castelmola. The road crosses steep, rock slopes, with a complex geological and tectonic history. The section of the road close to Castelmola is often affected by rockfall phenomena, causing injury to people and serious damage to buildings and traffic. The study analyzes the geostructural setting of the unstable rock masses, by evaluating their mechanical properties and the kinematics of potential failures. Rockfall simulations confirm that falling rocks would involve the Taorminese Road with different kinetic energy rates and prove useful for suggesting the most suitable mitigation technologies for future remedial works. The modified Rockfall Hazard Rating System has been applied to highlight the different levels of hazard along the road. The compiled hazard map shows that the slopes need urgent remedial works, especially because Taorminese is the only access road to Castelmola and its interruption would lead to the isolation of the entire village.

1 Introduction

Instability of rock slopes is a public safety issue, especially when its effects involve important communication routes. The economic impact of rockfalls on roads is considerable, because they often lead to traffic disruptions or delays and require expensive remedial measures (Turner and Schuster, 1996; Uribe-Etxebarria et al., 2005). When communication routes are located in mountain environments, it is also hard to find alternative viable ways. Therefore, rockfall has been a serious threat in many mountainous areas in the world (Chau et al., 2003). The Taorminese Road (TR), a two-lane mountain road running from Taormina to Castelmola (6 km), northeastern Sicily (Fig. 1), is the case study of this paper. Taormina is a charming hillside town representing one of the most important tourist centers in Sicily; Castelmola, which probably used to be the Taormina acropolis, is a densely inhabited village of pre-Hellenic origin, counted among the “Most Beautiful Italian Villages” (Bacilieri, 2012). We have surveyed the TR segment closest to Castelmola (1.7 km long; between km 6+100 and km 7+800), where several rockfall phenomena have occurred in recent years, causing not only damage to man-made structures, but also isolating the village for prolonged periods (Ferrara and Pappalardo, 2005). Indeed, TR is the only access to Castelmola and so the only escape route in case of natural or human disaster. Its disruption would mean major setbacks not only from a tourist and economic point of view but also for relief purposes. It crosses rock and steep slopes, greatly affected by active tectonic and intense fracturing. These factors, as well as water infiltration and weathering, influence the slope stability in accordance with Crosta and Agliardi (2003), Dorren (2003), Jaboyedoff and Derron (2005), Michoud et al. (2012). A few portions of the slopes, bordering the surveyed road segment, have wire meshes or retaining walls, while other unprotected areas are periodically subject to rockfalls, which represent a risk to vehicles and people on foot. Indeed, the Italian Hydrogeological Basin Plan (P.A.I., 2006), whose function is to identify high hazard and risk areas and provide regulations and limitations for land use and development (Poretti and De Amicis, 2011), classifies the study area as a high rockfall risk zone.

This research deals with the rockfall hazard assessment carried out along the unprotected slopes, through the following steps: (1) collection of historical and recent rockfall information; (2) geostructural surveys; (3) rock and slope mass rating (4); kinematic analysis; (5) two-dimensional rockfall trajectory simulations; (6) application of the modified Rockfall Hazard Rating System (RHRS) (Pierson et al., 1990; Budetta, 2004).

2 Geology and seismicity of the study area

The study area lies in the Peloritani Mountain Belt, which geologically represents the southern part of the Calabrian–Peloritani Orogen (Atzori et al., 2003; Punturo et al., 2005; Cirrincione et al., 2012). It consist of a Hercynian metamorphic basement and a cover of Mesozoic–Cenozoic Units (Punturo et al., 2005), displaced by regional fault systems, oriented W–E NW–SE (Lentini et al., 2006) and NNW–SSE. These structures are the main cause of the frequent seismic activity of the study area (Scandone et al., 1981; Tortorici et al., 1986), classified by the Italian Ordinance n.3274/2003 as a category II area (medium-high seismic hazard). This is significant because the hazard of rockfalls is obviously higher in areas with intense seismic activity, where earthquakes are among the principal triggering factors (Marinos and Tsiambaos, 2002; Saroglou et al., 2012).

The stratigraphic succession of the study area (Fig. 2) is given by a Hercynian crystalline basement (Paleozoic), which is overlain by sedimentary rocks (Taormina Unit) (Catalano et al., 1995). The crystalline basement is represented by slates, belonging to a low metamorphic-grade complex with a schistose texture and a green color due to the presence of chlorite. The sedimentary cover consists of conglomerates and Triassic sandstones occurring in Verrucano facies (Dueé, 1969), greyish-white limestones and lower Liassic dolostones in carbonate platform facies (Lentini, 2006).

3 Rockfall history

Several rockfall phenomena have affected the whole territory of Castelmola, as well as the slopes impending over TR. Information on some of these landslides is available in the national databases of AVI (AVI Project, 1998) and P.A.I. (PAI, 2006). In 1952, the local daily newspaper La Gazzetta del Sud (as reported in the AVI database) published an article on landslide movements along the "only way of access to Castelmola" occurring after heavy rain. More recently, the most memorable documented events, which interrupted TR near the access to the village, occurred in 1996, 1997 and 1999, when a significant volume of rock from the NW slope, fell down (Ferrara and Pappalardo, 2005). With respect to the 1999 event, AVI database reports that a falling boulder involved a car, but no victims are mentioned. After these episodes, the NW cliff was consolidated by deep anchors, concrete retaining structures and drainage gullies at the base of the slope.

In 2006, a boulder of about 6 m^3 fell close to houses in the south-eastern sector (Fig. 3), prompting the municipal administration to perform urgent provisional works in order to install rockfall protection barriers behind the threatened houses.

In February 2012, two landslides occurred: the first overcame a retaining wall and invaded the road near a narrow curve; the second took place only 100 m away, destroying the wire mesh protecting the cliff (La Sicilia, 2012). During the night between 29 February 2012 and 1 March 2012, a further landslide affected TR and threatened the water pipeline serving Taormina (Tempo Stretto.it, 2012).

However, since many events are not mentioned in the chronicles, most of the information regarding past rockfalls has been passed on to us orally by local people. Furthermore, during the surveys we noticed a number of boulders on the TR roadside (average size 50 cm × 40 cm × 50 cm), recently fallen and then moved away from the roadway (Fig. 3), as well as several detached rocks lying on the downstream slopes, testifying to how often rockfalls occur in this sector.

4 Geostructural survey

Geostructural surveys have been performed, following ISRM (2007) recommendations, in 9 stations sited on dolostone (D-St), limestone (L-St) and slate (S-St) outcrops. They were undertaken on slopes that were not fitted with rockfall protection measures and with evident unstable blocks that might be involved in rockfall phenomena.

The structural setting of dolostones is characterized by the presence of 4–5 intersecting discontinuity sets, whose spacing ranges from 2 to 60 cm and openings from 0.1 to > 5 mm. Discontinuities are usually filled with sand or calcite and the joint surfaces are mostly smooth and undulating, with a Joint Roughness Coefficient (JRC) ranging from 2 to 12.

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With respect to the limestone outcrops, 4 discontinuity sets are recognizable. These have a spacing generally ranging from 6 to 32 cm, sometimes with higher values, but never exceeding 100 cm. Openings are often > 5 mm and filling is mostly absent in dry discontinuities, while it is soft or massive in wet ones. JRC is between 5 and 17.

Slate rock masses are pervaded by 3–4 discontinuity sets, with a 6–9 cm spacing, except for the set F2 (dip / immersion = 336/8) whose spacing is about 150 cm. Opening ranges from 0 to > 5 mm and no filling is reported, while JRC ranges from 1.3 to 9.5.

Geomechanical characterization of the surveyed rock masses has been performed in accordance with the classifications of Bieniawski (1989) and Romana (1985, 1988, 1991), in order to acquire information on the slope stability grade, the potential failure mode and the possible stabilization works. All the surveyed rock masses fall in the III Bieniawski class (“Fair Rock”), with RMRb ranging between 42 and 58; mean cohesion values range between 211 KPa and 288 KPa; mean internal friction angle varies from 26 to 34. With reference to the Romana classification (1985), L-St-2, S-St2 and S-St-3 are classified as “Good Rock” (SMR class II). The others fall in the III class (“Fair”) with SMR between 45 and 60 (Table 1).

5 Kinematic analysis

A kinematic analysis has been performed using the Markland Test (Markland, 1972), by analyzing the angular relationships between discontinuities and slope surfaces (Kliche, 1999), in order to determine the potential modes of failures among wedge and planar siding and non-flexural toppling. Graphically, the great circle of a slope face and the friction angle circle (ϕ) of the joint are plotted on a stereogram. The zone between the great circle and the friction circle is called “sliding envelope” (Yoon et al., 2002) and represents Markland’s wedge and planar failure conditions (grey areas in Fig. 4). Instead, the condition for toppling failures occurs only if the layers strike parallel to the strike of the slope (Adebimpe et al., 2011) but with an opposite immersion (red area in Fig. 4). The friction angle values considered here are those resulting from the Bieniawski (1989) rock mass classification discussed above (Table 1).

With respect to the surveyed outcrops, the main instability condition has been registered on dolostones (D-St1, D-St-2, D-St-3, D-St-4). The recognized modes of failure are planar sliding (along discontinuities whose orientation is nearly parallel to the slope (±20°) but with a lower inclination), wedge sliding (between two intersecting planes) and toppling (along discontinuities whose orientation is nearly parallel to the slope but with an opposite immersion). Limestone rock masses result stable, while on slates, wedge sliding and toppling are only possible at S-St-1 (Fig. 4).

6 Rockfall analysis

In order to assess if potential falling blocks could reach TR and to estimate their total kinetic energy, we have performed 4 rockfall simulations. Sections cross the poorest quality rock masses with evident unstable blocks (Fig. 5). For simplicity, TR has been divided into upstream (UP) and downstream (DW) segments. The major difficulty in modelling the behaviour of a rockfall event is characterising all dependent variables thoroughly, by no means a simple problem (De Almeida and Kullberg, 2011). Indeed, the relative movement of a falling boulder down a slope may depend on a series of variable factors: the rock lithology, the topography and inclination of the slope and the size and shape of the boulder (Schweigl et al., 2003) and it is impossible to forecast a rockfall trajectory accurately.

For the two-dimensional analysis of the motion of falling blocks, the calculation method proposed by Pfeiffer and Bowen (1989), who introduced it in the numerical code Colorado Rockfall Simulation Programm (CRSP), has been chosen. The numerical code considers a single rock block as a simple point with a mass and a velocity (Massey et al., 2006) and, in order to describe the rockfall dynamic, it applies the equation of the parabolic motion of a free-falling mass and the principle of total energy conservation (Ferrero et al., 2011). Blocks can have spherical, cylindrical or discoid shape, with a circular section in the vertical plane of the motion. The analysis considers the combined effects of free falling, rebound, rolling and sliding; the block impact is influenced by the slope roughness and the block size (Giani, 1997).

With respect to the block size, a 50 kg boulder (50 cm × 40 cm × 50 cm) has been considered, similar to the ones recently found on the Taorminese roadside (Fig. 3). Its initial velocity, although Paronuzzi (1987) and Azzoni et al. (1995) consider it negligible because of its very low value, was here estimated by taking into account the seismic conditions of the area, according to Antoniou and Lekkas (2010), through the Eq. (1)

$$v = \sqrt{2as} \tag{1}$$

where a is the ground acceleration, here assumed as 0.25 g (according to the Italian Ordinance n. 3274/2003), s is the distance between the rock fragment and the slope, produced by the seismic wave action.

The most difficult variables to define in this type of analysis are the coefficients of restitution (R_n: normal and R_t: tangential) of the slope materials (Richards et al., 2001; Asteriou et al., 2012), strongly influenced by the impact conditions (Paronuzzi, 2009).

The events occurring in the study area have never been studied and all their traces have been obliterated by time and anthropogenic activity. Therefore, in order to find the most suitable coefficient to the surveyed slopes, we have taken into account both a back analysis performed in a neighboring area and the coefficients of restitution retrieved from the published literature (e.g. Pfeiffer and Bowen, 1989; Giani, 1992; Robotham et al., 1995; Chau et al., 1998; Dorren and Seijmonsbergen, 2003; Massey et al., 2006; Budetta, 2010; Pantelidis and Kokkalis, 2011; Saroglou et al., 2012) (Table 2).

The simulation results show that in the AA′ and BB′ sections 85 and 71 % respectively of the falling rocks stop on a secondary road, which connects Castelmola to some private properties. The remaining 15 and 28 % reach the TR UP segment and rebound on the DW segment, which, however, does not represent the rockfalls end point. With respect to the BB′ section, 1 % of the blocks ends its run along the slope, before reaching TR (Fig. 6). On the steepest slopes (CC′ and DD′ sections), 100 % of the boulders initially impact on the UP segment, then, after one or two rebounds along the slope, reach the DW segment (Fig. 6).

Blocks move along the slope rolling and rebounding, depending on the slope inclination and the presence of vegetation or bare rock. Kinetic energy values vary with respect to the type of movement; indeed lower energy can be related to rolling blocks, while higher rates are released at rebounding points. In particular, kinetic energy estimated on TR ranges between 1.2 and 20.2 kJ with a modal value of 8 kJ.

7 Rockfall hazard assessment

The Rockfall Hazard Rating System (RHRS) is a semi-quantitative classification system, developed by the Oregon Department of Transportation (USA), to assess the hazard associated with rockfalls (Pierson et al., 1990; National Highway Institute, 1993; Scesi et al., 2001), in order to identify dangerous slopes that require urgent remedial works or further studies. The method was subsequently modified to make it more suitable to the geometrical features and to the traffic standards of the Italian roads (Budetta, 2004).

It consists in assigning a score to 9 categories concerning the rockfall hazard (i.e. slope height, geologic characteristics, volume of rockfall/block size, climate and presence of water on slope and rockfall history) and the vehicle vulnerability (i.e. ditch effectiveness, average vehicle risk, percent of decision sight distance, roadway width). The summation of all the assigned scores assesses the degree of exposure to the hazard along roads. If the RHRS final value is lower than 300, the remedial works on the slope will be considered “with low urgency”; whereas if the final score is higher than 500, the slope will need “immediate stabilization works” (Pierson et al., 1990). Slopes with intermediate scores are considered with “high priority of remedial works”, although a case-by-case evaluation would be appropriate (Budetta, 2004).

In this paper, hazard has been assessed at 12 measure stations, located on slopes with no protection measures (between km 6 + 250–6 + 500 and km 6 + 900–7 + 300) (Fig. 7), in both directions of travel. Each required parameter has been calculated by the equations proposed by Budetta (2004):

1. Slope heights are all greater than 30 m.

2. Average Vehicle Risk (AVR) ranges from 3.75 to 10 %, with assigned scores between 1 and 2 depending on to the hazard zone length (speed limit 40 km h^{-1}). AVR has been calculated considering a daily traffic of 2500 units (cars, motorcycles, bicycles and buses), estimated by traffic measurements conducted on a two-day survey between 10 a.m. and 6 p.m. This value includes a rate of tourist units, whose maximum peak is usually registered during summer and weekends, and the daily commuters traveling by car to and from Castelmola (Corriere and Russo, 2003).

3. Decision Sight Distance (DSD) ranges between 6.99 and 69.93 %, with minimum values measured close to the bends (reduced visibility) located in the DW segment. This parameter has the largest influence on the final score.

4. Slope Mass Rating values have been taken from the Romana classification performed on the surveyed rock masses (see Sect. 4).

5. Block size has been assumed as 50 cm, similar to the ones recently found on the TR roadside (Fig. 3).

6. Annual rainfall value is related to the period 1921–2003 (900 mm yr^{-1}), according to Assessorato Regionale per i rifiuti e le acque-settore Osservatorio delle Acque (2004).

7. 6 events per year have been assumed as the rockfall frequency, according to the information retrieved during our surveys.

The calculated final scores range between 280 and 773; the minimum value has been estimated at section 6 (km 7 + 60) toward Castelmola, while the maximum value at section 12 (km 6 + 250) in both directions of travel (Fig. 7). According to these scores, the UP segment is classifiable as a road with “high priority of remedial works” ($300 < \text{RHRS} < 500$), although there is a short portion, in the direction of Castelmola, “with low urgency” (RHRS < 300) and three bend portions with RHRS > 500. The highest hazard has been detected along the DW segment, where “immediate stabilization works” (RHRS > 500) would be needed. This difference is due to higher number of bends on the DW than the UP segment, which causes considerable changes in DSD, leading to higher hazard at low-visibility-points (bends).

8 Conclusions

Communication routes in mountainous areas are often affected by slope instability problems. A segment of the Taorminese Road (TR) has been studied with the aim of assessing the hazard connected to rockfall phenomena. TR is a road of strategic importance because it is the only route connecting Taormina to Castelmola, two important tourist destinations in northeastern Sicily. The final segment of TR, which leads to of Castelmola, has a long history of rockfalls that have at times isolated the entire village, hindering social and economic activities.

The performed study indicates that the intricate geological history of the area, as well as its seismicity, contribute to slope instability. Indeed, the geological formations have been displaced, during several tectonic stages, by different fault systems. The effects are clearly visible on the outcrops and the geostructural study highlighted that several discontinuity sets pervade the rock masses, which have mainly been classified as “Fair” by Bieniawski and Romana indexes. Kinematic analysis performed on 9 survey stations recognized planar and wedge sliding, as well as toppling, among the potential failures.

Rockfall simulations showed that falling boulders would reach both the upstream and the downstream segments of TR. It should be noted that, with respect to the considered sections, we have placed emphasis only on a 50 kg falling block, in accordance with the size of previously fallen boulders, without taking into account the mobilization of further material during the impacts along the slope.

Hazard analysis was performed using the modified Rockfall Hazard Rating System (RHRS), which classified the road portions between km 6+250–6+500 and km 6+900–

7 + 300 as a high rockfall hazard road. It is therefore clear that remedial works are needed in order to protect the carriageway. Considering the high degree of rock mass fracturing and the possibility of occurring failures, the installation of wire meshes and deformable rockfall barriers would be appropriate. In particular, wire meshes should be affixed to vertical, bare slopes in order to contain block detachments, while rockfall barriers should be placed as a protection fence of the upstream segment. The estimated values of total kinetic energy may be useful for their design and dimensioning. Furthermore, the presence of several boulders lying along the vegetated slopes testifies to how shrubs and trees may decelerate their rolling. Thus, planting shrubs along the slopes would be a suitable additional remedial work, in conjunction with barriers and wire meshes.

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Table 1. Rock masses classifications parameters.

Survey station	RMR_b	Bieniawski class	c' (KPa)	Φ' (°)	SMR	Romana class
D-St-1	42	III (Fair Rock)	211	26	45	III (Fair Rock)
D-St-2	57	III (Fair Rock)	284	33	55	III (Fair Rock)
D-St-3	54	III (Fair Rock)	269	32	47	III (Fair Rock)
D-St-4	49	III (Fair Rock)	246	30	49	III (Fair Rock)
L-St-1	54	III (Fair Rock)	268	32	60	III (Fair Rock)
L-St-2	58	III (Fair Rock)	288	34	67	II (Good Rock)
S-St-1	51	III (Fair Rock)	254	30	52	III (Fair Rock)
S-St-2	52	III (Fair Rock)	261	31	63	II (Good Rock)
S-St-3	56	III (Fair Rock)	282	33	66	II (Good Rock)

Table 2. Coefficients of restitution applied for rockfall simulations.

Authors	Material Type	R_t	R_n
Crosta and Agliardi (2003)	Outcropping Rock, bare	0.75 ± 0.0150	0.50 ± 0.0125
	Outcropping Rock, forested	0.70 ± 0.0140	0.50 ± 0.01
Schweigl et al. (2003)	Asphalt	0.90 ± 0.04	0.40 ± 0.04
Hoek (1987)	Asphalt roadway	0.90	0.40
Pfeiffer and Bowen (1989)	Bedrock or boulders with little soil or vegetation	0.83–0.87	0.33–0.37
Neighboring back analysis	Bare rock	0.9	0.7
	Rock debris	0.65	0.15
	Rock debris with vegetation and shrubs	0.53	0.15

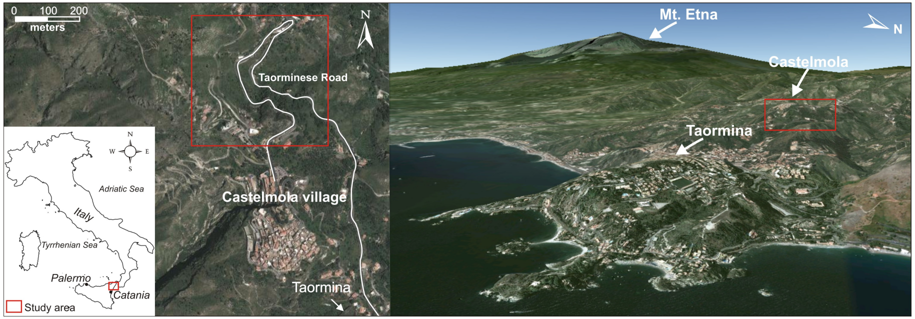

Fig. 1. Geographical location of the study area.

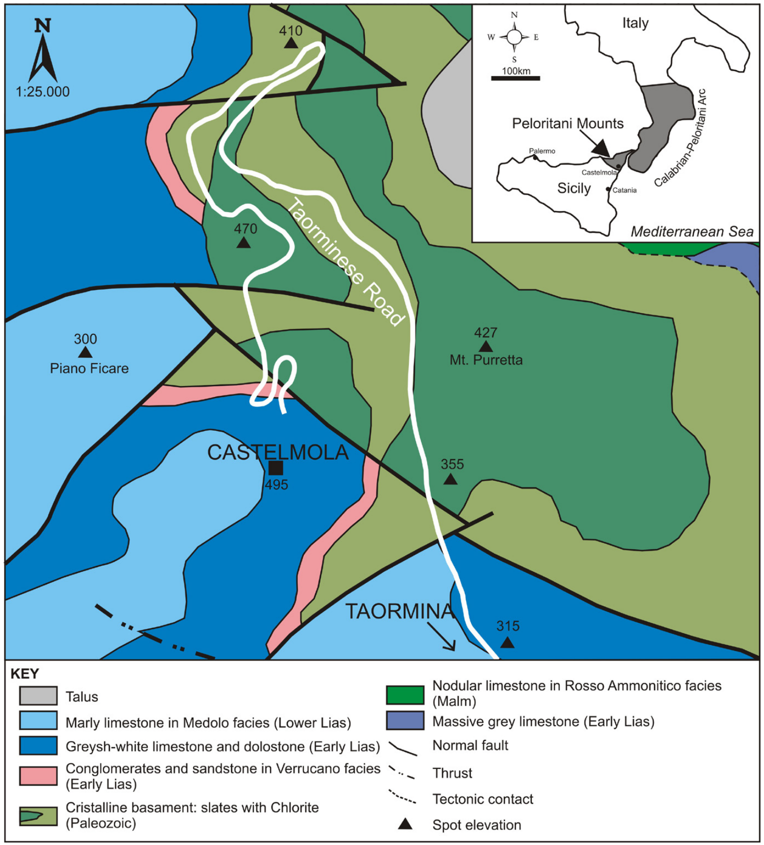

Fig. 2. Geological setting of the study area. White line indicates the surveyed TR segment.

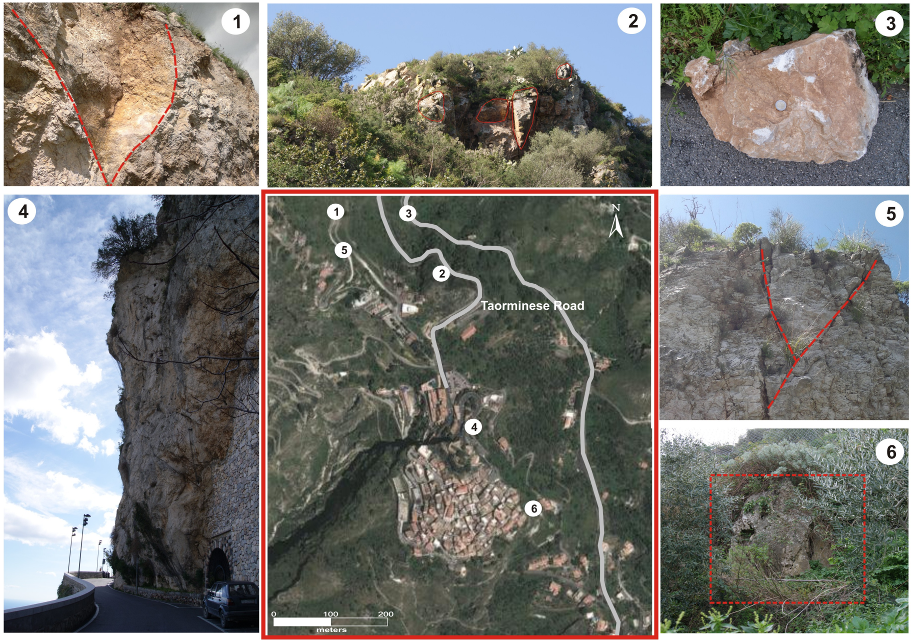

Fig. 3. Example of unstable areas and occurred events. Key: 1. wedge sliding already occurred; 2. unstable blocks projecting on TR; 3. one of the blocks found on the TR roadside; 4. cliff after consolidations works; 5. unstable wedge; 6. boulder fallen in 2006 close to some houses.

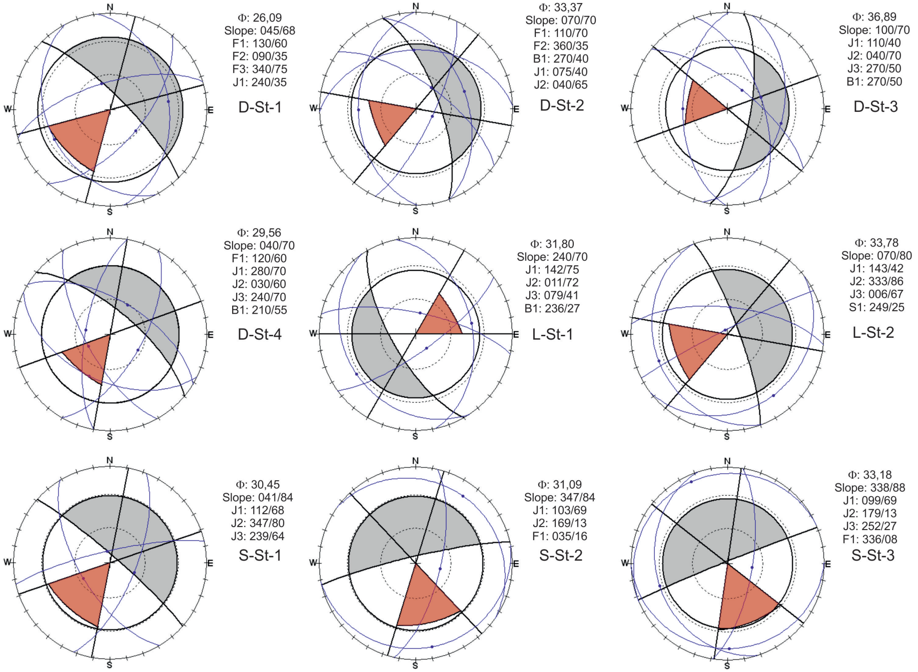

Fig. 4. Markland test stereographic projections. Grey areas represent wedge and planar failure critical area; red areas represent toppling failure critical area.

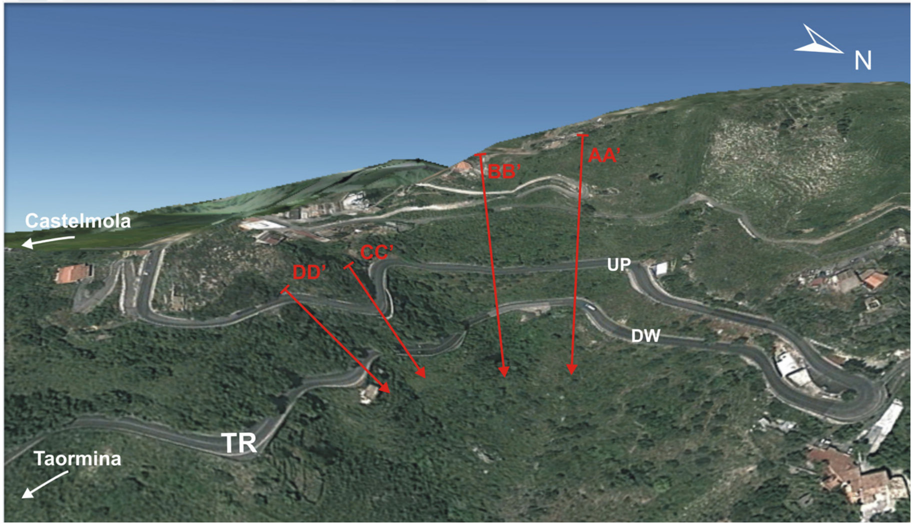

Fig. 5. Cross sections along the surveyed slopes.

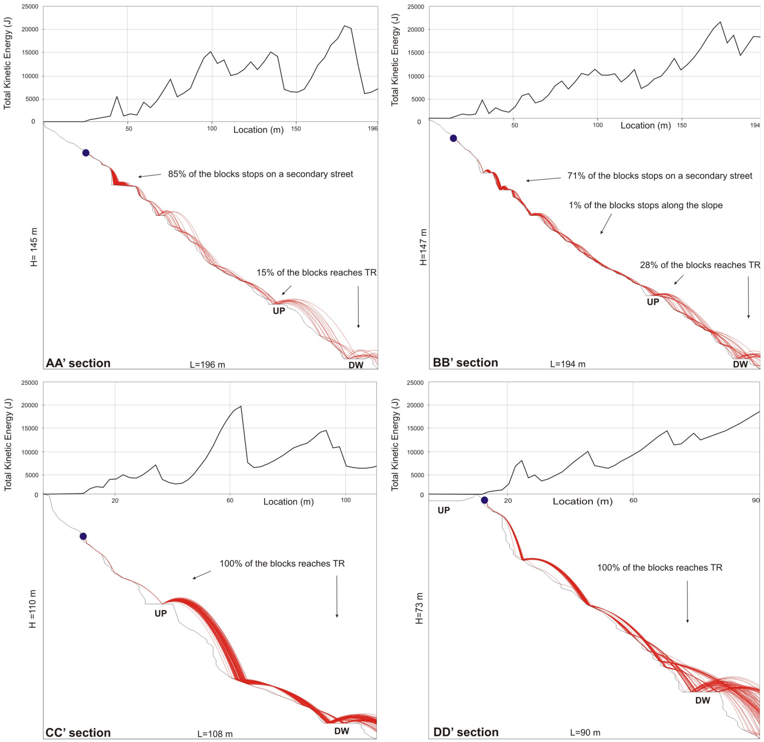

Fig. 6. Rockfall simulations and kinetic energy envelope. The blue circles indicate the detachment points.

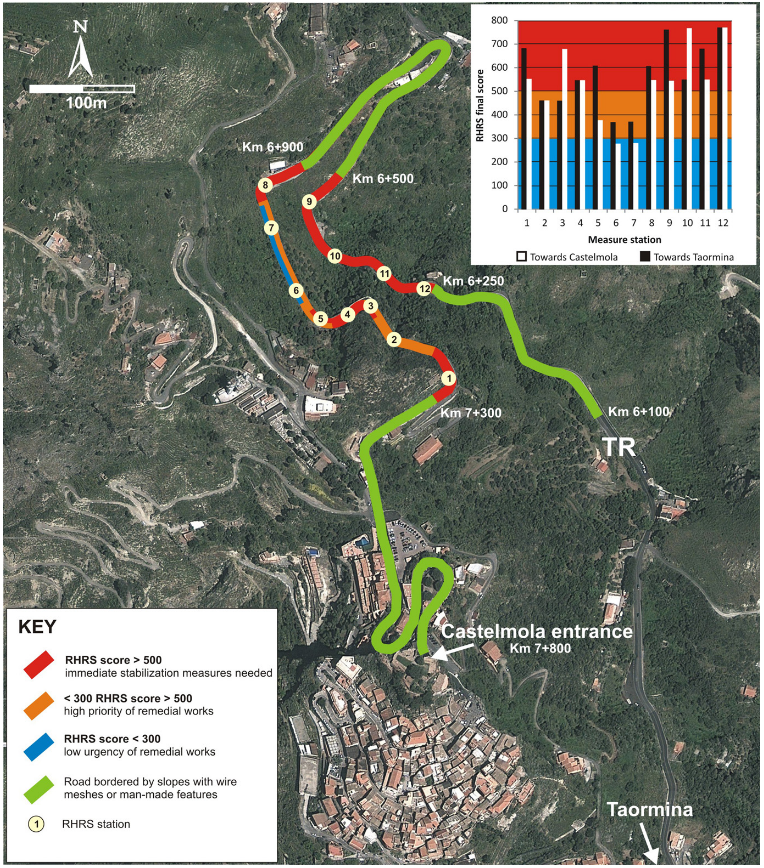

Fig. 7. Taorminese Road hazard distribution. The hystogram in the upper right corner shows the final RHRS scores for each measurement station.

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