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ORIGINAL ARTICLE

Slope Instability Processes Affecting the Pietra Di Bismantova Geosite (Northern Apennines, Italy)

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Abstract The Pietra di Bismantova, a vast biocalcarenite slab, is an impressive landmark and a unique feature in the gentle hilly landscape of the Reggio Emilia Apennines, Italy. It consists of a stratified calcareous rock type, rich in molluscs and other fossilised remains typical of a tropical climate. The site also has significant historical and cultural interests, including remains from Bronze Age and early Iron Age settlements. The perpendicular rock faces of the Pietra di Bismantova have for many years attracted rock climbers and hikers. Furthermore, the sheer calcareous walls are favoured sites for endemic plants and nesting of rare birds. Since the end of the last glaciation, the site has been subject to intense degradational processes affecting the rock slopes. Today, these pose serious problems for its conservation and the safety of visitors. The southern part is mainly affected by occasional rockfalls of varying magnitude. In contrast, the north-eastern part is much more jointed and dismembered and is subdivided into several loose blocks subject to slope movements with a complex style of activity. The results of a geomechanical and geomorphological survey are used to identify the area most prone to geomorphological hazards, particularly rockfalls. They show that the areas potentially most subject to landslides are the SE, NE and NW faces, where the rock parameters are poorest and degradational processes are particularly intense. Numerical modelling of rockfall phenomena indicates that the hazards are particularly high along the SE and W faces, where footpaths and climbing tracks are also located. Remedial measures should be introduced in these critical areas to stabilise the cliff and guarantee safe access for the numerous visitors to this geosite.

Keywords Geosite · Engineering rock classification · Rock fall hazard · Rock fall numerical modelling · Northern Apennines

Introduction

In the past two decades, numerous authors and research groups have investigated problems concerning the appraisal and conservation of geosites in relation to their value as cultural assets (Wimbledon 1990; Duff 1994; Poli 1999; Stanley 2002; Panizza and Piacente 2003; Piacente and Poli 2003; Reynard 2004; Piacente and Coratza 2005). Some of these sites are particularly important because they combine significant geological/geomorphological features and historical/artistic assets. This is the case of a vast biocalcarenite slab known as Pietra di Bismantova (Northern Apennines, Italy), which is important from both a historical and geological viewpoint. Since the end of the last glaciation, this unique landmark in the gentle hilly landscape of this part of the Apennine range (Fig. 1) has been subject to intense degradational processes affecting the rock slopes and posing serious problems regarding its conservation and safe access for visitors. The specific aim of the present

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Fig. 1 Aerial view of the Pietra di Bismantova geosite (summit altitude 1,047 m a.s.l.) from the NE. Mean geographical coordinates of the study area: 44°25′16″ latitude N; 10°24′43″ longitude E

investigation was to identify the most critical areas affected by active slope instability processes, with special reference to rockfalls, and propose adequate remedial measures, but with low environmental and visual impacts, in order to ensure the future conservation of this geosite and safe access to it.

Historical and Environmental Importance

The presence of early human settlements on Pietra di Bismantova is evident from remains of flint and ceramic artefacts ascribed to the late Bronze Age and the early Iron Age (eleventh to tenth centuries BC). In particular, in the north-eastern part of the site, a necropolis was found to contain various cremation burial sites. These ancient populations were probably in contact with settlements from Venetia and central Italy, and later gave rise to the Etruscan civilization. Also in Roman times, the area around Pietra di Bismantova was occupied by human settlements. The name “Bismantova” itself is derived from the Latin name “Castrum Bismantum”, as the village of Castelnovo ne' Monti was named in those days.

In the early Middle Ages, the area was conquered by the Longobards and, in the following centuries, it became part of the Canossa fief. In the eleventh century, Countess Matilda of Canossa built a stronghold on top of the cliff, of which nothing remains today. In the sixteenth century, the whole territory surrounding this geosite became part of the Estense possessions. At present, the only permanent human presence is a Benedictine monastery and chapel, dating originally from the Middle Ages but rebuilt in the eighteenth century (Fig. 2).

This geosite impressed the poet Dante Alighieri (1265–1321) who quoted it in his Divine Comedy.[1] It has also inspired several artists through the centuries (Fig. 3).

Interesting sedimentary structures and remains of sea-dwelling organisms, such as sharks and urchins, can easily be observed along the rock faces. Furthermore, its sheer walls are favoured sites for the growth of endemic plants and the nesting of rare birds.

In addition, owing to its perpendicular rock faces, the Pietra di Bismantova has long attracted rock climbers and hikers who, since the early twentieth century, have opened several climbing and bouldering paths and trails still in use today, with thousands of visitors each year.

Geological Setting and Structural Characteristics

The rock formations in the area adjacent to Pietra di Bismantova belong to the Ligurian thrust-nappe Units and the overlying Epi-Ligurian Units, here separated by tectonic boundaries (Fig. 4). The former, extensively cropping out around the northern and eastern margins of the slab, correspond essentially to the Argille Varicolori Formation (varicoloured clay shales of the Upper Cretaceous-Lower Eocene).

The Epi-Ligurian sequence is represented by the arenaceous and marly Ranzano (Upper Eocene-Lower Oligocene) and Antognola Formations (Upper Oligocene-Lower Miocene) and, finally, the biocalcarenites of the Pantano Formation (Mid-Lower Miocene) belonging to the Bismantova Group. The latter, which makes up the Bismantova relief, is composed of massive arenaceous limestones, often showing cross-bedding, with properly stratified limestones towards the top (Gelmini 1990; Conti and Tosatti 1994; Papani et al. 2002).

The longitudinal section of the slab (Fig. 5) shows two central areas that have been lowered along antithetic joints, forming wedge-shaped rocky masses. These features, typical of competent slabs overlying shaly clayey bedrock, are designated in the literature by the term “trench” (Fig. 6) (Pasuto and Soldati 1990).

The morphological depression located in the northern portion of the slab (Figs. 5, 7) defines two clearly distinct parts. The southern part has a tabular shape (rectangular in plan view) and describes a mild syncline with the axis directed towards the slab's western margin. This part is mainly affected by two systems of subvertical joints: one with a N 220°–250° strike and the other with a N 130°–160° strike.

[1] Dante described his ascent to the mount of Purgatory, comparing it to the steep trail going up Pietra di Bismantova: *A man may climb to San Leo or down to Noli or to Bismantova’s height on foot, but here a man must fly – I mean upon the urgent wings of great desire, led by the one who gave me hope and light* (Purgatory, canto IV).

Fig. 2 The chapel and monastery at the foot of the rock wall are typical historic assets of Pietra di Bismantova

Two other minor joint systems show orientations of about N 340°–350° and N 80° (Fig. 7).

The slab's arc-shaped portion extending to the north of the second main trench is much more jointed and dismembered than the tabular part, and is subdivided into several loose blocks, progressively lowered to the north and ending in a heap of large boulders (NE extremity). All fractures are open, with apertures that become very wide towards the slab's eastern margin.

The differences between the arcuate and tabular portions are not due to morphological and structural factors alone, but primarily to the geological characteristics of the bedrock underneath Pietra di Bismantova. These two portions are separated by a fault which displaces the boundary between the Epi-Ligurian Sequence and the varicoloured clay shales formation (Fig. 7). The latter make up the ductile substratum underlying the slab's arcuate portion, whereas the tabular portion rests entirely on the more competent Epi-Ligurian Sequence of the Ranzano-Antognola formations.

Geomorphological Evolution

From a morpho-structural standpoint, Pietra di Bismantova is an example of a *mesa*, whose summit corresponds to a lithologic-structural surface that developed in morphoclimatic conditions different from the present steady weathering regime (Bartolini and Peccerillo 2002; Tosatti 2004). In fact, all the area surrounding Pietra di Bismantova has been affected by considerable climatic changes since the end of the last glaciation, which first led to the formation of *glacis*-type slope deposits (Gruppo di Studio 1976) and subsequently to the development of vast landslides (Figs. 4, 7). In this area, due to the particular geological and morphological features of the Pietra, almost all landslide types (Cruden and Varnes 1996) are represented. In particular, it is clear that all these mass wasting process are strictly interrelated and control the evolution of the whole slab.

The larger landslides can generally be described as slow-moving and deep-seated landslides of the complex slide-flow type (Cruden and Varnes 1996; i.e. multiple rotational and rotational–translational slides at the crown, associated with earth slides and flows in the lower sector of the slopes). These landslide bodies are considered remnants of more severe climatic periods, but in spite of their ancient origin, they cannot be classified as inactive or relict. At present, periods of dormancy lasting between 10 and 100 years, alternate with reactivation events followed by periods of activity of varying duration. It has been suggested that within the present morphoclimatic context, the reactivations are connected to hydrogeological factors (Bertolini and Pellegrini 2001). When a total reactivation occurs, the first movements are large rotational slides in the source area that cause a regression of the main scarp and subsequent undermining of the rock cliffs. The landslide body can reach a state of plastic consistency, thus producing earth-flows moving downslope with displacement velocities that in some cases may be classified as rapid, according to WP/WLI 1993. A total reactivation is usually catastrophic for property, buildings and roads. Most reactivations are partial and less dangerous. In such cases, the velocity is usually very slow, and infrastructure and

Fig. 3 Altar-piece depicting the Pietra di Bismantova in the background (*circle*), by Francesco Bianchi Ferrari (1460–1510), now displayed at Galleria Civica in Modena

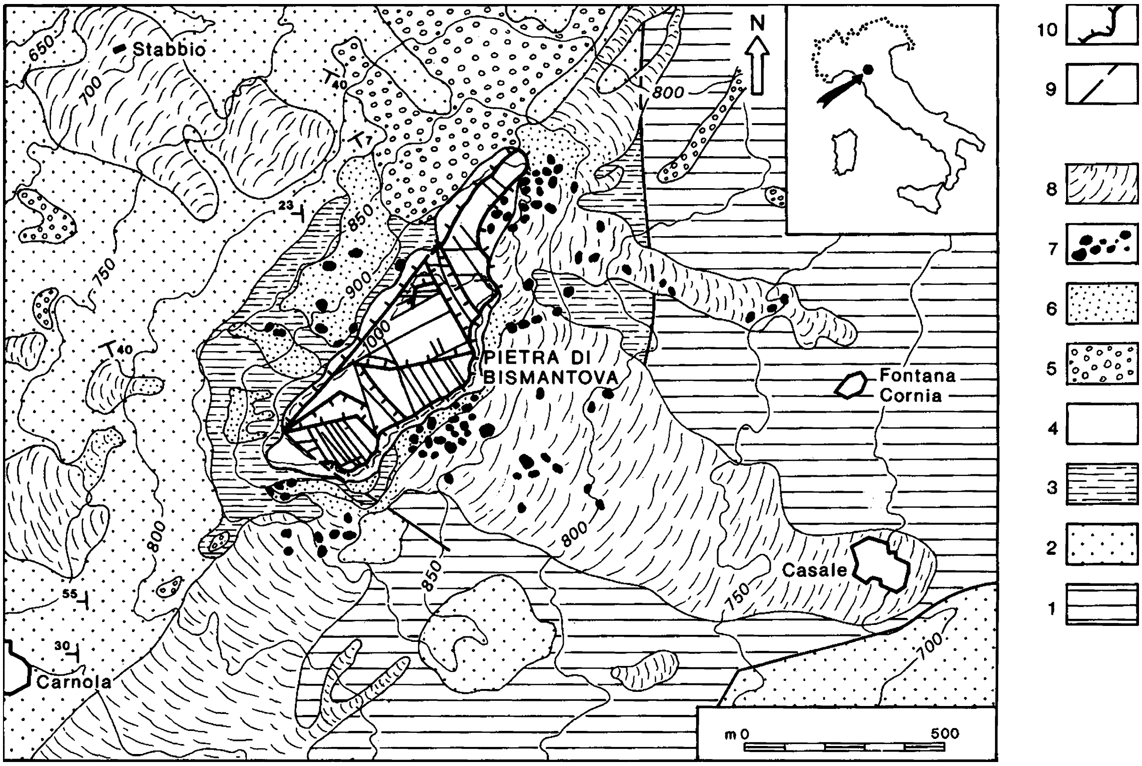

Fig. 4 Geological map of the study area: (*1*) Argille varicolori Formation (Upper Cretaceous-Lower Eocene); (*2*) Ranzano Formation (Upper Eocene-Lower Oligocene); (*3*) Antognola Formation (Upper Oligocene); (*4*) Pantano Formation-Pietra di Bismantova Member (Mid-Lower Miocene); (*5*) Coarse slope deposits; (*6*) Fine slope deposits; (*7*) Scattered rock blocks; (*8*) Earth flows–earth slides; (*9*) Joints and normal faults; (*10*) Overthrusts and reverse faults

villages lying on the active landslide body may be subject only to limited damage.

Apart from large but slow landslides, that pose a relatively low hazard to the elements at risk, the rocky cliffs are subject to lateral spreads, topples and falls (Cruden and Varnes 1996). These have caused large amounts of material to accumulate at the foot of the slopes (from large boulders with volumes up to 10^3 m^3 to small blocks) that can in turn be mobilised by earth slides and flows (Figs. 4, 8). Among these slope instability phenomena, rockfalls are the most hazardous in terms of intensity. In fact, even if their magnitude can be very low (fragmental rockfalls with volumes even much lower than 10^2 m^3), the sudden nature of the rockfall and its velocity can create a high hazard, especially to people present at the foot of the cliff.

Investigation Methods

Initial investigations were carried out by means of field surveys in order to evaluate the extent of unstable areas, the

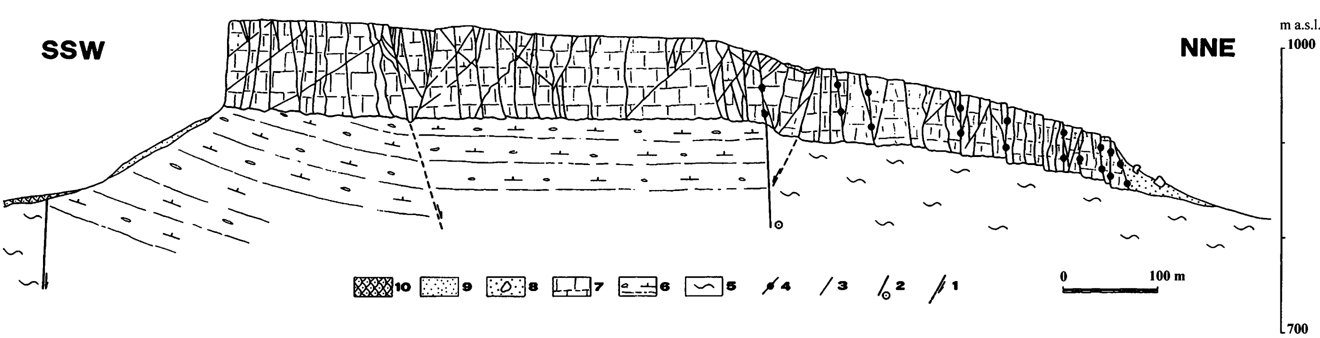

Fig. 5 Longitudinal section of Pietra di Bismantova: (*1*) Normal faults; (*2*) Transcurrent faults; (*3*) Main joints; (*4*) Open joints; (*5*) Varicoloured clay shales; (*6*) Antognola Formation; (*7*) Pantano Formation of the Bismantova Group; (*8*) Calcarenite boulders; (*9*) Slope debris; (*10*) Earth flows with scattered boulders

Fig. 6 The south-eastern face of Pietra di Bismantova showing the central lowered trench. Note the large boulders at the foot of the slope

volume of the material involved in mass movements, and to identify the most frequent failure mechanisms.

For assessing the geomechanical characteristics of the biocalcarenites making up the Bismantova cliff in relation to its proneness to instability processes, the modified Rock Mass Rating (RMR) system (Bieniawski 1989, 1993) was used, relating its parameters to the Q-System (Barton et al. 1974). These classification systems are based on semi-quantitative measurements and observations concerning the strength of the rock and the density and space orientation of its joints, such as roughness coefficient, spacing, separation, alteration, presence of groundwater etc. A numerical coefficient is attributed to each parameter and the corresponding rating is determined.

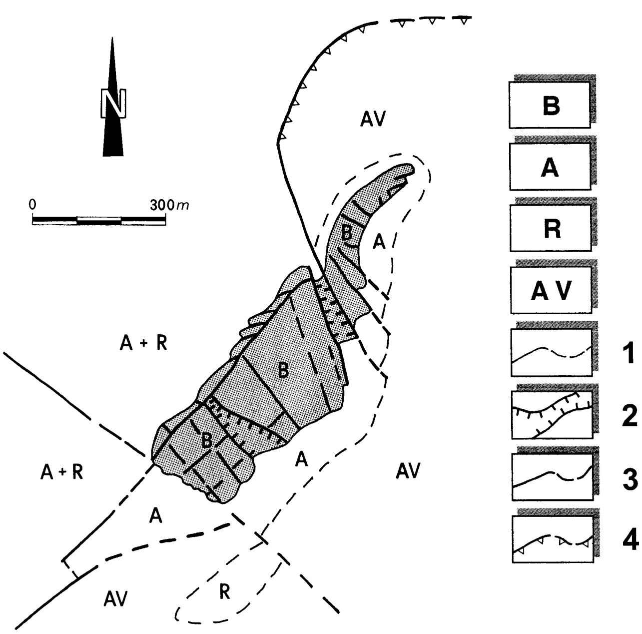

Fig. 7 Structural sketch of Pietra di Bismantova: *AV* Varicoloured clay shales (Upper Cretaceous); *R* Ranzano formation (Upper Eocene-Oligocene); *A* Antognola formation (Upper Oligocene-Lower Miocene); *B* Pantano formation of ismantova group (Middle Miocene); *1,* formational boundaries; *2,* trenches; *3*, normal and transcurrent faults; *4*, overthrusts and reverse faults

Geomechanical data were collected from ten different areas corresponding to significant points and structural regions on the cliff's walls, with reference to slope instability processes. Analyses and measurements carried out on the rock outcrops were preceded by bulk unit weight (γ) determinations on some biocalcarenite samples, in order to include this parameter in calculating the uniaxial compressive strength by means of Schmidt hammer measurements (Paganelli 2005).

The topography of the area and a number of relevant profiles were obtained from a High-Resolution (HR) airborne laser survey (airborne Light Detection And Ranging—LiDAR), with the construction of a filtered Digital Elevation Model (DEM). The survey was carried out by means of a helicopter-mounted Optech ALTM 3,100 laser scanner system, which is able to record up to four return echoes. Range measurement frequency was set to 50 kHz in order to balance the density of survey points with noise. The laser beam divergence is 0.2 mrad, resulting in a footprint of 0.17 m. At an average flight altitude of 800 m,

Fig. 8 Earth flows from the north-eastern arcuate slope. The blocks originate from rockfalls associated with the breakdown of the rocky cliffs as a consequence of lateral spreading and toppling

the acquisition parameters allowed a data density of about 3 to 4 points/m^2 to be obtained. Processing of on-board global positioning system and inertial measurement unit data yielded positional accuracy of 0.5 m in easting and northing and of 0.15 m in elevation. Geocoded laser points were classified and filtered using TerraScan software (Terrasolid 2005) in order to retrieve only those points that were associated with bare ground reflectors. The DEM was generated as grids of 0.5-m cell size using the triangulation with linear interpolation method, with anisotropy parameters ratio equal to 1 and angle equal to 0. This method is based on the algorithm presented in Guibas and Stolfi (1985). The HR-DEM was used to generate the profiles for 2D mathematical modelling as the detailed representation of the vertical cliffs in the existing technical cartography at 1:5,000 scale, which was not accurate. Moreover, the technical map dates back to the 1970s and in some areas the topography has changed significantly, as shown by the comparison of maps, aerial photos and DEMs.

The computer programme RocFall® was used to investigate the rockfall phenomena occurring on Pietra di Bismantova cliffs in order to forecast the runout, velocities, bounce heights and possible impact energy on the defence barriers. RocFall® is a commercial 2D modelling code designed to assess rockfall hazard (Rocscience 2002, 2003, 2004). The software performs rockfall simulations along user-defined topographic profiles, adopting a hybrid approach. In particular, RocFall® implements a lumped mass approach to model the free fall and the rolling phases of a rockfall, and a rigid body approach to model the impact of the boulder on the ground surface. RocFall® requires coefficients for the dynamic rolling friction, and for normal and tangential energy restitution to simulate the loss of energy during rolling and bouncing phases. To account for uncertainties in the definition of the input parameters, stochastic variability is used, specifying a standard deviation for some of the parameters (slope points and coefficients). Along the user-defined profile, RocFall® can calculate the bounce height, the velocity and energy and the run out. To obtain the rockfall energy, starting from the rockfall velocity, the volume and the unit weight of the boulder have to be specified. The results of the modelling, including the statistical distributions of the abovementioned parameters, are available as text, figures, graphs and tables.

The profiles were located in relation to the structural regions identified by means of geomechanical survey and taking into account the paths of antecedent rockfalls.

Geomechanical Characterization

After field surveys, the rock mass was characterised and the parameter ratings attributed in order to produce a clear and detailed picture of the overall mechanical conditions. The final results of the Rock Mass Rating system are presented in Table 1, giving the average ratings for each of the six parameters listed above measured at each of the ten areas. These ratings were then added together to give a value of RMR. This classification takes into account the influence of joint orientation which, in most cases, is unfavourable to stability conditions and is expressed by a negative number (average −10 in this case). The resulting average RMR value is 51, which corresponds to a “fair rock” (fair=41 to 60).

In Table 2 the ratings of each station are reported. Those that display a higher proneness to rockfall are numbers 5 and 10, on the eastern part of the Pietra, with poor rock mass quality. At the same time, even if it is characterised by fair to good rock mass conditions, the area from stations 2 to 4 is particularly interesting from the risk viewpoint owing to the presence of the hiking trail, the monastery and a large number of climbing and bouldering tracks.

Measurements of orientation allowed joints to be classified into six discontinuity families according to their attitude (Table 3 and Fig. 9). The intersection of these six joint families divides the Bismantova slab into numerous blocks which are affected by gravitational tensile stresses, leading eventually to wedge failures, rock slides and subsequent rockfalls.

In addition, rock mass cohesion (c_{M}) and friction angle (φ_{M}) were estimated by direct relationships (Bieniawski 1989):

$$c_{\mathrm{M}} = 5 \times \mathrm{RMR} = 0.25\ \mathrm{MPa}$$
$$\varphi_{\mathrm{M}} = 5 + (\mathrm{RMR}/2) = 30.5^{\circ}$$

with average bulk unit weight (γ)=25.02 kN/m^3.

Similarly, the Q-Index (Barton et al. 1974) was calculated by applying the following relation:

$$Q = \frac{\mathrm{RQD}}{\mathrm{Jn}} \times \frac{\mathrm{Jr}}{\mathrm{Ja}} \times \frac{\mathrm{Jw}}{\mathrm{SRF}}$$

where RQD is the Rock Quality Designation (as previously defined)

- J_n is the joint set number (systems of joints in the rock mass: 0.5 to 20)
- J_r is the joint roughness number (joint roughness: 0.5 to 4.0)
- J_a is the joint alteration number (degree of weathering: 0.75 to 20)
- J_w is the joint water reduction factor (0.05 to 1.0)
- SRF is the stress reduction factor (fault zones intersecting rock faces: 1.0 to 1.5)

In particular, the first quotient (RQD/J_n), representing the structure of the rock mass, is a crude but fairly realistic measure of the rock block size. In this case, the average volume of the blocks can be estimated in the order of 1 m^3.

Table 1 Total average ratings of RMR parameters from ten structural regions at Pietra di Bismantova, according to Bieniawski 1989

Average values of the RMR system determined from total ratings

Index	Parameter		Description	Value	Unit	Rating	Rating range
1	Uniaxial compressive strength		Moderate	52	MPa	7	4 to 7
2	Drill core quality RQD		Moderate	55	%	13	3 to 8
3	Spacing of discontinuities		High	0.6 to >2	m	16	15 to 20
4	Condition of discontinuities	Persistence	Medium	1 to 10	m	3	2 to 6
		Separation	Moderate-wide	1 to >10	mm	1	0 to 4
		Roughness	Rough	12	–	5	3 to 6
		Infilling	Cohesionless	<5	mm	2	2 to 6
		Weathering	Low to high	–	–	3	1 to 5
5	Groundwater conditions		Damp	0 to 0.1	l/min	11	7 to 15
6	Joint orientation		Unfavourable	–	–	−10	−5 to −15
Total	RMR value		"Fair rock"	III	–	51	36 to 66

The second quotient (J_r/J_a) represents the roughness and frictional characteristics of the joint walls or filling materials, whereas the third quotient (J_w/SRF), which can be regarded as a total stress parameter, is in this case equal to one (Table 4).

The resulting average Q-Index is 6.87 which, also with this method, corresponds to a "fair" quality rock (fair=4 to 10).

Starting from these results, the numerical modelling of rockfall runout was also carried out along several sections of the Bismantova cliff in order to obtain a preliminary assessment of rockfall hazard and to evaluate whether this geosite required particular stabilisation interventions, considering also the rockfalls occurring in recent times and the associated risk conditions.

Rock Fall Modelling

Rock falls can be considered one of the major hazards along both natural and engineered slopes, and can directly threaten lives, settlements and infrastructures. Rock fall processes typically involve limited volumes (Rochet 1987; Hungr and Evans 1988; Hungr and Evans 1989; Cruden and Varnes 1996) but at the same time are characterised by high energy and mobility. As a consequence, rockfalls are one of the main causes of landslide fatalities worldwide (Guzzetti et al. 2005).

Rock falls can be triggered by a large variety of causal factors, including earthquakes (Kobayashi et al. 1990), rainfall and physical, mechanical or chemical weathering of rock masses (Matsuoka and Sakai 1999). Static and dynamic stress conditions, rock mass strength and the mechanical and hydraulic conditions of discontinuities may also play a major role as preparatory factors.

Rock falls have been subdivided into four categories on the basis of their volume (Rochet 1987): single block falls (involved volume ranging between 10^{-2} and 10^2 m^3), mass falls (10^2 to 10^5 m^3), very large mass falls (10^5 to 10^7 m^3) and mass displacement (over 10^7 m^3). If the involved volume is less than 10^5 m^3, some researchers use the definition of fragmental rockfalls, specifying also that these phenomena are characterised by null or negligible interactions among the falling blocks (Hungr and Evans 1989; Evans and Hungr 1993). The evolution in space and time of fragmental rockfalls depends on the interaction among the falling block and the slope, which can be inherently

Table 2 Ratings of RMR parameters from each of the ten structural regions at Pietra di Bismantova, according to Bieniawski 1989

Geomechanical station	RMR value	Description of rock mass
1	55	Fair rock
2	54	Fair rock
3	43	Fair rock
4	66	Good rock
5	36	Poor rock
6	42	Fair rock
7	51	Fair rock
8	50	Fair rock
9	61	Good rock
10	37	Poor rock

Table 3 Average strike–dip values of the six joint families identified

Family	Strike–dip
1	N220°/90°
2	N250°/85°
3	N140°/90°
4	N170°/90°
5	N345°/85°
6	N80°/85°

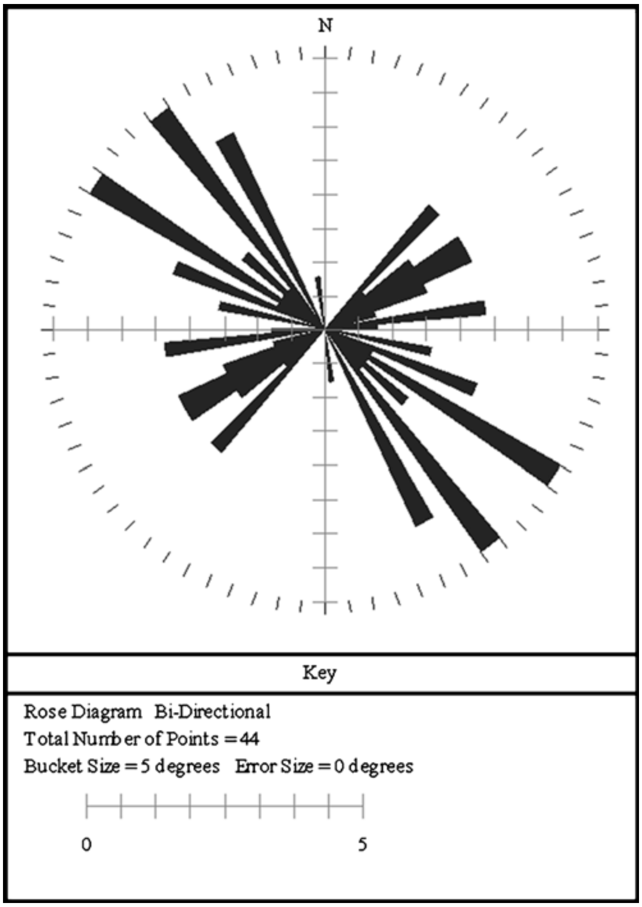

Fig. 9 Rose diagram of the six joint families identified

variable. In particular, trajectories and energy depend on the geomechanical properties of the falling block and the slope materials, the size and shape of the block, the slope geometry from the source area to downslope at the macro-, meso- and microscales and on 3D effects.

Rockfall modelling is part of hazard and risk assessment for land planning and civil protection purposes in areas prone to rockfalls. It allows the calculation of trajectories, maximum runout distance and distribution of kinematic parameters along the path and the probability for a specified location to be reached by blocks. Modelling can be performed with different degrees of complexity, ranging from empirical relations to dynamic models in two and three dimensions (see Dorren et al. 2007 and Frattini et al. 2008 for comprehensive reviews of the different methodologies). It is clear that 3D modelling captures the complexity of rockfall phenomena, allowing the interaction of blocks and slope and lateral dispersion to be described in detail. However, considering the specific features of the study site and the aim of the study, a 2D modelling strategy was chosen.

In particular, as far as the 3D dispersion of rockfall trajectories is concerned, in the case of the relatively short and very steep slopes, with very few channels and concavities found at Pietra di Bismantova, the lateral dispersion effect should be expected to be low, less than 15% according to Agliardi and Crosta (2003). Therefore, 2D models with a subjective choice of the most probable rockfall paths, based on geomorphological evidence, are acceptable and have been used in the preliminary assessment of rockfall hazard. Rockfall modelling was carried out on ten relevant paths, considering only single-block falls with a volume in the order of 1 m^3, as assessed by means of geomechanical characterization (Tagliavini et al. 2009). The topographic profiles are shown in Fig. 10.

A material coefficient of restitution can be separated into two components: a tangential coefficient of restitution (Rt) and a normal coefficient of restitution (Rn). The tangential coefficient defines the ratio of the outgoing velocity (tangential to the surface) to the incoming velocity (tangential to the surface). The normal coefficient defines the ratio of the outgoing velocity (normal to the surface) to the incoming velocity (normal to the surface). The tangential coefficient of restitution is generally equal to or larger than the normal coefficient of restitution. The friction angle is chosen on the basis of the particle shape and mode of movement. In general, lower values are more conservative (i.e., the rocks will tend to move farther downslope and provide the worst case scenario). In the simulation, empirical contact functions (Pfeiffer and Bowen 1989) are used and expressed as restitution and friction coefficients that can be calibrated using literature, in situ testing and historical data.

The option “Calculate friction angle from Rt” provides a method of defining the friction angle in terms of the coefficient of tangential restitution.

The coefficients of rock outcrops and vegetated slopes, as observed along each profile, were set on the basis of available literature for similar geological settings (Rocscience 2002; Del Maschio et al. 2004; Lombardi et al. 2006; Del Maschio et al. 2007) and by means of back analysis procedures and in situ testing in areas with similar geological and geomorphological characteristics. The coefficients are listed in Table 5.

Table 4 Total average Q-system parameters, according to Barton et al. 1974

Parameter	Value
RQD	55
J_n	6
J_r	3
J_a	4
J_w	1
SRF	1
Q-index	6.87

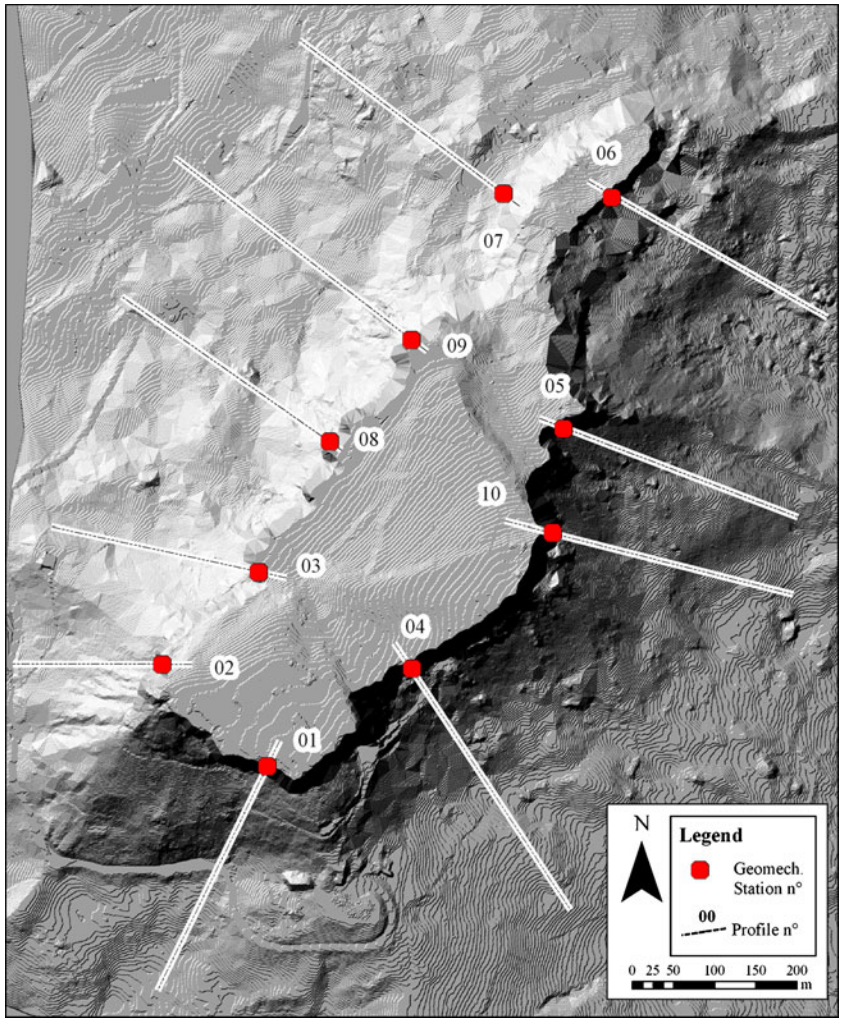

Fig. 10 Shaded view of the HR DEM of the Pietra di Bismantova. The map shows the location of the ten structural regions surveyed and the profiles investigated with numerical modelling

The normal scaling factor was applied to account for the decrease in normal coefficient of restitution as the impact velocity increases. This factor represents a transition from nearly elastic conditions at low velocities to highly inelastic conditions caused by increased fracturing of the rock and cratering of the slope surface at higher impact velocities.

Line seeders covering the whole length of the cliff were used as source areas and to specify the initial conditions of falling rocks. Note that 1,000 rocks were released during each trial. Each of the initial conditions (position/location, mass and velocity) was specified with a normal probability distribution. The initial velocity was set at 2.5 m/s, with a standard deviation of 2 m/s to account for all the possible velocities for rockfalls initiated as rock slides over pre-existing discontinuities (Giani 1992, 1997). The friction angle of the massive arenaceous limestones of the Pantano Formation was set at 30°, as estimated by geomechanical characterization, and the velocities are representative of sliding along planes from 0.1 to 2-m long, with inclinations of 31° to 60°.

Table 5 Parameters used in the simulation. Rn=coefficient of normal restitution; Rt=coefficient of tangential restitution

Material	Rn	Rt
Bedrock outcrops	0.41±0.04	0.85±0.04
Vegetated slope	0.30±0.04	0.40±0.04

A unit weight of 2,500 kg m^{-3} was used to calculate the energy, as measured by means of laboratory tests.

The output of the modelling yielded relevant results for eight profiles (Fig. 11). Profiles 06 and 07, because of the geometry of the slope, produced relatively low rockfall susceptibility. On profiles 01, 02, 04 and 10, the probability that a block can reach the foot of the cliff appears to be higher. Therefore, the SW and E area have to be fully investigated in order to assess rockfall hazard.

The numerical results of the modelling are shown with reference to profile 04 (Fig. 12), which is the most relevant

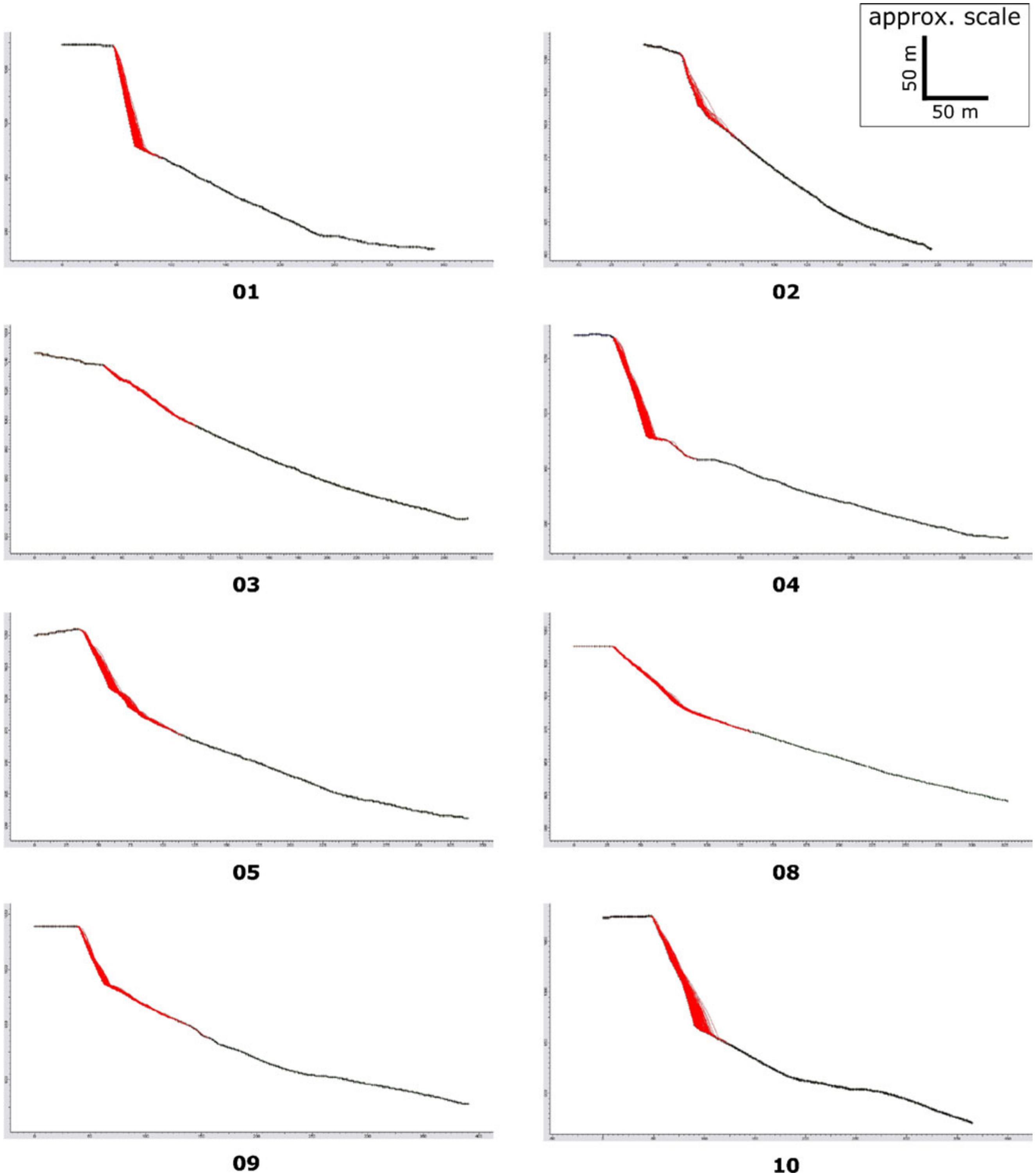

Fig. 11 Results of the numerical modelling on profiles 01, 02, 03, 04, 05, 08, 09, 10. The outputs are based on 1,000 single blocks with volumes in the order of 1 m^3 thrown along the entire cliffs. On the geometry of the profile, the single trajectories of the fallen blocks are represented with *red coloured lines*

in terms of risk conditions, as the footpath leading to the monastery and the monastery itself are located right at the foot of the cliff. The results show that the maximum bounce height along the entire profile is 22 m, with total kinetic energy higher than 1,800 kJ. The maximum runout is 110 m from the starting point of the profile, which is 45 m from the foot of the slope. Ninety-nine percent of the rocks thrown from the cliff fall within 15 m from the foot of the

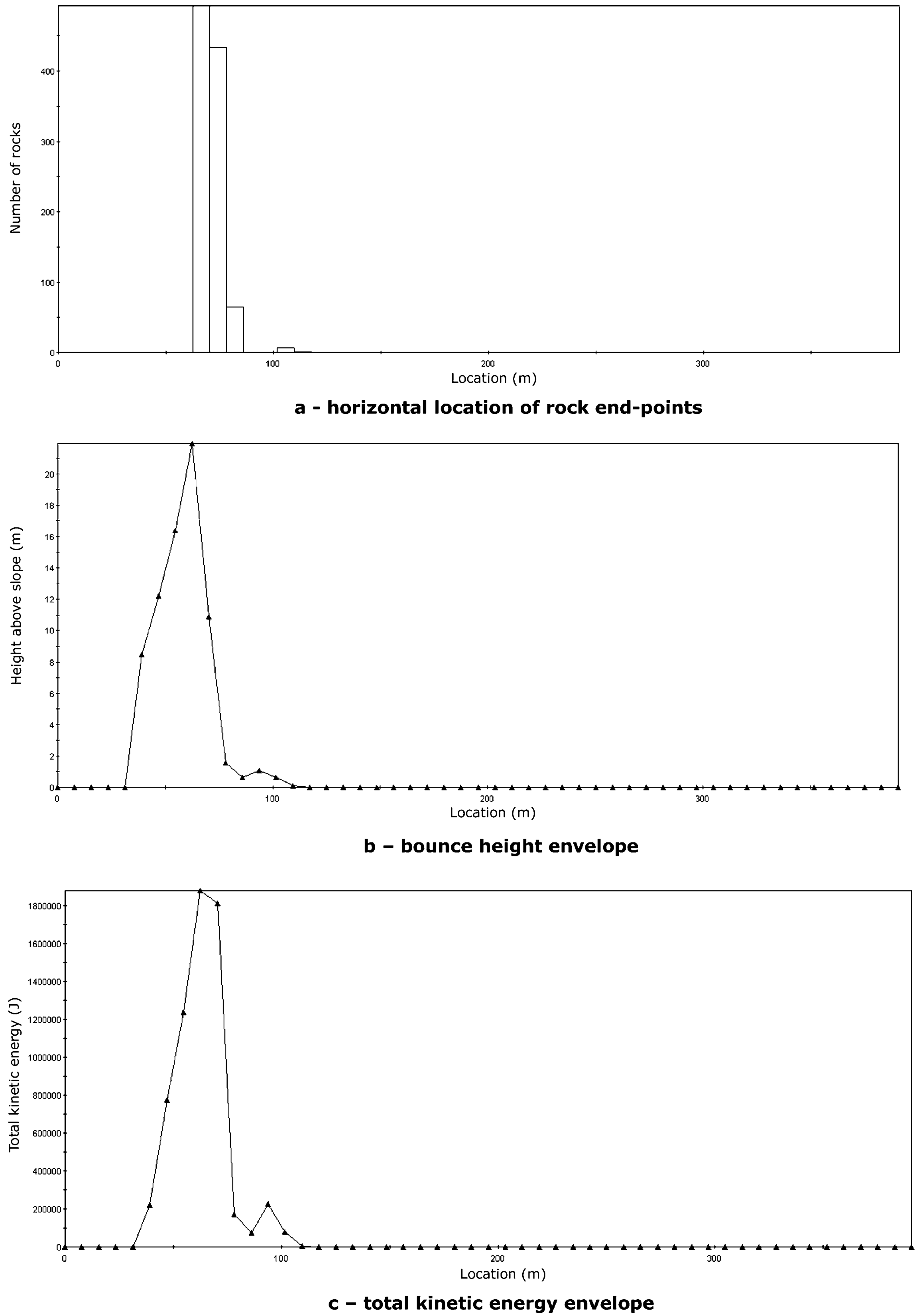

Fig. 12 Results of the numerical modelling on profile 04. The outputs are based on 1,000 rocks thrown along the entire cliff: **a** runout; **b** bounce height with reference to the slope; **c** total kinetic energy

slope, mainly thanks to the presence of the tree-covered area (Fig. 12). Therefore, due to the morphology of the rock wall, the footpath at the foot of the slope can be affected by falling blocks. It is clear that besides the relocation of the footpath and the trimming of unstable blocks, passive protection measures such as barriers and structural tunnels could be implemented along some specific tracts.

Site Management Implications

In general, geoheritage management of a site includes:

- documentation of its past and present condition;
- evaluation of conservation issues in the frame of its geomorphological evolution, including risks and impacts;
- eventual completion of different types of measures, both structural and non-structural.

This procedure is essential for site managers and planners, in order to cooperate with and support public administrations to ensure long-term conservation goals and safety for visitors.

In this context, the assessment of landslide risk and its mitigation in cultural and natural heritage sites is among the main goals of the International Consortium on Landslides and one of the most important topics of the International Programme on Landslides (Sassa 2004a, 2004b), with several ongoing Coordinating Projects. At the same time, landslide hazard in cultural heritage sites was a fundamental item in the general structure of the International Geological Correlation Programme (IUGS-UNESCO research project “Landslide Hazard Assessment and Cultural Heritage” IGCP-Project no. 425). This programme involved several outstanding sites of universal natural and cultural value included in the UNESCO World Heritage List (Sassa 1998). Therefore, within this framework, the impact of landsliding on cultural heritage has been considered a main theme of recent research in the field of landslide risk (Canuti et al. 2000; Manhart 2004; Margottini 2004; Chelli et al. 2005; Bromhead et al. 2006; Sdao and Simeone 2007; Tosatti 2008).

The varied approaches to the problem of landslides and cultural heritage reflect the complexity of this theme (Bromhead et al. 2006), which leads to very different views on this interaction, from the extremes of cultural history to advanced susceptibility analysis (Lollino and Audisio 2006), modern monitoring techniques (Canuti et al. 2005; Sassa et al. 2005; Fanti 2006) and almost pure landslide mechanics (Coppola et al. 2006; D'Amato Avanzi et al. 2006). In fact, owing to their intrinsic geomorphological and lithological features, many important geoheritage sites such as Pietra di Bismantova or, for example, the Italian Dolomites (Panizza 2009; Panizza and Piacente 2009), are often characterised by a conflict between safe access and hazards.

In the case of Pietra di Bismantova, all the analyses carried out to identify rock mechanic parameters and assess slope stability have shown that within the area examined, there are various levels of hazards. The areas potentially most subject to landslides are the SE, NE and NW faces, where the rock parameters are poorest and degradational processes are particularly intense. The numerical modelling of rockfall processes has shown that the hazard conditions are particularly high along the SE and W faces, where footpaths and climbing tracks are also located. Any geoconservation management and plans to regulate the flow of visitors and rock climbers into this site should take into account the results of this research with respect to the proneness of rock slopes to landsliding, and the subsequent risks posed to people. Access to certain areas will pose no or negligible threat to the human presence, whereas access to other areas should be forbidden and the hazards made known to the general public. Remedial measures should therefore be introduced in these critical areas in order to stabilise the cliff and guarantee safe access to all visitors. The appraisal and safe management measures of this geoheritage site should start from correct information about the hazard of rockfalls by means of warning panels set up at strategic points and the display of maps showing itineraries where the natural and cultural assets can be enjoyed with no risks for visitors.

Starting from these results, to protect the buildings and the people, some remedial works were carried out, mainly consisting of the removal of loose and unstable blocks. At this stage, the installation of wire meshes draped on the rock walls was avoided to minimise visual impact. However, further investigations are appropriate to attain a complete characterization of the rock mass and to carry out further slope modelling as a basis for an operational master plan to stabilise the cliff's critical areas.

Future research should include specific field work and further numerical modelling, in particular:

- completing a number of terrestrial LiDAR surveys at specific locations in order to carry out large-scale geomechanical characterization, kinematic analyses and 3D modelling on high-resolution DEMs of vertical cliffs;
- multitemporal large-scale mapping and characterization of fallen blocks and land use (mainly on forested slopes and vegetation-covered talus slopes), based on back analyses and testing the actual dimensions of the design block (i.e., the most probable or the largest block to be accounted for);
- in situ testing campaigns to assess kinematic variables and trajectories, mainly to verify the occurrence of the unsteady and highly scattered values of velocity and bounce height on steep rock walls and dispersion effects.

The results will allow a quantitative hazard and eventually risk assessment and zonation of the whole area, which is likely to include the relocation of the footpath and restrictions on access to some areas. The mitigation of the risk would also include the design of countermeasure works (reprofiling, trimming, shotcrete, consolidation with nails, anchors and grouting), associated with passive protection measures to reduce vulnerability (barriers and structural tunnels). In particular, as the entire rock cliff is a potential source area, the interventions should be designed with great care, according to the real local conditions and stability modelling of every single area, avoiding a standard intervention for the whole site.

As a final, relevant recommendation, all these interventions should be planned respecting low environmental impact issues and the importance of the area as an iconic cultural asset. The choice of suitable remedial measures, with particular reference to visual intrusion in scenic areas or to visual impact on the natural conditions of the site (i.e., shapes, colours, dimensions, materials etc.) is of paramount importance. An example of a "soft engineering" solution, more compatible with the environment in iconic geosites, is the stabilisation of slopes by the combined use of vegetation and man-made structural elements, known as biotechnical slope stabilisation. In particular, some possible low-impact solutions could be the implementation of structural tunnels along the footpath, possibly covered by local rock blocks and timber together with the use of ad hoc-coloured shotcrete and grouting on rock slopes.

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