Rock fall instabilities and safety of visitors in the historic rock cut monastery of Vardzia (Georgia)

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ABSTRACT: This paper reports the main results of a project developed in cooperation with National Agency for Cultural Heritage Preservation of Georgia, and aimed at envisaging the stability conditions of the Vardzia Monastery slope (rupestrian rock cut city cave in the south-western Georgia). The site has always been affected by instability processes along the entire slope, including small block falls from the upper breccia layer and large collapses from the middle layer. The study involves: rock mechanics characterization, geo-engineering survey, geo-structural and kinematic analysis, rockfalls modelling, geomatic acquisitions and elaboration. The geomechanical characteristics of volcaniclastic and pyroclastic rocks were determined by means of geomechanical field surveys, rock mass classification through scan lines techniques, and laboratory tests on rock blocks and cores. In order to carry out a semi-automatic detection of discontinuities and to implement mitigation activities, a 3D Terrestrial Laser Scanning survey has been carried out. Potential rockfalls have been simulated by the 3D modelling code HY-STONE. The model, used both with a downward and backward approach, allowed the recognition of most critical sectors belonging to the upper part of the cliff (volcanic breccia) and to provide a support for designing both short and long-term mitigation measures. A general master plan for landslide risk reduction and mitigation measures is actually under development for the entire rock cut city of Vardzia.

1 INTRODUCTION

1.1 *Historical and archaeological setting*

The rock-cut city of Vardzia is a cave monastery site in south western Georgia, excavated from the slopes of the Erusheti mountain on the left bank of the Mtkhvari river. The main period of construction was the second half of the twelfth century.

The caves stretch along the cliff for some 800 m and up to 50 m within the rocky wall (Figure 1).

Figure. 1 The rock-cut city of Vardzia (Georgia).

The monastery consists of more than 600 hidden rooms spread over 13 floors. The main site was carved from the cliff layer of volcanic and pyroclastic rocks, Gillespie & Styles (1999) at an elevation of 1300 m above sea level. The cave city included a church, a royal hall, and a complex irrigation system. The earthquake that struck Samstkhe in 1283 AD destroyed about two thirds of the city cave and the irrigation system, exposing the majority of the rooms to view outside. The site was largely abandoned after the Ottoman takeover in the sixteenth century. Now part of a state heritage reserve, the site has been submitted for future inscription on the UNESCO World Heritage List. Vardzia is an excellent example of a cultural landscape, Margottini & Spizzichino (2014) in which human activities (e.g., excavation, construction, and implementation of the cave monastery, painting), natural, geological, and geomorphological processes, are strictly connected and interdependent. Often, lithology (e.g., soft rock easy to excavate), geomorphological processes (e.g. landsliding, erosion and weathering), beautiful and impressive landscapes, and inaccessibility (settlement easier to defend and protect) have been the main elements in the history of humanity concerning the choice for the realization of towns, monuments, religious structures, and defence works, Margottini & Spizzichino (2014). The site is by the time affected by frequent slope instability processes along the entire volcanic cliff (Margottini et al, 2015). Similarly, the rapid onset falls and instabilities can become extremely dangerous also for the many visitors that are interested to discover the site. Due to these phenomena, the National Agency for Cultural Heritage Preservation of Georgia (NACHPG) has promoted, with the support of ISPRA, a landslide hazard assessment for the entire area through rock mechanics characterization, geotechnical engineering survey, geo-structural and kinematic analysis, rockfalls 3D model, terrestrial laser scanner acquisitions for the identification of the most hazardous areas. The present work, summarizes both the main results of the studies carried out from November 2014 to December 2014.

1.2 *Geological and Geomorphological setting*

The Vardzia monastery is entirely cut and carved in volcanic and pyroclastic rock formations, Gillespie & Styles (1999). From the geological point of view, the area is characterized by volcanic and pyroclastic rocks of the Upper Miocene ï Lower Pliocene Goderzi Fm. The entire geologic sequence is the final result of several volcaniclastic and pyroclastic falls, characterized by different explosion dynamics and chemical lava compositions (Figure 2).

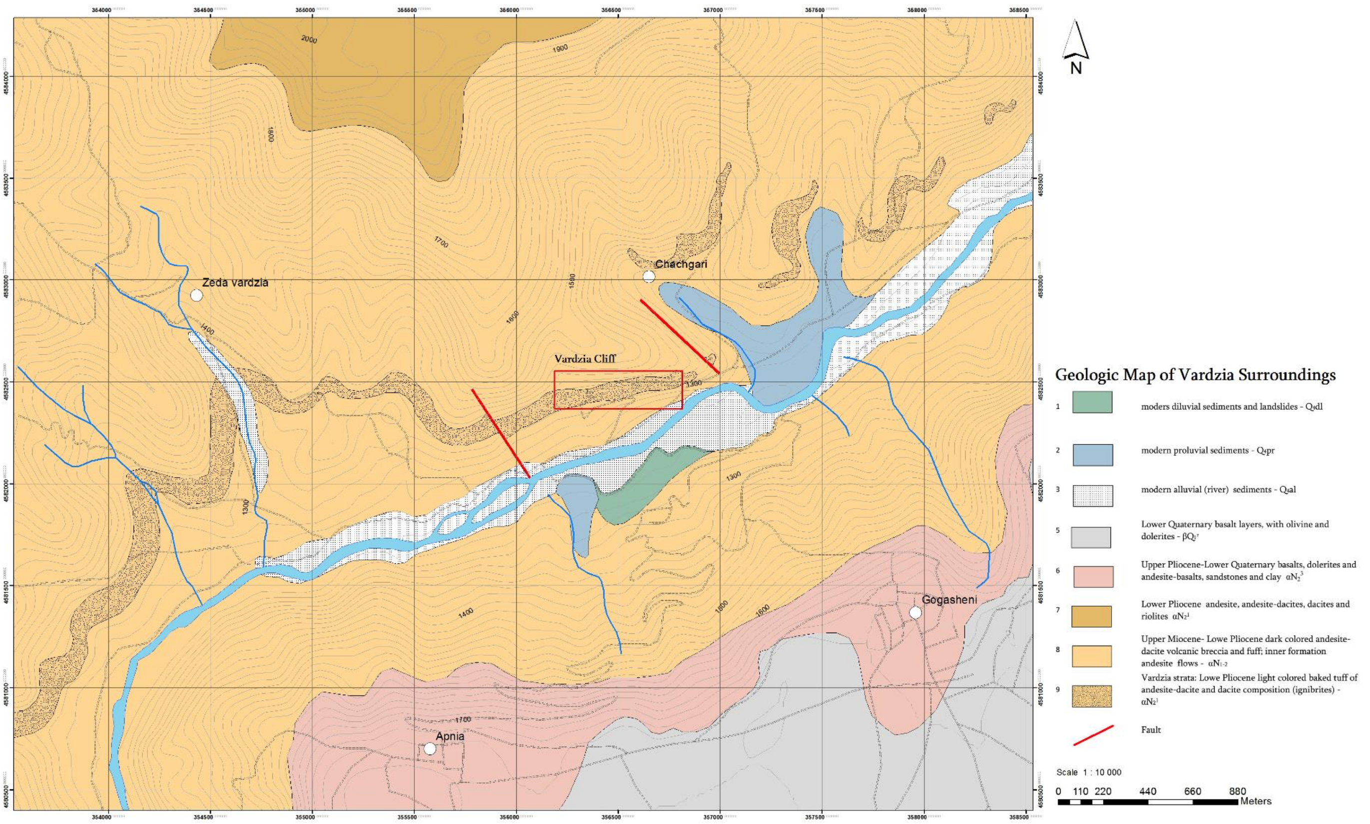

Figure. 2 The geology of Vardzia 1:10.000 scale (Courtesy from Ilia University, Tbilisi, Georgia).

Concerning the structural setting, at the slope scale, it is possible to define two main discontinuity systems, the first (sub vertical) due to cooling of the volcaniclastic sequence and a second one (locally parallel to the slope face) mainly due to stress release caused by the valley erosion.

The spacing decreases at depth moving within the rock mass as visible through some minor tunnels. The boundary between the different volcaniclastic levels is not always clearly marked but they are all sub-parallel according to the style of deposition.

The geomorphological aspect of the Vardzia monastery is the result of various long- and short-term factors (natural and human) that affected this part of Georgia. Active tectonics related to the Caucasian System jointly with the volcanic activity had a big influence on the present day morphology of the surrounding territory. Vardzia slopes are the final result of local seismicity, different volcaniclastic and pyroclastic falls, erosion, and deposition cycles of the Mtkhvari river.

The entire rock wall has a length of about 800 m and a height of 130 m with a general EW orientation.

The slopes, as a general rule, present a rupestrian aspect, mainly stratified and alternatively massive. Nevertheless, discontinuities of various types are present, potentially related to the following: cooling phase after volcanic activity (vertical), tectonic activity (faults, minor joints, mainly sub-vertical), and geomorphological activity (stress release caused by valley incision).

Sub-vertical and high-angle dipping joints intersecting horizontal bedding (layers of different pyroclastics falls) are quite frequent in the area and have been observed during field investigation (Ershov et al. 1999).

This situation causes potential falls, sliding, and toppling of blocks, whose type, dimension, and kinematics depend on local orientation, mechanical properties of pyroclastic layers,
spacing, and persistence of joints.

1.3 *Landslide types and slope evolution*

In order to provide a preliminary assessment according to landslide type and processes affecting the entire cliff rock (from the top to the bottom), most rock slope failures can be classified into one of the following categories listed below, Cruden & Varnes (1996), depending on the type and degree of structural and mechanical control:

a) Rock falls, topples or wedge failure often due to the lack of support of the underlying layer affected by planar sliding (Figure 3);

b) Large roto-translational rock slide involving both layers 1, 2 and 3 (Figure 4).

In layer 2 the main rock slope failure are mainly due to:

a) wedge failure and rock fall (figure 5);

b) high and low angle planar rock slide along the mains structural setting (Figure 6).

In layer 3 the main potential rock slope failure are:

a) planar sliding along the mains structural setting (Figure 7);

b) topples.

Furthermore, widespread superficial erosion has been recognized and mapped along the slope, mainly due to superficial water circulation and minor stream network able to create small depositional fan delta at the toe of the slope.

Figure 3. Rock falls in the upper part of the layer 1.

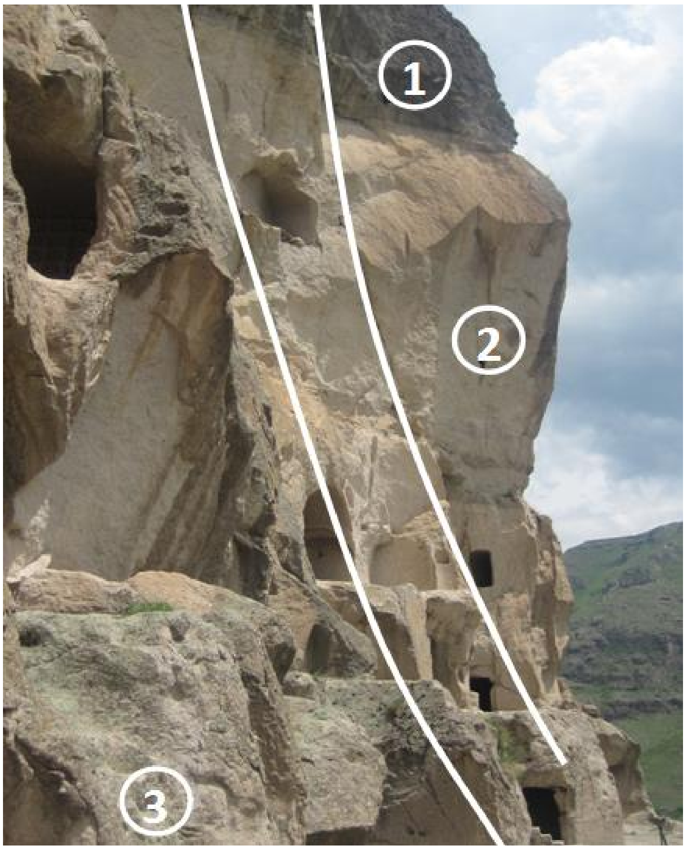

Figure 4. Large roto-translational rockslide involving layers 1, 2 and 3.

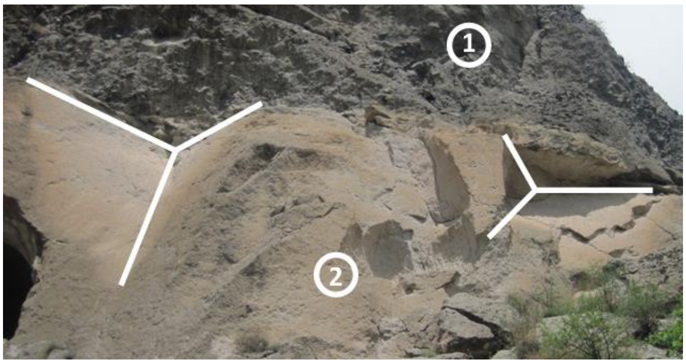

Figure 5. Wedge failure at the contact between layer 1 (on top) and layer 2.

Figure 6. High and low angle planar rock slide.

1.4 *Geo-mechanical setting of the area*

Geomechanical characteristics of the volcaniclastic and pyroclastic rocks outcropping in the study area have been determined by means of geotechnical field surveys and laboratory tests.

Figure 7. Planar sliding along the mains structural setting

The following activities have been carried out during the end of 2014 field survey:

ï Geomechanical rock mass classification through scan lines, in order to derive the main geomechanical characteristics and indexes (e.g. RMR, GSI);
ï Tilt test (Barton, 2008);
ï Schmidt-hammer test on joint surfaces and intact rock block for in situ analysis of UCS (unconfined compressive strength);
ï Point load test to provide UCS data from sampled blocks (ISRM 1978, 1981);
ï Strength and deformation parameters from scientific and technical literature (Hoek 2007; Barton 1973; ISRM 1981) as well as from local technical reports;
ï laboratory Uniaxial Compression tests and Brazilian tests on tuff rock blocks and cores (uniaxial and tensile strength parameters in dry and saturated conditions).

The main results are summarized in Table 1.

Table 1. Main geomechanical parameters for the Vardzia rocks

Lithology	Unit weight γ (KN/m^3)	porosity (%)	σ_c dry MPa	σ_c sat MPa
Grey tuff	16.3	37.2	10.3	3.6
White tuff	15.9	38.8	8.7	2.8
	Basic friction angle (ϕ°)	GSI	σ_t dry MPa	σ_t sat MPa
Grey tuff	22°-32°	70	0.8	0.3
White tuff	22°-32°	65	0.9	0.3

2 TLS FIELD SURVEY

In order to carry out a site-scale specific analysis and to support 3D rockfalls model, a detailed geodetic 3D laser scanning survey has been performed and implemented during the November 2014 field mission.

Terrestrial Laser Scanner (TLS) surveys were performed by a Riegl VZ1000 sensor from twelve different scan positions (Figure 8), in order to reduce the shadow zone.

The system was equipped with a GPS antenna, inclinometer sensor and a digital compass (for the georeferencing of the achieved data) and a high resolution digital camera, thus allowing the acquisition of real colour 3D point cloud.

The distance between the study area and the survey system ranged from 4 m to 910 m, while the scanning resolution angle ranged from 0.006° to 0.011° (Table 2).

In order to merge all point clouds in the same reference systems in the post-processing data management, optical reflectors were positioned in the scanning field of view, thus ensuring their visibility from different scan positions.

Table 2. TLS data settings collected from the six different scan positions.

Scan Position		number of points	Average angular stepwidth (deg)	Average distance from study area (m)	Average density of points (pt/m²)	
					Closest areas	Farthest areas
1		175.566.279	0,006	310	810	230
2		32.784.012	0,006	320	730	620
3		7.080.768	0,007	910	80	45
4		153.362.340	0,006	175	1.730	510
5		13.022.600	0,006	540	300	120
6	6.1	100.233.900	0,011	9	250.000	62.500
	6.2	89.119.944	0,005	80	27.700	10.000
7		42.960.435	0,011	4	1.000.000	62.500
8		59.487.675	0,011	13	111.000	62.500
9	9.1	63.172.665	0,011	20	62.500	27.700
	9.2	2.167.554	0,008	110	2.700	2.700
10		169.901.424	0,009	15	40.000	27.700
11		21.839.247	0,011	25	40.000	15.600
12		339.396.149	0,007	35	250.000	1.200

Furthermore, in order to determine absolute coordinates of the positioned optical reflectors (network of control points), a differential GPS survey was performed.

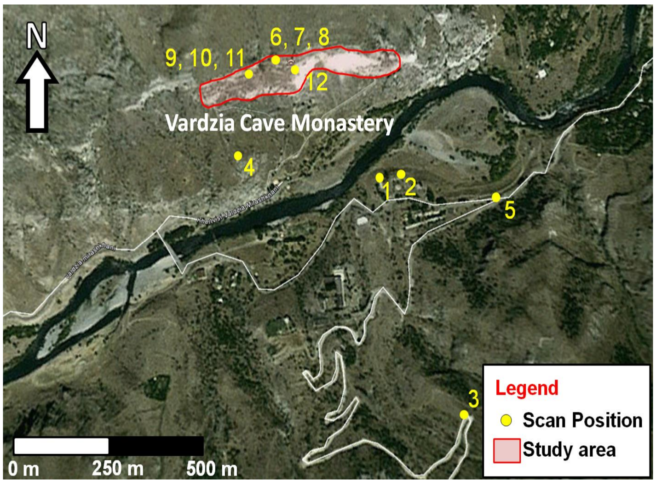

Figure. 8 Scan positions location on satellite image (UTM WGS84: 38 T, 356.642 m E, 4.582.505 m N).

The reference system of the coordinates of control points network is the UTM WGS84 38-zone. The software used for registration, alignment and processing of acquired point clouds was Riscan Pro (Riegl, 2008).

The geodetic surveying was aimed at the 3D reconstruction of the whole complex as well as to produce a detail DTM and derived maps (e.g. slope map, reflectivity maps).

All 3D data were collected in a local reference frame by means of a terrestrial high-resolution laser scanner (TLS).

Finally, the TLS can also be utilised to identify the different members of the volcanoclastic sequence.

In fact, the instrument records the RGB values and measures the incident and reflected ray energy, providing the reflectivity index I of the microportion surface (Ercoli et al., 2013).

Therefore, the reflectivity index associated to each TLS point can provide a indirect estimation of the litothype layers (Figure 9).

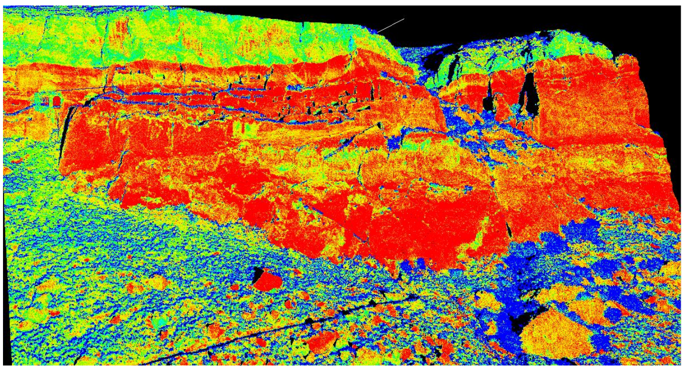

Figure. 9 Textured 3D model and reflectivity map of the cave monastery of Vardzia from TLS techniques.

3 3D ROCKFALL SIMULATION

During field activities, it has been recognized that the rocky cliff is frequently affected by small-volume fragmental rockfalls, especially from the upper breccia layer. Although historical events causing victims or injuries are not reported, the safety of both the monks and the visitors is one of the main topic for the management of the cultural heritage site.

3.1 *Sources of fall hazard*

The rock cliff of Vardzia is exhibiting either toppling phenomena as well as free fall of unstable small or medium size blocks (e.g. a cubic meter).
To investigate the most hazardous areas, reference was made to traditional kinematic analysis for toppling and direct survey for free fall (Saraglou et al., 2012).

In order to implement a kinematic analysis, discontinuities were obtained both during field survey and through the elaboration of TLS with a specific software, Coltopo3D®, suitable to detect slope and slope direction of the many outcropping surfaces. Coltop3D is a software that performs structural analysis by using digital elevation model (DEM) and 3D point clouds acquired through terrestrial laser scanners. A color representation merging slope aspect and slope angle is used in order to obtain a unique code of color for each orientation of a local slope (Figure 10). Thus a continuous planar structure appears in a unique color (Metzger at al., 2009).

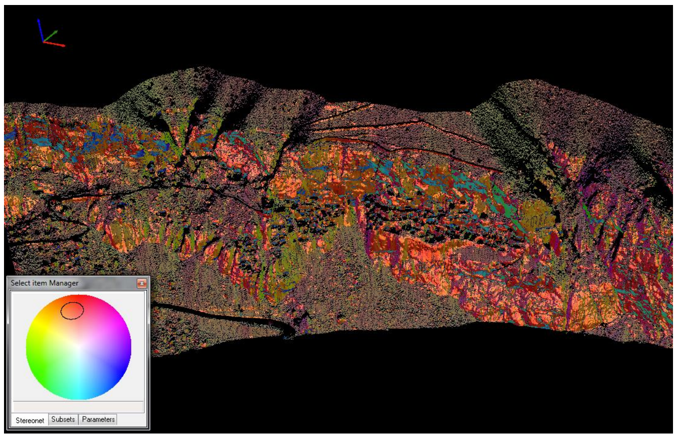

Figure. 10 ï The exposed rock faces of Vardzia cliff and detected slope aspect and slope angle, also on a Schmidt-Lambert stereonet.

The kinematic analysis was then providing the areas with conditions potentially suitable to generate direct toppling, for the shear strength defined from field classification, tilt tests and laboratory data (Figure 11). A preliminary map of potentially unstable blocks susceptible to free fall was prepared following the approach proposed in Saroglou

(2012). In the mean time, the upper part of the cliff, were the volcanic breccia is located, has been considered totally susceptible to generate free fall, especially in the most conglomeratic members.

All the potentially kinematically unstable areas, isolated unstable blocks and susceptible areas to free falls, have been utilized to produce the map of figure 12.

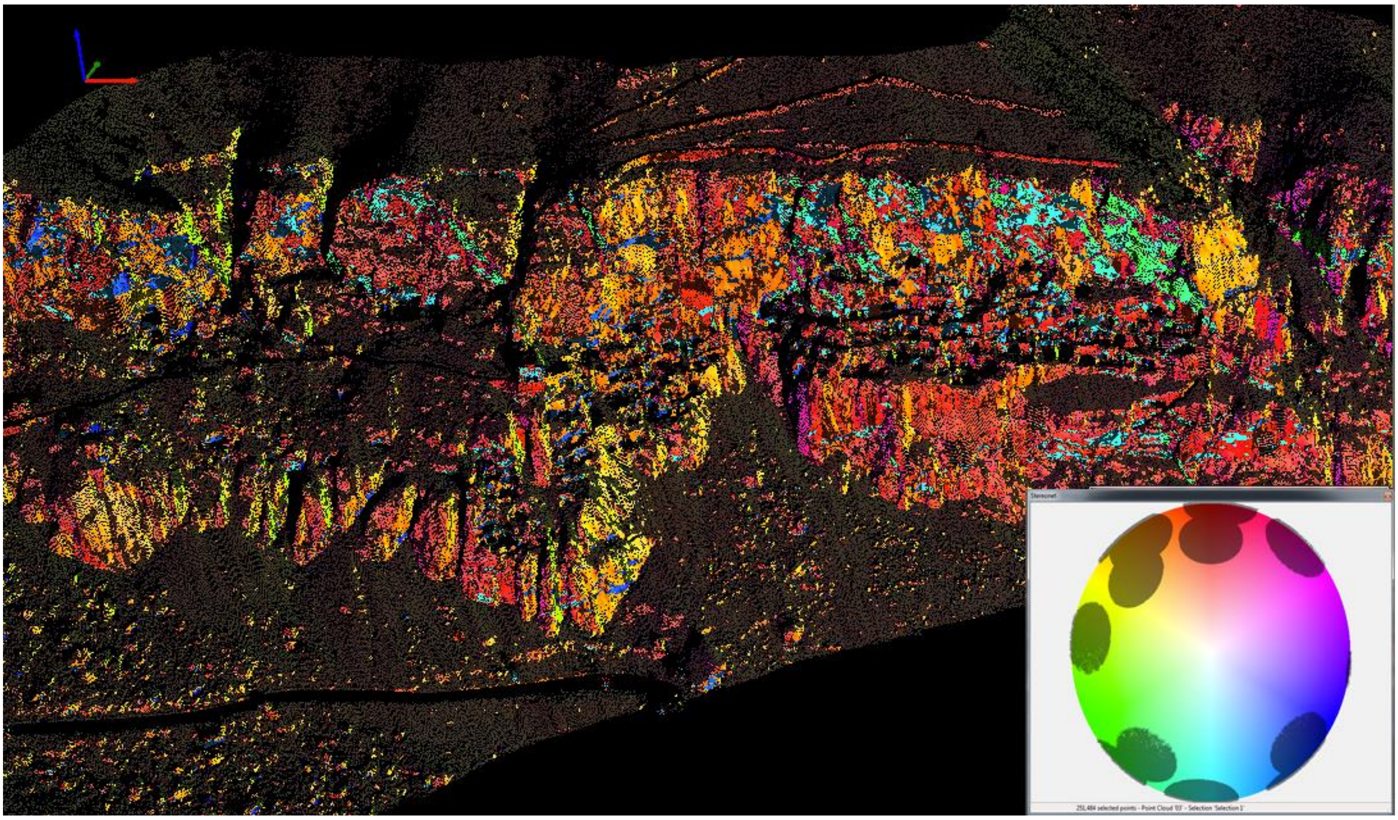

Figure. 11ï Areas with kinematic conditions suitable to generate direct toppling (red)

3.2 *Run out*

In order to investigate the propagation of blocks falling along the slope, and the potential visitors impact, a set of rockfall simulations was performed by means of the 3D numerical model HY-STONE (Crosta et al., 2004, Frattini et al., 2012). The code allows to simulate the motion of non-interacting rocky blocks in a three-dimensional framework. It is based on a hybrid (mixed kinematicï dynamic) algorithm with different damping relationships available to simulate energy loss at impact or by rolling.

Slope topography is described by a raster DEM, and all the relevant parameters are spatially distributed. The stochastic nature of rockfall processes and the variability of parameters are introduced by random sampling most parameters from different probability density distributions (e.g. uniform, normal, lognormal, exponential).

Block fragmentation and visco-plastic impact algorithms (Di Prisco & Vecchiotti, 2006) are also included in the code. Effects of impact on structures (i.e. buildings), nets (countermeasures) and trees can be also evaluated. The rocky block is described as a solid geometric shape with a certain volume and a certain mass. Rockfall runout modelling requires: (i) the preparation of spatially distributed input data (topography, superficial lithology and land use, rockfall source areas), (ii) the calibration of the model parameters, (iii) the simulation of rockfall scenarios.

A 1-m gridded Digital Elevation Model (DEM) was created starting from available TLS survey. In order to spatially distribute the restitution and rolling coefficients needed for runout simulation, we assigned initial values of these parameters to the different lithological classes mapped from geomorphological interpretation of photos, and through field survey.

Then, we calibrated these values by back-simulating the maximum extent of blocks recognized on field. Two future potential scenarios have been simulated: s1) detachments of small blocks from all rocky cliffs steeper than 50° (Figure 12); s2) detachment of larger blocks from 6 unstable blocks recognized on field and through aerial photo interpretation (Figure 13).

The first scenario (s1) shows that the entire site is potentially affected by rockfalls, with a higher concentration of potential events in the eastern lower part of the cliff. Here, a pedestrian track allows the visitor to access the site from the bottom of the cliff, through an historical tunnel that has been carved in the lower tuff layer.

This access appears to be completely and seriously exposed to rockfalls from above. Considering that high-energy defensive barriers could alter the aesthetic of the cultural heritage site, the optimal solution for the mitigation of rockfall risk consists in the identification and clearing of unstable blocks. The second scenario (s2) shows an example of simulation of specific unstable blocks that needs to be stabilized or removed for assuring the safety of monks and visitors. This kind of simulation allows to evaluate the possible kinematism associated to each unstable zone. The most hazardous area should then be investigated with analytical and numerical model in order to estimate the real safety factor and to prioritize the mitigation activities.

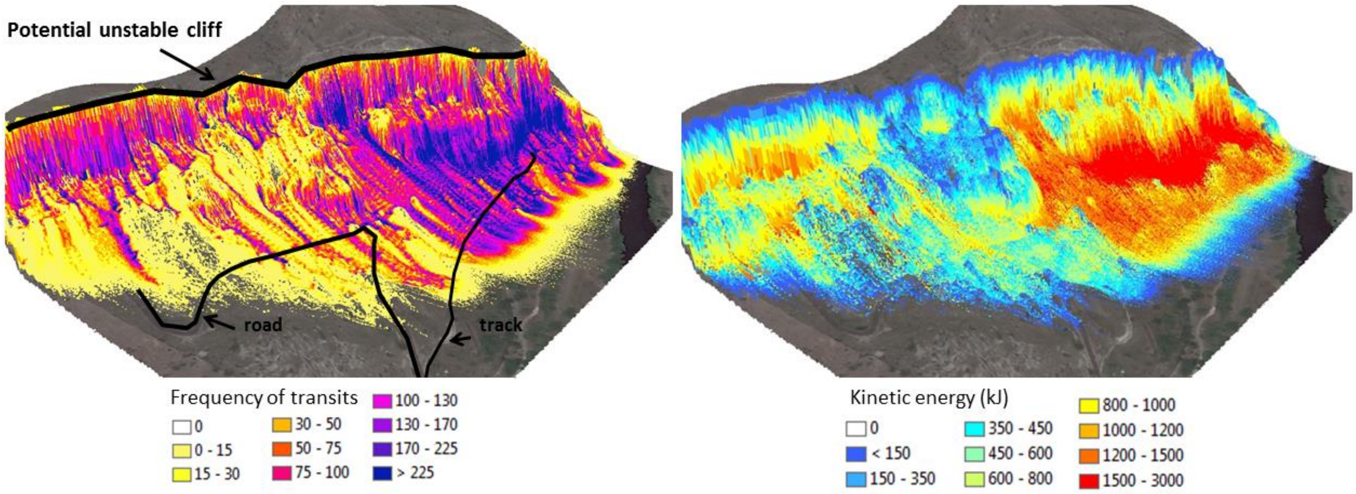

Figure. 12. Results of potential future scenarios showing a) the number of blocks passing through each grid cell and b) the maximum kinetic energy of blocks passing for each cell: (s1) - rockfalls from rocky cliffs with slope gradient steeper than 50°.

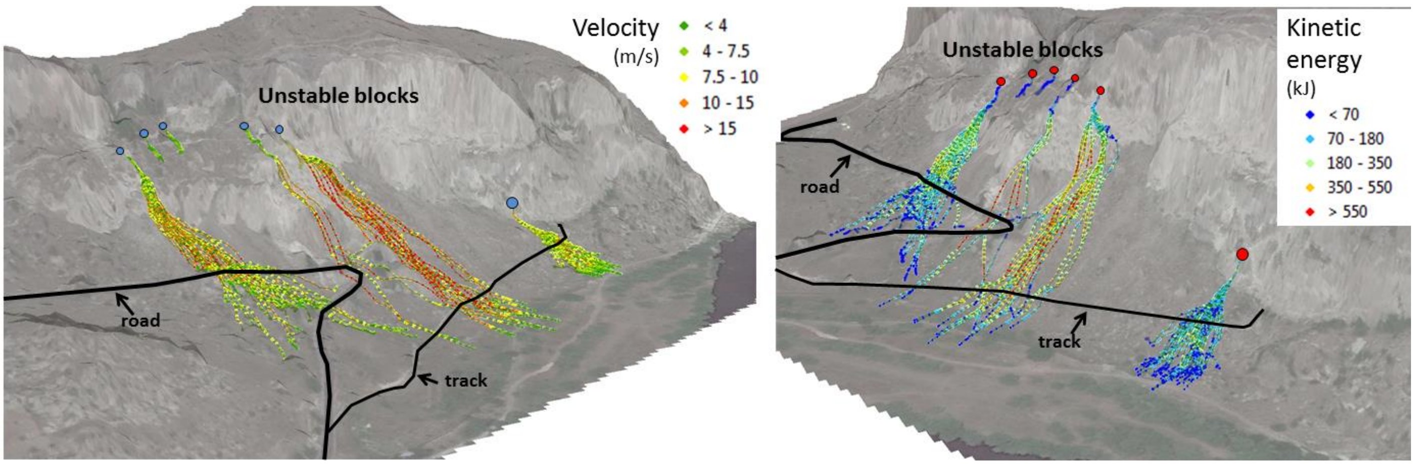

Figure. 13. Results of potential rockfalls from unstable blocks recognized on field (s2). a) velocity ; b) kinetic energy. Each point corresponds to the position of the block sampled along each trajectory every 4 meters.

4 CONCLUSIONS

The Vardzia Monastery is one of the most important Georgian Cultural Heritage. The site has always been affected by slope instability processes along the entire slope, threatening security of the site and future tourist exploitation.

National Agency for Cultural Heritage Preservation of Georgia has supported and promoted interdisciplinary landslide risk analysis, assessment and management during last three years. An integrated monitoring systems for the whole rock cliff using Ground Base Radar has been developed and implemented and it is still operative.

The main geomorphological, geo-structural and geomechanical evidences obtained after field missions suggest the following observations and recommendations:

- the potential instability processes and mechanisms observed for the entire rock cliff can be referred to different failure modes (or their combination): rock fall; planar rock slide; roto-translational rock slide; wedge and toppling failure;
- actual and/or potential instability processes at the Vardzia monastery are the result of a combination of different predisposing factors such as: lithology, presence, frequency and orientation of discontinuities vs. slope

orientation, physical and mechanical characteristics of materials, morphological and hydrological boundary conditions as well as human activities;

- relevant factor in Vardzia slope stability is the reduction of UCS and tensile strength, from laboratory tests, when saturated; such drop can reach up to 70% of original values (Table 1), then suggesting an important role in rainy period;
- the coupling of different survey techniques (e.g. 3D laser scanner, engineering geological and geomechanical field surveys) is the best strategy to be adopted in the interdisciplinary field of Cultural Heritage protection and conservation policies;
- the area is seriously affected by rockfall risk that could affect the safety of both the monks and the visitors. A feasible strategy for reducing this risk without deploying anaesthetic defensive works consists in the identification, modelling and stabilization or removal of unstable blocks. This requires the joint use of field survey, TLS point cloud interpretation and Ground Base Radar analysis.
- The future development for the Vardzia monastery provide mitigation measures both structural and non-structural for the next two years in order to reduce risk and increase safety of the site and visitors.

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