Landslide Hazard Assessment, Monitoring and Conservation of Vardzia Monastery Complex

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Abstract

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 Mtkvari River. The main period of construction was the second half of the twelfth century. The caves stretch along the cliff for some eight hundred meters and up to fifty meters within the rocky wall. The monastery consists of more than six hundred hidden rooms spread over thirteen floors, which made possible to protect the monastery from the Mongol domination. The site was largely abandoned after the Ottoman takeover in the sixteenth century. The site is by the time affected by frequent slope instability processes along the entire volcanic tuff façade of the slope. Due to this 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, slope stability model, 3D laser scanner acquisitions and elaborations, and a real time monitoring system (GB_Radar interferometry) for the identification of deformation path of the most hazardous areas. A field analysis was conducted to reconstruct geometry of the rocky cliff, characteristics of discontinuities, main failure modes and volume of potential unstable blocks and geomechanical parameters.

Keywords

Landslide • Monitoring • Georgia • GB-Radar • Laser scanning

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51.1 Vardzia Monastery

The town-monastery of Vardzia is an absolutely unique example of rock-cut architecture not only at national level, but world-wide as well and it is an outstanding and incomparable example of Georgian medieval art. The majestic complex was founded by order of King George III and enlarged by his daughter Queen Tamara (1184–1213 AD). Organized along the rock wall on thirteen levels for a height of 50 m and a length of about 800 m, it consists of several hundred rooms with aqueducts, subterranean tunnels and vertical connections between the various storey The History of Georgia also relates how Vardzia escaped the Mongol invaders in the 1290s (Stephen 2003). After the arrival of (Gaprindashvili 1975) the Ottomans in 1578, the monks departed and the site was largely abandoned. Infrastructure includes access tunnels, water facilities, and provision for defence (UNESCO 2012; ICOMOS 2001). In 1999 Vardzia Khertvisi was submitted for inscription on the UNESCO World Heritage List as a Cultural Site. In 2007 Vardzia Khertvisi was resubmitted as a mixed Cultural and Natural Site.

51.2 Geodetic Survey and Topographical Setting

In order to carry out a site-scale specific analysis and to support the monitoring system activities, a detailed geodetic 3D Laser Scanning survey has been performed and implemented. The geodetic surveying was aimed at the three-dimensional (3D) reconstruction of the cave monastery, and collection of data for future potential slope stability analysis. All 3D data were collected in a Local Reference Frame by means of a terrestrial high-resolution laser scanner (TLS), and then georeferenced by using high-precision dual frequency geodetic GNSS receivers (Baldo et al. 2009). Laser scanning is an automatic contact-free surveying technique (scanning laser range-finder) able to collect 3D surface coordinates at a very high spatial and geometric accuracy.

The intensity of the reflected laser pulse can be recorded, providing an indication of the reflection characteristics of the surface and enabling the creation of quasi images, but thigh resolution digital RGB images can be acquired with a built-in calibrated camera. All these characteristics make of TLS an extremely useful tool in the field of conservation and protection of Cultural Heritage. Surveying activities at the Vardzia site were performed using a topographical Riegl Z210i laser scanner both for measuring the 3D coordinates of the models and acquiring the RGB information linked to the point clouds. Ten TLS scans were acquired, in order to exactly reconstruct the topography of the site (Fig. 51.1), from two different scan positions by applying the multi-scanning technique. Average spatial resolution ranges from 10 × 10 cm up to some meters, depending on the distance between the laser and the object. In our study area such distance vary from 400 m (along the Line Of Signal) up to 550 m (average distance between the laser and the monastery). Purpose-built targets were used to link the scans together and to build up a high-resolution 3D model of the cave monastery. The final model consists of a point cloud made of about 8,000,000 points from which a DTM with a 1 m × 1 m cell size has been derived.

51.3 Geological Structural and Geomorphological Setting

The Vardzia monastery is entirely cut and carved in volcanic and pyroclastic rocks (Gillespie and Styles 1999) formations (upper Moitsen–lower Moitsen) (Gudjabidze and Gamkrelidze 2003). A representative lithologic cross section of the slope has been accomplished during the last field mission The entire geologic sequence is the final result of several volcaniclastic and pyroclastic falls, characterized by different explosion dynamics and chemical lava compositions. 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 are not always clearly marked but they are all sub-parallel according to the style of deposition.

Vardzia is an excellent example of the so called Cultural Landscape (Margottini and Spizzichino 2009). in which human activities (e.g. excavation, construction and implementation of the cave monastery, painting) and natural, geological and geomorphological processes are strictly connected and interdependent. 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 for a height of 130 m with a general E-W 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: cooling phase after volcanic activity (vertical); tectonic activity (faults, minor joints, mainly sub-vertical) 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

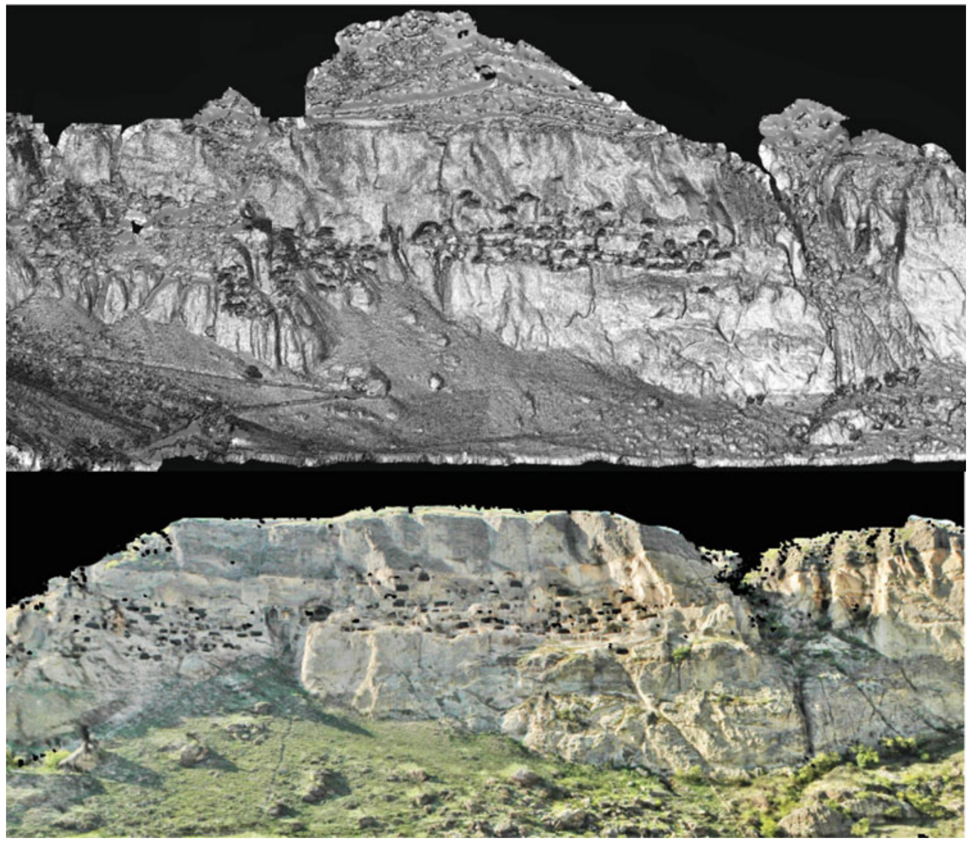

Fig. 51.1 DSM of the rock-cut city Monastery of Vardzia (textured)

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.

51.4 Monitoring System

Considering the morphological settings (slope extent ca. 10^5 m^2) and slope instability processes (different typologies in size, magnitude and probability of occurrence), a new advanced simple and flexible monitoring system has been implemented in order to obtain: measurements, processing and remote control in real time, and to transform in the future, the monitoring system into a warning system. The system adopted for the monitoring of the entire cliff is based on a ground based interferometric radar. This equipment allows the monitoring of displacement in the line of sight with a resolution of mm.

The radar system is a Stepped-Frequency Continuous Wave (SF-CW) coherent radar with SAR and interfeometric capabilities. The acquisition station has been realized with the valuable support of the NACHPG and the pre-acquisition and start up activities have been finalised and calibrated during the last field mission. The above mentioned technique (SF-CW) allows the resolution of the scenario along range direction independently from the distance (range resolution up to 0.75 m).

The SAR technique also allows the resolution of the scenario along cross-range direction independently (in the angular value) from the distance (cross-range resolution up to 4.3 mrad). The differential interferometry technique enables the measure of the displacement of the objects resolved through coupling SF-CW analysis. The system has been installed during the May 2012 field mission. During the period May–October 2012 the system has been initialized and tested. The radar configuration adopted is reported in the following table, the "selection mask" contains about 50,000 points (Table 51.1).

The TLS derived DTM has been used as 3D model for the visualization of the main monitored quantities (displacement and velocity) as collected and stored in real time by the

Table 51.1 Main parameters of radar configuration

Distance from the slope	(m)	350–500
Antenna beam width	(deg)	>70
Number of points	–	50,000
Range resolution	(m)	0.5
Cross range resolution	(mrad)	4.3
Scanning time	(min)	5

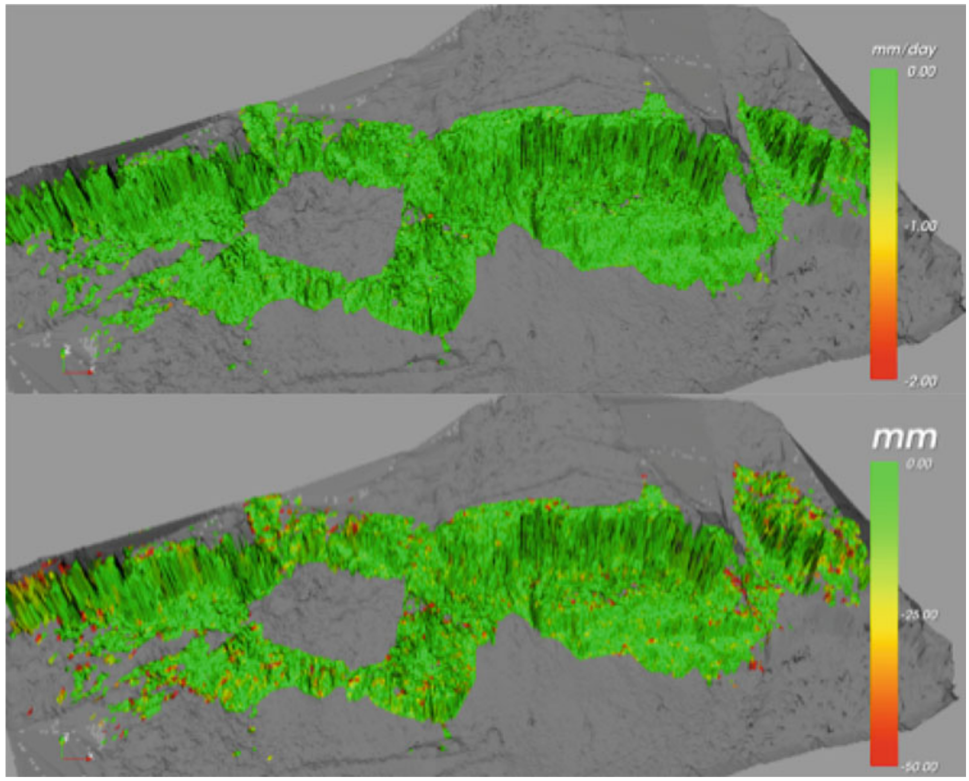

Fig. 51.2 Average velocity and displacement maps for the whole 5-month monitoring period

monitoring system. The monitoring system is actually close to the end of the first 6 months of acquisition and the preliminary results are quite stable and comfortable.

With the exception of some individual control points (mainly due to noise factors related to vegetation) the investigated area is stable and under control (Fig. 55.2). In the next 6 months on site verification of the main critical outcomes of the monitoring systems will be carried out along the cliff in order to calibrate and correct the results and define the most active zones in which downscaling of the landslide hazard and risk assessment is recommended.

51.5 Conclusion

The main geomorphological, geo-structural and geomechanical evidences obtained after two field missions (October 2011 and May 2012) suggest the following observations and recommendations:

1. 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;
2. such instability processes differ along the whole cliff in terms of activity, their state (temporal evolution), distribution (spatial evolution), style (combination and repetition of different failure mechanism) and magnitude (landslide intensity and potential volumes);
3. 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 versus slope orientation, physical and mechanical characteristics of materials, morphological and hydrological boundary conditions;
4. the coupling of different survey techniques (e.g. 3D laser scanner, engineering geological and geomechanical field surveys, Ground based radar Interferometry) is the best strategy to be adopted in the interdisciplinary field of Cultural Heritage protection and conservation policies.

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