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Advances in geotechnical investigations and monitoring in rupestrian settlements inscribed in the UNESCO's World Heritage List.

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Abstract

Rupestrian settlements were among the first man-made works in the history of humanity. The most relevant masterpieces of such human history have been included in the UNESCO World Heritage List. These sites and remains are not always in equilibrium with the environment. They are continuously impacted and weathered by several internal and external factors, both natural and human-induced, with rapid and/or slow onset. These include major sudden natural hazards, such as earthquakes or extreme meteorological events, but also slow, cumulative processes such the erosion of rocks, compounded by the effect of climate change, without disregarding the role of humans, especially in conflict situations. Many rupestrian sites have been carved into soft rock, generally with UCS<25 MPa (ISRM, 1981), in vertical cliffs, and showmajor conservation issues in the domain of rock slope stability and rock weathering. The present paper reports the experience of rock fall investigation and monitoring in rupestrian sites, mainly from the UNESCO World Heritage List (Bamiyan in Afghanistan; Lalibela in Ethiopia; Petra in Jordan and Vardzia in Georgia). The general approach, implemented in the activities, include an interdisciplinary study with advanced methodologies and technologies, with the objective to understand degradation processes and causative factors, followed by low impact, but highly effective, rock slope monitoring.

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Keywords: Rupestrian site, rock mechanic, geological threats, investigations, monitoring.

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1. Introduction

Rupestrian settlements were among the first man-made works in the history of humanity. During almost 3 million years, human kind has survival relied on two basic activities: hunting (or fishing) and gathering edible items of all kinds (from fruit to insects). A radical change came roughly 10,000 years ago, after the last glacial age, when people first learned to cultivate crops and to domesticate animals, in what can certainly be considered one of the most significant development in human history. This process took place during the Stone Age, when tools were still made of stone rather than metal[1].

In order to ensure long term conservation, especially for sites affected by natural threats, detail investigations and monitoring techniques both related to internal parameters (mechanicals and physical) and external agents responsible of their conservation, are required. The most advanced and non invasive investigation and monitoring techniques (direct and remote) should be adopted to define the present conservation condition and the future trend. The general approach must follow different scales of analysis, depending from the site threat, from micro scale to general processes scale (e.g. landslide, floods) involving large areas. The provided results are the main pillar for the next step that is the sustainable mitigation strategy.

2. Major threats affecting rupestrian sites

The sites and remains are not always in equilibrium with the environment. They are continuously impacted and weathered by several internal and external factors, both natural and human-induced, with rapid and/or slow onset. These include major sudden natural hazards, such as earthquakes or extreme meteorological events, but also slow, cumulative processes such the erosion of rocks, compounded by the effect of climate change, without disregarding the role of humans, especially in conflict situations.

Many rupestrian sites have been carved into soft rock, generally with UCS<25 MPa[2], in vertical cliffs and show major conservation issues in the domain of rock slope stability and rock weathering. The low strength range of rock might be influenced by physical characteristics, such as size, saturation degree, weathering and mineral content. Finally, the investigations generally show that the strength reduces significantly with saturation[3].

The previously described low strength of the rock, together with the discontinuity pattern in steep slopes and the weakening of the cliff produced by the man-made settlements, pose a serious concern for the long term stability of the sites.

As a confirmation, the following Fig.1 is reporting the relationship between UCS and porosity for some rupestrian sites discussed in this paper. It is evident that the low UCS value is generally coupled with high porosity, especially in volcanic materials (Lalibela and Vardzia). On the other hand, the continental/sedimentary geological formations of Bamiyan and Petra exhibit a relevant vertical heterogeneity, so values here reported are just rough estimates.

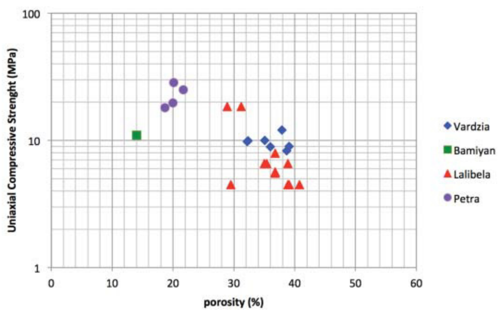


Fig. 1. The relationship between Uniaxial Compressive Strength and porosity for the case studies discussed in this paper.

The present paper reports some advances developed during rock fall and weathering analysis, monitoring and mitigation in rupestrian sites, mainly belonging to the UNESCO world heritage list (Bamiyan in Afghanistan; Lalibela in Ethiopia; Petra in Jordan and Vardzia in Georgia) and under UNESCO coordination. The general approach, implemented in the conservation activities, include a very detailed interdisciplinary study, to understand rock degradation processes and causative factors, followed by field conservation work. The latter is mainly related to the re-discovering of traditional knowledge and sustainable practices and is based on the application of local conservation techniques.

The described methodology is then primarily aimed at the protection of the heritage sites but, at the same time and when possible, at the empowerment of local communities to manage by themselves the site. Protecting heritage from natural threats is, in fact, not a luxury but a fundamental step to be given priority together with other humanitarian concerns. This is especially relevant at a time when traditional knowledge and sustainable practices, which ensured a certain level of protection from the worst effects of natural hazards or human-made disasters, are being progressively abandoned and/or forgotten.

Following is a brief description of some advanced techniques employed by the authors in selected case histories.

3. Investigation techniques

3.1. Laser scanner

As a result of the outstanding development of terrestrial laser scanner (TLS) in recent years, rock slopes and rupestrian settlements can now be investigated and mapped through high resolution point clouds.

Laser scanning for the generation of surface models acquires 3D surface information by determining the xyz co-ordinates of large numbers of surface points, referred to as a point cloud. The scanner (Fig. 2) can only measure and record surfaces in the field-of-view of the instrument and it is therefore necessary to move the instrument to multiple positions to cover an entire object. The scans acquired in this way must overlap each other sequentially to allow the combination of all acquired scans into a single point cloud. In subsequent processing the individual points are connected to form a triangulated mesh which can be further processed to create a complete, full surface. Finally, photos can be draped over the surface to create a photo-realistic appearance. The interval between points of the cloud, referred to as resolution, can be chosen by the operator depending on required detail and surface complexity.

Fig. 2. Laser Scanner (Z&F) above Al Khazneh (Petra. Jordan)

Finally, TLS can also be utilized to identify the different members of a stratigraphic sequence. In fact, the instrument records the RGB values and measures the reflected ray energy, providing the reflectivity index I of the micro-portion surface[4]. Therefore, the reflectivity index associated with each TLS point can provide an indirect estimation of the litothype layers (Fig.3). Intensity variations as a result of different angles of incident proved insignificant in this context.

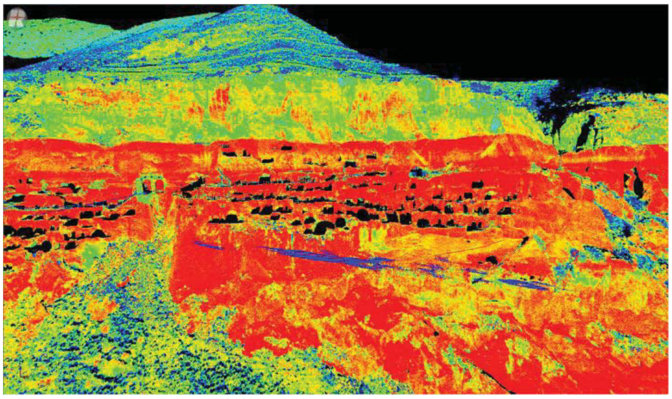


Fig. 3. Textured 3D model and reflectivity map of the cave monastery of Vardzia from TLS techniques.

3.1.1. The Siq of Petra

The Siq, the main entrance to the Nabatean archaeological site of Petra (Jordan), is a 1.2 km long, naturally formed gorge, with an irregular horizontal shape and a complex vertical slope.

For the rock-mechanics analysis of the Siq, a 3D computer model of the rock walls on both sides of the Siq was created[5]. Ideally this model should have covered the full height of both surfaces over the 1.2 km length of the Siq. which would have resulted in a model of 2.4 km length with heights varying from about 70 m to 120 m (Fig.4).

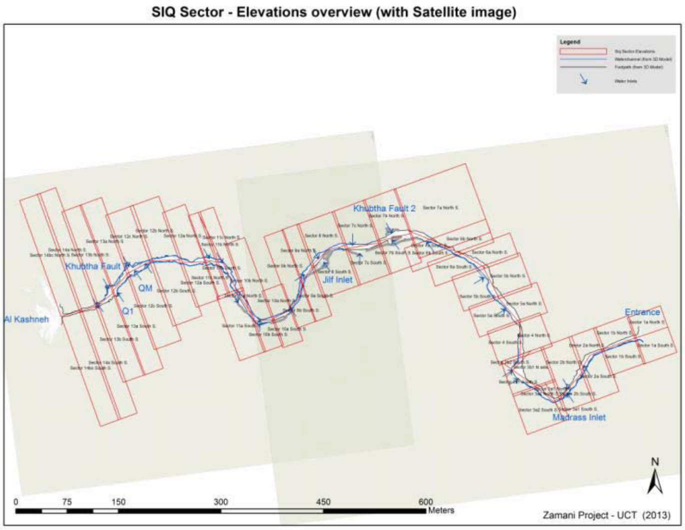
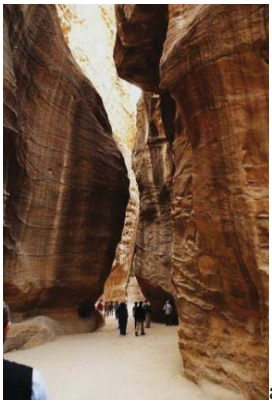


Fig. 4. Top view of 1.2 km Siq point cloud (Courtesy of Zamani Project)

Two methods were available for the development of the 3D surface model, laser scanning and photogrammetry. In lengthy investigations and discussions, the accuracy potential, the practicality and the cost of the two techniques were explored including considerations regarding the use of Unmanned Aerial Vehicles (UAVs), scaffolds and poles. It became obvious that neither method was capable in a practical sense of providing surface data beyond the areas which were visible from the ground, unless unrealistically high expenses were accepted. The final decision favored laser scanning as the most feasible method and an extensive lasers can survey, limited to the rock surfaces visible from ground level, was subsequently completed by the Zamani research team, from the University of Cape Town. A number of individual boulders and sections of rock walls were modelled by PNP surveyors using Structure-from-Motion-Photogrammetry. For the Siq survey, the scanner was positioned on the Siq floor at intervals not larger than 10 meters[6]. The lower wall areas over the entire length of the Siq were thus captured up to a height varying from 20 to 80m, depending on visibility (Fig. 5a). In addition, a number of scans could be taken from points at the upper edge of the Siq (Fig.5b). The scans at high elevations provided, in some cases, surface data from Siq floor to the top of the rock walls. The total number of scans in the Siq was 220 with an average point interval of approximately 3 cm, resulting in a point cloud of five billion points. This is only a part of the complete point cloud which the Zamani team acquired for the Siq, Wadi Musa and Wadi Farasa. This collective point cloud comprised 25 billion points. The relative accuracy of points, i.e. the accuracy of neighbouring points is estimated to be in the order of a cm or better, whereas the absolute accuracy, i.e. the accuracy of points over the entire length of the Siq is in the one or two decimeter range. The final model (example in Fig.6) can be viewed in 3D viewing and processing software. Coordinate and dimension measurements can be taken in applications such as the open source system Meshlab (*meshlab.sourceforge.net).* The 3D model and the GIS are referenced to UTM coordinates on WGS 84 (ITRF8) determined via GNSS survey by the Zamani team.


a


b

Fig. 5. Narrow passage in the Siq which make the acquisition of upper parts of the slopes by TLS impractical if not impossible(a) and scanner positioned at one of the few places where scanning from the top was possible.

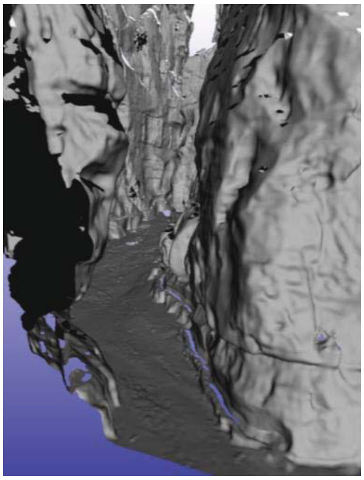


Fig. 6. Example of the Siq surface model. The large black area to the left is seen, in this perspective, from inside the rock wall whereas the smaller black patches inside the Siq are areas invisible to the scanner.

3.1.2. Cross-sections

The 3D model of the Siq walls also had to be available in 2D formats for processing and display in a variety of CAD and analysis software applications[4]. For this purpose sections and ortho-images were generated.

One hundred-and-twenty-one cross-sections at approximately right angle to the central axis of the Siq were generated from the 3D model at intervals of 10 m (Fig.7).

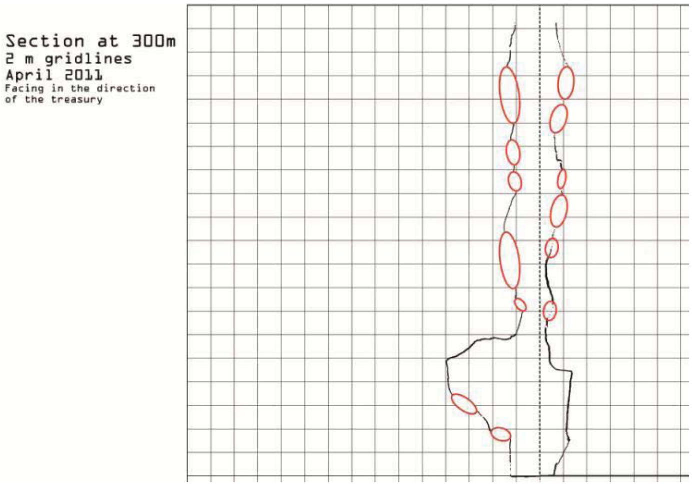


Fig. 7. Cross-section through the Siq. Invisible areas are indicated in red.

3.1.3. Ortho images

Sixty nine ortho-images (Fig.8) of the Siq wall were created covering the full extent of the Siq rock walls[4]. It is important to note that, due to the non-planar nature of the rock surface, it is not possible to create ortho-images which can be used for accurate measurements, as would normally be possible for ortho-images (Fig. 9). Thus these images are primarily useful for inspection of wall sections and annotations, whereas measurements should be done on the 3D model in 3D viewing and measurement software (such as Meshlab). Measurement on the ortho-image are only correct for surfaces which are parallel to the projection plane of the ortho-image. Deviations of the rock surface from this condition result in errors.

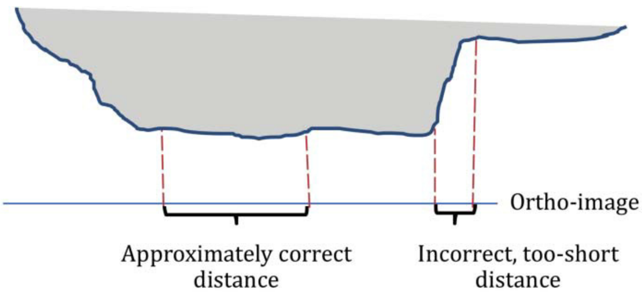


Fig. 8. Distortions in ortho image due to irregular surface shapes.

Fig. 9. Ortho image of rock wall showing surface details

3.2. Panoramas

One hundred and two full dome photographic panoramas were acquired for the Siq of Petra, at an average interval between panorama stations of about 10m[4]. Each panorama was generated from 21 to 49 images captured with a Nikon D 200 camera equipped with a 10.5 mm lens. In each case the camera was pointed into six horizontal and one zenith direction. Images were then taken with a view to High Dynamic Range (HDR) processing and depending on the light conditions 3, 5 or 7 bracketed images were acquired in each of the seven directions.

The panoramas were combined into a panorama tour which makes it possible to view the entire length of the Siq from the position of a person walking from the Siq entrance to Al Khazneh.

Such materials provided a very useful description and verification tool in the elaboration of the project, especially when not on site.

3.3. Mineralogy and petrography

Weathering of rock can have a wide range of causes, all of which must be considered in an integrated approach before embarking on conservation activities. An example for such an investigation is the conservation of the rock hewn churches of Lalibela in Ethiopia.

The rock-hewn churches of Lalibela, included since 1978 in the UNESCO's World Heritage List, attracted the attention of the conservation science community because of their severe chemical weathering and physical decay (Fig. 10).Thin section study, X-ray diffractometry (XRD) and SEM-EDS mineral composition of samples from seven rock-hewn churches (Biet Medhane-Alem, Biet Mariam, Trinity Church, Biet Giyorgis, Biet Emanuel, Biet Abba-Lebanos and Biet Gabriel/Rufael) were carried out. These investigations showed that the churches were carved in hydrothermally-altered and nearly aphyric vesicular basalts with incipient lateritization[6]. This is in contrast to the earlier literature on Lalibela which often reports the rock-hewn churches as being carved into "weathered basic tuffs". In reality, the geological materials are hydrothermally altered scoriaceous unit/s of the massive to slightly fractured basaltic lava itself still present as bedrock, and not a pyroclastic level stricto sensu. As a matter of fact, late-stage and post-magmatic phases (smectites, zeolites and calcite) scattered in the groundmass and filling the large subspherical vesicles represent a typical hydrothermal facies of continental flood basalts. Appropriate modal mineralogy and petrography of the Lalibela churches provided useful insights to unravel causes of deterioration of these World Heritage monuments.

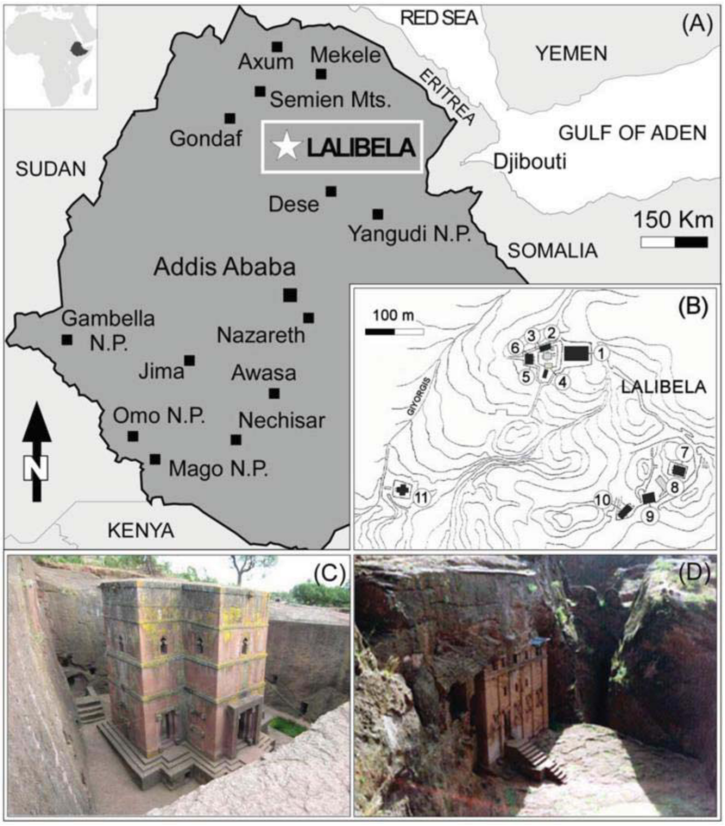


Fig. 10. (A) Location of the Lalibela site; (B) distribution of the 11 rock-hewn churches:1: Biet Medhane-Alem (BA); 2: Biet Maryam (BM); 3: Biet Masqal; 4: Biet Danagel; 5 and 6: Trinity Church (BT, i.e., Biet Debre-Sina and Biet Mikael-Golgota); 7. Biet Amanuel (BE); 8. Biet Maqorewos; 9. Biet Abba-Libanos (BL); 10. Biet GabrielRufael (BR); 11. Biet Giyorgis (BG); (C) view of Biet Giyorgis church; (D) view of Biet Abba-Lebanos church[7].

Considering the heavy deterioration affecting the investigated rocks, the correct petrographic (basalt) and lithological (partly lateritized vesicular lava) definitions, coupled with the comprehensive hydrothermal mineralogy areof paramount importance to better understand the causes of their chemical weathering and physical decay and to plan conservation actions. The presence of swelling clay minerals (due to hydrolytic weathering of silicates), minor dissolution-crystallization processes of soluble salts and the whole inexorable lateritization processes, typical of regions with dry and rainy seasons, all concur in the deterioration of the rocks. Additionally, a recent study[7]emphasises how the high microporosity of the abundant zeolites, coupled with the wide range of apparent density and porosity to water saturation should now be considered and further investigated in the framework of future conservation studies of the Lalibela rock-hewn churches.

In conclusion, very often weathering processes depend on a variety of factors, to be jointly investigated in a comprehensive manner. Such weathering, even if depending on micro processes may play a large role in the entire site conservation, as in the case of Lalibela reported in this paper.

3.4. Rock mechanic

Rock mechanic parameters are of paramount relevance for the conservation of rupestrial sites. Generally, since such sites are primarily carved on soft rocks, the strength and deformability parameters of rock material refer mainly to the rock mass, which is composed of the intact rock and the joint's family, depending on the scale of analysis. The intact rock is well described and characterized by UCS values while the rock mass is described and characterized by indices (e.g. RMR, Q_system, GSI) as a result of UCS, joints and water conditions combination. The following example is taken from the investigations for the consolidations of the remains of the destroyed Buddha Statues in Bamiyan (Afghanistan).

The rock mass of Bamiyan (Afghanistan) are composed of continental lithotypes, probably coming from the dismounting of surrounding morphological peaks and deposition in a flood plain and small lagoon. The subsequent river erosion produced the present morphology for the part where the rupestrial settlement is located[8].

The cliff and niches are composed of an alternance of conglomerate and siltstone (yellow at the bottom and red in the middle of the cliff); the conglomerate, with different sized pebbles (coarse-, mid- and fine-grained), is the predominant material in the cliff and exhibits a moderate cohesion. The siltstone is interlayering the conglomerate strata. The mean value for the uniaxial compressive strength of the conglomerate is 2.99 MPa, while the value for the uniaxial compressive strength of the siltstone is 6.91 MPa[9]. Point load data[10]show that the average UCS data are 11,0 MPa for siltstone and 5,6 MPa for conglomerate.

According the above the siltstone is apparently stronger than siltstone. A simple test with immersion in water, clearly shows a potential and relevant slaking attitude of the material, clearly not visible on site because of the low rainfall rate in the area (annual average rainfall equal to162.56 mm)[10].

The mechanism for the swelling is likely dependent on the presence of a cement carbonate in the conglomerate and the absence of such permanent cement into the sandstone, as clearly revealed by thin microscope section and x-ray diffractometry (Fig. 11 B and C).

Fig. 11. Stability of conglomerate (left in A) and degradation of siltstone (on the right in A) when saturated. Thin section of conglomerate with white carbonate cement (B) and thin section of siltstone (C)[10].

As a general conclusion it can be stated that relevant geomechanical parameters also depend on the local environment and a global and detailed investigation must be performed to avoid unexpected problems. In this case, considering the importance of water with respect to the adherence of potential anchors, as well as the use of water or air as drilling head cooling fluid, the complete understanding of rock behavior in different conditions is essential.

3.5. Semi-automatic discontinuities detection and analysis

In order to implement a kinematic analysis and further hazard analysis in rock slopes, discontinuities must be identified and mapped. Availability of TLS data make this step more advanced, allowing the structural analysis to be implemented through a semi-automatic method. As an example, the case study of rock-cut city of Vardziais reported. Vardzia is a cave monastery located 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 range in height over up to fifty meters within the rocky wall. The monastery consists of more than six hundred hidden rooms spread over thirteen floors, which protected the monastery from the Mongol domination (Fig. 12).

Fig. 12. General view of rock-cut city of Vardzia

Discontinuities data were obtained, in Vardzia (Georgia) 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[11]. 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 (Fig. 13). Thus a continuous planar structure appears in a unique color[12].

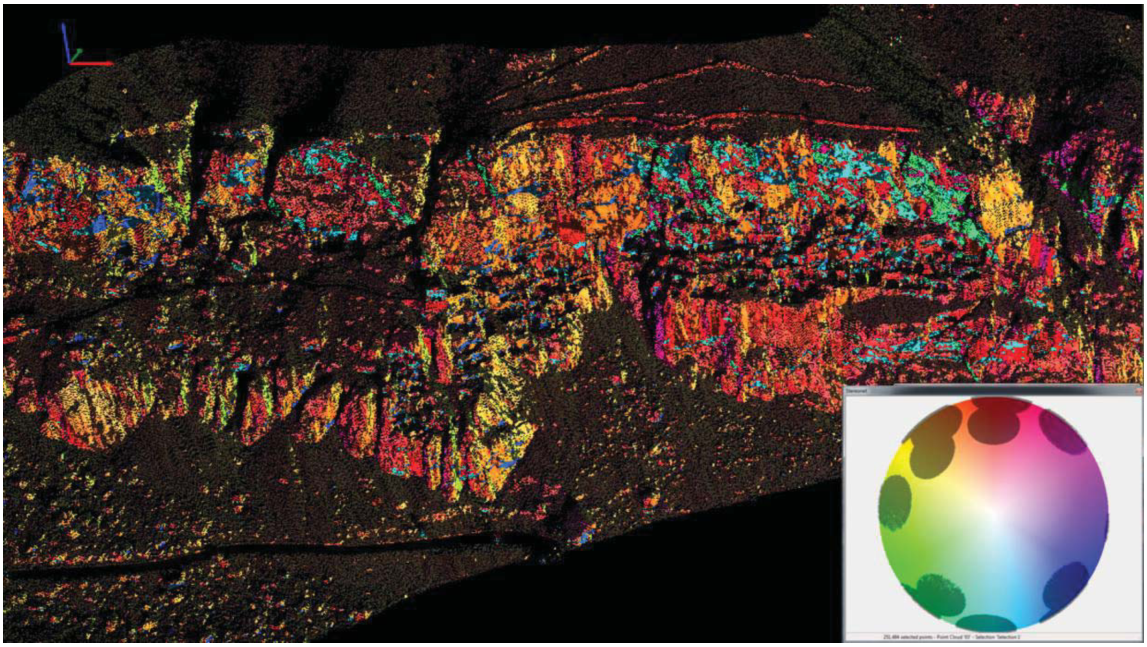


Fig. 13. The exposed rock faces of Vardzia cliff and detected slope aspect and slope angle, also on a Schmidt-Lambert stereonet [10]

With the aim of extracting 2D and 3D structural information from high resolution point clouds, a Matlab tool called DiAna (Discontinuity Analysis) has been recently compiled[13]. The 3D approach is based on the definition of least squares fitting planes on clusters of points selected by moving in the space a searching cube with variable dimensions. If the associated standard deviation is below a defined threshold, the cluster is considered valid. By applying geometric criteria it is possible to join all the clusters lying on the same surface; in this way discontinuity planes can be reconstructed, and rock mass geometrical properties are calculated. One of the main outcomes of the described procedures is the definition of surface roughness at different scales. For low scales this operation is however limited by the accuracy of the point cloud. The 2D approach is suitable for planar rock faces with no relief, and is based on the analysis of geometrical properties of discontinuity traces. Six of the ten parameters suggested by ISRM[14] for the quantitative description of discontinuities (orientation, spacing, persistence, roughness, number of sets and block size) can be semi-automatically calculated with the proposed method. The remaining four parameters (aperture, seepage, wall strength and filling) cannot be assessed from conventional high resolution point clouds, as their estimation requires direct access to the rock face.

Such approach was implemented in Petra and compared with manual field survey.

3.6. Kinematic analysis

Most classifications of mass movements and hazard assessment in rock slopes use relatively simple, idealized geometries for the basal sliding surface (BSS), like planar sliding, wedge sliding, toppling or columnar failures. For small volumes, the real BSS can often be well described by such simple geometries[15]. Extended and complex rock surfaces, however, can exhibit a large number of mass movements, also showing various kind of kinematic motions.As a consequence, the real situation in large rock surfaces with a complicated geometry is generally very complex and a site depending analysis, such as field work and compass, cannot comprehensively reveal the real situation.

The availability of digital slope surface data can offer a unique chance to determine potential kinematic motions in a wide area for all the investigated geomorphological processes. In more detail, the proposed method is based on least-squares-fitting of planes to point clusters extracted by moving a sampling cube over the point cloud. If the associated standard deviation is below a defined threshold, the cluster is considered acceptable. By applying geometric criteria it is possible to join all clusters lying on the same surface; in this way discontinuity planes can be reconstructed, rock mass geometrical properties can be calculated and, finally, potential kinematic motions established.

As previously mentioned, the Siq of Petra (Jordan), is a 1.2 km naturally formed gorge, with an irregular horizontal shape and a complex vertical slope, that represents the main entrance to Nabatean archaeological site. In the Siq, discontinuities of various type (bedding, joints, faults), mainly related to geomorphological evolution of the slope, lateral stress released, stratigraphic setting and tectonic activity can be recognized. Rock-falls have been occurring, even recently, with unstable rock mass volumes ranging from 0.1 m^3 up to over some hundreds m^3. Slope instability, acceleration of crack deformation and consequent increasing of rock-fall hazard conditions, could threaten the safety of tourist as well as the integrity of the heritage.

Thus, for the identification of the main rockfall source areas, a spatial kinematic analysis for the whole Siq has been performed, by using discontinuity orientation data extracted from the point cloud by means of the software Diana[14]. Orientation, number of sets, spacing/frequency, persistence, block size and scale dependent roughness were obtained combining fieldwork and automatic analysis. This kind of analysis is able to establish where a particular instability mechanism is kinematically feasible, given the geometry of the slope, the orientation of discontinuities and shear strength of the rock. The final outcome of this project was a detailed landslide kinematic index map, reporting main potential instability mechanisms for a given area. The kinematic index was finally calibrated for each instability mechanism (plane failure; wedge failure; block toppling; flexural toppling) surveyed in the site.

A synthetic view was also provided, integrating all the different probability of occurrence for the different kinematic conditions, into a single evaluation. This elaboration, as in the following Fig. 14, may help the general management of the site, identifying most endangered places, however a detailed case by case investigation is still required.

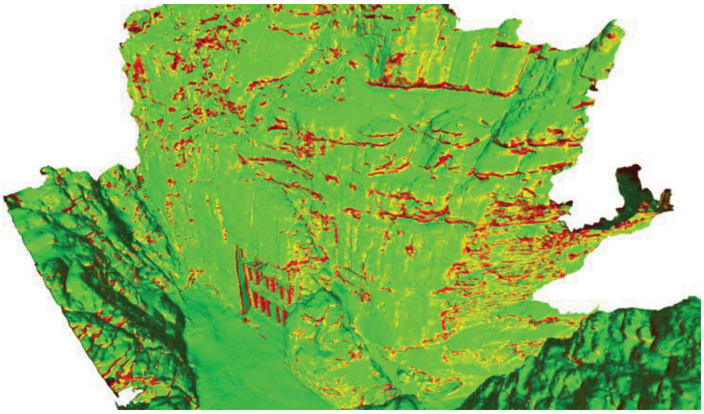


Fig. 14. Integrated result from the 3D individual kinematic analysis for the different analyzed instability mechanisms (block toppling, flexural toppling, wedge failure, plane failure and free fall) in the Treasury area (Petra, Jordan). The probability of occurrence (hazard) is expressed following a common colour scale (0%-30% of probability to be involved in a kinematic process).

3.7. Infrared thermographic analysis (IRT)

The InfraRed Thermography (IRT) is a non invasive technique that has also recently been applied to the rapid detection of slope portions, mainly investigating thermal anomalies on the rock mass and along the discontinuities..

Thermal imaging is based on the detection of electromagnetic waves in the thermal infrared spectrum, which are converted to electrical signals. All objects with temperature above 0 K (−273.15 °C) emit characteristic IR radiation, which can then be displayed in the visible spectrum by thermal imaging cameras.

The IRT detection method relies on air circulation and ventilation through open joints and cracks when, in winter, the warmer subsurface communicates with the (colder) ground surface; cracks can thereby be identified as relatively warm areas using IRT. The contrast between temperatures deep in the rock, which at depths of several meters generally correspond to the local mean annual temperature, and the actual temperature at the ground surface is accentuated by airflow in the open joints, cracks, and cavities. In winter, air circulating through open joints absorbs heat from deep within the rock mass, becomes warmer and lighter than the ambient air, rises, and is expelled through joints and caverns at the ground surface[16].

In the obtained surface temperature maps (thermograms) shown in Fig. 15, the temperature is represented through a colour scale, in which higher temperatures correspond to lighter colours, while colder temperatures to the darker ones. In order to obtain a comparison with TLS data, IRT data can be referenced to the laser scan data[17].

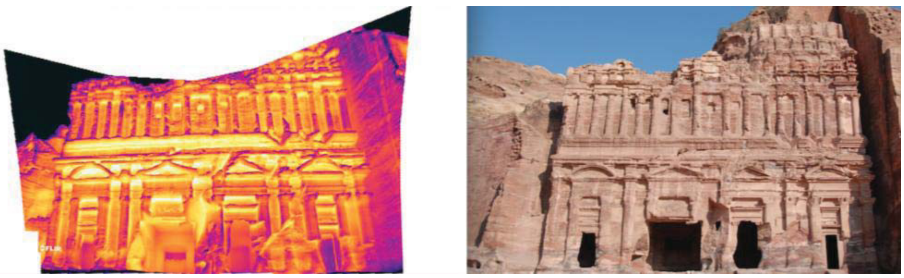


Fig. 15. Thermal image of the Palace Tombin Petra, compared with the image as seen by a normal camera.

The higher the temperature of an object of interest, the greater will be the intensity of emitted radiation. This means that larger temperature differences in an assessed area present brighter contrast levels in the image.

Water leaks and moisture zones are also potentially visible and detectable by using IR images, due to the lowering effect of evaporation which cools moist areas[18].

4. Monitoring

Landslide monitoring is required for a wide variety of reasons. These may include: the determination of the extent, magnitude and style of landslide movement, risk and even emergency risk management assessments and/or assistance with the design and implementation of site remedial and/or mitigation works.

Since each monitoring project has specific requirements, the measuring device used for deformation monitoring depends on the application, the chosen method and the required regularity and accuracy. Therefore, monitoring of slopes or landslide areas can only be defined, designed and realized in an interdisciplinary approach[19]. A close cooperation with experts from geology, geophysics and hydrology together with experts from any measurement discipline such as geodesy and remote sensing and other academic fields is an indispensable requirement.

Following are some example of advanced monitoring systems for the control of important archaeological sites.

4.1. Ground based radar interferometry

Large vertical rupestrian site, in open space conditions, can be effectively monitored, with high resolution and accuracy, through a new ground based remote sensing investigation: radar interferometry. An application is visible in the case study of Vardzia[20].

Considering the morphological settings of Vardzia, (slope extent ca. 105 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 future, the monitoring system into a warning system. The system adopted for the monitoring of the entire cliff is based on ground based interferometric radar. This equipment allows the monitoring of ground surface displacement, along 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 interferometric capabilities. The acquisition station has been realized with the valuable support of the NACHPG and the pre-acquisition and start up activities have been finalized and calibrated during the last field mission. The above mentioned technique (SF-CW) allows the resolution of the scenario along range direction independently of 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) of 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 in May 2012. Up to now it has been continuously operating. The radar configuration adopted is reported in the following table, the “selection mask” contains about 50.000 points.

Table 1. Main parameters of radar configuration in Vardzia (Georgia).

Topic	Dimension	Value
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

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

With the exception of some ostensible changes in individual control points (mainly due to noise factors related to vegetation) the investigated area is stable and under control (Fig. 4.1). 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.

Recent elaboration from Ilia University in Tbilisi, covering the time period 2013-2014, clearly identified 5 major areas of deformation (Fig. 16), one of which was stabilized in summer 2015.

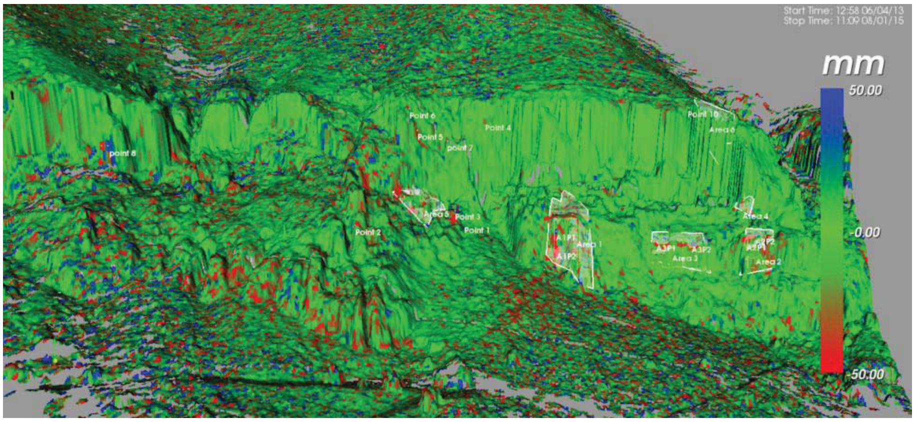


Fig. 16. Displacement detected from Gorund based radar interferometry on the rock cliff of Vardzia in the period 6 April 2013 – 8 January 2015. Displacements are plotted against distance from the Radar installation.

4.2. Reflector-less robotic surveying

For monitoring rock slope instability processes, geomatics methods are largely applied. Landslides are monitored by using Total Stations[21,22]and laser scanners, both conventional[23,24]and recent models capable of full-waveform analysis[25,26]. All geomatics-related activities should be integrated with geomorphological and geotechnical surveys, in order to better understand the potential failure mode of the landslide and set up a model; this analysis is also useful for early warning.

In the Siq of Petra, a robotic total station (LEICA TM 30), in reflector-less modality, was selected, to get the benefit of a high accuracy method as well as the largest capability to detect an analyze individual observation points selected by the rock mechanic specialists.

From a practical point of view, in any selected area one or more stations can be established. Such stations do not require precise permanent positions or ground markers, instead, a new highly precise position is determined for every new survey epoch, using a method referred to as Free-Station-Adjustment'. This approach can be adopted if at least three permanently fixed prisms are visible from the Total Station set up point.

At present, more than 1600 individual points have been selected in potentially unstable areas of the Siq for reflector-less surveying. Fig. 17 reports the point distribution in the treasury area.

4.3. Traditional geotechnical monitoring in Wireless environment

The low environmental impact, even from monitoring system, is a pre-requisite for any intervention in a high value cultural heritage site.

In order to define possible deformation paths and with the final aim to measure active displacement upon selected medium-large rock blocks affected by potential instability process, a proper permanent monitoring network was designed, implemented and installed along the entire Siq of Petra. The monitoring network(Fig. 18) consists of :

- n.2 Tiltmeters sentries;
- n.2 wire deformometer sentries;
- n.2 crack meter/gauges sentries;
- n.6 air humidity and temperature sentries;
- n.1 meteorological station.
- Geomechanical sentries are manufactured by Sisgeo and have been re-assembled by Minteos to provide longer duration measurement periods (about five years with four measurements per hour).

In order to solve the problem of the high visual impact of the monitoring network and related energy supplies and cables in the archaeological site of Petra, a wireless network equipped with long lasting batteries was designed, customized, implemented and installed. The present network is ensuring flexibility, remote control and future possibility to shift the system from monitoring to warning. The potentially unstable rock blocks were selected from the landslide inventory map, due to their potential hazard, size and typologies.

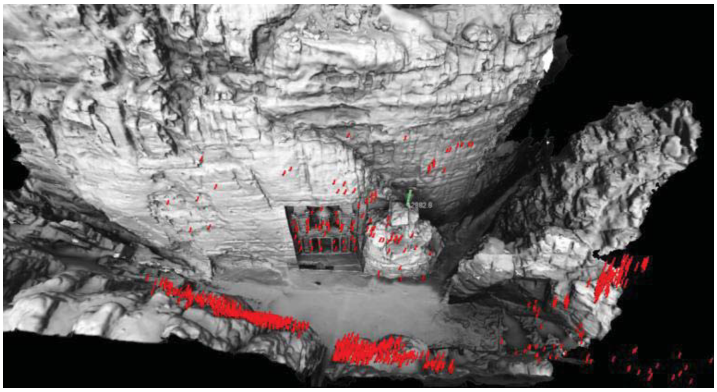


Fig. 17. Reflector-less surveyed points in the Treasury area (Petra, Jordan), superimposed onthe terrestrial laser scanner.

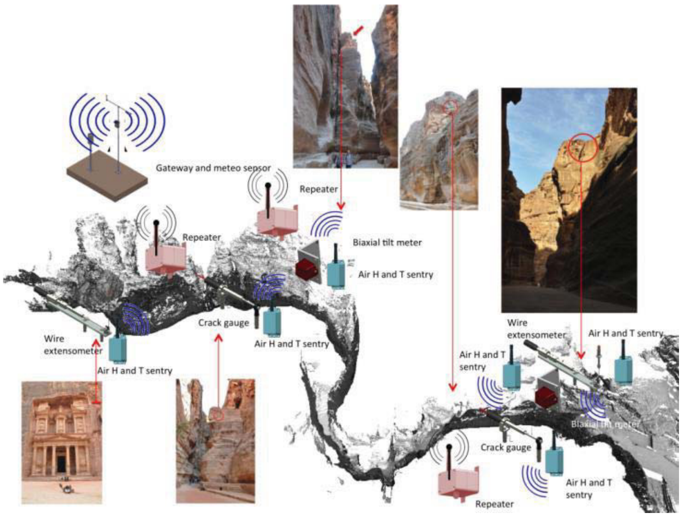


Fig. 18. Details of the geotechnical wireless monitoring network in the Siq of Petra (Jordan), superimposed onthe 3D laser scanner of Siq.

5. Conclusion

Understanding and monitoring the geotechnical and geological hazards threats, that are affecting rupestrian sites, is an interdisciplinary effort, involving, many branches of Earth Science. The latter include primarily rock mechanic, engineering geology, geomatics, physics and engineering.

The present paper demonstrates how the investigation and monitoring of rupestrian sites requires an interdisciplinary approach, developing comprehensive field investigations and monitoring processes, aimed at providing the scientific support to the required mitigation measurements. Clearly this paper is not reporting the comprehensive methodology, generally well known, but highlighting the contribution of emerging technologies and interdisciplinary approaches to some specific issue. In this light, major recent achievements for application in cultural heritage, without being exhaustive, involve the following. In the field of basic data collection: laser scanning, new panorama photo utilization, mineralogy and petrography, rock mechanic parameters, semi-automatic discontinuities detection and analysis; kinematic analysis, infrared thermographic analysis. In the field of monitoring: ground based radar interferometry; reflector-less robotic surveying, laser scanning and traditional geotechnical monitoring in wireless environment.

The collected data, jointly with traditional information mainly from rock mechanic and rock fall/slide investigation, allow the deep understanding of processes affecting a given site. The consequent mitigation strategy[27] can then be prepared in order to ensure effectiveness of adopted solutions, non-invasive infrastructures and hopefully, feasible employment of local materials and manpower.

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