



The Fourth Italian Workshop on Landslides

Advances in sustainable conservation practices 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 show major conservation issues in the domain of rock slope stability and rock weathering. The present paper reports the experience of rock fall mitigation 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 reported activities, include field conservation works enhancing traditional knowledge and sustainable practices, primarily based on local conservation techniques.

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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<sup>1</sup>.

A subsequent significant change concerned the process of planning, designing and building structures for human settlements. Architectural works, in the material form of buildings and/or rupestrian settlements, are often perceived as cultural symbols and as works of art and historical civilizations are often identified with their architectural achievements. However, architectural works are not merely physical construction. They represent the synthesis of a complex system that, in all ages, is guided by human genius, and it depends on the availability and types of construction materials (natural geological resources). Their form is determined by social and economic conditions, by local morphological situations (e.g. defensive settlements on top of cliff), and it is influenced by local meteorological conditions. The most relevant masterpieces of such human history, have been included in the UNESCO World Heritage List.

Following is a brief description of some advanced sustainable conservation practices, employed by the authors in selected case histories.

## 2. Conservation policies and management

Conservation of rupestrian sites is a complex endeavour, requiring expertise from the sciences of conservation, geotechnical engineering and earth science. On the other hand there is a high need for innovation, addressing the central and exclusive role of conservators in the past and looking toward a truly holistic and interdisciplinary approach. As a matter of fact, measures to be adopted need to be as much as possible:

- effective
- non-invasive
- feasible for the employment of local materials and manpower.

The first requirement is obviously aimed at solving the problem; the second to emphasize the maximum preservation of the original aspect of the site, while the third is meant to maximize the reproducibility, both in time and space, of the adopted techniques in case of further interventions. The latter also includes the involvement of local community in protection and development of the site. This is not a minor point, since local expertise and traditional knowledge may enrich the sustainability of the conservation policies, ensuring local management and the long term maintenance.

Clearly, since any site is showing a different problem, no standard procedures can be established. The following figure is trying to synthesize the potential interconnections among landslide science and science for cultural heritage conservation<sup>2</sup>.

Following are some example of rupestrian sites where the above approach was pursued. Clearly, any case is unique, showing peculiar natural processes and social elements. As a consequence any site must be investigated with high attention and avoiding the imposition of techniques and solutions that are not balanced in the specific cultural, natural and human “environment, then balancing mitigation strategies with local expertise and traditional knowledge.

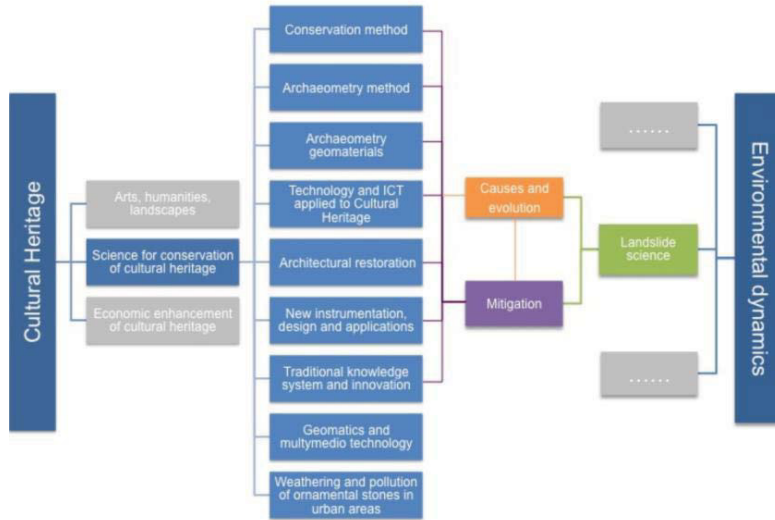


Fig. 1. Relationship between science for the conservation of cultural heritage and landslide science<sup>2</sup>.

2.1. Bamiyan

The historical site of Bamiyan is affected by geomorphological deformation processes which were worsened by the blowing up of the Buddhas in March 2001, which destroyed the statues, dating back to the 6th century AD (Fig. 2). Not only was invaluable cultural heritage irremediably lost, but the consequences of the explosions as well as the collapse of the giant statues also added greatly to the geological instability of the area. Traces of rocks which recently slid and fell, are relevant proofs of the deterioration of its stability conditions and most parts of the site now appear prone to collapse in the near future.



Fig. 2. Explosion and destruction of the Western (left) and Eastern (right) Giant Buddha Statues.

Under the coordination of UNESCO, a global project to assess the feasibility conditions for the site’s restoration was developed<sup>4</sup>; field data were collected and a mechanism for the potential cliff and niches’ evolution was provided. In the meantime some consolidation works were carried out in the most critical rock fall-prone areas, to avoid any further collapse in the coming winter season, but also to enable archaeologists the safely catalogue and recovering of the Buddha statues’ remains, still lying on the floor of the niches. The emergency activities started in October 2003 and finished on 2012, and included:

- the installation of a monitoring system, to evaluate in real time any possible deformation of the cliff. Sensor were designed to monitor the entire working area, connected with an alarm system, to guarantee the safety of those working inn site;
- the realization of temporary protection with steel ropes, and two iron beams suitable to avoid lateral deformation, inside the niche, from blocks destabilized by the explosion. Among the temporary work, just after the consolidation of the niche’s wall, a wire net was installed over the back wall of both niches to allow archaeologists to work on the ground floor in safe conditions,;
- the final stabilization of the East niche. In these area anchors, nails and grouting were introduced (figure 20), in order to reduce the risk of rock fall and collapse; particular care was given to the problem of grouting material because of the very high slaking capability of siltstone. The anchors placed in 2003 were pre-grouted to avoid any oxidation and then percolated inside the niche. From 2004 it was decide to use only stainless steel materials, even if not pre-grouted.
- minimization of intervention (anchor/nail head finishing) complete the execution of work. Anchor and nail heads were designed to be placed slightly inside the rock and then covered by a mortar allowing a total camouflage of the work. A number of tests for the best mixture of cement, local clay/silt and water, used to cover the anchor/bolt heads, were also developed in 2003, in cooperation with ICOMOS experts. The results provided the best chromatic, stability and robustness of the mixture.

Some minor consolidation and impermeabilization works were implemented in the Western Buddha niche in 2009.

Consolidation works were mainly implemented by professional climbers, directly operating on the cliff as well as by means of inner niche scaffolding (Fig. 3).

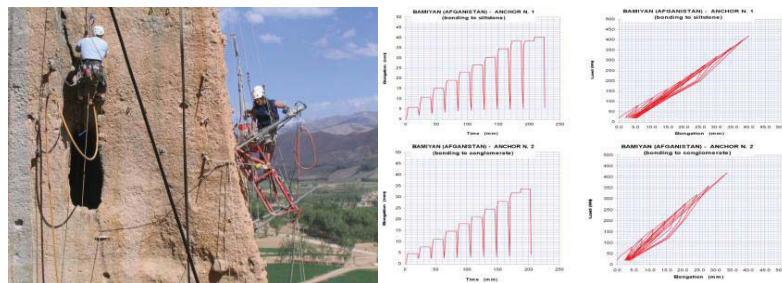


Fig. 3. Anchoring the Eastern Buddha niche (left) and pull-out tests for the use of 1 m length anchor in siltstone and conglomerate (right). The load (kN) and respective time (min) and elongation (mm) are reported showing, till 40 ton, the uphold of elastic domain and still the missing of any permanent deformation for the tested anchors.

Finally, after the stabilization of the external part of the Eastern Buddha niche, in 2009-2012 the inner back wall (shear zone of explosion) was stabilized by means of small anchors and limited grouting also aimed at fixing the still existing original part of the Statue plaster, jointly executed by Engineering Geologists and Conservators (Fig. 4).

## 2.2. Lalibela

Lalibela is located in the northern-central part of Ethiopia. The town, which has a population of about twelve thousand, is situated at an altitude of 2,600 meters in the Lasta province of the Amhara region.

The construction of the eleven rock-hewn churches is attributed to King Lalibela (1167-1207) of the Zagwe dynasty. They are still in daily use for religious practices and ceremonies, and on important religious occasions large crowds of believers and pilgrims gather at the site. The eleven churches and their surrounding area form a complex that is unique in the world. In 1978 the churches of Lalibela were included in UNESCO’s World Heritage List.

The churches have been exposed to physical erosion for approximately eight hundred years. As a result, their condition has worsened over the years, and has now become critical. To protect the churches from direct exposure to the rain, five churches, namely Bete Medhane-Alem, Bete Maryam, Bete Masqal, Bete Amanuel and Bete Abba-Libanos, have been covered by temporary shelters.

The shelter design had to respect the following requirements:

- complete reversibility;
- perspiration;
- non alteration of the aesthetic qualities and absolute respect of the harmonic shape of the complex and of the texture and colours of the materials
- to be implemented in a way to allow local management and maintenance.

Up to now no proper investigation nor restoration has been implemented. Only new shelters were introduced, but with an impact that was altering the aesthetic value of the site. Thus, the shelters are protecting from water infiltration and can be considered as a temporary reliable measurement before a correct conservation plan can be realized (Fig. 5).



Fig. 4. The scaffolding for the stabilization of back wall shear zone and the position and typology of installed anchors (diam. 22mm, 12mm, 6mm)

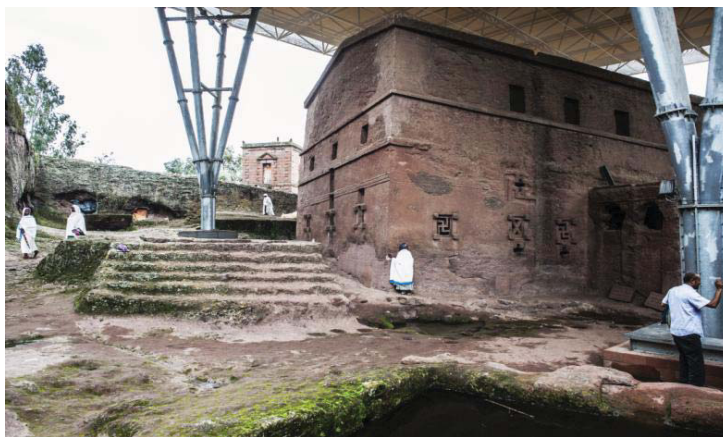


Fig. 5. The modern shelters covering the rock-hewn churches of Lalibela (Ethiopia) (source [www.flickr.com](http://www.flickr.com))



### 2.3. Petra

The Siq of Petra is entirely formed of fractured rock slopes and potential detachment of rock materials represents possible hazard to people. Slope stability mitigation techniques are briefly described according to the materials involved, as well as typology and magnitude of potential failures in the Siq slopes, focusing on the most common and feasible typologies that can be successfully applied to the mitigation of landslides.

The selection of a specific mitigation typology for the stabilization of blocks/slopes in the Siq has to be done according to several basic conditions that take into account the following: volume of the unstable block; height of the block above the ground; potential impact on archaeological remains; local technical feasibility; and cost/benefit analysis.

Field geological and geo-structural investigation of potential rock slope failures conducted in the Siq have determined that failure modes affecting the rock masses of the Siq slopes can be classified into the following categories, according to the type and degree of structural control (kinematic movement): i) Planar failures; ii) Wedge failures; iii) Toppling failures; iv) Free fall; v) Unstable loose blocks and debris.

According to the inventory map produced for the Siq Stability project<sup>3</sup>, the volumes of potentially unstable rock blocks have been differentiated into 3 classes: i) small blocks with volume  $<5\text{m}^3$ ; ii) medium blocks with  $5\text{-}15\text{m}^3$  volume; and iii) large blocks with volume  $>15\text{m}^3$ .

Depending on typology and volume, several kinds of mitigation works have been suggested. In any case, such technique cannot be applied without a local investigation on the considered site. In detail, the selection of potential working typologies has to take into account their impact on the peculiarity of the site geo-cultural environment (geomorphology, landslide types, presence of archaeological remains) so that only some specific typologies of consolidation interventions are recommended. Clearly, any intervention has to take into consideration the minimization of the environmental/visual impact of works, the local sustainability and feasibility, and the transfer of know-how to the local system. All these details are included in specific Guidelines<sup>4</sup> for the benefit of Jordanian authorities. Particular attention is given to the traditional techniques and the proper maintenance of such practices (Fig. 6).



Fig. 6. Manual and proper cleaning of stone dams, to protect the Siq of Petra from flash flood.

### 2.4. Vardzia

Vardzia represents an excellent example of a rock-cut city, which unites architectural monuments with an outstanding natural-geological environment. Such monuments are particularly vulnerable and their restoration and conservation requires a complex approach. The site is carved in various layers of volcanic tuffs and covers several hectares, with chronologically different segments of construction. This monument, as many similar monuments worldwide, is subjected to slow but permanent process of destruction, through the following factors: surface

weathering of rock, active tectonics (seismic displacement along the active faults and earthquakes), interaction between lithologically different rock layers, existence of major cracks and associated complex block structure, surface rainwater runoff and infiltrated ground water, temperature variations, etc. During its lifetime, Vardzia was heavily damaged by Historical Earthquake, such as in 1283, and only partly restored afterwards.

Currently there is major threat related to rock fall and rock slide<sup>5</sup>.

During summer 2015, after a joint collaboration with local Universities and Research Agencies, a first consolidation intervention was established. The mitigation project was based on an advanced monitoring system<sup>19</sup> and the following field survey:

- Geomechanical rock mass classification through scan lines, in order to derive the main geomechanical characteristics and indexes (e.g. RMR, GSI);
- Tilt test;
- Schmidt-hammer test on joint surfaces and intact rock block for in situ analysis of UCS (unconfined compressive strength);
- Point load test to provide UCS data from sampled blocks<sup>6,7</sup>;
- Strength and deformation parameters from scientific and technical literature<sup>7,8,9</sup> as well as from local technical reports;
- laboratory 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 of Vardzia rocks.

| Lithology  | Unit weight<br>$\gamma$ (KN/m <sup>3</sup> ) | porosity (%) | $\sigma$ dry<br>MPa | $\sigma$ sat<br>MPa | Basic friction angle ( $\phi^\circ$ ) | GSI | $\sigma$ dry<br>MPa | $\sigma$ sat<br>MPa |
|------------|--|--------------|---------------------|---------------------|---------------------------------------|-----|---------------------|---------------------|
| Grey tuff  | 16.3   | 37.2         | 10.3                | 3.6                 | 22°-32°                               | 70  | 0.8                 | 0.3                 |
| White tuff | 15.9   | 38.8         | 8.7                 | 2.8                 | 22°-32°                               | 65  | 0.9                 | 0.3                 |

All the performed investigations allowed the definition of the most unstable areas. The map is reported in the following Fig. 7.



Fig. 7. Joints, cracks and unstable blocks in Vardzia cliff.

It was then decided to stabilize one of the potentially unstable blocks, located in the lower-right portion of Fig. 6, the largest among the selected ones. Such block is also interesting because of an archaeological tunnel, connecting the flood plain with the rock-cut city.

The block, partially overhanging, is delimited on its back by a joint characterized by a high dip (in average 80°) and dip direction between 170° and 178°. Its length is about 11.5 m along this section, while the area of the block is about 20,8 m<sup>2</sup>. The more likely failure mechanism, based on the numerous in situ observations conducted along the cliff, is that of sliding along the joint described before. This discontinuity is also characterized by a significant opening in some of its portions, highlighting the precarious stability conditions of the rock-mass under investigation.

The stability of the block was then evaluated adopting the limit equilibrium approach, with reference to possible sliding along the joint above described, together with the effectiveness of the proposed mitigation measurements consisting of passive rock dowels. The safety factor *FS* for the potential sliding can be expressed as:

$$FS = \frac{C_{\text{rock bridges}} + N \tan \left( \varphi_r + JRC \log_{10} \frac{JCS}{\sigma_n} \right)}{T} \quad (1)$$

where the symbol  $C_{\text{rock bridges}}$  indicates the strength contribution of the rock bridges potentially acting along the joint.

The final calculation was then elaborated, also taking into consideration the block reinforcement constituted by the installation of 32 mm diameter steel dowels, characterized by improved adherence, with reference to a Feb44k concrete. The dowels should show a minimum characteristic yielding stress equal to 430 MPa, for a corresponding yielding load of 346 kN.

Unfortunately no experienced drilling company was available in Georgia, nor a proper scaffolding for the site. It was then decided to initiate a large capacity building exercise of a local company contracted by the Agency for Cultural Heritage Preservation of Georgia. An Italian engineer with considerable field work experience then accompanied the purchasing of equipment and the field work, including the construction of the scaffolding. The final successful result is shown in the following figure showing the realized wood scaffolding and the 48 installed dowels (Fig. 8).

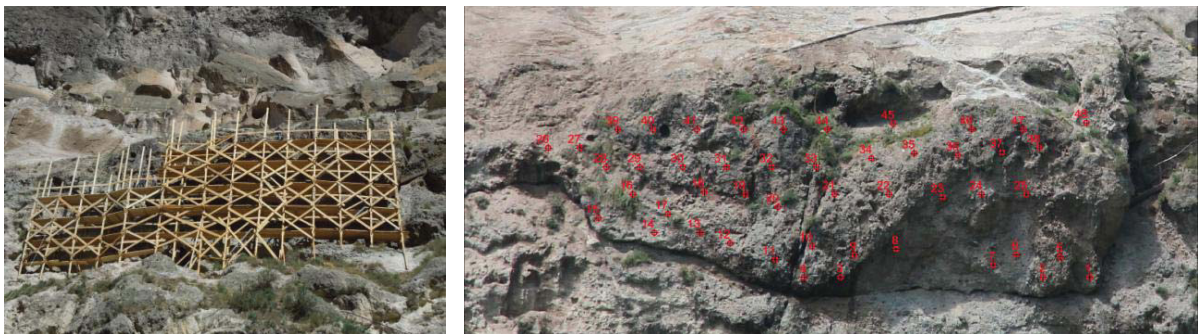


Fig. 8. The wood scaffolding and the map of the 48 installed dowels.

### 3. Conclusion

The protection of rupestrian sites, from geotechnical and geological hazards is an interdisciplinary effort, involving, at least, the Science of Conservation of Cultural Heritages and Earth Science. The conservator has to develop the proper restoration project, taking into consideration and having understood geological processes acting on the site and the monument; in the mean time, the engineering geologist has to implement a mitigation plan and monitoring system which fulfill the request for low impact and perfect integration of solutions into the



archaeological contest. A typical example of connection points between these two major branches of science in heritage conservation, is the usage of solutions with low environmental impact, that cannot damage the site or the cultural landscape, while clearly reducing the natural processes acting on the site; similarly it is required to use materials that, over time, cannot lose original properties, generating salts, oxides, etc., that may affect the integrity and conservation of the heritage site.

The above considerations, without being exhaustive, clearly underline the impact that the Earth Sciences have had in understanding and monitoring threats, as well as in the conservation of the cultural properties; it is self evident that the same disciplines have to assume, today and in the future, a fundamental role in all the policies that are necessary for the protection and conservation of the heritage affected by geological threats.

This aspect of conservation has never been very clear in the past, since the archaeology and the conservation aspects had a strong centrality and autonomy. This point of view is now less evident, with more attention to the integration of different sciences. Indeed it is possible to affirm that the protection of the cultural heritage represents an interdisciplinary process (and not multi-disciplinary) at the border-lines of art, history, science, policies for management and exploitation.

The present paper demonstrates how the conservation of rupestrian sites requires an interdisciplinary approach, developing comprehensive field investigations and monitoring processes but, finally, implementing conservation practices and management of the sites that are based on local expertise and traditional knowledge. 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.

The collected data, jointly with traditional information mainly from rock mechanic and rock fall/slide investigation<sup>10</sup>, allow the deep understanding of processes affecting a given site. The consequent mitigation strategy can then be prepared in order to ensure effectiveness of adopted solutions, non-invasive infrastructures and hopefully, feasible employment of local materials and manpower. More in detail, a proper investigation on local expertise joined with traditional and indigenous knowledge should address the proposed solutions in order to facilitate their execution and maintenance in time, and then, in other words, to enhance sustainability.

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## References

1. Margottini C., Spizzichino D. How Geology Shapes Human Settlements. In Bandarin F., van Oers R. (eds.) 2014. *Reconnecting the City. The Historic Urban Landscape Approach and the Future of Urban Heritage*. Chichester: Wiley Blackwell; 2014. p. 47-84.
2. Margottini C., On the protection of Cultural Heritage from landslides . In Margottini C., Canuti P., Sassa K. (eds.), *Landslide Science and Practice: risk assessment and mitigation*. Key note in Landslide and Cultural Heritage session. HEIDELBERG-BERLIN-NEW YORK: SpringerVerlag Inc.. ISBN: 978-3-642-31318-9
3. Margottini C., editor. *After the destruction of Giant Buddha Statues in Bamiyan (Afghanistan) in 2001. A UNESCO's emergency activity for the recovering and rehabilitation of cliff and niches*. Berlin-Heidelberg: Springer-Verlag, 2014
4. Margottini C., editor. *Guidelines for the sustainable mitigation and management of landslides at the Siq - Petra World Heritage Site*. ISPRA Internal Report to UNESCO-Draft; 2015
5. Margottini C., Antidze N., Corominas J., Crosta G.B., Frattini P., Gigli G., Giordan D., Iwasaki I., Lollino G., Manconi A., Marinos P., Scavia C., Sonnessa A., Spizzichino D., Vacheisvili N. Landslide hazard assessment, monitoring and conservation of Vardzia Byzantine monastery complex, Georgia. *Landslides* 2015; **12**:193–204
6. ISRM- Commission On Classification Of Rocks And Rock Masses - Basic Geotechnical Description of Rock Masses. *Int. Journ. Rock Mech. Min. Sci. & Geomech. Abstracts* 1981; **18**:85-110.
7. ISRM - Commission On Standardization Of Laboratory And Field Tests – Suggested methods for the quantitative description of discontinuities in rock masses. *Int. Journ. Rock Mech. Min. Sci. & Geomech. Abstracts*, 1978; **15n.6**:319-368.
8. Hoek, E. *Practical Rock Engineering* 2007. <http://www.rocsience.com> (access Sept. 2015)
9. Barton, N.R.. Review of a new shear-strength criterion for rock joints. *Engineering Geology*, 1973; **7**:287-332.
10. Margottini C., Gigli G., Ruther H., Spizzichino D. Advances in geotechnical investigations and monitoring in rupestrian settlements inscribed in the UNESCO's World Heritage List. *The Fourth Italian Workshop on Landslides* (This volume).