Innov. Infrastruct. Solut. (2017) 2:25
DOI 10.1007/s41062-017-0074-7

REVIEW

Historical accesses to UNESCO cultural heritages: engineering geology for the sustainable conservation of Petra Siq

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Received: 4 May 2017 / Accepted: 2 June 2017 / Published online: 19 June 2017

Abstract Cultural heritage represents the legacy of the human kind on the planet earth. It is evidence of millennia of adaptation of humans to the environment. Cultural heritage can be intangible (e.g., traditional knowledge, customs, ritual practises or beliefs) and tangible, the latter including various categories of places, from cultural landscapes and sacred sites to archaeological complexes, individual architectural or artistic monuments and historic urban centres. The most world wide representative Cultural and Natural Heritages are included within "UNESCO Convention Concerning the Protection of the World Cultural and Natural Heritage". They are the flagship of a large number of monuments and sites diffused at both national and local level. 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 as the erosion of rocks, compounded by the effect of climate change, without disregarding the role of humans, especially in conflict situations. Cultural Heritages required proper infrastructures to be used by local populations. Such infrastructures are part of the heritage itself and nowadays need adequate attention for a sustainable conservation and maintenance. Typical example is the Siq of Petra (Jordan). In the present paper the role of engineering geology and earth science in general is described for the conservation and management of a masterpiece of cultural properties such as the Siq of Petra. The relevance and potential of these areas of study was not fully appreciated in the past. At present, however, their contribution is increasingly acknowledged as the need for an inter-disciplinary approach, which would bring together art history, science, management and socio-economic concerns, has become more and more apparent. This paper will focus on the relevance of modern technologies for investigation and monitoring, as a fundamental step for a safeguarding project that have to enhance, as much as possible, traditional knowledge and local sustainable practises, in conservation techniques.

Keywords Petra · Siq · Main entrance · Slope instabilities · Sustainable risk mitigation

Introduction

The rock cut city of Petra (SW Jordan) is a world wide famous UNESCO (United Nations Educational, Scientific and Cultural Organization) cultural heritage site known for the beauty and uniqueness of its monumental area. The access to the archaeological area, since Nabataean times, is guaranteed by the Siq—a 1.2 km naturally formed deep gorge characterised by very steep slopes of variable height, up to several tens of meters. The Siq connects the urban area of Wadi Musa with the monumental area of Petra and represents, since Nabataean times, the main narrow entrance for some thousands tourists that access Petra

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This paper was selected from GeoMEast 2017—Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology.

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every day. Recent active landslide processes involving the whole Siq and other sectors of the archaeological park have rised the attention on the conservation of the site as well as on the safety of tourists. An international project, managed by UNESCO (Sustainable Monitoring Techniques for Assessing Instability of Slopes in the Siq of Petra, Jordan), was funded by the Italian Ministry of Foreign Affairs for the analysis of slope stability conditions of the Siq and for the implementation of an integrated remote and field monitoring system aimed at the detection and control of deformation processes. [4]. The project ended on last June 2015.

The present paper focuses on the stability conditions of the Siq and the monitoring activities that have been implemented during the project. Clearly the Siq, is showing an important archaeological and landscape value and then requiring high attention. On the other side, this was one of the examples of major infrastructure developed and maintained for the access to Petra site. The Siq was in fact used for approaching the site, but also for other supplies such as the water discharge. Regular maintenance was implemented during the time, e.g., diverting the ephemeral water discharging form upper Wadi Musa till today cleaning and mitigation of rock fall.

Surface model of the siq

A 3D computer model of the rock walls on both sides of the Siq was carried out for the reconstruction of the whole Siq geometry, characterised by a 1.2 km length with heights varying from about 70–120 m (Fig. 1). The adopted solution was the laser scanning, making the site of Petra likely the largest scanned archaeological site in the world [24]. The total number of scans in the Siq was 220 with an average point interval of approximately 3 cm. The lower wall areas over the entire length of the Siq were thus captured up to a height of 20–80 m, depending on visibility The scans at high elevations provided, in some cases, surface data from Siq floor to the top of the rock walls. Given this a point cloud of five billion points was generated.

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 can be viewed in 3D viewing and processing software [30].

Geological and geomorphological features of siq

Petra is located on the eastern side of the Dead Sea Wadi Araba tectonic depression, a ca. 15 km-wide topographic low formed by shearing along the transform fault separating the Arabian and Sinai plates [11, 26] (Fig. 2).

The local stratigraphic succession [2, 23] starts with ca. 50 m thick Salib Arkose arenitic formation, overlain by >500 m thick massive and poorly stratified Cambrian-Ordovician quartzarenites of the Umm Ishrin and Disi formations where the hand-carved rock monuments of Petra are entirely cut. The lithological and petrographic characteristics of the two formations are responsible of the weathering processes affecting all the area. As above mentioned, the Siq has a length of ca. 1.2 km with a general E-W orientation and a meandering course. It is entirely formed within the Umm Ishrin Sandstone Formation that can be subdivided into three main units, according to texture, mineralogical composition and engineering classification (Fig. 3). The Upper Sandstone, called “honeycomb sandstone”, is composed of white and mauve-red, coarse to medium grained, hard sandstone, forming very steep slopes. It is characterised by typical cavernous weathering caused by dissolution of cement and consequent granular

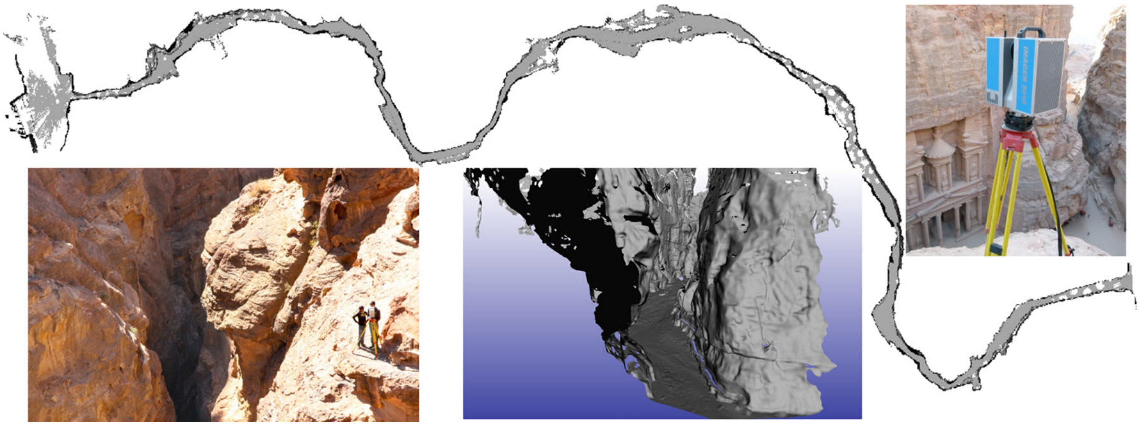


Fig. 1 Top view of the Petra Siq and laser scanning survey [20]

Fig. 2 Satellite image of the Siq (*red circle*) and Petra archaeological area [27]

disintegration that form the typical honeycomb structures. The Middle Sandstone (tear sandstone) consists of multi-coloured, medium to fine-grained, well-bedded and friable sandstone. The Lower Sandstone (smooth sandstone) is made of white, medium to coarse-grained, hard sandstone.

A geo-structural characterisation of discontinuities was performed in the Siq to provide the reconstruction of the structural setting of the area. Generally in the Petra area straight, individual joints, with mostly vertical planes, can be followed in the field for long distances (up to 500 m), mainly related to tectonics. Medium-angle joints are related to lateral unloading due to water erosion coupled with tectonic uplift. The intensity of jointing is variable depending on distance from faults and strength of materials (i.e., higher within the sandstone sequences, lower within sandstone layers). The rose diagram (Fig. 4) on the left, shows that the major trend of joint systems in the whole Siq is distributed along a ENE-SSE direction coupled with high dip angles (70–90°) exhibiting a trend parallel to local slope faces.

These systems are in accordance with the dominant joint systems surveyed, (Fig. 3) right, in the area that strike between 50°–60° and 160°–170° and are characteristic of the Umm Ishrin Sandstone and Disi Sandstone Formations [16]. Also inclined joints, that represent the potential failure plane of sliding-mode blocks, are usually parallel to the main joint directions.

The geomorphology of the Siq is the result of long and short-term factors affecting this part of the Petra territory such as tectonic uplift, erosion due to runoff, differential erosion and weathering of sandstone materials. The presence of brittle sandstone in the Siq area and in the whole Petra park promotes a block composition of rocks due to high frequency of discontinuities of various origin (i.e., faults, joints, weathering).

All geomorphological processes and slope instability, acting along the Siq of Petra, are the results of different structural combination of the main joints families. This situation may cause potential sliding of blocks, whose dimensions are depending on local, orientation, density and persistence of joints. Rock slope failures and potential magnitude occurring in the Siq of Petra were recognised considering the main failure type (fall, topple, slide). They can be classified as: planar failures, wedge failures, toppling failures, and unstable isolated blocks (toppling/sliding) [5].

All the above geomorphological processes were collected and elaborated through a geo-database and a preliminary landslide inventory map (Fig. 5).

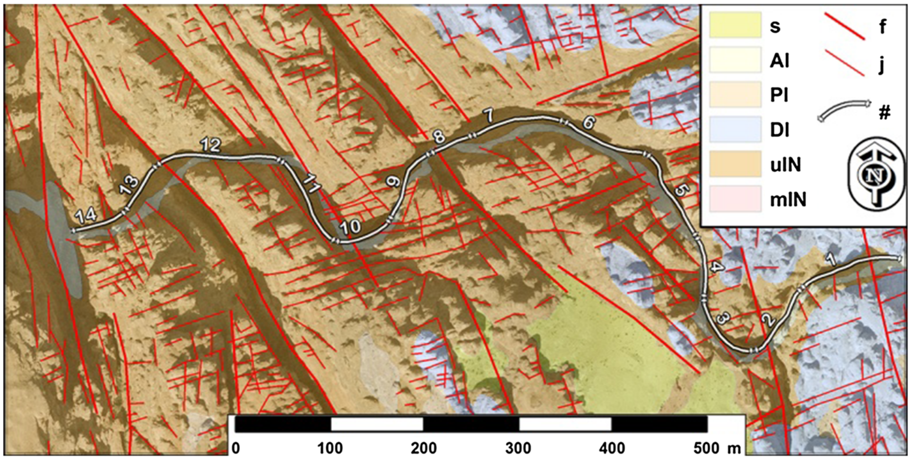
Geotechnical characterisation

Field investigations and sampling were conducted to identify the geomechanical characteristics of the Siq slope-forming rocks [27].

In most part of the Siq, two different main lithotypes were identified:

- a massive sandstone, present in the central portion of the slope;

Fig. 3 Sketch of main discontinuities of the Siq area performed by aerial photo interpretation and field survey. Legend: *s* (Pleistocene soil); *Al* (Alluvium and wadi sediments; *Pl* (Pleistocene gravel); *DI* (Disi Sandstone); *uIN* (upper Umm Ishrin Sandstone); *mIN* (middle Umm Ishrin Sandstone); *f* (fault); *j* (joint); # (sector number) [27]



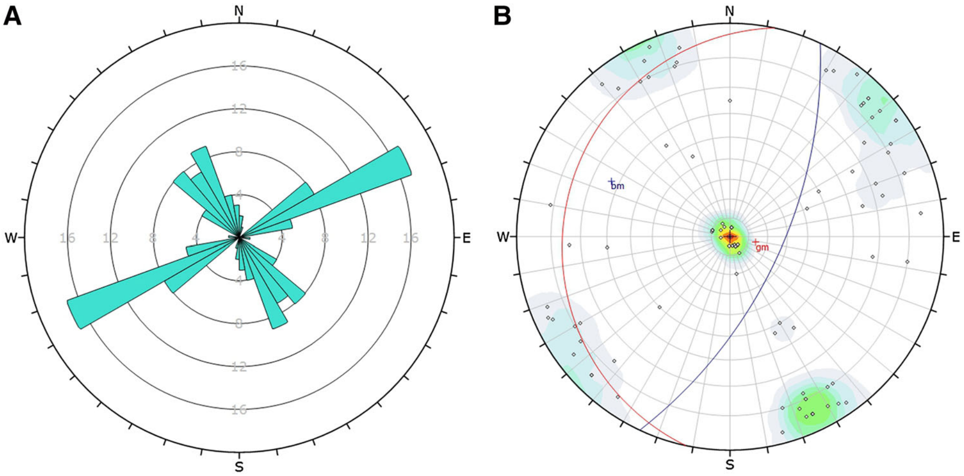


Fig. 4 Rose diagram (*left*) and plot (*right*) of joints surveyed in potential unstable sectors in the Siq [27]

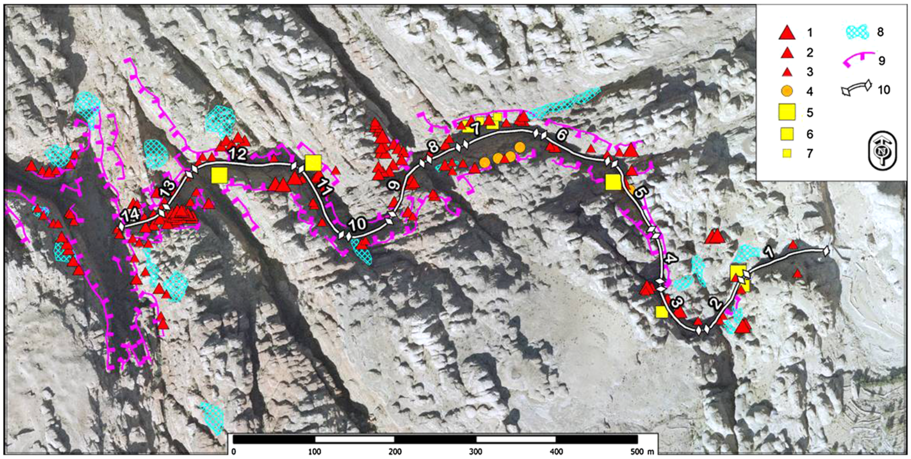


Fig. 5 Landslide inventory map of Petra area. Legend: *1* large rockfall; *2* medium rockfall; *3* small rockfall; *4* large toppling; *5* large slide; *6* medium slide; *7* small slide; *8* unstable debris; *9* scarp; *10* Siq sectors (numbered) [27]

- a weathered sandstone, at the top and at the bottom of the slope;
- a highly weathered sandstone, recognisable in small thickness layers at the base of the massive sandstone.

Some level of a highly weathered sandstone, can be recognisable at the base of the massive sandstone.

Laboratory tests on specimens obtained from core and natural blocks collected in the weathered sandstone layer provided values of the uniaxial compressive strength (UCS), elastic moduli, tensile strength and dynamic properties.

A summary of the main geotechnical parameters obtained by laboratory tests conducted on weathered sandstone samples is provided in Table 1.

Additional Brazilian tests were carried out on samples collected in a highly weathered silty sandstone outcropping in some portion of the cliff near the investigated block. The average value of the tensile strength resulted to be 0.33 MPa.

Table 1 Synthesis of the main geotechnical parameters of weathered sandstone from laboratory tests [27]

γ_{dry} (kN/m^3)	V_p (km/s)	V_s (km/s)	ν_{dyn}
20.8	2.15	1.18	0.28
UCS (MPa)	E_{sec} (GPa)	E_{tan} (GPa)	s_t (MPa)
22.85	6.45	9.46	2.84

In situ investigations were carried out along several scan-lines. In particular, the following tests were performed:

- Schmidt hammer tests both on discontinuities and intact rock;
- point load tests with portable equipment for the assessment of UCS;
- tilt tests on core rock blocks for the determination of the base friction angle fb;
- JRC measurements by the Barton profilometer.

The resulting in situ geotechnical parameters are reported in Table 2.

An estimate of the geomechanical index GSI and of the corresponding mechanical parameters of the rock mass according to Bieniawski [3], Trunk et al. [29] and Marinos and Hoek [21] are summarised in Table 3.

Kinematic analysis

Slopes in rock masses are usually characterised by marked steepness and variable predisposition to generate instability phenomena, that often threaten valuable elements at risk, such as villages, single buildings, cultural heritage or communication routes [7, 9, 10]. Petra constitutes an outstanding example of these contexts, where the instability mechanisms are mainly controlled by the spacing, orientation and shear strength of discontinuities, as well as by the local slope dip and dip direction.

Stability analyses of rock slopes can be carried out through deterministic (usually single slope or wedge analyses) or statistic approaches, such as the kinematic analysis. When large rock walls outcrop and diffuse and multiple instability mechanisms are generated by heavily fractured rock mass (like in Petra), the second approach is advisable.

As discussed in the previous section, advanced surveying methods, such as terrestrial laser scanning, are able to provide accurate and high resolution 3D reconstruction of slope morphology, from which the position and orientation of the main rock mass discontinuities can be extracted [8]. In the same time, the high resolution DEM obtained from the point clouds is a valuable input for a true 3D kinematic analysis (Fig. 6).

Moreover, the possibility to extract information from large and remote areas is suitable for applications in the field of engineering geology and emergency management, when it is often advisable to minimize survey time in dangerous environments and, in the same time, it is necessary to gather all the required information as fast as possible.

Traditional geomechanical surveys are performed in situ, either in one dimension (scanline method) or two dimensions (window method), and require direct access to the rock face for the collection of the relevant parameters. ISRM [14] selected the following ten parameters for the quantitative description of discontinuities in rock masses: orientation, spacing, persistence, roughness, wall strength, aperture, filling, seepage, number of sets, block size. For practical and safety reasons, traditional geomechanical surveys are often carried out on limited sectors of the rock mass, and usually they do not provide data for a complete reconstruction of the full variability of a rock mass.

Table 2 Geotechnical parameters estimated from in situ tests [27]

Lithotype	1	2	3
γ_{nat} (kN/m^3)	21.7	20.1	19.2
UCS (MPa) (Point Load test)	100	20	5
f_b (°) (Tilt test)	–	40–45	35–43
JRC (Barton profilometer)	4–6	4–6	4–6

Table 3 Geotechnical parameters estimated from GSI [27]

Lithotype	GSI	c (MPa)	f (°)	E (GPa)
1	73	0.35–0.40	36–50	9–18
2	66	0.30–0.35	33–47	6–12
3	59	0.25–0.30	31–45	2–4

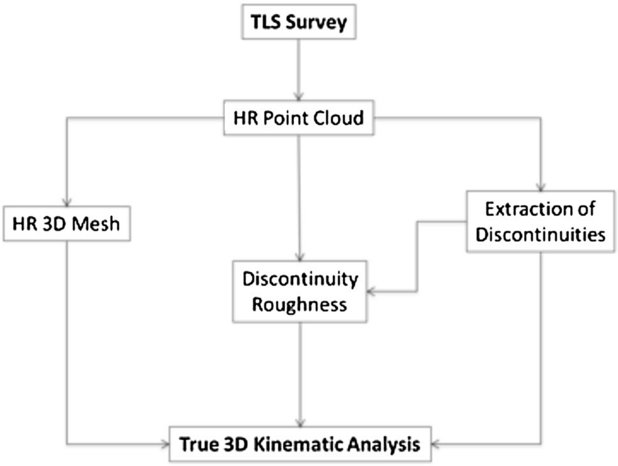


Fig. 6 Flow chart of the proposed approach for True 3D kinematic analysis from high resolution TLS data [20]

During the last years many authors have been working on the extraction of 3D rock mass properties from remotely acquired high resolution data, mainly digital photogrammetry and LIDAR [6, 15, 19, 25, 28].

Rock faces with rugged shape can be investigated by inspecting the discontinuity surfaces exposed on the slope. Such 3D approach requires the extraction of clusters of points belonging to the same discontinuity plane from the point cloud; subsequently, a spatial analysis for the quantitative description of discontinuities within the rock mass has to be performed.

The proposed approach is described in detail in [8], and is based on the definition of least squares fitting planes on clusters of points extracted by moving a sampling cube on the point cloud. 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.

The advantage of using this procedure lies in its capability to investigate all the geomechanical parameters that do not require direct access to the rock mass, thus, making this a more complete analysis with respect to the existing methods. The output ISRM [14] parameters are: orientation, number of sets, spacing/frequency (and derived RQD), persistence, block size and scale dependent roughness, the latter being an important input parameter for the kinematic analysis.

Finally, for the identification of the potential rockfall source areas, a spatial kinematic analysis has been performed for the whole Siq, using discontinuity orientation data extracted from the point cloud by Diana and the high resolution DEM obtained from the TLS survey.

This kind of analysis is able to establish where a particular instability mechanism is kinematically feasible, given the geometry of the slope and the orientation of discontinuities [13, 17, 18, 22]. The main instability mechanisms investigated with this approach are: plane failure; wedge failure; block toppling; flexural toppling, and free fall.

The following (Fig. 7) reports the elaboration for the Southern side of the Siq, along the 1.2 km length. It is possible to notice the flow path [8] from laser scanning survey, the individual parameters that can be reconstructed (slope, aspect, global and overhanging), the assessment of separate kinematism (planar failure, wedge, flexural toppling, direct toppling and free fall) and, finally, the possibility to integrate all data in a unique view reporting the overall global kinematic index (courtesy G. Gigli). Such index, even if quite general, can provide a useful information to involved managers, addressing the most potentially vulnerable parts of the slope.

Monitoring system

According to the above results, and considering the morphological setting and slope instability processes, the following monitoring techniques have been proposed, designed, implemented and installed for the monitoring of the Siq slopes in Petra [4] (Fig. 8):

- Satellite SqueeSAR$^{\text{TM}}$ analysis with permanent scatters techniques, to evaluate potential regional deformation pattern of the site and possible Siq border effects;
- automated crack gauge network, with wireless connection, to monitor main cracks and isolated potentially unstable blocks, with a low environmental impact technology;
- high resolution total station network measuring a prisms network, individual reflectorless points network and reflectorless grid network in the Siq slopes, for monitoring slope/blocks deformation; manual crack gauge network on 25 main discontinuities;
- manual crack gauge in relevant discontinuities.

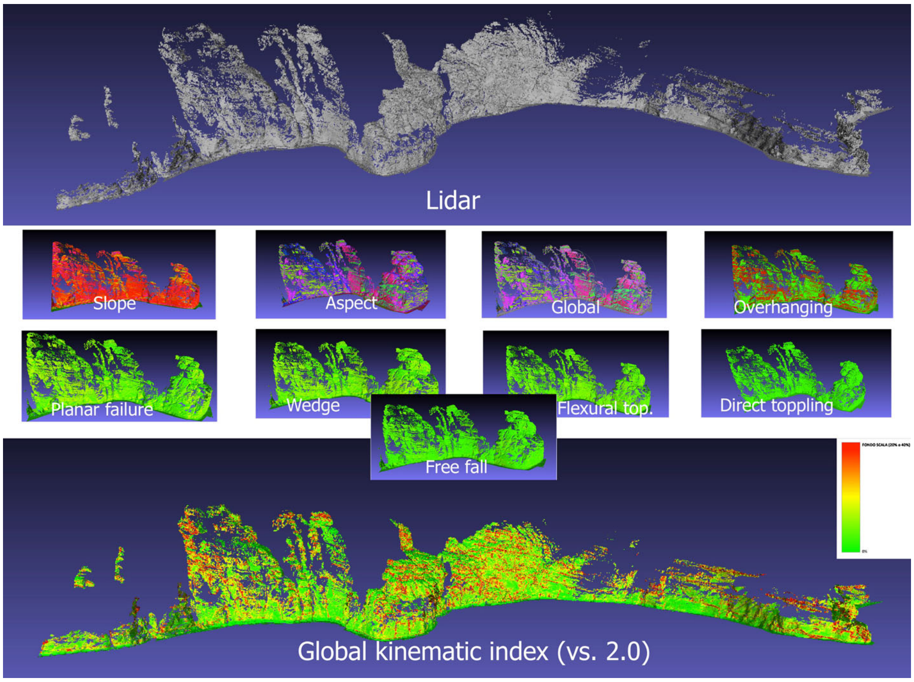


Fig. 7 Kinematic analysis in the Siq of Petra for the different typology of instabilities. A global integration of all data have also been produced, for a general overview (courtesy G. Gigli)

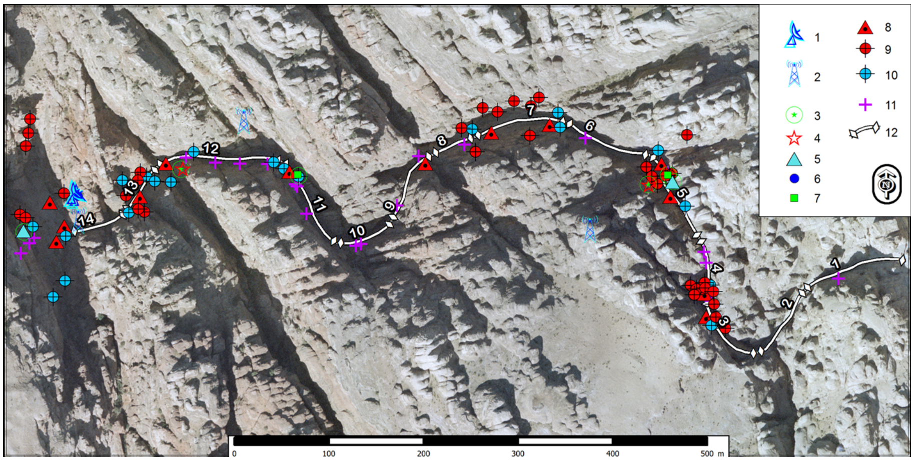


Fig. 8 Monitoring system map: *1* gateway; *2* repeater; *3* air-temperature/humidity sensor; *4* crackmeter, *5* wire deformometer; *6* meteorological station; *7* tiltmeter; *8* TM30 robotized station; *9* TM30 monitoring prism; *10* TM30 reference prism; *11* Manual crack gauge, 12 Siq sector [4]

Satellite SqueeSAR^{TM}

A large area of Petra Park, involving the Siq and major monuments, was analyzed with SqueeSAR^{TM} technique, provided by TRE® [1]. The SqueeSAR^{TM} algorithm, recently developed, provide further improvement of PSInSAR^{TM} technology, providing distinct properties of the signal from radar satellites to detect millimetre-scale changes of the ground. The analysis has provided 62.000 PS measurement points from 2003 to 2010 and related time histories of the yearly average displacement velocity (Fig. 9). In the analysis, 38 images with only a descending orbit have been used; this means that any potential displacement along the main E-W and vertical components cannot be distinguished. This is related to the available dataset of ENVISAT images, used in this project. The theoretical time difference of an ENVISAT satellite image acquisition is 35 days, but the time series of the image used for the analysis exhibit a much higher temporal gap with a maximum of 280 days. This type of problem has a low influence on area affected by slow or very slow deformation. The minimum pixel resolution is 20 m × 5 m for the acquisition of a reliable PS so that actual deformation processes involving surfaces <100 m^2 cannot be evidenced with the PS technique. The C-band utilized in the analysis corresponds to a wave-length (λ) of 5.66 cm that allows the detection and measurement between two consecutive images (on a single isolated target) equal to 1.4 cm.

All PS dataset actually displayed consist of coherent measurement point with a ground deformation <1.4 cm during the all temporal distance covered by two consecutive images; any deformation exceeding such a threshold during the acquisition of two consecutive images has not been recorded due to loss of coherence and no longer displayed in the final dataset. All measurement points have a geographic accuracy variable from 7 m (along E direction) and 2 m along N direction so that the respective deformation data can be actually attributed to a different position in that field of accuracy, whereas the precision of the average velocity is equal to ±1 mm/year, with differential displacement measures of ±5 mm.

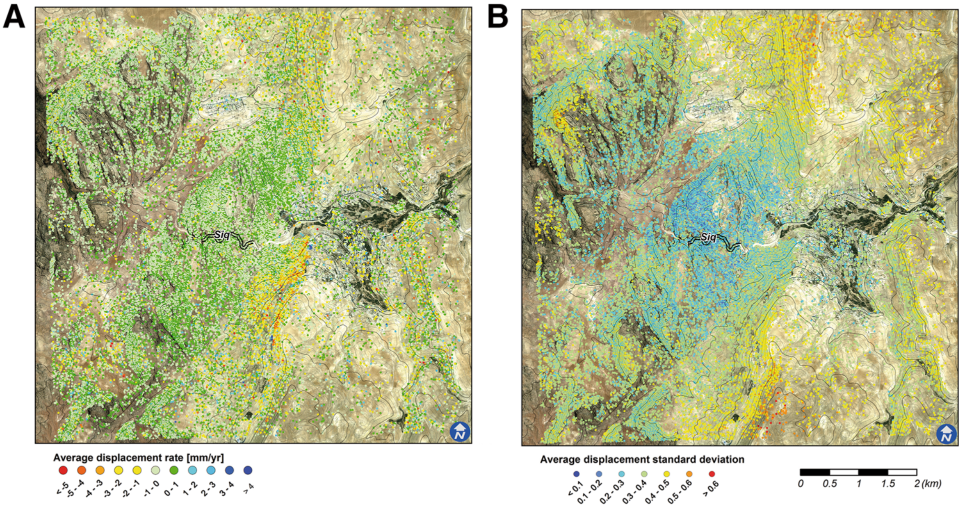


Fig. 9 Average LOS displacement rate of the MPs identified from the ENVISAT descending dataset (**a**) and average LOS displacement rate standard deviation plot of the MPs identified with the ENVISAT descending elaboration (**b**) [1]

The spatial density of identified MPs within the area of interest is extremely good in built-up and rocky areas (higher than 1000 MPs/km^2), while in areas characterised by a layer of moving sand it drops to a few MPs/km^2.

As a general conclusion [1], there is no evidence of major ground deformation phenomena in the Petra archaeological park, at least during the 2003–2010 period, covered by our satellite dataset.

Only a large block on the Siq, sector 5, is slightly tilting, according to ground based geotechnical sensors, not confirmed from satellite interferometry due to missing of vertical displacement. Another large block in the Treasury area is exhibiting some sinking MPs, at the limit of resolution for the radar interferometry. Thus, in this case, considering the presence of wide cracks on surface, the implementation of a ground based monitoring system will be useful. Also in the Royal tombs sector there are few MPs with a limited vertical sinking, surrounded by stable MPs, suggesting the need of a periodical inspection of such sites. The ancient rock falls in the Facades street are presently stable, for the adopted methodology.

From a methodological point of view [1], results obtained in this study confirmed the main advantage of remote sensing techniques: the ability to obtain a synoptic view of possible surface deformation phenomena affecting large areas and the possibility to then integrate this information with other in situ observations. In general, satellite InSAR measurements do not replace traditional ground monitoring instrumentations, but are complementary to them, due to the much larger spatial distribution.

On the other hand, minor small rock falls, of the order of cubic meters, clearly recognisable on site are hardly detectable with medium resolution interferometric data provided by the Envisat ASAR sensor due to decorrelation phenomena that might occur considering volumes/magnitude or involved surfaces of potentially unstable rocks with respect to the minimum detectable area of the technique (with ENVISAT about 20 m × 5 m) and the geotechnical behaviour of the Petra cliff and rock, characterised by a brittle rupture mode. In the latter case, the analysis could be better concentrated in a smaller time window, generally prior to collapse).

Finally a further improvement of InSAR data should be based on satellite data with much higher temporal and spatial resolution, such as the X-band COSMO-SkyMed constellation or TerraSAR-X/Tandem-X sensors.

Direct rock block monitoring with wireless network

An integrated network composed by two wire deformometers, two crack deformometers and two tiltmeters, six air-temperature sensors, a meteorological station, provided by Minteos® s.r.l., with wireless technology sensors for on-time registration and transmission of data, has been installed in the Siq in June 2013 (Fig. 10). Displacement of the main fractures, inclination of the blocks and meteorological parameters are the main data collected by the system.

The general structure of the platform for the storage and management of the collected data from the sensors is based on the following components: field devices, constituted by wireless sentries that measure and send via radio, the values of displacement (resolution 0.01 mm) and inclination (resolution 0.01°) to a short-range repeater (SSR); the SSR routes the sentries radio message in the Siq adding temperature and humidity data forwarding these to the long-range repeater (LRR); the LLR add rainfall, shielded temperature, humidity and wind direction forwarding all data to the main gateway, located in front of the Treasure (end of the Siq); the gateway collects and send the data to the Minteos server via GPRS and, in turn, to the main Siq Project servers for storage and analysis of results. The sensors will be provided with long-life batteries capable to manage 24 h measures per day per 5 years and further provided with solar cells to assure measurements in the event of a breakdown.

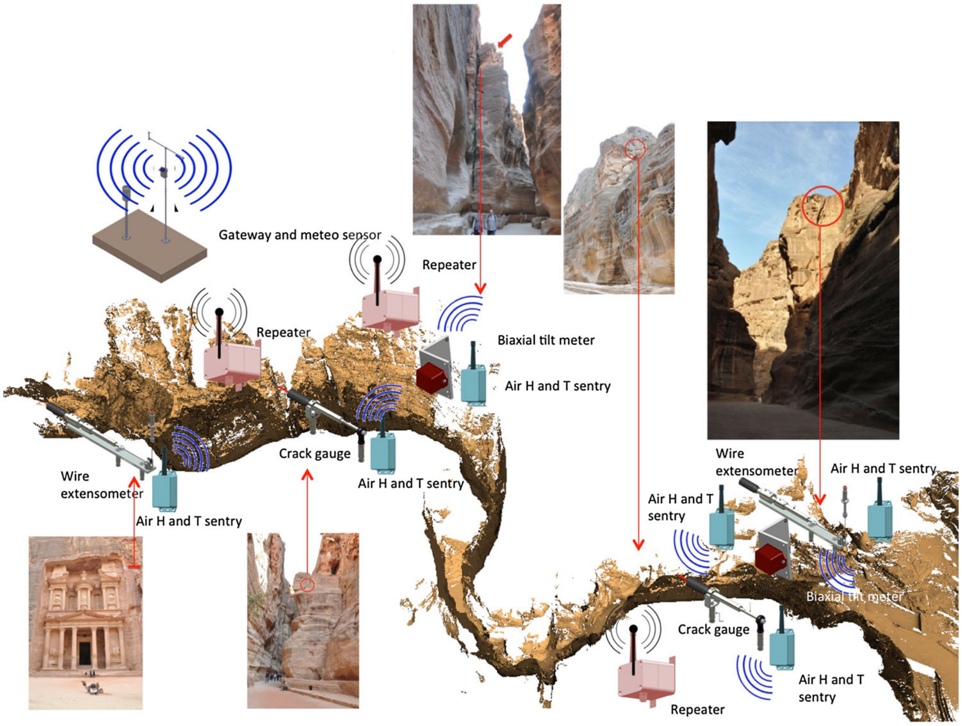
The system, at this stage of the research, is not purposely aimed to work as a near-time alarm or early warning system device [12], but to provide displacement data and trends to be analyzed with those of meteo-climatic parameters.

Reflectorless total station monitoring network

A Leica® TM30 reflectorless total station has been used to extend deformation control and analysis of the 6 potentially unstable blocks as well as provide information on movements of 15 slope faces located inside the Siq and in the Outer Siq (Treasury area). A total of 81 micro prisms, (22 prisms in stable areas as reference points and 59 as monitoring targets) properly designed to reduce visual impacts, have been installed by local climbers. The technique (acquisition and elaboration of different 3D model compared during time) will provide 3D movement of unstable blocks/slope sectors and further movement (2D analysis) of the deformation of slopes through the acquisition of some thousands reflectorless monitoring points.

In detail, the TM30 monitoring system is based on a polygonal constituted by prisms located in the lower portions of the Siq, working as reference points. Bimonthly lectures with the total station along the base polygonal will provide a regular time–space acquisition of control point clouds in the slope sectors to be monitored. Point clouds are constituted by prisms, working as base monitoring points, and reflectorless points that the total station is capable to detect and measure in the field between consecutive acquisitions. The precision with such a

Fig. 10 Wireless system network along the Siq



topographic monitoring system is sub-millimetric. The monitoring output is given by differences between distinct lectures and 3D topographic models derived by point clouds analysis in any monitored sector of the Siq. Such differences will provide deformation of points in the slopes for further analysis of actual/potential unstable areas of the Siq.

Rock slope stability analysis

A first stability assessment of a large-volume sandstone rock block located in the northern side of sector 5 of the Siq of Petra, has already been implemented [27]. The potential unstable rock block was equipped with a wire deformometer located on the top and a biaxial tiltmeter installed on the East face. Displacement of the main fractures, inclination of the blocks and meteorological parameters are the main data collected from 10 June 2013 to 10 August 2015. The available data show that after an initial stabilisation, the displacement plot shows two evident increase in the cumulative displacement occurred during the winter seasons. The total closure is now equal to 5.5 mm. The combined analysis of the measurements provided by the wire deformometer and the tilt meter is suggesting a closure of the sub-vertical fracture.

A limit equilibrium analysis for sliding and toppling failure mechanisms was performed to investigate the influence of geometrical and strength parameters and to assess the present stability conditions. The strength parameters were obtained from several laboratory and field tests jointly with field survey. The main output is that the block stability is always verified. The block will remain stable also for a significant reduction in strength and length of the base joint. The most critical mechanics is the toppling one, which is activated when the length of the base joint reduces itself of the 20%.

A preliminary Finite Different Method analysis, through the commercial FLAC® code, was also implemented to investigate with a major detail about the influence of the different parameters controlling the stability conditions (Fig. 11).

The toppling mechanism, correlated to a sliding mechanism along the base layer, seems to be the most critical one when the strength parameters of a highly weathered sandstone are progressively reduced.

The stability of the rock block is a typical three-dimensional problem. The two-dimensional schematisation, disregarding the additional contribution of the lateral surfaces to the stability, should be then considered as a safe hypothesis.

Future research activities will have to investigate the stability problem in its completeness, taking into account both the additional resistant forces, mobilized by rock bridges, and the de-stabilizing forces due to a potential seismic input.

At the moment, the cumulative displacement data provided by the wireless monitoring system, although of small

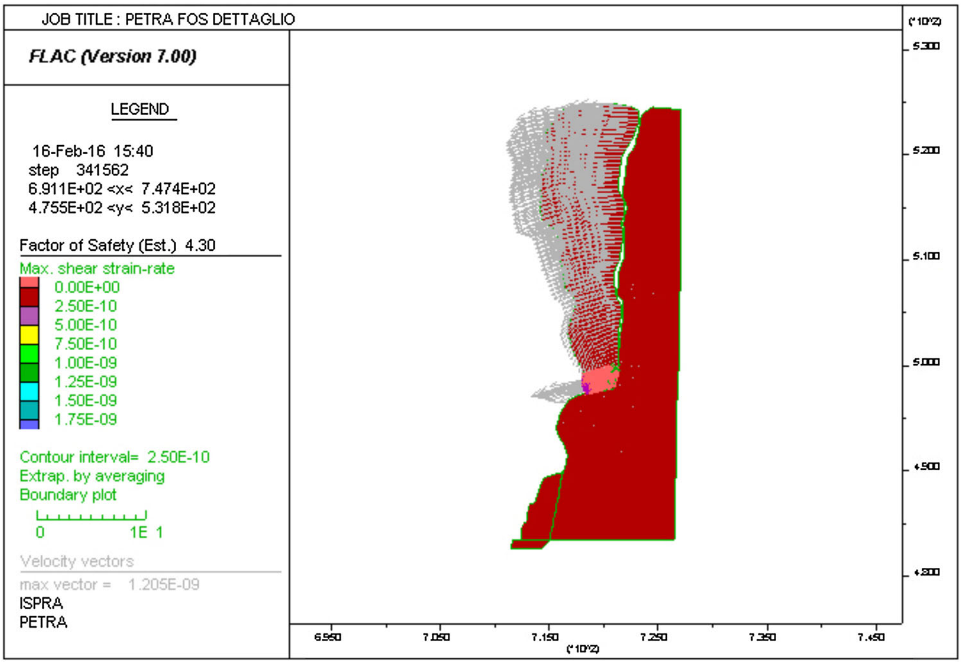


Fig. 11 Factor of Safety for analysis results [27]

entity, do not seem to confirm the simulation results obtained by the stress–strain analysis. More complex failure mechanisms may therefore be possible.

Given the relevance of the investigated area (the Siq is the only access to the archaeological area), the implementation of additional monitoring systems and further investigation activities are strictly recommended in the future.

All the collected data, associated to the outcome of the stability analyses, will help in identifying the most sustainable actions to be implemented to mitigate the risk of potential collapse in such vulnerable and complex context.

In the specific investigated case, it seems important to reduce the weathering and the erosion at the base of the block, also preventing water infiltration along the subvertical open fracture.

Mitigation works

According to the above investigation, a guideline for mitigating rock fall hazard has been implemented at the end of the project. The guideline was mainly focusing, as much as possible, to enhance traditional knowledge and local sustainable practises, in conservation techniques.

The selection of a specific mitigation typology for the stabilisation 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. More in detail, a feasibility design has been implemented to mitigate the hazard from rock fall; rock slide (planar and wedge); toppling; unstable loose blocks and debris.

As an example, a preliminary feasibility project has been implemented for the large block located in sector 5 of the Siq and described above in terms of factor of safety (Fig. 10). This block is safe in present conditions, but becomes unstable under a seismic action or, in case of progressive deterioration and reduction of the surface of the highly weathered sandstone located at the bottom of the block. The consolidation of the block is clearly very important for the maintenance of the historical landscape, the safety of visitors and for the block of the main access to Petra Archaeological Park.

Taking into account the relevance of low impact intervention in such archaeological site, it was decided to propose (Fig. 12): sealing of large crack behind the rock block to avoid rainy water infiltration; nailing/anchoring the block to the inner compact rock; consolidation of the lowest highly weathered rock to avoid further reduction of support area.

As an example, the activities developed during 2016 were mainly addressed to the removal of loose blocks on the top of Siq, to avoid the collapse during the presence of visitors (Fig. 13). More engineered solutions will likely be implemented in the near future.

Conclusions

An integrated project was developed to evaluate the risk of collapse and potential impact on visitors of the slopes composing the entrance canyon (Siq) to Petra archaeological

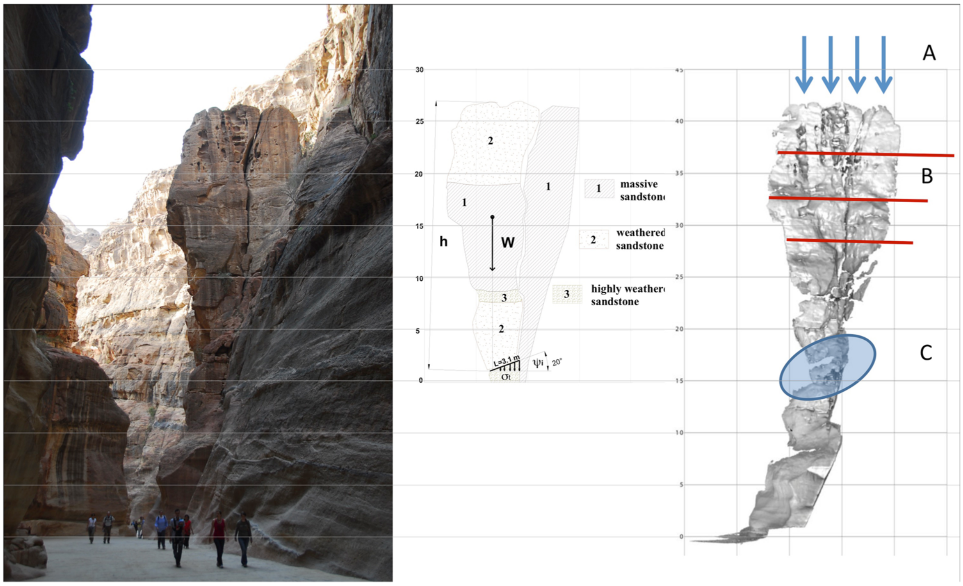


Fig. 12 Proposed mitigation strategy for a large unstable block located in sector 5 of Siq: **a** sealing of large crack behind the rock block to avoid rainy water infiltration; **b** nailing/anchoring the block to the inner compact rock; **c** consolidation of the lowest highly weathered rock to avoid further reduction of support area

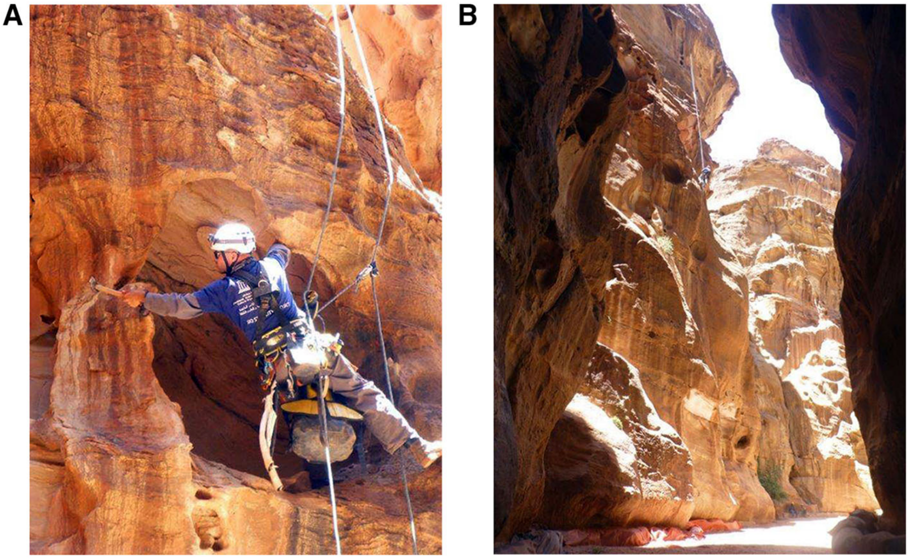


Fig. 13 Removal of loose block in the Siq of Petra (source https://www.facebook.com/UNESCOAmman/)

park. A set of direct and remote distinct monitoring systems and techniques has been implemented for the analysis of rock slope deformations. The overall system has been designed and installed according to potential capability of the different techniques as well as cost/benefit and long-term sustainability, considering the specific geological and cultural environment of the Siq of Petra.

Local geology and rock mechanic survey has clearly demonstrated the existence of potential slope instabilities in the Siq of Petra.

Kinematic analysis is revealing the presence of many potential unstable blocks, one of them collapsing on May 2015 [20].

A regional scale analysis of the potential unstable points, derived by SqueeSAR$^{\mathrm{TM}}$technique, has provided evidence of a general stability of the Petra area in the time span considered (2003–2010). The areas where some movement (>2 mm/year) occurred, are characterised by presence of incoherent material (e.g., debris, sands) removed by human activities and/or natural erosion and mostly located out of the Siq.

The crack and wire-gauge system, based on 2 years observation dataset (2013–2015), has provided a generally constant trend of movements, with negligible displacements (<1 mm), mostly related with daily temperature and humidity fluctuations. Only in the case of a large size block, located in sector 5 of the Siq, there is the evidence of permanent displacement of about 5.5 mm.

The analysis with reflectorless total station is actually in the stage of set up finalization (i.e., reference and monitoring prisms georeference, implementation of reflectorless monitoring plan, zero cycle measurement) so that no data are yet available. For this technique, a correct design of the network is fundamental to determine and assess relative movements of points, so that a particular attention and intense field work is being devoted to provide the highest accuracy in the system configuration.

Measurements of the manual crack gauge network, since June 2011, has provided records that exhibit a general enlargement of the monitored discontinuities (average of ca. 1 mm) during winter seasons and a slight shrinking of the fractures apertures in the summer seasons. Nevertheless, considering the limited number of measurements taken, it is still insufficient to define a clear displacement trend versus climate-related parameters and local geomorphic conditions of the blocks/slope portions examined.

In conclusion, in the Siq of Petra, conventional geotechnical and topographic instrumentation, with innovative and powerful components, has been installed to provide a wide set of techniques to produce evidence of displacement in the Siq slopes. These site-scale field techniques have been integrated with a satellite interferometric analysis to also provide a large-scale analysis of ground displacement in the Petra Park.

Finally, it is expected that the knowledge developed during this project and the installed monitoring sensors, may provide a permanent basis of information at service of local managers, for the safety of sites and security of visitors.

Acknowledgements The present work is an advancement of the UNESCO Project Siq STABILITY—Sustainable Monitoring Techniques for Assessing Instability of Slopes in the Siq of Petra, Jordan. Authors are very grateful to UNESCO Amman Office namely former Director Ms. Anna Paolini and present Director Ms. Costanza Farina, for their efforts on project implementation and continuous support in the field activities. We would like to express a special thanks to Mr. Emad Hi-jazeen, Director of Petra Archaeological Park and Ms. Tahani Sahli for support and assistance on project activities.

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