

Geomorphological processes and rock slope instabilities affecting the AIUla archaeological region

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ABSTRACT: The paper focuses on the preliminary assessment of the potential geo-hazards affecting the cultural heritage rock-cut sites of AIUla region. Its best-known site is Hegra, with more than 110 monumental tombs with elaborated facades carved directly into the sandstone rock. In addition, AIUla hosts a number of fascinating historical and archaeological sites such as its Old Town, surrounded by an ancient oasis, and Dadan, the capital of the Dadan and Lihyan kingdoms. The study is based on an interdisciplinary approach mainly aimed at evaluating characteristics of rock masses, rock degradation processes, slope instabilities and best practices for heritage preservation and future management. The most appropriate mitigation and consolidation measures to contrast the ongoing threats, also in the view of rediscovering the traditional knowledge of local conservation techniques and implementing sustainable low impact monitoring technologies, are also analysed.

1 INTRODUCTION

The present paper focuses on the preliminary assessment of the ongoing and potential geo-hazards affecting the AIUla region. Located at 1.100 km West from Riyadh, AIUla covers an archaeological area (e.g., necropolis, quarries and settlements) of more than 22.000 sqm. (Figure 1), where it is possible to walk in a luxury oasis through ancient world heritage sites in a rock cut landscape shaped for thousand years (Margottini & Spizzichino 2021). Its best-known site is Hegra, the main southern city of the Nabataean kingdom, before becoming a Roman outpost, and the first UNESCO world heritage site in Saudi Arabia, conserving over 110 monumental tombs with elaborated facades carved into the sandstone rock. In addition to Hegra, AIUla hosts a number of fascinating historical and archaeological sites such as its Old Town, surrounded by an ancient oasis; Dadan, the capital of the Dadan and Lihyan kingdoms, considered one of the most developed cities of the first millennium BC in the Arabian Peninsula; and thousands of ancient rock-art sites (e.g. Abu Ud, Jabal Ikmah). Many rock-cut monuments are affected by different natural threats such as surface weathering and erosion, rising dampness, rock surface detachment and larger-volume slope instabilities. To ensure the long-term conservation of sites affected by such natural threats, detailed investigations,

monitoring and consolidation measures are required, specifically developed for rupestrian cultural heritage sites (Boldini et al., 2017; Margottini & Spizzichino 2022; Spizzichino et al., 2016). The activities are characterised by a thorough multidisciplinary approach including competencies in archaeology, engineering geology, rock mechanics, landslide risk assessment and management as well as in conservation, protection and mitigation measures. To define the main physical and mechanical proprieties of the rock materials, a preliminary laboratory test campaign was carried out. The structural setting of the rock-mass (bedding planes, joints, faults), related to the stratigraphical genesis, the tectonic activity of the Red sea, and the geomorphological evolution of the slope, was identified and classified. Local rock-mass conditions promote slope instabilities (e.g., rockfall, sliding, toppling) that may affect both the heritage itself and visitors. This preliminary assessment of prevailing kinematics and potential geo-hazards will allow the implementation of a general master plan, to be considered as a first step for the following detailed design stage. It will contain a first selection of the most appropriated mitigation and consolidation measures, characterised by a low environmental impact and employing traditional knowledge to site preservation.

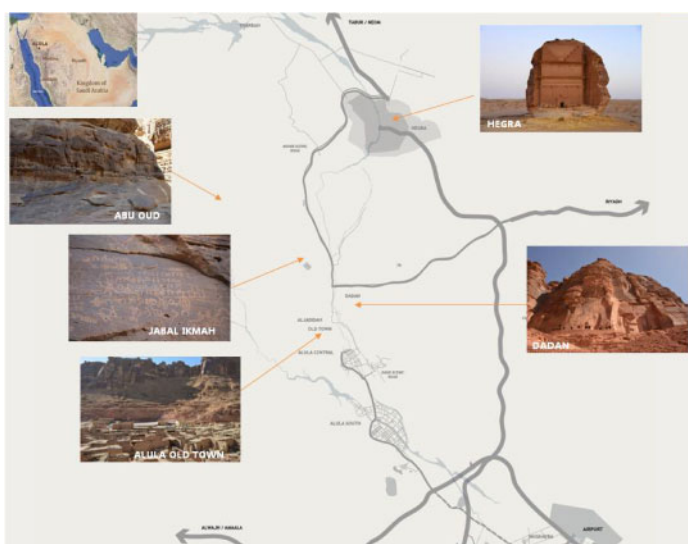


Figure 1. Map of AIUla investigated archaeological sites.

2 THE ALULA REGION ARCHAEOLOGICAL SETTING

The province of AIUla keeps and shows extraordinary human and natural heritage. Its homonym capital is in the center of Wadi Al-Qura, an impressive valley carved out of sandstone, in which there is evidence of human presence, at least, since 200,000 BP. The AIUla *wadis*, and particularly this one, were a meeting point and a natural route for millennia, crossed by important trade routes used since prehistory, and with special intensity since the first millennium BC. With the flourishing of the cultures of Dadan - Lihyan, and Nabatean one later, the Incense Route, which from the south of the Arabian Peninsula crossed the AIUla region, reached the main eastern ports of the Mediterranean sea. In this sense, the discussion on the introduction and dispersal of the Neolithic phenomenon in the peninsula is also particularly interesting. These traditional communication routes are punctuated by an astonishing dispersion of rock art and monumental rock structures that provide us with a wealth of information. Regarding the latter, the research projects promoted by the Kingdoms Institute of the Royal Commission for AIUla (Thomas et al. 2021) detected close to 1.400 Mustatils. It was possible to obtain the absolute dating of them with a radiocarbon dating that takes us to the late Neolithic, around 6,000 BC (Ramsey 2020; Reimer et al. 2020). AIUla is

home to some of the main archaeological landmarks of Arabia, such as the site of Al-Khuraybah, ancient Dadan, capital city of the Dadanite and Lihyanite kingdoms. Dadan was likely one of the most developed cities of the first millennium BC. of the region. As an indisputable heritage legacy, the sandstone valleys also protect thousands of inscriptions in several different languages and alphabets, from Dadanite to modern Arabic. Jabal 'Ikma, Abu Ud or Al-Aqra'a are an undoubted and powerful human testimony in the area. The most recognized archaeological site is Hegra. An ancient city of 52 hectares, Hegra was the most important Nabatean city and royal cemetery in the south of their kingdom, since at least the 1st century BC (Figure 2).



Figure 2. Nabatean tombs in the Hegra archaeological site.

UNESCO world heritage site since 2008, Hegra protects more than a hundred monumental tombs from this period, and had continuity during the Roman period, probably as one of the southernmost places in the province of Arabia Petraea. After the transition to Islam in the 7th century, the cities of Q'uhr and AIUla appeared in written sources as important places for pilgrimage routes. Testimony of this is reflected both in the archaeological remains of the first, next to the town of Mughaira, and in the Old Town of AIUla, whose streets, squares, and farms seem frozen in time. The latest reflection of this evolution is made up of the characteristic elements of the Ottoman presence, both in the form of various fortifications and military equipment, as well as that of the Hijaz railway. Its construction, which was intended to complete the connection of Damascus with Madinah, was suspended by the First World War.

3 GEOLOGICAL SETTING

From the geological point of view, the area of AIUla is located at the border between the basement complex and the Arabian foreland, constituted by coarse clastic sediments (mainly sandstone). The detail distribution of various geological formations is reported in Figure 3 (modified after Donald et al. 1998). Outcropping succession in the AIUla archaeological region includes the Siq Sandstone and Quweira Sandstone and the upper Quaternary alluvial deposits. The sandstone layers are sub-horizontal, gently dipping about 5° in N-NE (330° N). From the geological profile reconstructed by Buro Happold Engineering (2019) it is possible to notice that, due to this gentle dipping and due to topography, the Siq Red Sandstone is mainly outcropping in AIUla and surrounding (Dadan, Old Town, etc.) while, in the Hegra area, the Quweira Sandstone is dominant. The Quweira occurs in cross-bedded stratifications with bed thicknesses of 2 to 5 m.

The Siq Sandstone, dark red to brownish-red and medium-grained, is divided into three sub-units, namely the Lower (sandstone conglomerate of white quartz cobbles), Middle (fine, fractured strata) and Upper Siq (massive and very compact) Sandstones.

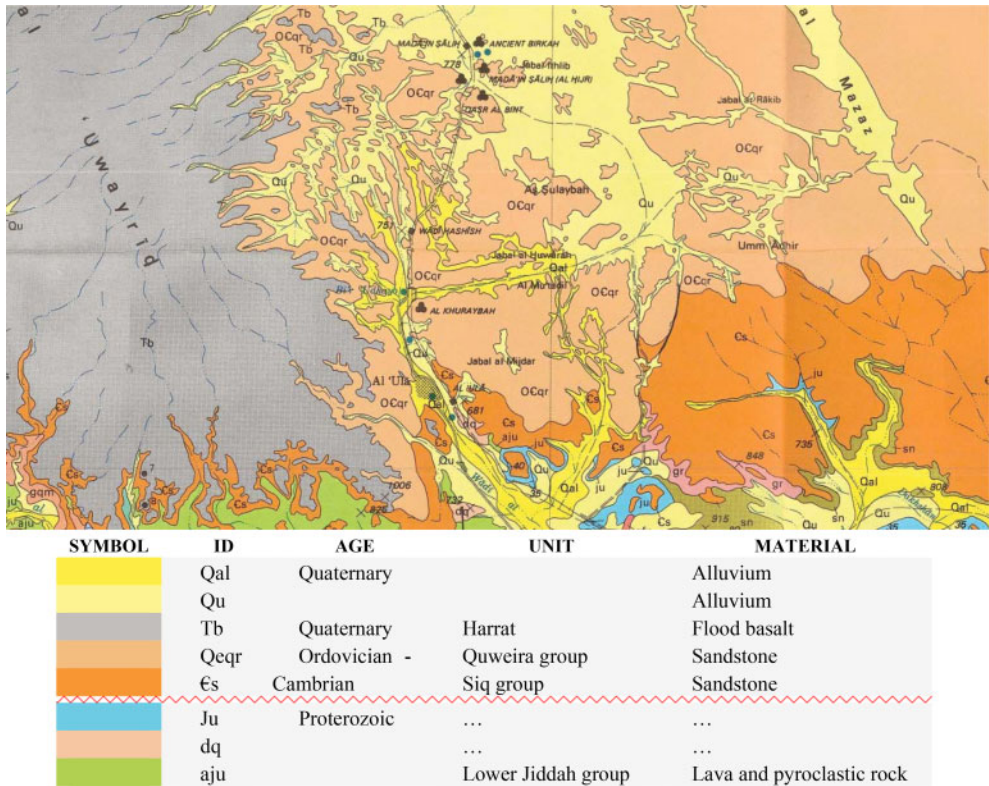


Figure 3. Geological map of AIUla region (modified after Donald et al. 1998).

The panoramic photograph in Figure 4, taken from the “highpoint” on top of Harrat (lava plain or volcanic field of Al Uwayrid west of AIUla – Wahbi 2014), displays most of the lytho-stratigraphic succession in the area. This division is evident from the weathering profile of the outcrops in the area (Figure 4).



Figure 4. Panoramic view (slightly vertically-exaggerated) of the litho-stratigraphic succession in the AIUla area, taken from the highpoint of Harrat Al Uwayrid, West of the town of AIUla. Sandstone units are recognized in this section, except for the Saq Sandstone, which outcrops out further North of this area (Wahbi 2014).

Table 1. Litho-stratigraphic units and sub-units in the region of AIUla.

AGE (PERIOD)	GEOLOGICAL UNIT	SUB UNIT
Early Ordovician	Saq Sandstone	
Late Cambrian	Quweira Sandstone	
Middle Cambrian		
Early Cambrian	Siq Sandstone	Upper Middle Lower
Proterozoic basement (pre-Cambrian Arabian shield)	Jibalah Group and basement	

4 PHYSICAL AND MECHANICAL CHARACTERISATION OF THE ROCK MASSES AND MATERIALS

4.1 *Field survey and rock-mass characterisation*

Geo-mechanical characteristics of the AIUla rock formations were investigated through geomechanical field surveys and laboratory tests, these latter executed directly in Italy. The surveys were carried out following the recommendation of the International Society for Rock Mechanics (ISRM 1978a; 1978b, 1981). The following activities were carried out directly during field surveys (December 2020 mission) in Hegra and Dadan (Table 2):

1. geo-structural analysis of the slope facades (orientation and main characteristics of discontinuities);
2. Barton's profilometer tests for reconstructing the joint roughness (JRC);
3. sampling of blocks to be used for laboratory analysis;
4. Schmidt-hammer tests on joint surfaces and intact rock blocks for in-situ assessment of the uniaxial compressive strength (JCS);
5. tilt tests for base friction angle assessment (ϕ_b).

Table 2. Average rock mass parameters for Hegra and Dadan sites.

	JCS MPa	JRC –	ϕ_b (°)	GSI –
Hegra	32–42	2–6	37–43	67
Dadan	28–41	4–8	40–45	65

From a geo-structural point of view, the AIUla area reflects trends and characteristics of the regional tectonics, mainly connected with the oceanic spreading of Red sea, initiated first on the Sheba Ridge east of the AIUla-Fartaq fracture zone at ~19–18 Ma (Bosworth 2015). In addition, syngenetic strata joints and local stress conditions of the slope (possibly associated to stress release) are responsible for the other sets of discontinuities.

4.2 *Laboratory tests*

During the December 2020 campaign, five rock samples were collected near the cities of *Mada'in Salih* (better known as Hegra) and Dadan (Figure 5). They consist of two Yellowish Sandstone blocks, belonging to the Quweira Group, and three Red Sandstone blocks of the Siq Group (Figure 6). A total of 40 specimens were prepared for the mechanical tests, of which 22 for the uniaxial compression test (Figure 7a), with a diameter of about 25 mm, and 18 for the Brazilian test (Figure 7b), with a diameter of about 50 mm. Uniaxial compression tests and Brazilian tests were performed using a 10 and 50 kN load cells, applying respectively a load rate of 0.5 MPa/s and

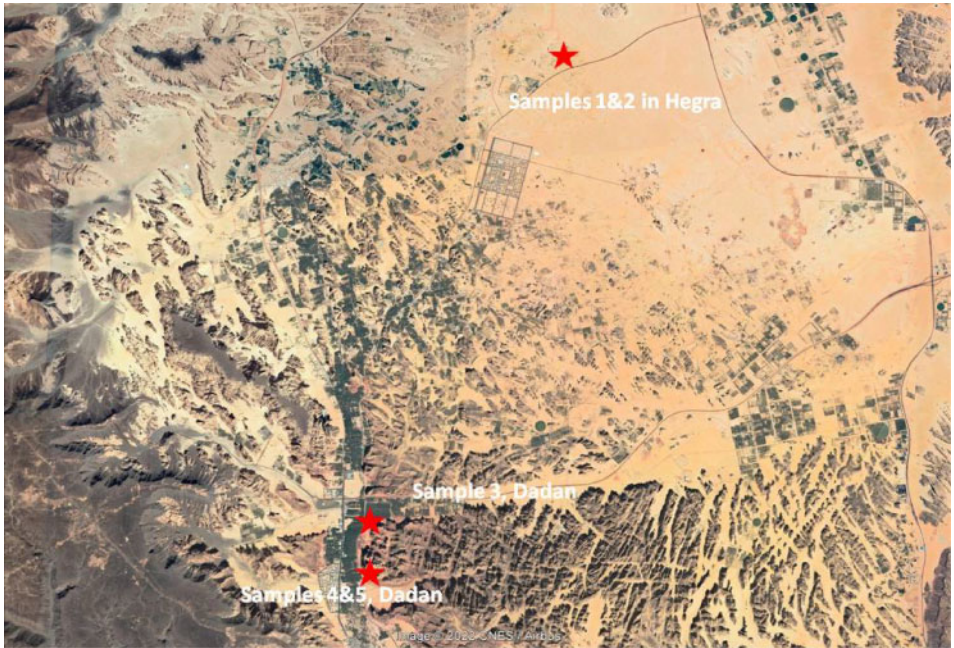


Figure 5. Location of rock blocks collection.



Figure 6. The five rock samples collected and analysed in the laboratory.

200 N/s (ISRM 1978). Before the mechanical tests, the P wave velocity was also measured on all the specimens (Figure 7c). The average values of the physical and mechanical properties for each sample are summarised in Table 3.

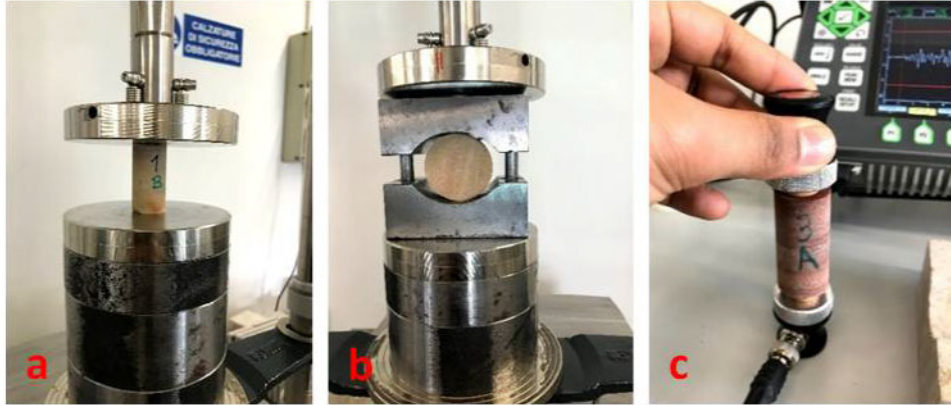


Figure 7. Uniaxial compression test (a), Brazilian test (b) and P wave velocity measurement (c).

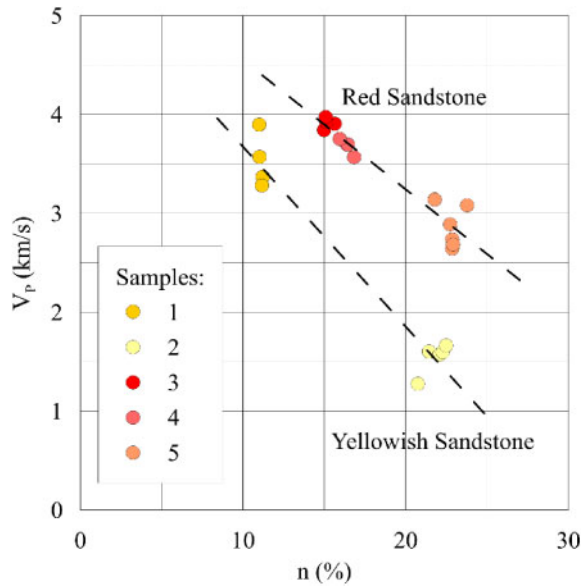


Figure 8. P wave velocity against total porosity.

Table 3. Summary of the physical and mechanical properties of the rock materials.

Sample	ρ_{dry} [Mg/m ³]	ρ_s [Mg/m ³]	n [%]	V_p [km/s]	σ_c [MPa]	σ_t [MPa]
1	2.390	2.688	11.1	3.5	50.24	6.83
2	2.087	2.669	21.8	1.5	9.93	0.50
3	2.265	2.679	15.8	3.9	38.51	7.68
4	2.238	2.678	16.4	3.7	41.18	6.46
5	2.060	2.694	23.6	2.9	24.85	2.74

The increase in porosity reduces significantly V_p values for both rock formations, with differentiated trends for the Yellowish and Red Sandstone samples.

Figure 9 shows the strength values obtained by the two tests.

The uniaxial compressive strength σ_c ranges from less than 10 MPa for a specimen of the sample 2 to over 50 MPa for a specimen of the sample 1, both belonging to the yellowish sandstone lithotype. Specimens prepared from the red sandstone blocks are characterized by σ_c values in the range 18–42 MPa.

Consistently, specimens from samples 1 and 2 display respectively the highest and lowest values of the tensile strength σ_t , from almost 8 MPa in the case of the first block down to about 0.5 MPa in the second one. Values of σ_t similar to those obtained for the sample 1 were identified for specimens of samples 3 and 4, while significantly lower values were attained by the two specimens of sample 5. In general, inspection of the two figures highlights the substantial influence of porosity on the rock material strength.

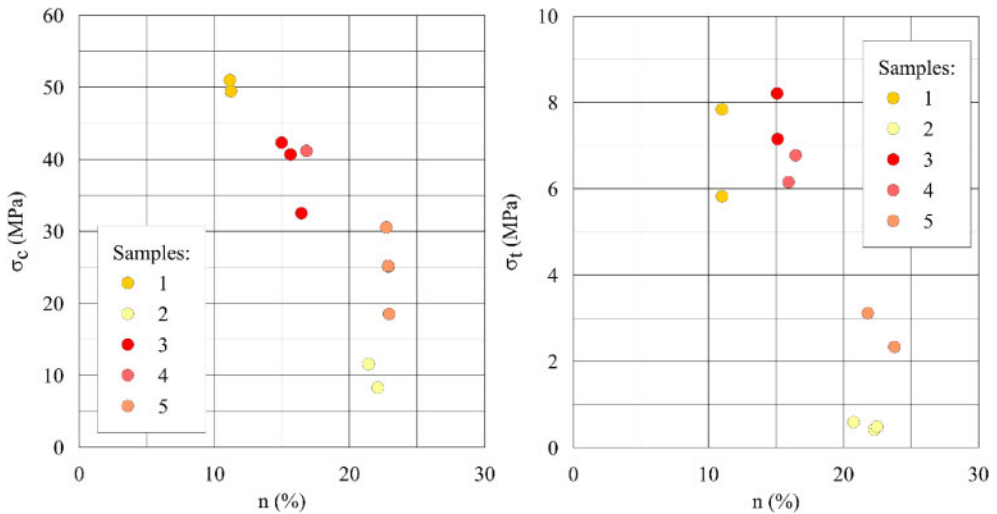


Figure 9. Uniaxial compressive strength (left) and tensile strength (right) against total porosity.

5 GEO-HAZARDS AND MORPHOLOGICAL PROCESSES THREATENING THE SITES

The term geo-hazards includes very different types of morphological processes and involve both long-term and short-term geological processes. In the following the main instability and weathering problems affecting the sites at different scales are briefly described.

The different archaeological sites of AlUla region are completely carved and realised into the Quweira and Siq Sandstones. The local quality of the rock-mass is directly depending on:

- lithology and rock material of depositional layers (e.g. minerals, texture and composition);
- level and typology of weathering and erosion;
- structural setting (e.g. joint, fractures, faults).

The slope angle for most of the rock faces is prevalently larger 80° , with frequent overhanging surfaces consequent to erosive processes or block collapses at their base. Slope kinematics, and thus potential failure modes, is mainly ruled by high and medium dip angle of the main discontinuities versus local slope orientation. Also the presence of horizontal discontinuities (bedding planes) causes failure modes and volumes of potential instability (see Figure 10).

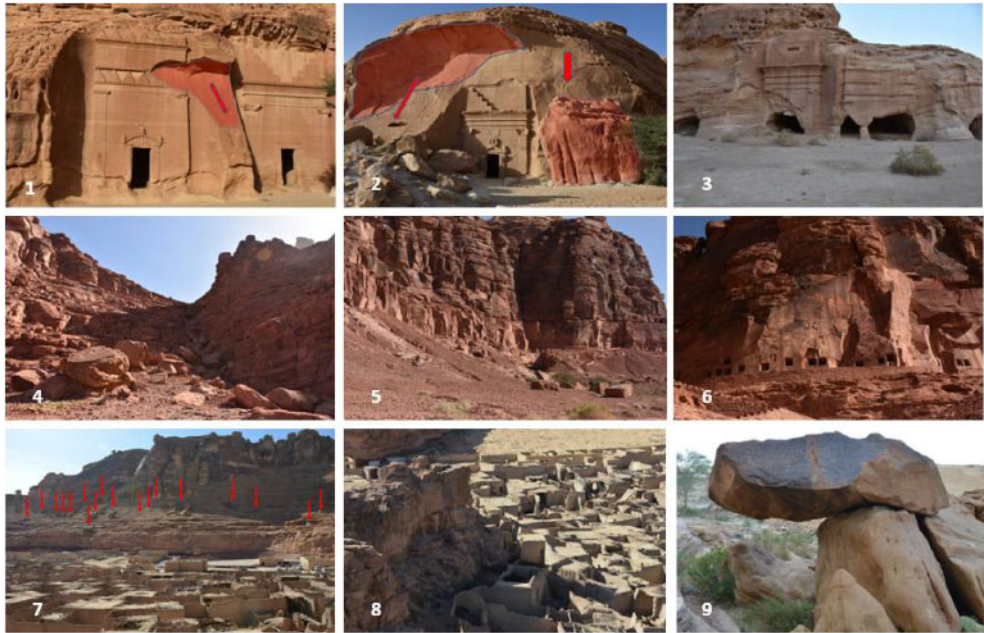


Figure 10. Example of the main instability processes affecting the different archaeological sites belonging to AIUla region: 1&2 rock slide and free fall in Hegra; 3 basal erosion affecting pillars and rock facades in Hegra; 4&5 rock blocks fallen in Dadan; 6 condition of rock cliff affecting the Lions tomb in Dadan; 7 rock blocks accumulation in AIUla Old town western cliff; 8 potential slope instability inside AIUla Old town; 9 unstable and fractured rock arts block in Jabal Ikmah.

According to a preliminary assessment, the main instability processes affecting the whole archaeological area are:

1. rock fall, toppling and sliding (from small to medium to large dimensions) affecting the slope façade;
2. collapse (from very small to medium dimensions) involving directly the carved architectonic structure of the tombs;
3. weathering and erosion processes (from small to large scale) affecting both the slope facade and tombs.

6 SHORT- AND LONG-TERM MITIGATION MEASURES MASTER PLAN

In the whole archaeological area of AIUla, and considering that the site has been abandoned for many centuries, the present and active morphological processes should be framed within a management and conservation master plan having two different timeline references: emergency mitigation measures to be defined and undertaken in the short-medium term and preventive mitigation measures to be implemented in the medium-long term.

Short-medium term actions should be preceded by an investigation phase including:

- detailed geomatics Terrestrial Laser Scanner (TLS) acquisition coupled with UAV flight acquisition, in order to provide high-resolution 3D topographical models of the whole heritage area;
- laboratory test execution;

- detail geomorphological and geomechanical survey of the rock slope;
- global kinematic analysis of the rock facades including the calculation of the most probable rock fall trajectories;
- detailed landslide hazard/risk assessment (rock fall, wedge and rock slide detailed mapping);
- thermal infra-red analysis;
- detailed survey of each tomb and of the whole archaeological complex (including tailored data sheet and TLS for the most endangered sites);
- slope stability modeling (2D and 3D) for specific blocks and/or unstable portions of the cliff.

According to the results of these investigations, the following activities should be also programmed:

- cleaning and scaling of the sites from loose material;
- temporary supports of instable rock portions;
- urgent reinforcement in the most instable volumes to avoid detachments;
- redefinition of touristic paths and accesses to each single tombs/archeological complex to prevent tourists from being exposed to potential collapses or instabilities (e.g. definition of minimum safety distances, prohibitions in the accesses of some tombs or complex);
- new communication plan and billboard for touristic management;

Long-term actions include:

- detailed design of mitigation and consolidation measures;
- design of an integrated monitoring system (e.g. traditional geotechnical in situ monitoring through crack gauges and tiltmeter, GBR or topographical traditional through robotic total station).

The adopted monitoring integrated system could also be set, with some small modifications and thresholds definition, as a warning system for flash flood as well as for detection of large rock block deformations.

7 CONCLUSION

The AIUla oasis covers a wide archaeological area where it is possible to visit ancient heritage sites in a rock cut landscape shaped for thousand years. In addition to its best-known World Heritage site of Hegra, the region hosts a number of fascinating historical and archaeological sites such as its Old Town; Dadan and thousands of ancient rock-art sites.

The entire area is characterized by the presence of low to medium strength sandstone formations. More in detail, the north area shows the outcropping of the Quweira Red Sandstone unit while in the area of the Old Town and further south the Siq Yellowish Sandstone appears, divided into three main sub-units (Lower, Middle and Upper). The geological and geomechanical characteristics of these two formations affect the potential instability and weathering of the cultural heritages sites carved into them.

The geological formations are characterized by a significant internal variability, both vertical and lateral. The Quweira Yellowish Sandstone is mainly interested by diffused weathering and erosion phenomena as well as rock fall connected to internal structural asset. The archaeological areas in the Siq Red Sandstone are mainly affected by rock fall and slides as a consequence of the local discontinuities pattern.

The present paper has the main scope of developing a preliminary analysis of the geomorphological evidences, the mechanical properties of the rock materials, the rock slope instabilities and main threats affecting the cultural heritage sites in AIUla, providing first ideas to be further validated by additional investigations and monitoring. Preliminary short and long term mitigation actions (both structural and non structural) were suggested in order to develop a future conservation management plan.

ACKNOWLEDGMENT

The present activity has been funded by the French Agency for the Development of AIUla (AFALULA), in agreement with the Royal Commission for AIUla (RCU), Kingdom of Saudi Arabia. A special thanks is due to Ingrid Perisse and Jean François Charnier, both from AFALULA, for their inspiration and useful scientific support and discussion. The authors wish to thank all the involved people from RCU for their continuous logistic help and scientific cooperation. The laboratory tests were performed at the LAGIRN laboratory of the University of Bologna. We fully appreciate and thank the expert support by Eng. Barbara Ravaglia and Geol. Fausto Peddis in performing and interpreting the laboratory data.

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