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IPL Project (IPL-259) Annual report 2024-2025

March 2024 to March 2025

1) **Project Number and Title**: IPL-259 Landslide Risk assessment in AlUla Archaeological sites – Kingdom of Saudi Arabia
2) **Main Project Fields**
   (1) Technology Development
      B. Hazard Mapping, Vulnerability and Risk Assessment
   (2) Targeted Landslides: Mechanisms and Impacts
      B. Landslides Threatening Heritage Sites
   (3) Capacity Building
      A. Enhancing Human and Institutional Capacities
   (4) Mitigation, Preparedness and Recovery
      B. Mitigation
3) **Name of Project leader** - Claudio Margottini

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Core members of the Project:

Names/Affiliations: Daniele Spizzichino - The Italian Institute for Environmental Protection and Research – ISPRA, Rome, Italy);

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4) **Objectives** - The focus of the project is to mitigate the risk from rockfall in the spectacular cultural heritages of AlUla archaeological area (HEGRA, DADAN and AlUla old Town), as well as to raise the awareness against geomorphological processes within the site's management plan. Capacity building with local authority will be carried out as a first step for training local expertise in landslide risk assessment and for enhancing resilience and landslide risk perception of the local Oasis community.
5) **Study area** – The site is located in the North of Saudi Arabia, 1100 km West from Riyadh, AlUla covers an archaeological area (e.g., necropolis, quarries and settlements) of more than 22,000 m^2. The project is covering the 130 Nabatean tombs of Hegra, the 1,7 km long cliff of Dadan, where mainly Dadanite tombs are located as well as a huge archaeological quarry, and the surrounding of AlUla old Town. Its best-known site is Hegra, the first UNESCO World Heritage Site in Saudi Arabia, main southern city of the Nabataean kingdom, and a Roman outpost, that conserves over 130 monumental tombs with elaborated facades carved into the sandstone rock. In addition to Hegra, AlUla

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.

6) **Project Duration** – 3 years (July 2022 – June 2025)

7) **Report -**

a) Progress in the project in 2024-2025

The period 2024-2025 was mainly dedicated to the investigation of slope stability in the archaeological sites of Khaybar, where some villages on top of hills, are suffering for geomorphological processes that are conditioning a possible future development. Khaybar is an oasis in Medina Province, Saudi Arabia, situated some 150 kilometres South of AlUla. Prior to the arrival of Islam in the 7th century, the area had been inhabited by Arabian Jewish tribes until it fell to Muslim conquerors under Muhammad during the Battle of Khaybar in 628 CE.

The work is based on the survey conducted on the two main Khaybar selected sites. The Al Nizar Villages and the Al Qamus Fortress (figure 1).

Fig. 1 Location of the two sites,

Both the aspects of geological hazard and slope stability (mainly due to rock fall phenomena) as well as those linked to the static-structural conditions of the buildings for the two sites, were analyzed and treated to finalize the formulation of mitigation proposals and a master plan of the interventions.

In order to carry out 3D slope stability model for the village of Al Nizar and the fortress of Al Qamus, the UAV Digital Surface Model (DSM) with a 4 cm resolution, provided by CNRS, was resampled to a

grid resolution of 0.5 x 0.5 m. **This downscaling ensure that the cell size is of the same order of magnitude of the blocks, which is crucial for preventing any unpredictable and unrealistic subscale effects**.
Following is the 3D modelling of the two investigate villages.

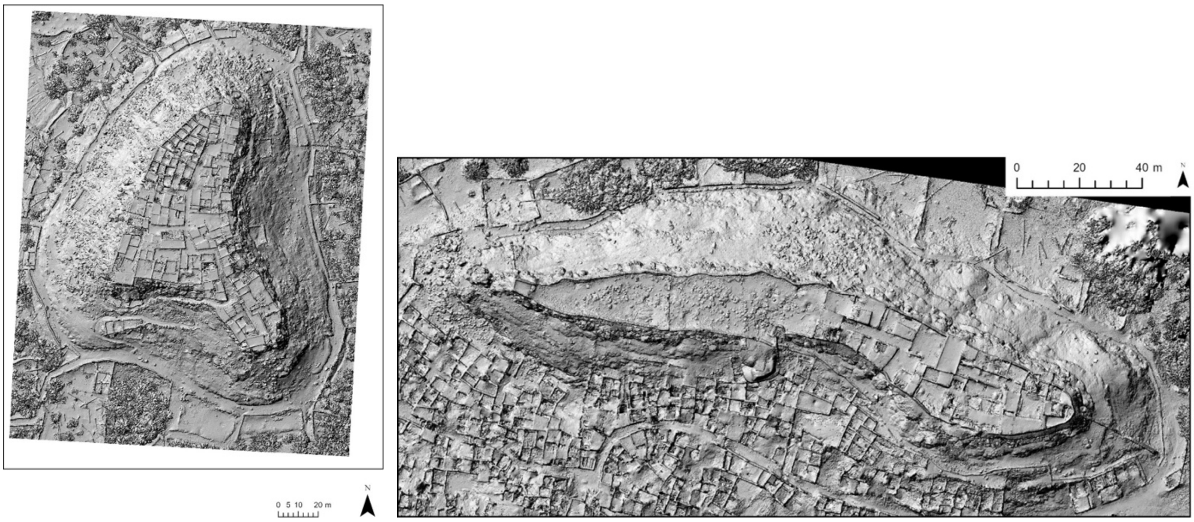

Fig. 2 Digital Terrain Modes of Al Nizar (left) and AlQamus (right): original 4 x 4 cm DSM from CNRS

Al-Nizar village and Al Quamus fortresses constitute two topographic reliefs of the Harrat Khaybar. Harrat are the results of intra-continental volcanism, forming thick piles of sheet-like basaltic lava flows with associated networks of shield and fissure fed volcanoes, as well as more silicic lava domes ranging in composition from mugearite to trachyte (Moufti et al., 2012). In the western margin of the Arabian Peninsula the harrat formation is associated with the spreading of the Red Sea Rift which has been active over the last 30 Ma (Camp and Roobol, 1992). The Harrat Khaybar covers approximately 14,000 km2 (Figure 5) and its formation started 5My to present.
At local scale, Al-Nizar and Al Quamus hill tops are wholly constituted by basalts. Based on their physical appearance, three lava flows were recognized, from the top to bottom (Figure 3):

- Upper lava flow: stiff rock, with pervasive fractures isolating large volumes of rock, some potentially unstable (A1 rock blocks).
- Intermediate lava flow: lava with thin layering, locally weaker (A2 rock blocks).
- Lower lava layer: lava with white inclusion, locally weak (B rock blocks).

Fig. 3 Al- Nizar: upper and intermediate lava flow

As an example, following is the geo-lithological map of AlNizar.

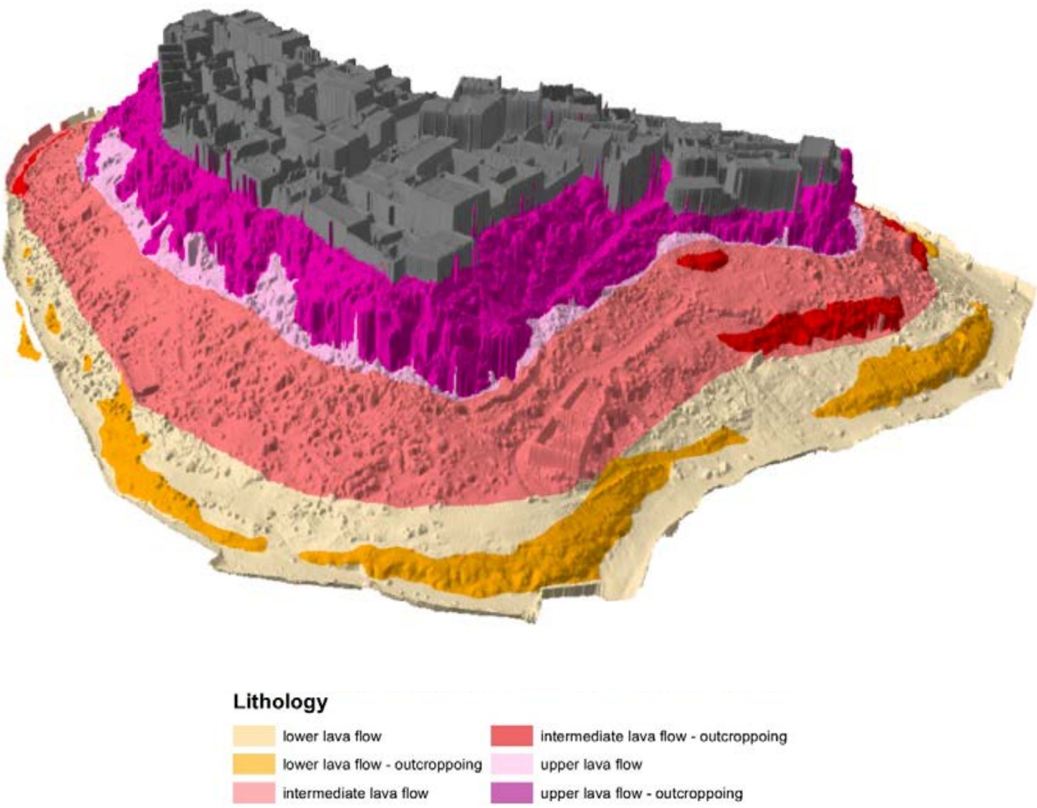

Fig. 3 Geo-lithological map of Al- Nizar.

The landslide collection and classification in the study area has been implemented to define a general setting of the main typologies and processes acting along the rock plateau and facade.

Starting from rock samples collection directly in the field several laboratory tests were implemented.

They include physical characterization as well as, by the controlled drilling in laboratory:

- 16 core samples for UCS test;
- 26 core samples for Tensile Test (Brazialian)

After having developed a detail a geophysical prospection (seismic profiles and electric tomography) and a proper seismic risk analysis the rockfall analysis was implemented.

The modelling of rockfall phenomena was carried out using a physically based mathematical model such as HY-STONE (Crosta et al., 2004; Frattini et al., 2008; Agliardi et al., 2009). This model is capable of simulating the trajectories of rock blocks from previously identified source areas, using a detailed 3D description of the topography.

Several sources of information were used to carry out the study, including

1. High resolution DEM provided by the CNRS
2. Orthophotos
3. Dimensional analysis of blocks to estimate design volumes for modelling
4. Field observations
5. Photographic material of the area

Simulation results are produced partly in raster and partly in vector format. These data are processed and visualised using GIS, allowing statistical analysis and spatial representation at a sophisticated level.

Raster-type outputs include:

- Transit frequency: the number of boulders passing through each cell;
- Velocities: the translational and rotational velocities (minimum, average and maximum) of the boulders transited for each cell;
- Heights: the minimum, average and maximum heights of the boulder trajectories for each cell;
- Kinetic energy: the translational and rotational kinetic energy (minimum, average and maximum) of the boulders for each cell.
- Transit probability: the number of boulders passing through each cell, weighted by their susceptibility to detachment (considering feasible kinematics, the state of maintenance of nets, and the quality of the rock mass).

Vector-type outputs include:

- Instantaneous motion data: points sampled along the representing the motion characteristics at each instant;

- Three-dimensional trajectories: the complete paths of the boulders in three dimensions.
- Trajectory endpoints: the starting and stopping points of the trajectories
- Impact points: the locations where the boulders make contact with the ground or structures.

Following is an example of the number of transit (frequency map) and the position of arrested blocks.

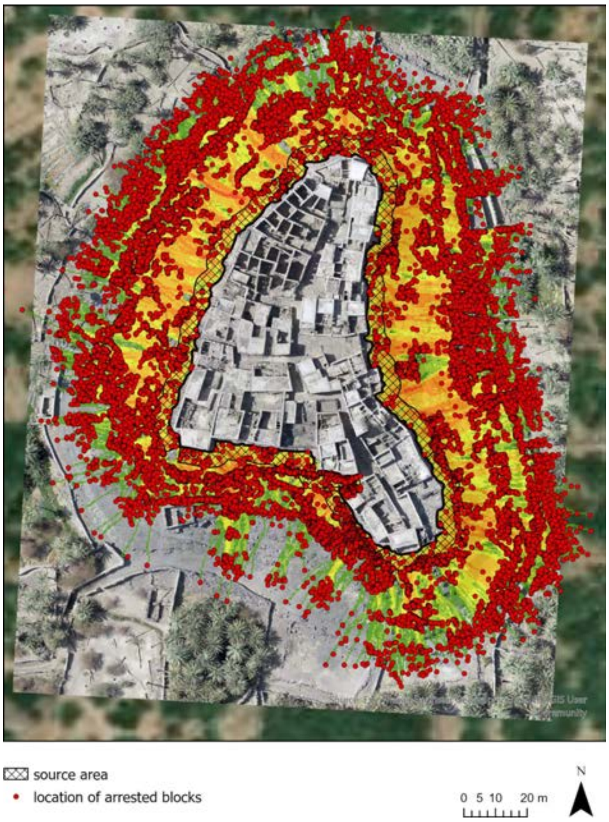

Fig. 4 Location of arrested blocks. The number of transits is shown as background.

This work, after the approval of AFALULA and RCU, is currently under elaboration for a scientific publication.

b) Planned future activities

In the period 2025 and 2026, further investigations will include the archaeological sites of Hegra, namely the settlements where the people used to live, that are now days affected by slope instabilities (e.g. the Nabataean Temple; the Roman Citadel).

In the meantime, an international conference on rock mechanics applied to the stability of rupestrian sites is under organization for late 2025 or spring 2026.

c) Beneficiaries of the projects.

The Royal Commission for AlUla (local conservation Agency), is the main beneficiary of the project, since it is responsible for the conservation and management of the archaeological site. The project is also providing an innovative approach in conservation of rock-cut heritage sites that may be applied in other sites of the region, for the benefit of local restorers and conservators. Local and Governmental authorities, including site managers, will finally benefit from this project, having a site protected for the medium-long term and allowing tourists to visit the area in a safer manner. A special meeting with site managers was organized in 2023.

d) Results

Tommaso Beni . Daniela Boldini . Giovanni Battista Crosta . William Frodella . Jos. Ignacio Gallego . Edoardo Lusini . Claudio Margottini . Daniele Spizzichino (2023). Rock instabilities at the archaeological site of Dadan (Kingdom of Saudi Arabia). Landslides DOI 10.1007/s10346-023-02122-7

Tommaso Beni, Lorenzo Nava, Giovanni Gigli, William Frodella, Filippo Catani, Nicola Casagli, Jos´e Ignacio Gallego, Claudio Margottini, Daniele Spizzichino (2023). Classification of rock slope cavernous weathering on UAV photogrammetric point clouds: The example of Hegra (UNESCO World Heritage Site, Kingdom of Saudi Arabia). Engineering Geology 325 (2023) 107286

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