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Geomechanical and geophysical investigations for sustainable conservation of the Temple of the Winged Lions in Petra (Jordan)

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ABSTRACT: The paper describes the main outcomes of a multidisciplinary study conducted to support the Jordanian authorities in developing a long-term management and conservation strategy for the Temple of the Winged Lions (Petra, Jordan). Field investigations included geotechnical tests, geoelectrical surveys, passive and active seismic tests. Geophysical methods were performed to reconstruct lithological and structural features of the subsoil. Passive seismic recordings were implemented to highlight possible seismic motion amplification phenomena and estimate the fundamental resonance frequency of the site through a spectral ratios technique. Active seismic tests were implemented aiming at the reconstruction of shear wave profiles across the site. Finally, a 1D numerical analysis of the seismic site response, based on the subsoil model reconstructed by means of geophysical investigation, was carried out in order to address future seismic risk mitigation actions for the temple.

1 INTRODUCTION

Engineering geological multi-discipline approach can help archaeologists in many aspects of excavation and conservation of cultural heritage, especially in a preliminary stage, in order to establish priorities that will result in optimization of cultural, budgetary and time benefits. In this perspective, geomechanical and geophysical surveys have been undertaken in support of the ongoing Temple of the Winged Lions conservation and restoration activities. The Nabataean Temple of the Winged Lions (TWL) is located in the Petra Archaeological Park, one of the most known World Heritage Sites in Jordan, (30.19'49.72"N; 35.16'39.35"E), along the Colonnade Street in the right N bank of Wadi Musa (Figure 1).

Built around 27 AD, the temple takes its name from sculptures of winged lions that formed the capitals of the double colonnade that surrounded the altar near the back of the cella. The TWL was affected and partially destroyed by two earthquakes occurred respectively in 113 AD and 363 AD. From a geological point of view, 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 separating the Arabian and Sinai plates (Sneh 1996, Ginat et al. 1998).

The TWL is sited along the Colonnade Street in the right N bank of Wadi Musa, with local mean elevation of 885 m a.s.l. The area is characterized by the outcropping of extensive Holocene terrains (soils, alluvial deposits and anthropogenic debris/rubble) that overlain the Umm Ishrin Formation – middle part (Cambrian). From a geological point of view the structure is located inside a tectonic depression (Petra Graben) comprised between two main faults (i.e. Abu Ullayqa and Al Mataha faults) oriented NE-SW. The TWL site has been excavated from 1974 (Hammond, 1996) to 2005 for a total extension of the site of ca. 2000 m^2. Many sections, therefore, have been exposed to weathering and some of them need for urgent conservation. In particular, walls and columns located in the TWL SW quadrant are in serious danger of collapse as well as some stone inclined pillars that surround the temple cella.

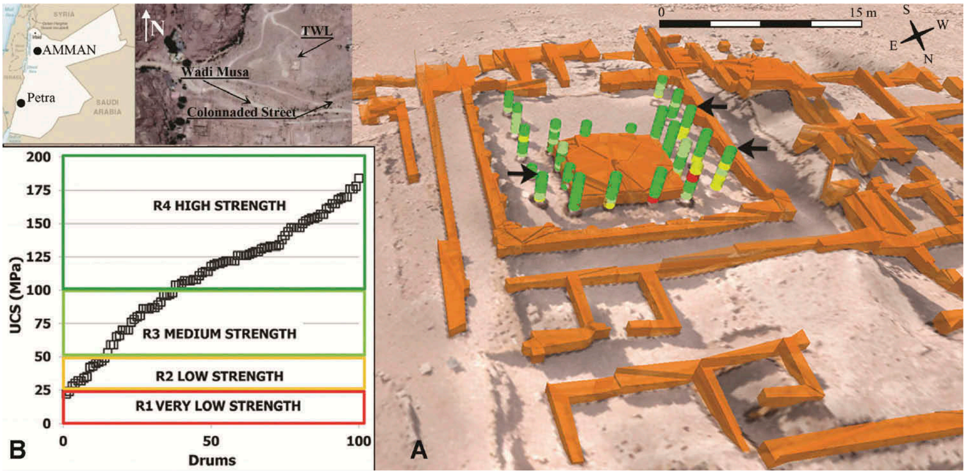

Figure 1. 3D view of the Temple of Winged Lion area (A) with the assessment of uniaxial compressive strength (UCS) for the columns drums obtained by Schmidt-hammer tests (B). The black arrows indicate the columns surveyed by mean of passive recordings (see also Figure 3)

Despite the great number of excavation seasons, many key aspects such as the geological setting of the area, geotechnical characteristics of terrains and materials, seismic site response have been never investigated so far. Recently, archaeological trenches were excavated along the SW quadrant with the scope to reach the arenaceous bedrock, that was assumed to be close to the surface. The excavations were unsuccessful, therefore deeper insights on the geological and geotechnical setting of the whole area were reputed necessary for the reconstruction of the local geology and geomechanical characteristics of the sandstone in order to address future conservation and restoration actions. Investigations were focused mainly on geological and geotechnical parametrization of the subsoil through geotechnical and geophysical methods. The field investigations included geotechnical tests, geoelectrical surveys (for archeological purposes only), passive and active seismic surveys.

Non-destructive geomechanical analysis with Schmidt-hammer were performed on 104 drums forming 22 columns in the TWL cella (Deere & Miller, 1966; ISRM, 1981). The analysis provided evidence of 14 column sandstone blocks (drums) with low and very low strength mainly due to weathering and mechanical degradation of materials.

Lowest strength conditions were detected for columns sited in the NW corner of the altar as well as in the western and eastern corridors of the cella where anastylosis of the columns and capitals was initially planned by archaeologists. In order to ease the analysis of the data and support the archeologists in visualizing results, the same information was implemented into a GIS environment by using Qgis software (v.2.14, https://www.qgis.org) exploiting the 3D visualization options provided by the Qgis2threejs plugin (https://github.com/minorua/Qgis2threejs). Passive tests were used also to achieve a preliminary assessment of seismic site response, applying Nakamura's technique (Nakamura, 1989). The same tests were also implemented on top of unstable stone pillars to investigate their behavior under dynamic conditions.

2 ACTIVE AND PASSIVE SEISMIC TESTS

The use of ambient vibrations for the estimation of local site effects started to be popular after Nakamura (1989). According to such technique, the peaks of a Horizontal-to-Vertical Spectral Ratio curve (HVSR, namely the ratio between the Fourier spectra of horizontal and vertical components) occurs close to the frequency peaks at the resonance frequencies of investigated site. Inside the TWL area, single station ambient vibration measurements have been collected along 30 sites by using the Moho instrument Tromino. Location of passive and

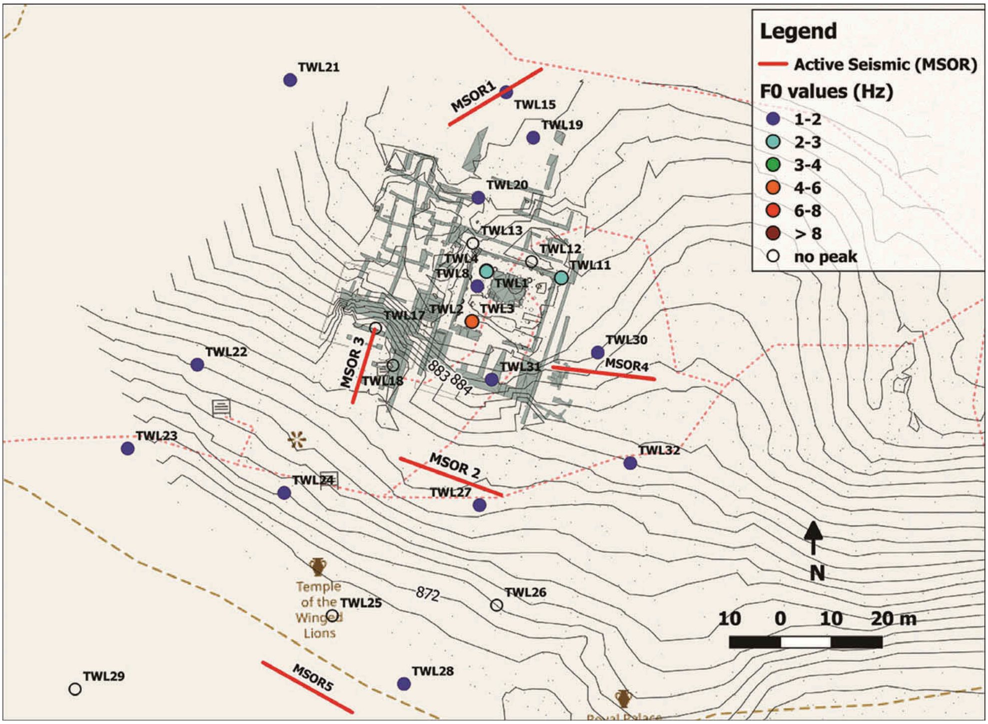

Figure 2. Study area with location of the active and passive seismic tests. The inferred F_0 ranges are also reported

active tests is reported in Figure 2. A consistent number of recordings (27) were collected on the ground. The survey has been extended to columns (3 recordings) located inside the temple cella to investigate their dynamic behavior (see Figure 1).

Tests were performed using a sampling frequency of 128Hz and a recording time of at least 20 minutes, processing of data have been conducted using Geopsy software following the SESAME guidelines (2004). All the spectra of passive seismic tests collected on the ground have been elaborated in the range 0.5Hz ÷20 Hz, being higher frequencies almost useless for engineering purposes and seismic site-response studies.

As shown in Figure 2 a consistent number of HVSR showed a frequency peaks in the range 1–3 Hz with a mean value of about 2.1 Hz. Some curves showed low amplitude for the entire analyzed frequency range, probably due to the low level of ambient vibrations and also due to the difficulties faced in providing a good ground coupling of the instrument. As previously mentioned, some registrations were performed at the base and on top of the columns. Curves retrieved from TWL-7, TWL-9 and TWL-10 tests are illustrated in Figure 3A showing peak frequencies at 2Hz and around 9–11Hz: while the former is very close to the mean value of F_0 for the site, the latter could be likely related to their actual poor state of conservation.

A Multichannel Simulation with One Receiver (MSOR) technique has been also applied (Lin and Ashlock, 2016). This technique exploit the use of a single geophone fixed at a surface point and receiving signals from different shots, performed at increasing distance from the start position. Each single shot is registered as a single trace and, if triggering had been performed correctly with respect to each hammer impact, the final seismogram is composed by assembling the traces to simulate a multichannel array. Thus, the dispersion analysis can be implemented aiming at the geotechnical characterization of buried materials in terms of shear waves velocity. In the TWL area, the Tromino velocimeter (http://www.moho.world/) has been used as fixed geophone. This 3C (3-Component) geophone allows to collect as many traces for each single shot: for travelling surface waves the vertical geophone recorded the

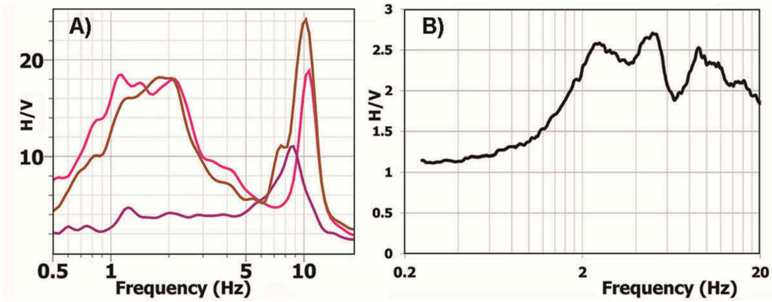

Figure 3. HVSR curves retrieved for the passive recordings conducted on top of three columns sited around the cella (A). Spectral ratio obtained from 1D numerical modeling (B)

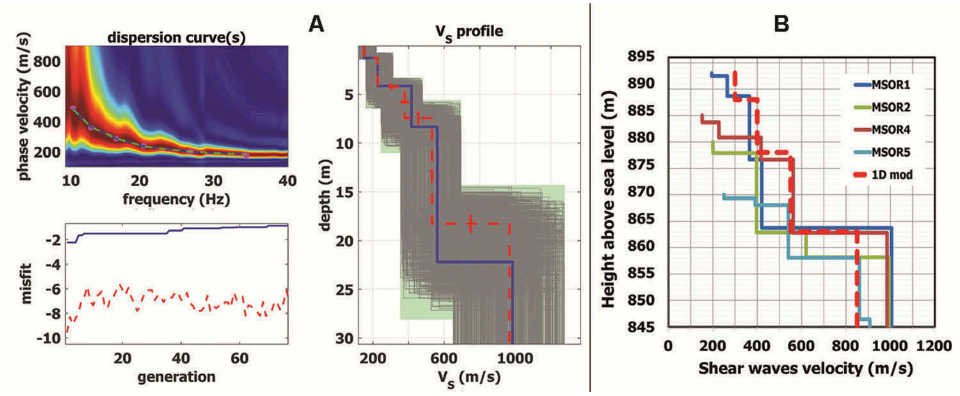

Figure 4. Example of MASW inversion for the MSOR 4 test site (A) and the shear waves velocity profiles vs. elevation, considered for the geotechnical characterization of the subsoil (B): the 1D Vs model adopted for the numerical analysis of the site response is also reported (1D mod).

ground motion pertaining to the vertical component of Rayleigh waves (Z), while the EW horizontal geophone records the radial one (R).

Inside the TWL site, a vertical active source has been used to generate surface waves, thus the Rayleigh-vertical and Rayleigh-radial components were both available for the analysis.

The deployment of the seismic profiles was challenging due to the limited accessibility to the site, mainly due to archeological structures. Active tests were performed along 5 relatively short arrays, using an offset of 2.5–3.0 m between subsequent shot positions. To retrieve the final Vs profiles, the analysis of dispersion data was constrained by means of passive data (HVSR) to achieve more reliable Vs profiles. The analyses were implemented using winMASW software by Eliosoft (http://www.winmasw.com). Shear-waves velocity models in each site are shown in Figure 4.

3 NUMERICAL MODELLING OF SITE RESPONSE

The seismicity of Petra and, thus, of the TWL site, is strongly dominated by the presence of the Dead Sea Transform (DTS) fault system. Several large earthquakes ($M \geq 7.0$) are known to have occurred along the DTS according to the historical seismic catalogues (e.g. Kovach, 1987; Amiran et al. 1994; Ambraseys et al. 1994; Guidoboni, 1994) causing heavy damage in Petra. Strong earthquakes occurred in 363 and 551 caused massive disruption at the TWL and other major temples in Petra (Russel, 1980; Guidoboni, 1994; Bedal et al., 2007). According to studies focused on seismic hazard assessment in Jordan (Jimenez 2004, Jimenez et al. 2005, 2008), the study area is characterized by moderate seismicity. Furthermore, following Jimenez et al. (2008), the upper bound magnitude associated to the seismogenic source areas nearest to Petra is 6.5 and 6.6 for the Gulf of Aqaba and Wadi Araba zones. Much stronger earthquakes (Mmax equal 7.5) are expected inside the Dead Sea-Jordan River seismogenic source zone, located ca. 80 km N from Petra. The seismic hazard for the Jordan territory proposed by Jimenez et al. (2008) was assessed by using the attenuation relationship proposed by Ambraseys et al. (1996) and considering a Vs> 750 m/s for the site bedrock (the same as the Jordanian code spectrum).

The proposed hazard maps show a 0.25–0.3 g of maximum PGA values and SA values at 0.2 s and 1.0 s ranging between 0.6–0.7 g and 0.15–0.20g respectively, both calculated for a 10% probability of exceedance in 50 years (i.e. for a return period of 475 years).

In order to address future seismic risk mitigation actions in the study area, a numerical analysis of local seismic response for the TWL area has been implemented. A 1D scheme for modelling was applied since the complexity of the subsoil and topography played a minor role due to the very limited extension of the study area. Since boreholes and in-hole geotechnical tests could not be performed at this stage, the reconstruction of the subsoil model in the TWL area was assessed through the joint use of field survey observation and velocity profiles. The geotechnical 1D model adopted is resumed in Table 1. The superficial layer is composed by a ca. 5 m of medium to coarse slope deposits made by angular and sub- angular clasts, mixed with the Wadi Musa alluvial sediments, with rare lenses of sand and yellow silt (as observed along some outcrops). Shear wave velocities for this layer spans between 200–300 m/s. A second layer, made by dense to very dense coarse slope deposits with sub-angular clasts, is characterized by Vs values between 400–580 m/s and a thickness of 10÷12 m. A third layer, with undefined thickness, is characterized by Vs values spanning from 800 to 1000 m/s and, according to the local geology, can be associated to the sandstone geological bedrock, found at a ca. 30÷35 meters below the archeological area (elevation 862÷857 m a.s.l.).

STRATA calculation code (Kottke & Rathje, 2008) that operates in the frequency domain and models the non-linear behavior of the soils using the equivalent linear method was adopted. In this software, the subsoil is schematized as a succession of homogeneous superimposed horizontal layers (i.e. 1D model) and the main data required as input are: 1) seismic shaking (accelerogram) representing the input motion for the numerical analysis; 2) shear waves velocity profile up to the depth corresponding to the rigid ground, namely a soil characterized by Vs ≥ 750–800 m/s with a thickness assessed in relation to the geological model of the site; 3) decay curve of the normalized shear modulus (G/G_0) and curve of the damping ratio D curve vs. shear strain amplitude for each of the materials included in the 1D model.

It is noteworthy that the seismic bedrock depth does not correspond to the buried contact between the gravel deposits and the geological bedrock; such contact is actually deeper. The value of 1500 m/s was estimated by modeling the V_S profiles jointly with HVSR curves to match the HVSR peaks at 2.0 Hz (not presented here). Since coarse gravel soils prevail in depth and their sampling was not possible for dynamic laboratory tests, their seismic behavior was simulated with curves of normalized and damping ratio values from literature (i.e. Rollins

Table 1. Geotechnical subsoil model adopted for 1D numerical analysis

Soil Layer	Thick (m)	V_S (m/s)	Density (kN/m^3)	Dynamic Behavior
Alluv*	5	300	18.00	Rollins et al. 1998
Debris l	10	400	19.00	Rollins et al. 1998
Debris 2	15	550	19.00	Rollins et al. 1998
Umm-Ish.	50	850	22.00	Linear (1%)
Bedrock	undef.	1500	24.00	Linear (0.5%)

* Alluv –superficial layer made by debris mixed to alluvial sediments

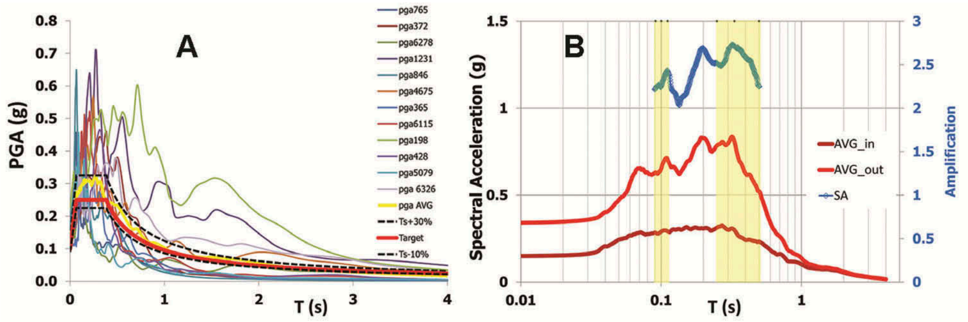

Figure 5. Spectra of the 12 selected motions (A) compared to the target spectrum, according to Jimenez et al. (2008). Results of the numerical analysis (B) as mean output spectrum (AVG_out) compared to the input one (AVG_in).

et al., 1998). An elastic behavior was adopted for the sandstone rock. Concerning the seismic input for the numerical analysis, the approach followed in this study was based on the selection of time-histories matching the reference spectrum provided by Jimenez et al. (2008) for the Seismic Zone n.2. Actually, due to access restriction of data from Jordanian Seismological Network (JS) seismic stations, suitable accelerograms via REXEL software (see Iervolino et al. 2010 for technical details) were analysed. The software allows to extract time-histories from the European Strong-motion Database (ESD), the Italian Accelerometric Archive (ITACA) and the Selected Input Motions for displacement-Based Assessment and Design (SIMBAD). A set of twelve records were used for the numerical simulation, selected through REXEL software matching the seismogenetic features of the study area (i.e. magnitude, epicentral distance, and fault mechanism). The Eurocode 8 site class A (CEN, 2003) of the recording stations was also considered.

In diagram A of Figure 5, the spectra of the selected motions are shown, along with the target spectrum (red line). The mean PGA (yellow line) resulted equal to 0.25 g or higher. The results of the numerical analysis in terms of output spectra is presented in diagram B of Figure 5. According to the numerical analysis, the S_A values (i.e. the values of the ratio between the two mean spectra) are ~2 or even higher in the range 0.07–0.5 s. In addition, the periods related to the range of the natural frequency peaks (0.5÷0.25 s) seem to be affected by spectral amplification on par with those (0.11÷0.09 s) associated to the columns.

4 CONCLUSIONS

A preliminary multi-disciplinary study based on field surveys, geotechnical and geophysical investigations was carried out at the Temple of the Winged Lions in Petra (Jordan) as a support provided to the local authorities for the sustainable long-term archaeological conservation of the monument.

As described in the paper, since earthquakes historically affected this area, a local analysis of the seismic risk was carried out through the reconstruction of the subsoil model, mainly based on the near surface measurements. The implementation of a 1D numerical analysis of the seismic site response provided evidences of possible amplification of ground motion in the range 0.07–0.5 s. Possible resonance effects can likely affect the temple columns characterized by a 0.09–0.11 s period.

As a first achievement and taking into account the seismic hazard of Petra, any partial reconstruction of the temple seems not advisable considering the poor mechanical characteristic of the sandstone drums and possible seismic amplification phenomena. Further direct investigations (boreholes) along with borehole (e.g. down-hole seismic test) and laboratory tests on samples will be necessary to improve the subsoil model and, thus, the local seismic site response assessment via numerical modeling.

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