STRUCTURAL ASSESSMENT, MONITORING AND EVALUATION OF MIDAS MONUMENT IN ESKISEHIR, TURKEY

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Abstract. Midas Monument is located in Eskisehir city in central Anatolia. The monument is in the form of a gate with ancient encryptions on it dating back to 7\textsuperscript{th} century BC. The 17m high and about 20m wide monument was carved out of a volcanic rock tuff and was made for the honor of antique Phrygian King Midas. The structural evaluation was carried out in two phases. The first phase included instrumentation of a major crack existing in the middle of the monument and another larger crack at the connection to the main rock to monitor if the crack is active and moving in time. The second phase included finite element modelling and dynamic measurement of the structure. The results indicated that the cracks are active. The deterioration observed in the monument was mainly due to environmental effects such as snow, rain, and temperature. Freezing thawing and wet-dry cycles were the major damage mechanisms. Earthquakes in the area are also investigated. The study concluded with structural interventions to elongate the remaining life of the monument.
1 INTRODUCTION

Midas Monument is located at Eskisehir city, Han district, Yazilikaya village area (Fig. 1), which is also known as the Midas City. The area was urbanized since the First Bronze Age (B.C.2000) and later occupied by the Phrygian, Roman societies. The monument is in the form of a gate with ancient encryptions on it dating back to 7th century BC. Midas city was one of the most important centers in Anatolia with its large scale religious monument as a religion center.

First studies regarding the Midas Monument were started at 1936 by A. Gabriel and excavation continued in 1937. Studies were paused during the World War II and resumed after the war, which took place between 1946-1958. During late 1980’s Italian researcher Geza de Francovich also studies in the area; then, Eskisehir Archeology Museum started field studies in 1981 and numerous historic remains were found in the region related to Hellenistic, Roman, and Byzantine periods.

The Monument Midas was named after the word which is inscribed at the upper left corner as “MIDAI”. The front side of the monument face to East having 17 m of height and 16.5 m width (Fig. 2). Carvings on the front are the rarest examples of stone carvings related to Phrygian structures. The alcove at the mid of the monument has the dimensions of 2.32 m x 4.40 m and 1.02 m depth. It has the aim of highlighting the entrance to the temple.

Figure 1: Location and satellite image of Yazilikaya Midas Gate (ref. Google Maps).
CURRENT WORK CARRIED OUT ON THE MIDAS GATE

The recent restoration work had started in 2013, funded by the Ministry of Culture and carried out by ANB Architecture Ltd. Company. During the preparation phase of the restoration projects, the main aimed was to protect the monument in its existing condition and find out the most suitable structural intervention method which are absolutely necessary to implement. The first phase was to determine the structural problems and emergency conditions which require immediate attention. Laser point cloud was taken and related drawings were prepared (Fig. 3); structural engineers examined the monument to investigate structural problems. This paper mostly concentrates on the structural issues and possible remedies for determined problems. Visual inspections were carried out to identify major obvious problems and instrumented monitoring was carried out to collect environmental data as well as structural response to the environmental changes and time. Furthermore, ambient vibration based dynamic data was collected using highly sensitive accelerometers to obtain dynamic characteristics of the monument and indirectly and non-destructively collect structural information about the monument.

Long term monitoring sensors were mainly crackmeters located on the existing cracks on the rock which is a soft, easy to shape volcanic rock (tuff) but at the same time open to environmental abrasives such as thermal swings, wetting and drying, freezing and thawing, sunlight, wind, etc. In addition to crack width changes over time, the environmental temperature and relative humidity were recorded at 15 minutes intervals for a duration of 12 months. Monitoring for a full year is necessary to capture the yearly temperature cycle since the crack width changes as a function of the temperature and humidity can ring alarm bells although crack width may return back to its original position at the end of the year. The dynamic tests and long term monitoring was carried out by a team of university academics (Dr. Ahmet Turer) and Opteng Engineering Ltd. Co. (Mr. Ozek Sazak), who are the authors of this paper. On-site support was provided by ANB Architecture Ltd. Co. and control authority representatives from Ministry of Culture attended and controlled the field studies.
2.1 Finite Element Modeling (FEM) and dynamic modal testing

The analytical model of the monument was constructed using simplistic shell model (Fig. 4) to simulate general behavior of the structure. Shell members have 4 nodes and 6 degrees of freedom at each node. Construction of a complicated 3D FEM is also possible (Fig. 5); however, deemed to be over too complicated for this study although already constructed using laser scanned point cloud. The main aim of FE modeling being structural identification and earthquake simulation, a simplistic shell model assumed to serve the purpose well. The intent of the study was not accurately simulate the post cracking behavior but to guess if there will be cracking and damage during an earthquake. Normally, Modal Assurance Criterion (MAC) value as shown in Equation 1 would be used to correlate two mode shapes. MAC calculation may be simplified by square of two mode vectors’ dot product and then divided by dot product of each mode vector by itself. Usually more than one experimental and analytical modes are obtained, which would yield a matrix of MAC values showing the correlation between analytical and experimental modes. MAC values are between zero and one, one indicating exact match between two modes and zero indicates two modes are orthogonal to each other.

\[ MAC_{ide} = \frac{\left| \sum_{q=1}^{N} \psi_{ide}^q \psi_{ex}^q \right|^2}{\sum_{q=1}^{N} \psi_{ide}^q \psi_{ide}^q \sum_{q=1}^{N} \psi_{ex}^q \psi_{ex}^q} \]  

The experimental ambient vibration data was collected using four sensors of PCB piezometric accelerometers (type 393B05) and National Instruments NI 9239 4-Channel, 24-Bit analog input data acquisition system. The 8 locations of measurement points in Fig. 4 are selected such that out of plane bending characteristics can be obtained properly. The 2 sensors out of 4 are moved over the structure while keeping two sensors stationary for linking dynamically collected
data to each other. The post processing of the data was carried out using ARTeMIS software. The experimentally obtained mode shapes, modal frequencies, and damping ratios are shown in Fig. 6. The experimentally obtained modes have correlated with the analytical counterpart to some extend but the analytical frequencies were higher and modes didn’t correlate well. As a part of calibration study, the observed cracks at the main rock to monument interface as well as an existing crack in the middle of the monument were modelled in the analytical model. The frequencies and modes have correlated better after this modification. Fine tuning of the frequencies were not necessary since the modal frequencies were in the same range and mode shapes were similar. Very good correlation between an analytical model and experimental results is desirable, but the study should be target oriented rather than pure seek of perfection and excellence.

Matching the mode shapes and frequencies in this study was necessary for a reliable earthquake (EQ) analysis: A response spectrum based EQ analysis calculates the response spectrum coefficients for each mode and then uses them to calculate equivalent earthquake forces using mode combination. The response spectrum coefficients would not differ too much for periods being smaller than 0.3 seconds on rock which corresponds to frequencies being higher than 3.33 Hz. All of the obtained analytical frequencies (Fig. 6) and experimental counterparts are larger than 3.33 Hz. The monument is located in a 2nd degree zone according to Turkish Code with pga 0.3 g (Fig. 7) and the EQ analysis revealed low compressive stresses (about 2 MPa); however, tensile stress ranges in the order of 1 MPa (Fig. 8) when combined with the dead load (Fig. 9). This value exceeds commonly accepted tensile capacity of tuff 0.69 MPa and moderate damage is expected during an earthquake especially at the upper regions. A linear model can only give hints about EQ performance and a nonlinear model can more accurately simulate the response. However, 2600 year old monument does not show obvious seismic damage which might have already experienced one or more large earthquakes. The insignificant observed damage might be due to soft edges and expanding thickness of the monument towards the bottom.

Figure 4: Simplistic modeling of the Yazilikaya Midas Gate (shell members).

Figure 5: Detailed Modeling of the Yazilikaya Midas Gate (3D solid members).
Figure 6: Experimentally obtained mode shapes and damping ratios.

Figure 7: Earthquake seismicity map of the area (2\textsuperscript{nd} degree zone pga=0.3g).

Figure 8: Earthquake simulation results, vertical stresses (MPa).
2.2 Long term monitoring

The monument was monitored for about a year to investigate if the cracks are opening and the level of crack movement throughout the course of a year. Total of six crackmeters were used during the studies. Three of them were installed on the front side of the monument to monitor the main crack at three levels (Fig. 10). The crack meter located at the lower level has not shown any movement during the course of first few months, which was then relocated to a new location after discussions with the control team; the new location was chosen as the upper left corner of the monument where the monument is separated from the main rock with a large crack (Fig. 10). One of the crackmeters was installed on the northern edge to track any possible movement of a slightly diagonal cracked piece and the rest two were installed on a large block of stone (about 3×4×4 m size) at the western back face of the monument which was critically positioned and might fall jeopardizing public safety (Fig. 11).

Crackmeter 1 which was located at the very bottom of the middle crack was expected to record the lowest deformation of the three crack meters located on it (Fig. 10). When the readings were analyzed it was showed that there was nearly no deformation where a total of 0.1 mm change at total after three months of period. The sensor was moved to another place which was also be considered as a critical location to be monitored. The new location was chosen to monitor any possible movement between the monument and the main rock since a large crack exists between the two. Data sets recorded a total of 0.5 mm of opening deformation during five months of data collection. The data shows a general opening trend, however more data needs to be collected since some of the movement might return back. Crackmeter 2 was also installed on the middle crack at a mid-height level on the front side of the monument. Results were expected to be a little larger than the bottom crackmeter recordings. Readings showed some movement of about 0.2 mm during 9 months of monitoring which was obviously larger than the first crackmeter as expected. Crackmeter 3 which was located at the top of three sensors group located on the front side middle crack also showed the similar behavior with crackmeter 2; however, the magnitude of the recorded deformation was lower than expected. A slight deformation of 0.1 to 0.2 mm was recorded during the course of long term data collection (Fig. 12).
A swing of 20 Celsius degree for average daily temperature and about 15 C between day and night was recorded during the course of long term monitoring and thermal expansion coefficient between steel and tuff rock is taken as about $6 \mu e/C$ degree. The crackmeter sensor itself expanding more than the rock would generate $6 \times 10^{-6} \times 20 \times 200 = 0.024$ mm change which is much smaller than 0.1 to 0.2 mm change. However, closer examination of recorded crackmeter data in Fig. 12 shows that some of the cracks move about 0.2 mm on a daily basis. Since the sensor cannot change temperature in the order of 200 C degree, the recorded crack width change data
have to be structural. The daily temperature swings as well as the sun exposure angle is deemed to be responsible for movement of the monument causing crack width changes.

Figure 12: Crackmeter measurements.
3 CONCLUSIONS

Measurement and analytical modeling based structural assessment and evaluation of Midas monument in Eskisehir, Turkey was carried out. Short term ambient vibration testing and long term monitoring of important cracks and environmental temperature/humidity was utilized to support the assessment and evaluation studies. One of the major outcomes of the study was obtaining dynamic properties which led to more realistic EQ analysis. The accelerometer measurements at both sides of an existing crack indicated the crack is active and moving in one of the modes where two sides of the crack move in opposite out-of-plane directions.

The instrumented monitoring of the cracks for close to a year has indicated cyclic movement of the cracks in the order of 0.2 mm to 0.5 mm at the monument-main rock interface and supported findings of the dynamic tests. The cracks not only move in a seasonal manner but experience about 0.1 to 0.2 mm movement on a daily basis as well. The daily movement deemed to be mainly due to sunlight exposure as daily crack width change cycles during winter are relatively smaller than those during summer.

The cracks opening and closing on a daily and seasonal basis is not desirable for multiple reasons: water entering cracks would not only deteriorate the tuff material by wetting and drying but also may result significant damage in narrow cracks by freezing and thawing cycles. Another mechanism of damage is the crack being filled by dust and small rock particles at the bottom of the crack and closing the crack would cause crack to grow gradually. Therefore, the existing cracks should be filled and treated using compatible material with the natural rock which has similar composition, stiffness, thermal properties, strength, etc. Capping with compatible materials might be advantageous.

The earthquake analysis has shown that upper parts of the monument is risky; therefore, filling the empty gap at the top was proposed. Additional stress concentrations at the bottom part of the north edge was requested to be supported by vertical steel props or stone columns.

The unstable rock at the back (eastern) side of the monument was in an unstable condition and steel based support at the base and controlled removal of the large stone in small pieces was recommended.

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