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The numerical analysis of response and stability of stone masonry bridges in Aizanoi Antique City in Kütahya Province of Turkey

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ABSTRACT: Aizanoi or Azan antique city was first established by Phrygians and later become a part of Roman Empire. This city was the first city in the world to construct the flood protection measures such as dams and embankment walls. Out of the four stone masonry bridges, two masonry bridges are remaining and they are still used today. The authors carried out some site investigations and surveying of these remaining stone bridges. In this study, the response and stability of stone bridges are investigated using finite element method under various loading conditions. Furthermore, some Eigen value analysis utilizing the FEM were also carried out, and the results of the investigations and analyses are presented and discussed.

1 INTRODUCTION

The antique city called Azan in Phrygian or Aizanoi in ancient Greek, located in Kütahya Province of Turkey, was established by Phrygians at 3000 B.C. and become a part of Roman Empire in 133 B.C. and then become of a part of Seljuk in 13th Century, later Ottoman Empire and finally Modern Turkey (Figure 1). One can find traces of various civilizations in this city. This city was the first to introduce the fundamentals of the modern stock exchange and modern civil engineering principles.

This city was also the first city in the world to construct the flood protection measures such as dams and embankment walls. In other words, it is the city of the birth of the hydraulic engineering of modern civil engineering. The city had four stone masonry bridges made of marble. The bridges have performed very well even under very heavy trucks of modern times. However, the traffic has been recently restricted to light vehicles such as cars and they are still in use.

The authors have performed some site investigations and surveying on two remaining stone bridges constructed during the Roman period. In this study, the response and stability of stone bridge denoted as Bridge-L are investigated using finite element method under various loading conditions in order to find out why these stone bridges performed very well so far since their construction about 1850 years ago. Furthermore, some modal analysis utilizing the FEM were also carried out. The results of the investigations and analyses are presented and discussed in this paper.

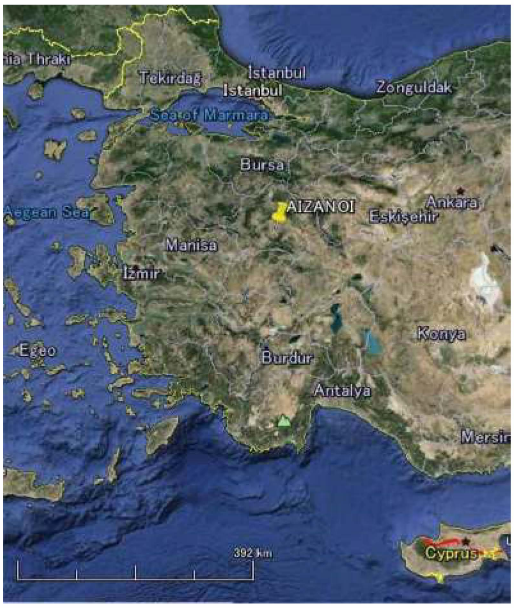


Figure 1. Location of Aizanoi

2 DESCRIPTION OF BRIDGES

There were four stone masonry bridges over Koca (Bedir) Çay in Turkish, which was called Penkalas in Roman period. However, it is very likely that the river could have been called with a different name by Phrygians as western historical sources generally

Figure 2. Views and locations of Bridges

Figure 3. Relative separation and sliding observed in both bridges.

quote ancient Greek or Roman names rather than the original names. Two of these four bridges are remaining and they are still being used today (Figure 2). Two of the bridges are missing while the building stones of one of the missing bridges were recently retrieved during the rehabilitation works. The bridges were made of white marbles presumed to be extracted from nearby ancient quarries at Göynükören, which is about 12 km to the east.

There are no official or historical names for these remaining bridges. The authors would denote bridges as Bridge-L and Bridge-S with the consideration of their length. Some spalling and slight relative separation and sliding of blocks were observed at both bridges as seen in Figure 3. The bridges were subjected to freezing and thawing cycles for the last 1850 years at least. In this study, the bridge denoted Bridge-L, which is about 33m long, would be investigated in details.

The Bridge-L consists of semi-circular five-arches with different radii (Figure 4) built in 157 AD. The maximum arch width is 6.6m and foundation width is about 1m. It is known that wooden piles are employed in the foundations of Cybele (wrongly known as Zeus) temple. Therefore, it is very likely that the wooden piles might have been used in the

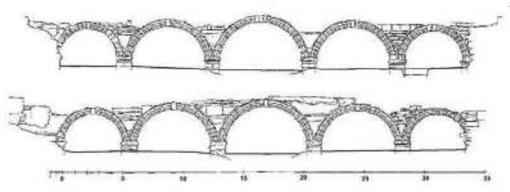


Figure 4. Drawing of Bridge-L (Hoffman and Rheidt, 1995).

Figure 5. A view of Bridge-L after dismantling the asphalt pavement.

foundations of the bridges against erosion as well as their uneven settlement in soft ground in river beds, which may eventually lead the collapse of the bridges. It must be also noted the region is prone to earthquakes, the use of wooden piles could be also as a counter measure against earthquakes (Aydan et al. 2003a,b), which is not well-understood by western archeologists from non-seismic countries (i.e. Rheidt 1990). The asphalt pavement of this bridge has been recently dismantled to observe the original structure as shown in Figure 5.

3 REGIONAL SEISMICITY

The region is no exception in Turkey and it suffers earthquakes from time to time. Figure 6 shows the earthquakes with a magnitude of 4 or more in the last 50 years. The most recent largest event was the 1970 Gediz earthquake with a magnitude of 7.2. The epicentral distance of this earthquake to

Figure 6. Seismicity in the vicinity of Aizanoi.

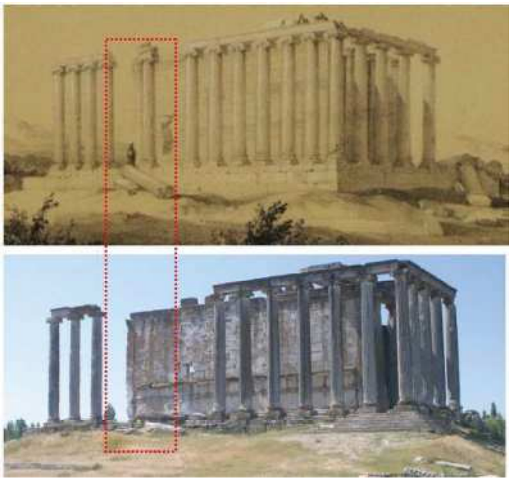


Figure 7. Damaged and partially restored section of the Cybele temple due to the 1970 Gediz earthquake.

Figure 8. Damage to columns of the Cybele temple and walls and stairs of the theatre.

the Aizanoi was about 10 km and four columns and one free standing column at the NE corner of the Cybele temple toppled in the direction towards the epicenter. Three columns were re-erected and two columns remain on the ground (Figure 7). One can also see various damage to columns and walls of this temple and other monumental structures in Aizanoi antique city (Figure 8).

Another large earthquake with a surface magnitude of 6.0 occurred in Simav on May19, 2011. However, this earthquake did not cause any damage to Aizanoi (Kumsar et al. 2015) as the epicentral distance was more than 50 km and the estimated acceleration was less than 30 gals (Aydan 2012).

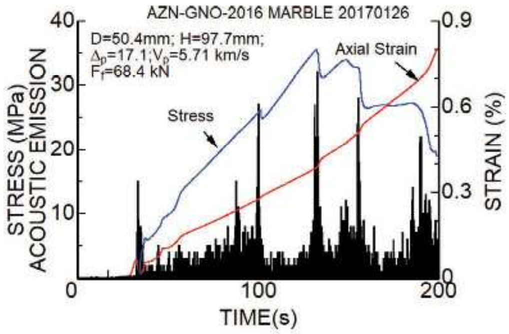
4 MECHANICAL PROPERTIES OF MARBLES AND BLOCK INTERFACES

The mechanical properties of marbles and block interfaces have not been tested as sampling are not allowed from this historical bridges. The authors located the ancient quarries for sampling on rock blocks and their interfaces. The ancient quarries are found to be at Göynükören and Örencik villages (Figure 9). The investigation at the ancient quarries indicated that the quarrymen at ancient times utilized rock discontinuities to their advantage to extract marble blocks. The authors have recently obtained rock samples for uniaxial and Brazilian

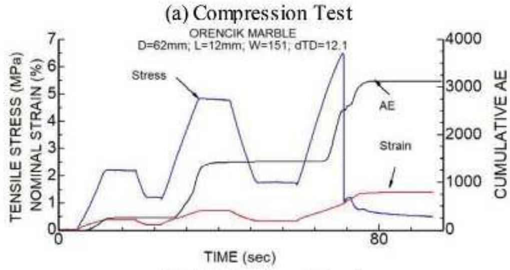
(a) Göynükören antique quarries

(b) Örencik antique quarry

Figure 9. Views of antique quarries



(a) Compression Test



(b) Brazilian tensile test

Figure 10. Strain-stress relations of marble samples of Aizanoi under uniaxial compression and Brazilian tests.

tensile tests as well as the rock plates for friction properties of block interfaces. Although the experiments have not been completed yet, some preliminary tests are shown in Figure 10.

The mechanical behaviour of contacts between blocks is the most important parameter governing the overall stability of the masonry structures. An experimental program has been initiated to test the mechanical behaviour of the contact conditions of marble blocks under static and dynamic direct shear loading conditions using a high capacity dynamic shear testing machine at the Civil Eng. Dept., the University of the Ryukyus. In addition of some tilting tests are performed on the marble and limestone blocks with surface conditions. Table 1 summarizes the friction angle obtained from tilting tests. The friction angle of dimension stones of marble and limestone is generally high unless polished and they approach to their intrinsic friction angles under high normal stresses. Figure 11 shows a shear strength criterion for conventional marble contacts using the criterion of Aydan et al (1996).

5 NUMERICAL ANALYSES

A series of numerical analyses were carried out using the non-linear finite element code MIDAS-Civil (2015). Four different conditions are analysed as listed in Table 2. The material properties used in the analyses are given in Table 3. Figure 12 shows the details of the finite element meshes for each part of the bridge. Figure 13 shows the boundary conditions. Subgrade stiffnesses were introduced

Table 1. Friction properties of marble contacts.

Surface condition	Friction angle (degrees)
Polished	22-27
Saw-cut	32-33
Rough	38-41

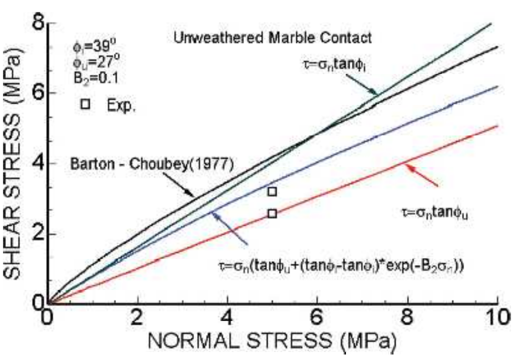


Figure 11. Shear strength envelope of marble block contacts

Table 2. Details of numerical analyses cases

Case No	Details
1	Modal analyses (Eigen values)
2	Self-weight only
3	Self-weight + 20 ton vehicle on the center arch
4	Self-weight + 20 ton vehicles on three arches

Table 3. Friction properties of marble and limestone blocks.

Parameter	Marble	Contact
Density (kN/m^3)	26.5	
Elastic Modulus (GPa)	17.72	
Poisson's ratio	0.23	
Cohesion (MPa)		0
Friction angle (degree)		30
Normal stiffness (N/mm^3)		10^{10}
Shear stiffness (N/mm^3)		1.12

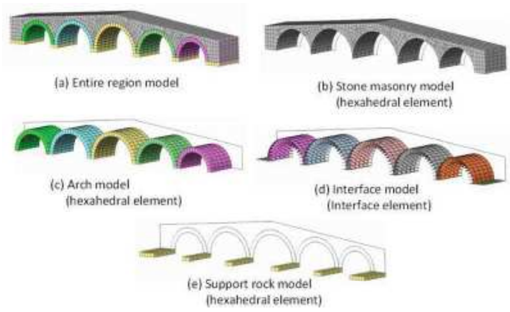


Figure 12. Exploded view of finite element meshes for each part of the arch bridge

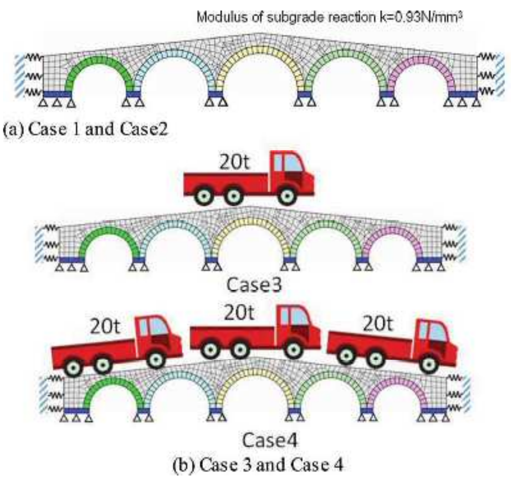


Figure 13. Illustration of boundary and loading conditions for different cases.

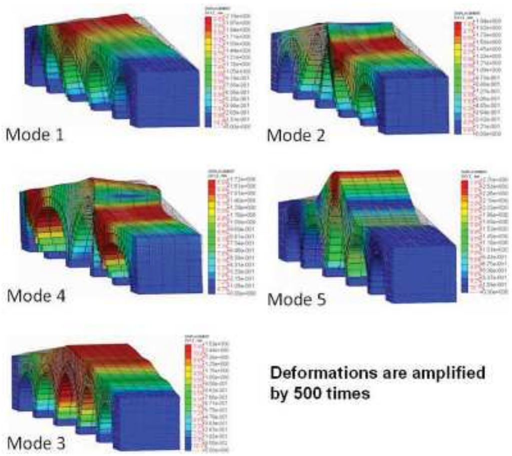


Figure 14. Deformed configuration of the bridge for five different modes

Table 4. Results of the modal analyses.

Mode No	Natural Frequency (Hz)	Natural Period (s)
1	11.82	0.084
2	18.40	0.054
3	24.36	0.041
4	27.64	0.036
5	28.90	0.035

in order to account the lateral ground reaction and possible relative settellement of foundations.

5.1 *Modal Analyses (Case 1)*

Figure 14 shows the deformation of the bridge for five different modes. Table 4 summarizes the eigen values of the bridge for each mode. One of important feature of this results is that the natural frequency is quite different from the frequency content of earthquakes which ranges between 1-5 Hz.

5.2 *Self-weight Loading (Case 2)*

The stone masonry bridges are designed on the concept of arch action, which induced compressive stresses within the blocks without any inter-block sliding. Different arch configurations are utilized for this purpose. The original arching concept was developed by Sumerians more than 5000 years ago and it has been used widely since then (Aydan 2008, 2014). Figure 15 shows the deformation of the arch bridge under its own self-weight. The maximum displacement occurs at the center of the widest arch.

Figure 16 shows the principal stress distributions in the arch (tension is assumed to be positive). It is interesting to note that the arch is subjected to

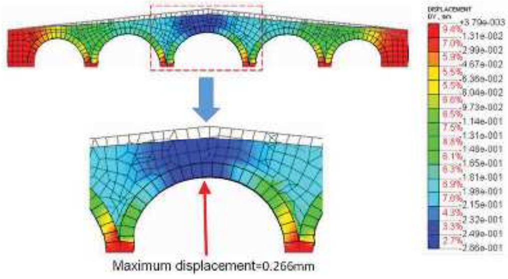


Figure 15. Deformed configuration of the arches under their own self-weight.

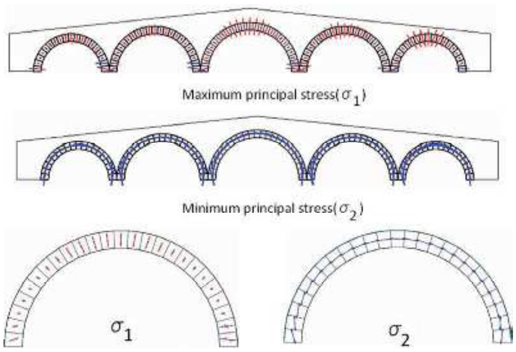


Figure 16. Principal stress distribution in the arches of the bridge.

all around tangential compressive stresses, which is of paramount importance for the validity of the arching concept. Nevertheless, small radial tensile stresses develop in the arch blocks. This may imply that the blocks may split at the mid point if such stresses exceed their tensile strength.

5.3 *Self-weight and Vehicle Loading (Case 3 & 4)*

The passage of the trucks and buses (generally more than 10 tons and may be up-to 20 tons) is now forbidden. However, it was known that some heavy trucks up to 20 tons passed over the bridge. Sometimes, three trucks might have passed over the bridges. These two possible conditions were carried out. Following the application of the self-weight loading, loads resulting from the vehicles are applied to the model and a series of non-linear finite element analyses which allow the relative slip among blocks along contacts, were carried out. Figure 17 shows the deformed configuration of the arch bridge for the final step of computation. The number of vehicles did not have much influence on the overall deformation and stress state within the bridge. The numerical analyses indicated that the overall deformation and stress state are influenced by the self-weight of the arch bridge. Nevertheless, the consideration of dynamic loading conditions may lead to the different conclusions.

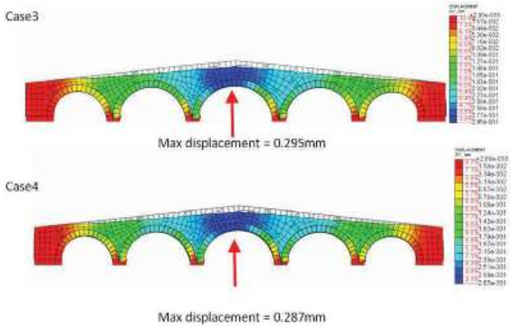


Figure 17. Deformed configuration of the bridge for Case 3 and Case 4 loading condition at the final step of the computation.

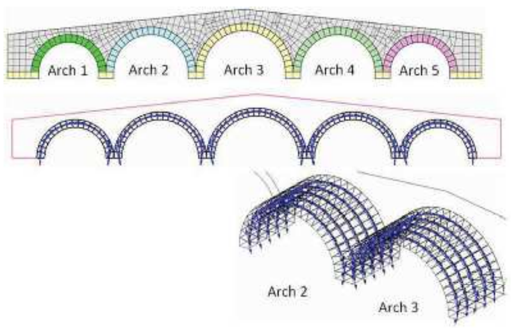


Figure 18. Compressive principle stresses in the arches of the bridge for Case 4 at the last step of computation.

Figure 18 shows the compressive principle stresses in the arches of the bridge for Case 4 at the final step of computation. As pointed above, the self-weight of the structure has much more influence than the loads induced by the vehicles. Despite additional 60 tons load due to vehicles, the stresses in the arches are compressive, which implying the arch action is not disturbed by the vehicles.

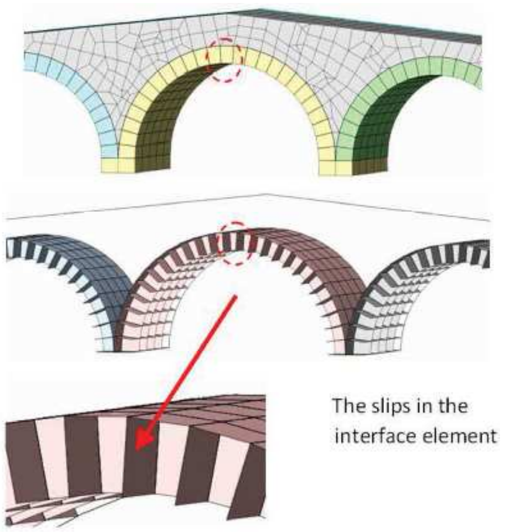


Figure 19. Relative slips at the crown of the widest arch.

In order to see the slip among blocks along contact surfaces, a close-up view of the deformation in the crown of the widest arch is shown in Figure 19 for CASE 4 at the final step of computation. The computations indicated that the relative slips along the contacts of the marble blocks are quite small and the computation is stable. In other words, the computations are convergent.

6 CONCLUSIONS

The authors investigated the response and stability stone masonry bridges constructed during the Roman period in Azan (Aizanoi) antique city under different loading conditions. This study on the stone masonry bridges existing in this ancient city is of the first kind, and the in-situ investigations, experiments and numerical analyses clearly showed why these bridges have performed very well so far since their construction about 1850 years ago. Nevertheless, further experiments on the mechanical characteristics of marble blocks and contacts are necessary.

The region is subjected to earthquakes from time to time. Further numerical analyses are necessary on the dynamics response and stability of the bridges in this ancient city.

Two bridges are missing. The causes of the collapse of these bridges need to be clarified by further investigations.

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