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Damage assessment within the Kathmandu valley's World Heritage Monument Zones after 2015 Gorkha Earthquake

Evaluation des dommages dans les zones des monuments du patrimoine mondial de la vallée de Kathmandu après le tremblement de terre de Gorkha de 2015

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ABSTRACT: Kathmandu, the capital city of Nepal experienced a cultural catastrophe in the aftermath of the 2015 Gorkha Earthquake (M_w=7.8) which destroyed hundreds of historical and cultural monuments. Five out of the seven mountain zones within Kathmandu's UNESCO World Heritage Sites suffered damage ranging from the complete collapse of several temples near Hanumandhoka's Durbar Square to partial damage at Changu Narayan. This study presents the results of reconnaissance surveys conducted in December 2017 and June 2018 within the Pashupati and Changu Narayan monument zones investigating the plausible causes of damage incurred. Geotechnical assessment of soils reveals the presence of gravelly sand at Pashupati and clayey silt at Changu Narayan. The soil-water retention characteristics and strength parameters of these soil were also obtained in the laboratory. Evidence of rotation and differential settlements in the foundations of the ancient structures was not observed suggesting that soil liquefaction had not taken place at these locations. Structural damage patterns observed at these sites indicated a lack of periodic maintenance and low bending and shear stiffness of the masonry walls of the temples. This study suggests engineering interventions and monitoring systems that could safeguard these structures in the event of future earthquakes.

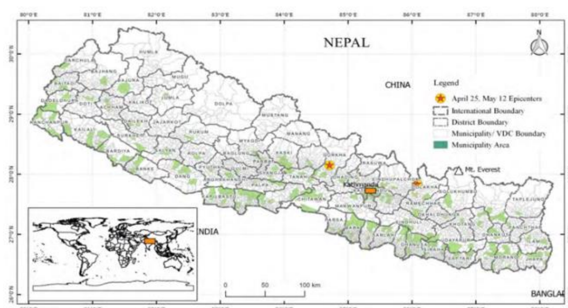
RÉSUMÉ: Katmandou, la capitale du Népal, a connu une catastrophe culturelle à la suite du tremblement de terre de Gorkha en 2015 (Mw = 7,8), qui a détruit des centaines de monuments historiques et culturels. Cinq des sept zones de montagne au sein du patrimoine mondial de l'UNESCO à Katmandou ont subi des dommages allant de l'effondrement complet de plusieurs temples situés près de la place Durbar de Hanumandhoka à des dégâts partiels à Changu Narayan. Cette étude présente les résultats des enquêtes de reconnaissance menées en décembre 2017 et en juin 2018 dans les zones des monuments Pashupati et Changu Narayan, qui recherchent les causes plausibles des dommages subis. L'évaluation géotechnique des sols révèle la présence de sable graveleux à Pashupati et de limon argileux à Changu Narayan. Les caractéristiques de rétention en eau et les paramètres de résistance de ces sols ont également été obtenus en laboratoire. Aucune preuve de rotation et de tassement différentiel dans les fondations des anciennes structures n'a été observée, ce qui suggère que la liquéfaction du sol n'avait pas eu lieu à ces endroits. Les dommages structuraux observés sur ces sites indiquaient un manque d'entretien périodique et une faible rigidité en flexion et en cisaillement des murs de maçonnerie des temples. Cette étude suggère des interventions d'ingénierie et des systèmes de surveillance susceptibles de protéger ces structures en cas de séismes.

Keywords: Nepal Earthquake; damage; liquefaction; heritage; monuments; forensic engineering

1 INTRODUCTION

Kathmandu, the capital city of Nepal is located in the Kathmandu Valley surrounded by the Himalayan mountain range (Dhital, 2015). Medieval temples built centuries ago in Kathmandu are known for their historic and archeological importance. The city is home to seven UNESCO world heritage monument zones and derives 7.6% of its total GDP through tourism. Numerous earthquakes have occurred in the region causing huge damage to life and properties. On April 25, 2015, a very strong earthquake of M_w 7.8 shook entire Nepal and some neighbouring areas of India at 11:56 local time. The epicente location of the earthquake was near the Barpak village of Gorkha District, 77 km N-W from Kathmandu and estimated focal depth was 15 km, as shown in Figure 1. Figure 2 illustrates acceleration-time history measured at Kantipath location in Kathmandu. The earthquake was followed by a number of aftershocks resulting in additional damage in the already jolted structures. The earthquake was one of the most powerful and devastating earthquakes since the 1934 Bihar Nepal Earthquake (M_w=8.1). The main shock (M_w=7.8) and two major aftershocks (M_w=6.6 and 6.7) killed around 9000 people, displaced 2.8 million people, destroyed 500,000 homes and undermined the sustainability of Nepal's tourist industry (Gautam et al. 2016). Gautam (2017) reported this earthquake as a cultural catastrophe damaging 403 monuments of Kathmandu's historic urban infra-structure.

Figure 1. Map of Nepal District Boundaries, with an



inset map of Nepal's location on a world map (source: NSET, 2015)

Weise et al. (2017) stated that this earthquake damaged many vernacular buildings and historical monuments, including 190 collapsed and 663 partially damaged. Coningham et al. (2016) reported the death of over 70 people by the collapse of one of the Kathmandu's oldest monument, the Kasthamandap. Over the years, the conservation of these historic structures has drawn both national and international concern. These structures are multi-tiered, having brick masonry as a main load-bearing structural system and they have already suffered from minor to major damage in other seismic events due to their low tensile and shear strength, brittle failure characteristics. Assessment of these structures from seismic standpoint has now become very important in order to safeguard them from future possible earthquake hazards.

This study focuses on identifying the causes of collapse or damage in a sample of medieval structures by investigating the geotechnical characteristics of the soil supporting them and also by collecting associated damage evidence in the substructure and superstructure portion of the monuments present in Pashupati and Changu Narayan. Two reconnaissance surveys during December 2017 and May 2018 have been carried out to achieve this goal. A team of geotechnical engineers from Durham University and structural engineers from Newcastle University has conducted a geotechnical site investigation and also studied structural damage patterns at five heritage sites in Kathmandu. This paper gives the geotechnical assessment of the soil samples collected from Pashupati (27°42'37.47"N, 85°20'55.23"E) and Changu Narayan (27°42'58.59"N 85°25'40.41"E) sites and also highlights the causes of structural damage patterns exhibited at this site. It suggests the precauctionary measures to be adopted to safeguard these structures from future earthquake hazards.

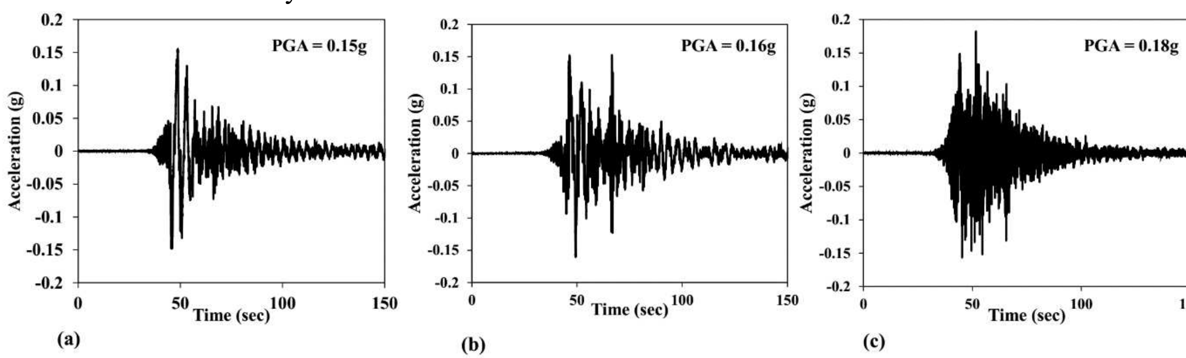


Fig. 2. Acceleration-time history record of 2015 Gorkha Earthquake mainshock event recorded at Kantipath Station in Kathmandu (27.71235N 85.31561E) (Data from: https://strongmotioncenter.org/)

2 GEOTECHNICAL FEATURES AT PASHUPATI AND CHANGU NARAYAN

Pashupati is located in the central Kathmandu region resting on Chandragiri formation characterised by limestone deposits of approximately 2000 m thickness (Sakai, 2001). The hertiage site Pashupatinath temple complex lies on the bank of Bagmati river. On the other hand, Changu Narayan is situated in the Bhaktapur district of the Kathmandu Valley overlying Kulekhani geological formation comprises of quartzite and schists of approximately 2000 m thickness (Sakai, 2001). Changu Narayan temple heritage site is located on the hilltop. Topographically, both the sites have the advantage of sitting on the stiff soil deposits followed by rock formation continuing to greater depth. In order to undertand the local soil stratigraphy, a borehole was drilled by cable percussion drilling after careful recording and removal of archeological materials present from ground level to a depth of 2.43 m at Pashupati site and 1.4 m at Changu Narayan site. This was to avoid unrecorded destruction of the archaeological deposits within the World Heritage Site. Standard Penetration Tests (SPT) were conducted in the borehole at 1.5 m depth intervals during excavation (SPT testing is shown in Figure 3).

Figure 3. Drilling operation at Changu Narayan

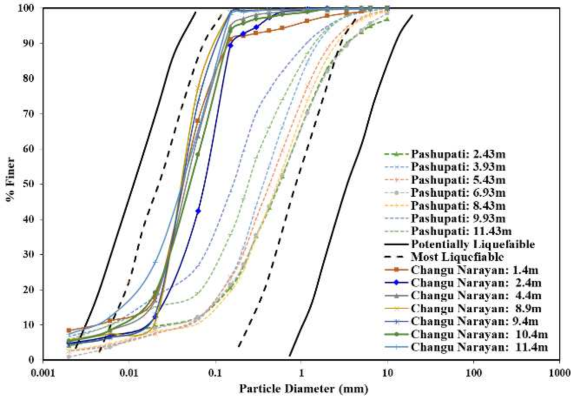


Figure 4. Gradation curves for soil samples collected from Pashupati in the Kathmandu valley also range of liquefiable zones given by Tsuchida and Hayashi 1971.

Soil samples were also collected for a program of laboratory testing and engineering characterisation. At the Pashupati site, the SPT-N values recorded ranged from 33 to 50 for the full depth of the borehole (12.5 m) indicating the presence of dense granular sand with a thin layer of medium dense sand (SPT-N=15) at 8 m. At the Changu Narayan location, the SPT-N values ranged from 35-50 for the full depth of borehole (11.5 m) indicating the presence of a dense clayey silt layer. The presence of dense material at both the sites and local geologic settings lowers the possibilty of any wave amplification or period elongation of response spectrum during an earthquake event.

Particle size distribution analysis and Atterberg limit tests were carried out on the collected soil samples as per the procedure in BS 1377 (BSI, 1990). Thereafter, the soil water retention curve and the strength parameters of these soils were also obtained. Figure 4 illustrates the gradation curve for the soil samples collected at different depths for both the locations which indicates a uniformly graded shape for all the curves. Table 1 gives the details of the percentage of gravel, sand, fines content and Atterberg limits for Pashupati and Changu Narayan.

Table 1. Results from gradation curve for soil samples collected from Pashupati and Changu Narayan in Kathmandu

No.	Sample depth (m)	Test results		
		% (Gravel, Sand, Fines)	C_u, C_c	LL, PI
Pashupati				
S1	2.43	17.1,70.6,12.3	40, 3.9	33.3,NP
S2	3.93	6.4, 82.2,11.4	10, 1.6	34.7,NP
S3	5.43	11.5, 76.5, 11	13, 1.5	34, NP
S4	6.93	17.9,69.8,12.3	27, 2.6	32.3,NP
S5	8.43	14.1,75.5,10.4	14, 1.8	32.6,NP
S6	9.93	5.1, 68.1, 26.8	33, 3.5	40, 7
S7	11.43	5.7, 75.1,19.2	57, 7.1	36, 5
Changu Narayan				
S1	1.4	2.3, 29.8,67.9	13,3.9	44,12
S2	2.4	0,57.6, 42.4	5.6,1.4	35,6
S3	4.4	0.4, 35.8,63.8	6.7,1.7	44,7
S4	8.9	0.1, 22.6,77.3	2.3,1	43,14
S5	9.4	0.1, 26.7,73.2	3.1,1.1	45,12
S6	10.4	0.2, 41.4,58.4	8.1,1.7	44,9
S7	11.4	0.17,34.7,65.4	14,2	39,10

C_u- Uniformity coefficient, Cc- Coefficient of curvature, LL- Liquid limit, PI- Plasticity index, NP- non Plastic

2.1 Determination of water retention characteristics

The soil-water retention behaviour is very important for understanding the unsaturated behaviour of geomaterials represented in terms of soil suction and water content. It plays a crucial role in dictating the behaviour of shallow foundations. Most of the heritage structures in Kathmandu are resting on the shallow mat foundation, hence, obtaining the unsaturated behaviour of the soil would be required for back analyzing the soil response. Here, water retention characteristics of the soil samples collected from Pashupati and Changu Narayan heritage sites are determined in the laboratory using the tensiometer and water retention frame developed at Durham University, as shown in Figure 5. The apparatus allows the continuous measurement of water content, suction and volume change. The tensiometers used herein are capable of measuring suction up to 2000 kPa. It is fitted through a hole in the sample support plate and also at the top to measure the suction at the top and bottom of the soil sample. Specimens of 20 mm thickness were prepared by using a 100 mm diameter mould where dry densities of soil from Pashupati and Changu Narayan were maintained at 1.78 Mg/m^3 and 1.55 Mg/m^3 respectively. The samples were compacted at the water content of 16.8% (Pashupati) and 24.9% (Changu Narayan). The sample is dried by allowing evaporation to the air.

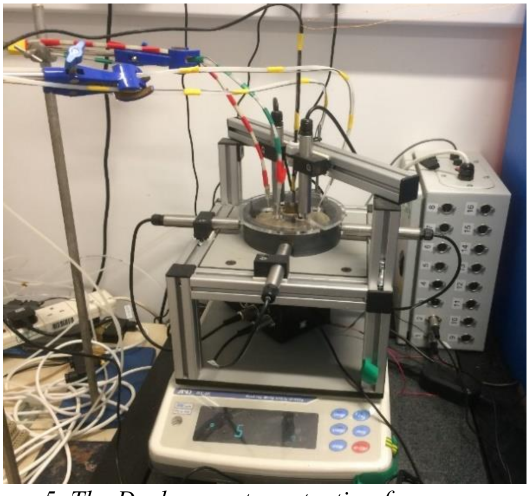


Figure 5. The Durham water retention frame

During the tests, the soils from both locations did not exhibit any volume change during the continuous drying process. The change in water content with respect to changes in the suction characteristics were measured and results are presented in terms of variation of volumetric water content with respect to changes in the suction of the soil samples, as illustrated in Figure 6.

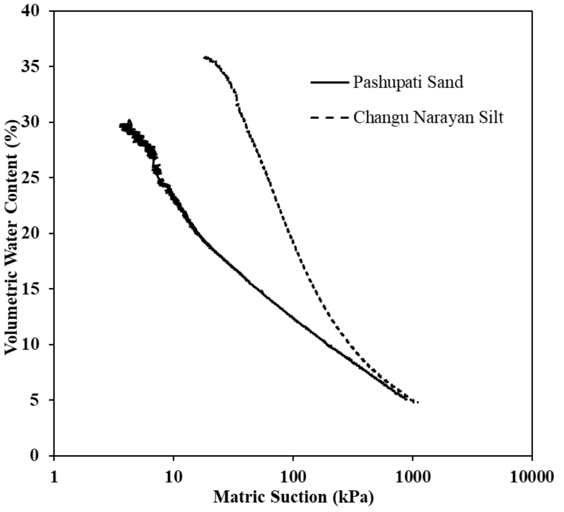
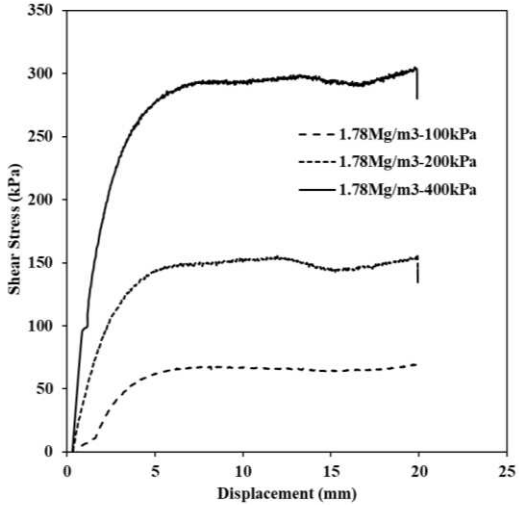


Figure 6. Soil water retention curves from laboratory measurements

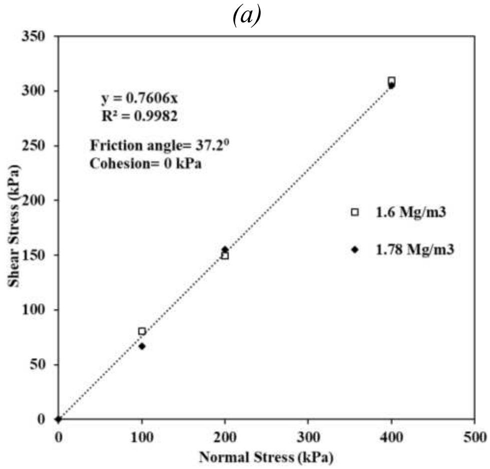
2.2 Determination of shear strength

The shear strength parameters of the soil are important design parameters which can be used for back analysing the failure of the temple structure. In this study, these parameters were determined by using a GDS back pressure shearbox apparatus which is capable of performing unsaturated and saturated direct shear testing of soil whilst controlling the sample pore pressure during the test. The soil samples were prepared by tamping the soil into the direct shear sample chamber.

Figure 7 (a, b) shows the variation of shear stress with respect to shear displacement for different consolidation pressure that gives the angle of internal friction equal to 37^0 for Pashupati sand.

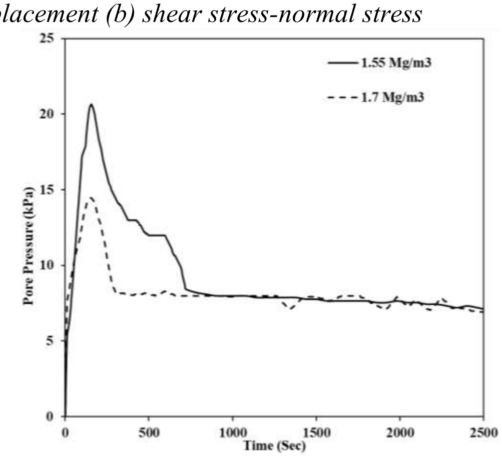


(a)

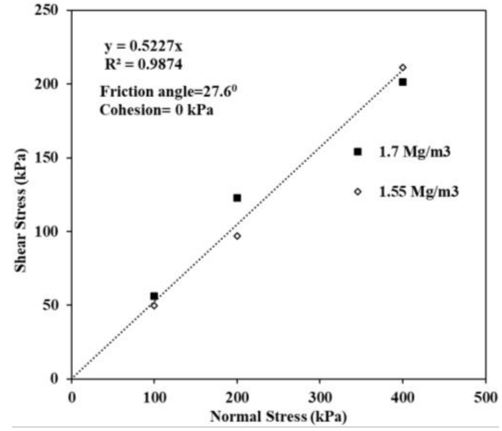


(b)

Figure 7. Pashupati soil response (a) shear stress-displacement (b) shear stress-normal stress



(a)



(b)

Fig. 8. Changu Narayan Soil sample (a) Pore-pressure response during consolidation (b) Shear stress-normal stress

Figure 8 (a) illustrates the variation of pore pressure with respect to the elapsed time during the the test at consolidation pressure of 200 kPa at the time of shear testing for Changu Narayan's dense clayey silt. Figure 8(b) gives the value of the angle of internal friction which found to be equal to 27.6^0.

3 SEISMIC LIQUEFACTION FEATURE

Liquefaction is defined as a phenomenon in which strength and stiffness of saturated cohesionless soil are reduced by seismic shaking leading to the generation of excess pore water pressure that finally results in a complete loss of shear strength. Figure 4 shows grain size boundary curves indicating the range in which soils are most susceptible to liquefaction as defined by Tsuchida and Hayashi (1971) based on compositional criteria. From Figure 4, it can be seen that almost all the curves for the soil samples recovered fall within the range of most liquefiable to potentially liquefiable. However, evidence of liquefaction at the sites was not observed during site visits and have not been reported by other researchers. This may be due to the absence of groundwater at shallow depth when the earthquake hit the site on April 2015. This was the beginning of the summer season in

Kathmandu and groundwater abstraction may have been responsible for artificially lowering water levels. During the borehole investigation reported in this paper (in December 2017), groundwater was observed to be 7.5 m below ground level for Pashupati.

4 DAMAGE PATTERN IN HERITAGE STRUCTURES

Field reconnaissance was performed to study the damage patterns of the ancient structures near the Pashupatinath Temple complex and nearby Changu Narayan temple during the last week of May 2018. Symmetrical geometric configuration was the main feature of these ancient structures as shown in Figure 9. Brick masonry walls act as a load-bearing system where wall thickness varies between walls on different stories. Inclined timber struts transfer the roof loads from tiled roofs to the masonry walls. It is important to note that these temples have already survived the 1934 Nepal-Bihar Earthquake (M_w=8.1), the 1988 Udaypur Earthquake (M_w=6.9) and the 2011 Sikkim-Nepal Earthquake (M_w=6.9). During post-earthquake reconnaissance surveys conducted in 2015, minor to serious levels of damage were identified in most of the structures surveyed. Most of this has been attributed to age related deterioration of construction materials and also the lack of regular maintenance; however the rehabilitated strength of these temples is yet to be established. Diagonal and vertical line cracks near the corners of the masonry walls, cracks in the crown portion of the temples and the out-of-plane collapse of masonry walls were the main damage mechanism observed during the survey conducted in 2018.

Figure 10 illustrates the out-of-plane collapse of an unreinforced masonry wall of a courtyard building located south-west of the main Pashupati temple complex. This may be mainly due to the inability of the mud mortar present in the masonry walls to resist the lateral forces induced by the Gorkha Earthquake. Inspection within the building revealed vertical cracks in many masonry wall panels. Such level of cracking is difficult to repair and requires rebuilding parts of the wall. Figure 11 highlights a wide visible crack in the crown portion of a brick masonry temple located 300 m north of the main Pashupatinath temple complex. This damage pattern is attributed to stress concentration near the crown portion of the temples and their inability to bear bending stress induced during seismic shaking.

Figure 9. View of Pashupati temple region three years after 2015 Gorkha earthquake

Figure 10 View of the collapsed portion of the courtyard building

The Changu Narayan temple experienced minimal damage during the earthquake which is mainly due to its location at the hilltop and presence of dense soil media. The possibility of rotation and differential settlements in the foundation components of these structures were also explored during the reconnaissance survey. However, no evidence of such movement was identified by the team at Pashupati and Changu Narayan. It was also noted that the heritage structures were more affected as compared to modern reinforced concrete structures. At present, restoration works of many structures in the Pashupati complex are ongoing with an aim to rebuild and preserve their ancient architecture

Figure 11 View of visible crack in a temple made of brick masonry and no such crack in a stone temple.

5 CONCLUSIONS

This study presents an investigation of geotechnical characteristics of the soil and the damage patterns observed in the ancient infrastructure around the World Heritage Monument zones of Kathmandu. The soil at Pashupati was mainly uniformly graded dense silty sand and at Changu Narayan was dense clayey silt. The presence of dense soil reduces the liklihood of seismic wave amplification or period elongation of the response spectrum at both these sites. The ground water table was found at the depth of 7.5 m at Pashupati location however, Changu Narayan does not show any indication of ground water table to a depth of 11.5 m. This indicate that the unsatruaed shear strength parameters of the soil might dictate the behaviour of the foundation present in these regions. Hence, the obtained shear strength parameters alongwith soil-water retention characteristics may be used to back-analyse the behaviour of soil under the prescribed earthqukae conditions. Changu Narayan experienced minimal damage as compared to other heritage sites due to its topographical location at the hilltop and presence of dense soil medium. No evidence of excessive total or differential settlements in the foundations of the structures was observed. The out-of-plane collapse noted in some of the structures was due to their inability to resist the lateral forces induced by the recent earthquake, rather than failure of the foundaing material. In summary, the primary cause of damage in these structures appeared to be associated with insufficient structural resistance, rather than foundation failure and this structural inadequacy has been exacerbated by a lack of regular maintenance, inadequate bending and shear stiffness of the masonry walls.

To safeguard these structures from future earthquakes, it is suggested that periodic inspection and maintenance of existing archeological infrastructure, together with a program of more detailed structural assessment has the potential to increase the seismic resilience of these structures; however, it is also necessary to implement maintenance programs that are consistent with the historical importance of these structures. Data acquisition techniques could be effectively used to record damage at a large scale on a regular basis (Dhonju et al. 2017 and 2018). In such a scenario, individual effort is not sufficient to survey all of the heritage structures in an emergency situation. Community or citizen participation, consisting of heritage digitization and documentation, could potentially contribute significantly to heritage preservation. Advances in digitization and documentation of heritage structures could be coupled with advanced numerical modelling strategies can significantly reduce the cost of structural inspection and assessment (Kassotakis et al. 2018).

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