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Some examples of damage to rock masonry structures caused by recent earthquakes

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ABSTRACT: Historical structures are mainly masonry structures, and they are composed of blocks made of natural stones, bricks or both, and they are built in different patterns with or without mortar. As Japan is a seismically active country, an emphasis was given on the seismic response and stability of restored masonry structures such as arches and walls during earthquakes and natural rock structures. Furthermore, The deterioration by atmospheric agents, bombing and seismic shaking damaged some of these structures. The authors describes the outcomes of experimental, limiting equilibrium and numerical studies on the stability of historical masonry structures under dynamic loads such as those induced by earthquakes and their implications are discussed.

1 INTRODUCTION

Historical structures are mainly masonry type, and they are composed of blocks made of natural stones, bricks or both, and they are built in different patterns with or without mortar. The authors have been recently involved with the restoration of the famous historical structure in Okinawa Island such as Shuri Castle, Nakagusuku Castle, Katsuren Castle, Gushikawa Castle, an arch bridge in Iedonchi royal garden and Yodore royal mausoleum of the Ryukyu Imperial period, as well as the assessment of static and dynamic stability of some natural rock structures such as Wakariji.

As Japan is a seismically active country, an emphasis was given on the seismic response and stability of restored masonry structures such as arches and walls during earthquakes and natural rock structures. Furthermore, The deterioration by atmospheric agents, bombing and seismic shaking damaged some of these structures.

Different arch configurations used in Shuri Castle in Okinawa Island were tested. The stability of the dynamic arch bridge of Iedonchi Royal Garden and Wakariji natural rock structure were investigated using the physical models (Tokashiki et al. 2007). Furthermore, dynamic limiting equilibrium methods (D-LEM) as well as numerical methods (i.e. conventional finite element method (FEM), discrete finite element method (Aydan 1998; Aydan et al. 1996; Mamaghani et al. 1989).

The authors describes the outcomes of experimental, limiting equilibrium and numerical studies on the stability of historical masonry structures under dynamic loads such as those induced by earthquakes and their implications are discussed.

2 RETAINING WALL COLLAPSE OF KATSUREN CASTLE

An earthquake with a magnitude of 7.2 on Japan Meteorological Agency Scale occurred near Okinawa Island of Japan (Fig. 1). The focal depth of the quake, which occurred at 5:31 a.m. local time (2031 GMT Friday), was about 40 km under the sea 107 km east off Naha, capital of Okinawa.

The 2010 earthquake caused the collapse of some parts of castle walls at Katsuren Castle, which is designated as a world heritage site. The castle is located over a hill in Uruma City and the nearest

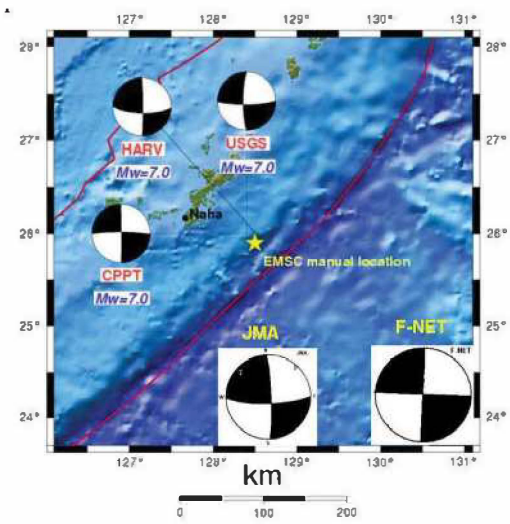


Figure 1. Location and focal mechanism of the 2010 earthquake

Figure 2. A views of the failed retaining wall

strong motion station of the K-NET strong motion network is Gushikawa. The NW corner of the castle wall with a height of 4m collapsed and there were numerous dislocations and rotation of blocks in the castle as seen in Fig. 2.

The authors carried out a series of analyses using the dynamic limit equilibrium method (D-LEM) and the acceleration records at Chinen and Gushikawa strong motion stations of the K-NET strong motion network. The typical size of the blocks ranges between 50 to 60 cm. Fig. 3 illustrates the geometry of retaining wall.

The authors used their method (Tokashiki et al. 2007) to back-analyze the collapse of the wall using the strong motion records taken at Gushikawa and Chinen. The wall is stable against toppling mode for strong motions recorded at Gushikawa and Chinen strong motion stations. If the records taken at Gushikawa are used, the relative sliding can not be greater than 10cm, which implies that the wall should be stable although some slip might take place. However, if the records taken for EW and NS components at Chinen are used the relative sliding can be greater than 60 cm for $\theta = 5°$, which exceeds the half size of the block and this implies that the wall should collapse (Fig. 4). The bulging of the wall and inclination of the foundation rock strongly supports that this condition would be prevailing at the location of the collapse. As the castle is situated on the top of the hill, it is likely that ground motions might have been amplified also.

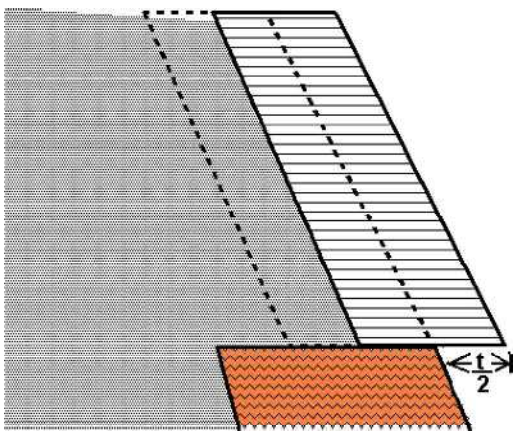


Figure 3. The idealized geometry of the failed retaining wall.

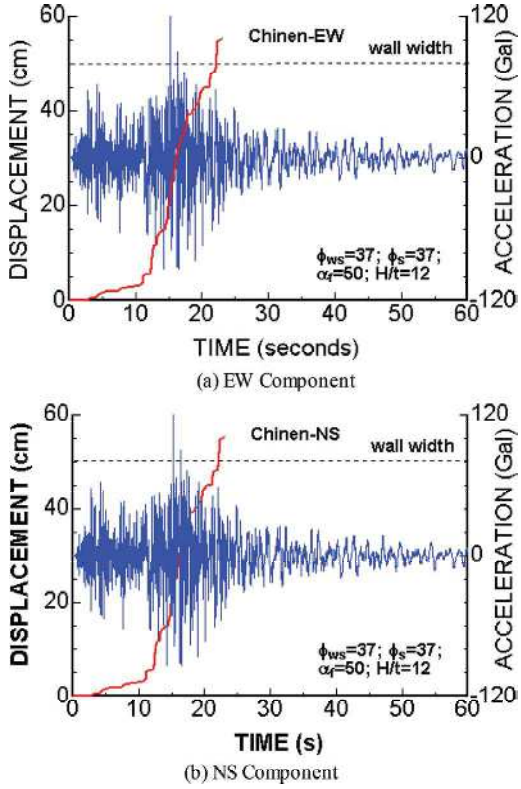
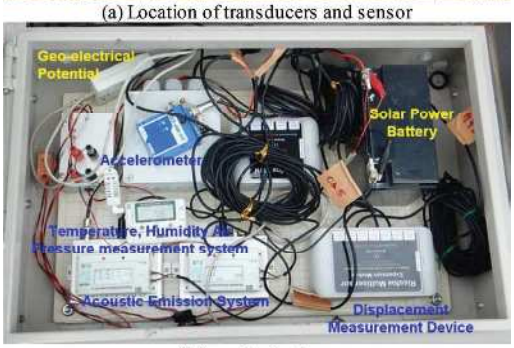


Figure 4. Sliding response of collapsed retaining wall for EW and NS components taken at the Chinen strong motion station

The authors have initiated a multi-parameter monitoring program at the Katsuren Castle and micro-tremor measurements. The multi-parameter monitoring system was installed at the north east corner of the castle, where some spalling and separation of blocks were observed. The system involves the real-time monitoring of relative displacement, acoustic emissions, temperature, humidity, air pressure, geo-electrical potential and accelerations (Fig. 5). A OA-SYC stand-alone type three component accelerometer is installed. This accelerometer can be set into different modes. For long-time monitoring, the accelerometer is set to trigger mode

(a) Location of transducers and sensor



(b) monitoring box.

Figure 5. View of installed devices and monitoring box

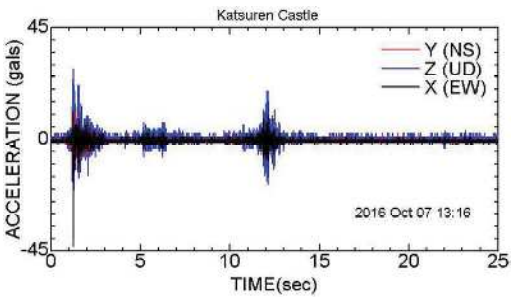


Figure 6. An acceleration record taken at the Katsuren Castle.

with a chosen threshold. Fig. 6 shows an example of acceleration record measured by the system in 2016, The system utilizes solar energy as a power source and it is an environment-friendly.

Some micro-tremor measurements are undertaken at the Katsuren Castle at different level. One of the purposes was to evaluate the frequency characteristics of the castle at various levels (Fig. 7). In addition, some measurements were also taken at the top of the retaining walls including the one collapsed and restored after the 2010 earthquake. The Fourier spectra of each channel at three levels were evaluated from the measurements and they

Figure 7. Locations of micro-tremor measurements

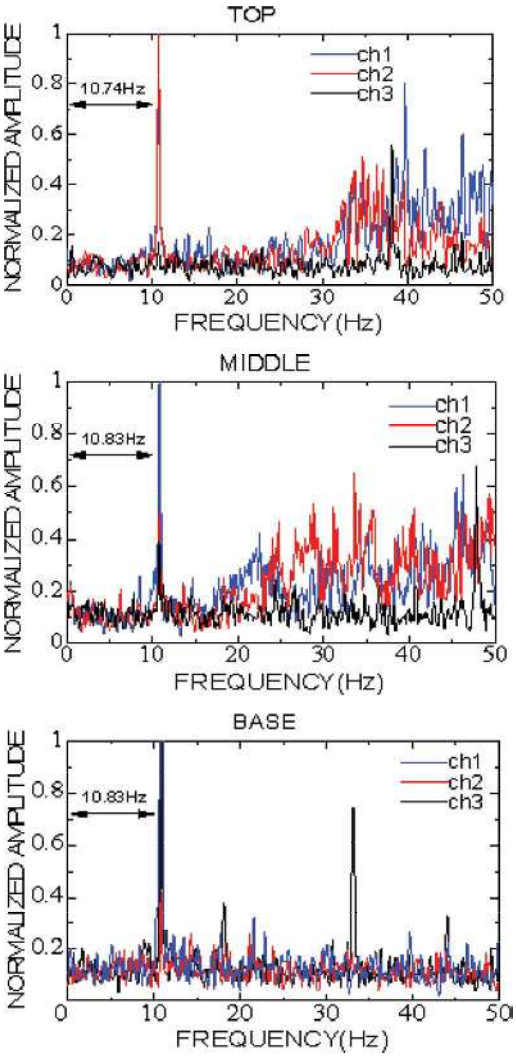


Figure 8. Fourier spectra of records at three levels.

are shown in Figure 8. The Fourier spectra was almost same for three levels and there was no big difference.

3 MEASUREMENTS AND OBSERVATIONS NAKAGUSUKU CASTLE

A multi-parameter monitoring system was also initiated by the authors at Nakagusuku Castle. The system at the castle was actually installed about 3 years before the one installed at the Katsuren Castle, which is probably the first attempt regarding the masonry structures in the world. The monitoring was initiated in December 2013 and it has been still continued. During the period of measurements, some earthquakes occurred and long-term creep-like separation of a huge crack in Ryukyu Limestone layer extending to the Shimajiri formation layer has been taking place. Fig. 9 shows the installation location.

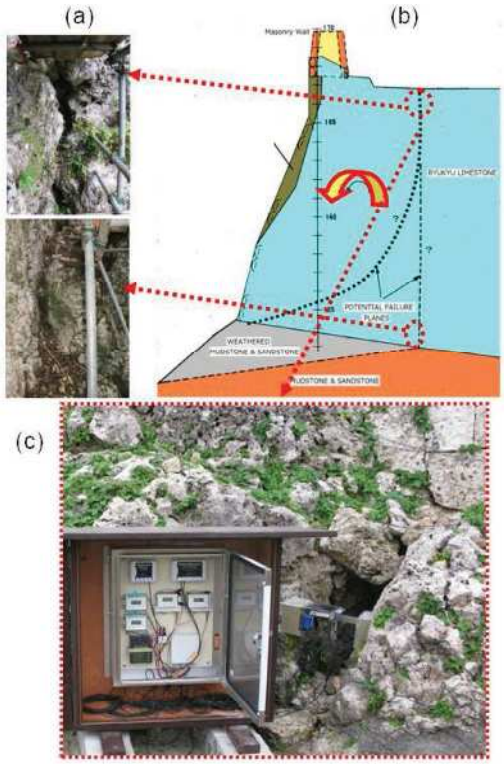


Figure 9. Views of monitoring location and instrumentation

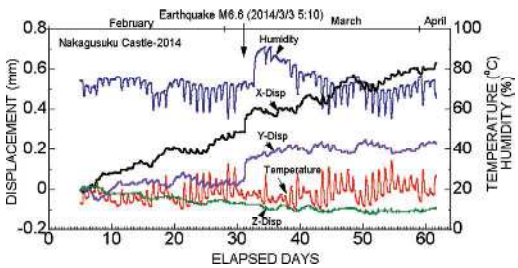


Figure 10. Monitoring results during Feb. to March, 2014.

An earthquake with a moment magnitude of 6.5 occurred at 5:10 AM on 2014 March 13 (JST) in East China Sea at a depth of 120 km on the western side of the Okinawa Island. Another earthquake occurred at 11:27 AM on the same day near Kumejima Island. Although the magnitude of the earthquake was intermediate and far from the location, some permanent displacement occurred as seen in Fig. 10.

A series of analysis using DFEM (Aydan et al. 1996) together with implementation of softening and hardening process of weathered rock mass in relation to rainfall (Aydan 2016) was carried out. Figure 11 shows the mesh used in analyses and comparison of computed results with measurements. The computational model can simulate both permanent displacement induced by the earthquake as well as rainfall induced softening process of weathered rock mass.

At this site, there is a monumental natural rock block used for religious purpose in historical times. According to archeologists, this natural block was toppled about 400 years ago during an earthquake. It was restored to its original position about 3 years ago (Fig. 12). It was also an important evidence of past earthquakes occurring in Okinawa Island or its close vicinity. A series of dynamic analyses on

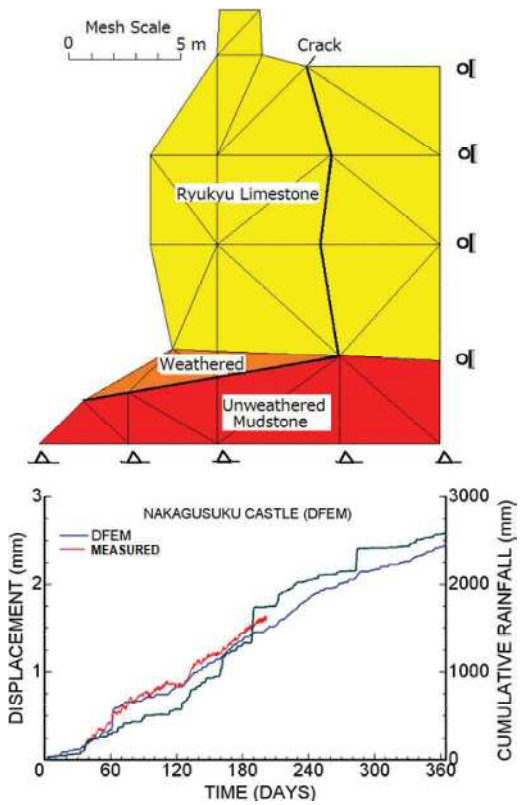


Figure 11. Mesh used DFEM analysis and comparison with measured responses.

Figure 12. Views of toppled block before and after restoration

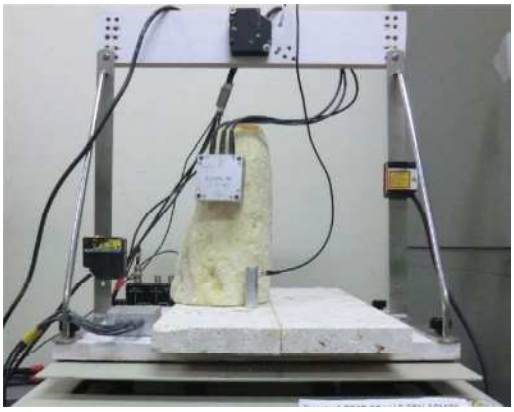


Figure 13. A view of shaking experimental set-up.

the toppling condition of this block was carried out and it was found that the amplitude of the ground acceleration at the base of this block should have been more than 0.7g. As the block seats on the rock base, it implied that the moment magnitude of the earthquake should had been about 8.1 for intra-plate earthquakes and 9.1 for off-shore subduction plate earthquake utilizing the empirical relations proposed by Aydan (2012).

A coral limestone block, which had a very similar geometrical configuration, was subjected to shaking and its stability was investigated. Fig. 13 shows a view of the coral limestone block together with the experimental set-up, which involves the measurement of accelerations, relative displacement and acoustic emissions. Fig. 14 shows the acceleration, acoustic emissions (AE) and relative displacement responses during the experiment. As the friction angle between the limestone and coral limestone was saw-cut, the block instability occurred due to sliding rather than toppling. Nevertheless, some rocking type movements was also observed.

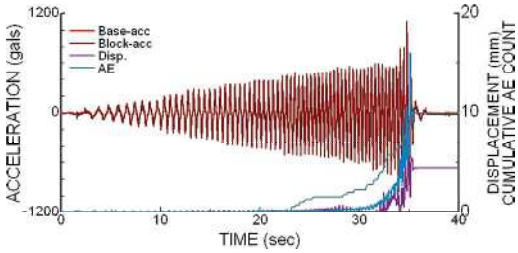


Figure 14. Measured responses of acceleration, relative slip and acoustic emissions.

4 THE DYNAMIC STABILITY OF WAKARIJI NATURAL ROCK BLOCK

There is a natural rock block, known as "Wakariji Stone" in Urasoe City of Okinawa Island, Japan, which is made of Ryukyu Limestone. It is also known as "Needle Rock" internationally. Wakariji stone is about 13m high with an eliptical base. The short axis is about 7.8m wide while the long axis is about 10m.

The authors were asked to evaluate the stability of this natural rock block under both static and dynamic conditions. As stability chart as shown in Fig. 15 was prepared for different modes of failure of rock block. The friction angle of the block with its base was estimated to be ranging between 40 and 46 degrees. As seen from the figure, the block is likely to topple rather than slide over of its base.

Besides site investigations and kinematic analyses of Wakariji Stone and kinematic analyses, a physical model of Wakariji Stone was prepared at a scale of 1/50 using a material having density similar to original rock material.

Two type of experiments were carried out. First several tilt tests were carried out in order to estimate the initiation of instability of the physical model and to check the validity of the stability chart. The second type experiment was shaking experiments. However, the base of the physical model was not fully corresponding to the actual situation and it was

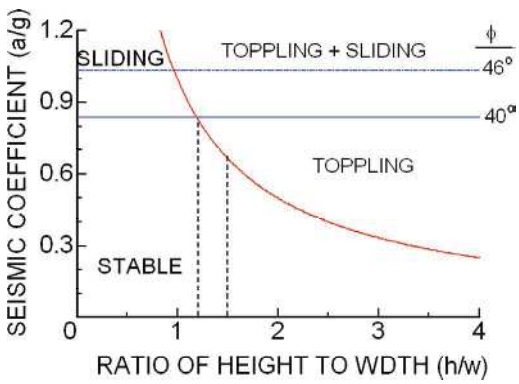


Figure 15. Stability chart for the Wakariji stone

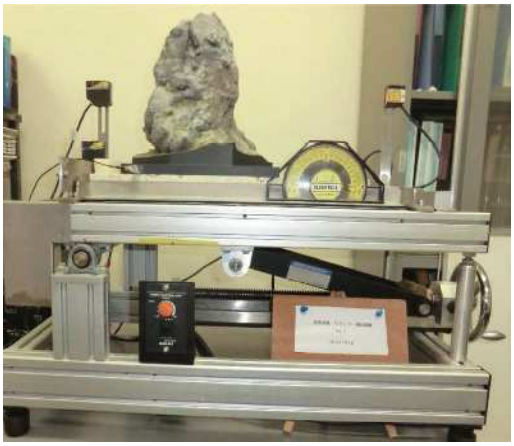


Figure 16. A view of tilting experimental set-up.

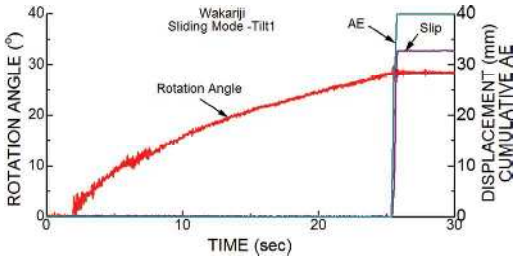


Figure 17. Measured responses of acceleration, relative slip and acoustic emissions.

Figure 18. A view of tilting experimental set-up.

build on a base with a width 0.923 time its height. Futhermore, the base was smooth with a friction angle of 30 degrees on the Ryukyu Limestone base plate. Fig. 16 shows the physical model in a tilting test while Fig. 17 shows the relation between the rotation angle and relative slip. The physical model slip over the base platen when the rotation angle reached the value of 28.5 degrees.

Next shaking table experiments were carried out. Fig. 18 shows the physical model during

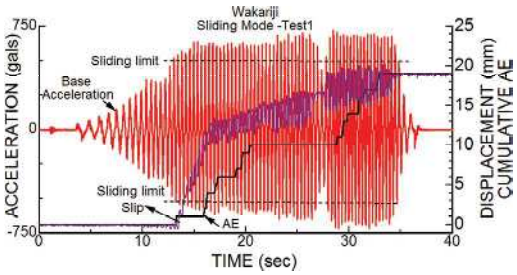


Figure 19. Measured responses of acceleration, relative slip and acoustic emissions.

shaking-table test while Fig 19 shows the acceleration, AE and relative slip responses as a function of time. The slip of the model occurred at the base acceleration estimated from friction angle.

5 CONCLUSIONS

Historical structures are mainly masonry structures and there are also monumental natural rocks. The historical structures, which are generally composed of blocks made of natural stones, bricks or both, are the ones remain over centuries or thousands years. In this study, the authors considered the stability of some masonry structures and monumental natural rock structures. The stability and response of these structures were investigated through an integrated approach involving multi-parameter in-situ monitoring system, dynamic physical tests, dynamic limiting equilibrium and numerical methods. It is shown that the stability and responses of various masonry structures and monumental natural rock structures can be estimated using the dynamic limiting equilibrium and numerical methods if appropriate considerations are given to the structure in hand.

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