Rock Dynamics – Experiments, Theories and Applications – Li, Li & Zhang (Eds)
© 2018 Tokashiki et al., ISBN 978-0-8153-9667-3

Dynamic response and stability of some historical masonry structures subjected to ground shaking

N. Tokashiki, Ö. Aydan & N.Z. Nasiry
University of the Ryukyus, Okinawa, Japan

T. Ito
Toyota National College of Technology, Toyota, Japan

M. Geniş
Bülent Ecevit University, Zonguldak, Turkey

ABSTRACT: Historical structures are mainly masonry structures, which are composed of blocks made of natural stones, bricks or both, and they are assembled in different patterns with or without mortar. The authors have been recently involved with the restoration of the famous Shuri Castle, Nakagusuku Castle, Gushikawa Castle, an arch bridge in Iedonchi Royal garden and Yodore Royal Mausoleum of the Ryukyu Imperial period as well as static and dynamic stability assessment of some natural rock structures such as Perry Banner Rock. The deterioration by atmospheric agents, bombing and seismic shaking damaged some of these structures. The recent earthquakes in Kumamoto also caused severe damage to historical masonry 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 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. The authors have been recently involved with the restoration of the famous historical structure in Okinawa Island such as Shuri Castle, Nakagusuku 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 Perry Banner Rock (Figure 1).

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 (Figure 2). 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, Perry Banner Rock were investigated using the physical models. Furthermore, dynamic

Figure 1. Some of historical masonry structures in Okinawa Island.

limiting equilibrium methods (D-LEM) as well as numerical methods (i.e. conventional finite element method (FEM), discrete finite element method (DFEM), finite difference based Fast Lagrangian Code (FLAC)) used for stability assessment

Figure 2. Damage induced by 2010 Off-Okinawa earthquake on Katsuren Castle.

of these masonry structures (Aydan 1998, Aydan et al. 1996, 2001, Itasca 2005, Geniş et al. 2009, Tokashiki et al. 2007).

2 MASONRY STRUCTURES

2.1 *Shuri castle*

The Shuri Castle, whose ruins remain in Naha City of Okinawa Prefecture, is said to date back to the 12th century or earlier. The castle grounds and buildings were completely destroyed by the bombing of US Army during the Battle of Okinawa in 1945. The castle has been under restoration according to a map drawn at Meiji period. Besides the main buildings of the castle, castle walls, retaining walls and arches have been re-constructed. Since these structures are of masonry type without reinforcement, their seismic stability during earthquakes is of great concern.

The arches of Shuri Castle generally consist of two monolithic blocks in the form of a semi-circle or an ovaloidic shape. As the shaking table was uniaxial, the effect of the direction of input acceleration wave was investigated by changing the longitudinal axis of the arches (Figure 3). In this article, one of such experiments is presented.

The experimental results indicated that the common form of failure for all arch types for a shaking direction of 0° is sliding at abutments and inward rotational fall of arch blocks, subsequently. As for 90° shaking, the arch failed in the form of toppling. The failure for 45° shaking was a combination of sliding and toppling. The experiments clearly indicated that the amplitude of acceleration waves to cause failure was the lowest for 90° shaking while it was maximum for 0° shaking (Figure 4b).

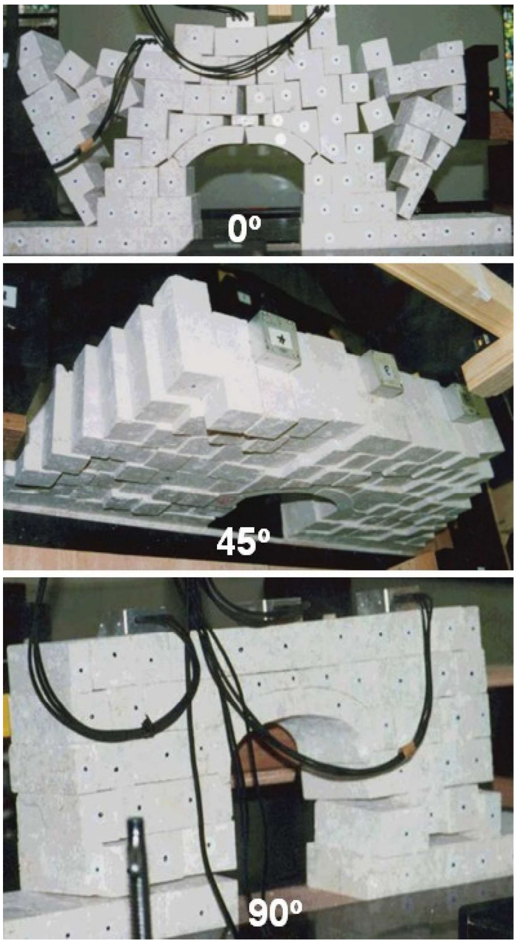

Figure 3. Effect of inclination of on the failure modes of model arches subjected to shaking.

A series of analyses using the discrete finite element method (DFEM) were performed on arch gates of Shuri Castle. Figure 5 shows a computational example on the arch gate under a horizontal seismic load and gravity. As noted from Figure 5, the failure occurs due to sliding of the sidewall and subsequent rotation and fall of the arch blocks.

2.2 *Yodore royal mausoleum*

Yodore Royal Mausoleum is located in Urasoe City (Figure 1). It was recently restored as a part of restoration project of masonry historical structures in Ryukyu Islands. A very high retaining wall of about 12 m high was constructed as a part of

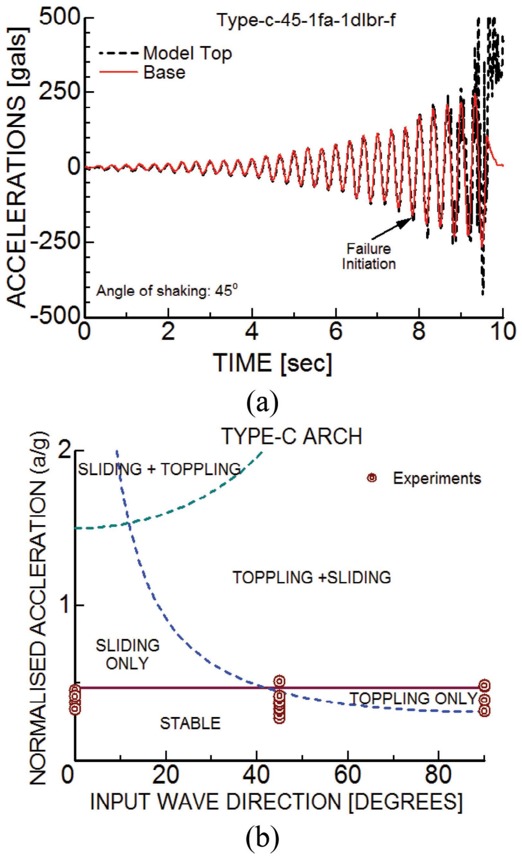

Figure 4. An acceleration record during a model test and stability chart.

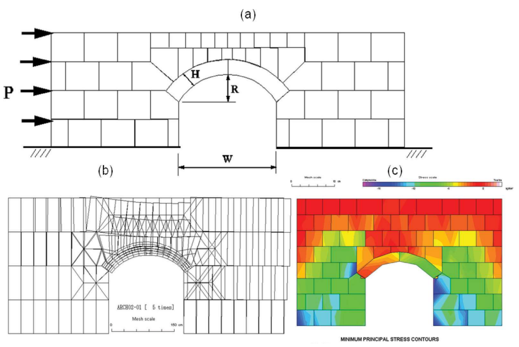

Figure 5. Numerical for DFEM analyses for arches and computational results.

the overall project. The slope behind the retaining wall was cut at an angle of 45°. The wall was stable under gravitational load. However, it failed during a heavy season following backfilling. The authors investigated the causes of this failure through some

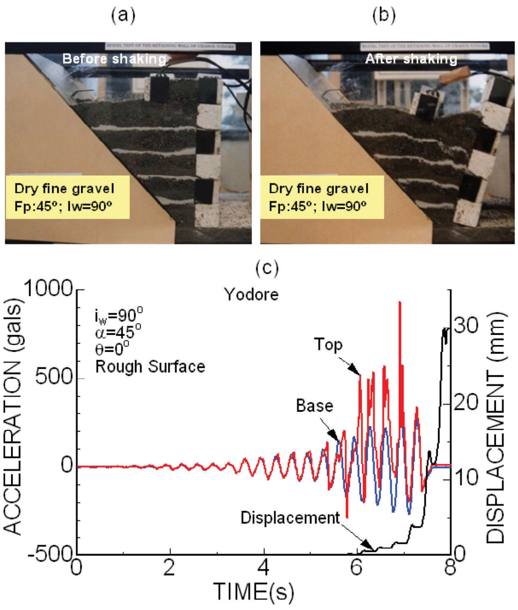

Figure 6. A view of the physical model before and after the shaking.

physical model tests (Figure 6). A physical model of retaining wall with a back filling was constructed. The model was stable under dry condition. When the model was fully saturated and the retaining wall has no drainage holes, it was found that the retaining-wall would fail. Next, the stability of the retaining wall was investigated under dynamic conditions. Figure 6 shows an example of a physical model before and after shaking together with displacement response of the wall. As noted from the figure, the retaining wall starts to exhibit non-linear behavior when the acceleration level is about 100 gals. After each cycle of shaking, the displacement of the wall increases. This deformation mode involves both relative slip and rotation of the wall with respect to its base.

2.3 *Arch bridge of iedonchi imperial garden*

Iedonchi imperial garden is very close to Shuri Castle. There are many stone structures carved into different artistic configurations in this garden. It has been recently found that that one of the arch bridges is dilapidating (Figure 1). The authorities were concerned with the stability of this arch bridge and the authors were asked to investigate the causes of dilapidation of the bridge and to propose possible counter measures. The authors have been investigating the stability of the arch bridge by model experiments using the base-friction appa-

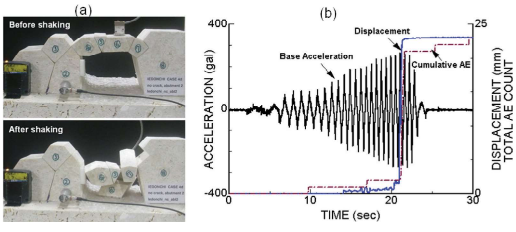

Figure 7. Views of the arch bridge before and after shaking, shaking response.

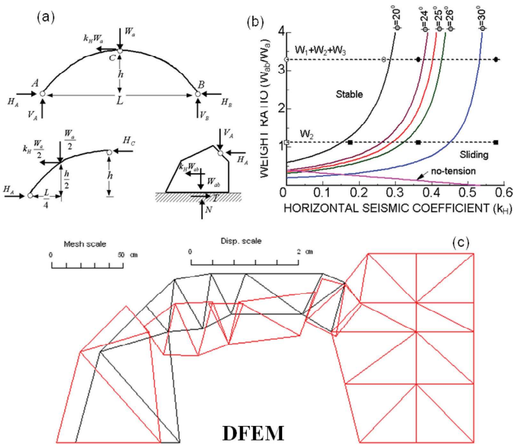

Figure 8. Mechanical model and computed results for PD-LEM and DFEM.

ratus and shaking table. The preliminary results indicated that the bridge must be stable under gravitational loading condition. Figure 7a shows views of the model arch bridge before and after shaking. Figure 7b shows the measured responses for the experiments shown in Figure 7a. The vibration, which may result from nearby constructions, bombing during the Second World War and/or earthquakes, causes the loss of the arching effect and may result in the collapse of the bridge. However, it was experimentally found that the increase of contact strength of block interfaces through grouting dramatically increases the resistance of the arch bridge against horizontal shaking.

Figure 8a shows a pseudo-dynamic limiting equilibrium method (PD-LEM) for the arch bridge. Figure 8b compares the computational results with measured limiting accelerations to induce failure. Figure 8c shows a computed deformation configuration of the arch bridge using the DFEM.

2.4 *Katsuren castle wall failure*

An earthquake with a magnitude of 7.2 on Japan Meteorological Agency Scale occurred near Okinawa Island of Japan (Figure 9a). 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 collapse of some parts of castle walls at Katsuren Castle, which is designated as a world heritage site, occurred. The castle is located over a hill in Uruma City and the nearest 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 Figure 9b.

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. 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 at Gushikawa and Chinen. If the records taken at Gushikawa are used, the relative sliding cannot be greater than 10cm, which implies that the wall should be stable although some slip might take place. However, if the records taken 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 (Figure 9c, d). 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.

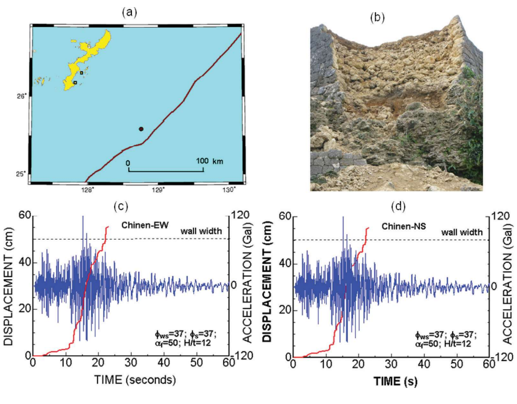

Figure 9. Location of the earthquake, views of the failed wall and computed displacement responses for acceleration records taken at Chinen.

3 NATURAL MONUMENTAL STRUCTURES

3.1 *Gushikawa castle*

Two karstic caves exist beneath Gushikawa Castle remains in Itoman City in Okinawa Island of Japan (Figure 1). These caves are large (more than 20 m wide) and they may result in their collapse by the continuing erosion process (Geniş et al. 2009).

As it is difficult to model an actual structure in a reduced scale of the geometry, stress conditions and constitutive parameters of materials, the model experiments presented in this sub-section are intended to illustrate what we should expect under natural conditions and to understand the underlying mechanism of the response and stability of natural underground openings subjected to earthquakes. A two-dimensional model with a scale of 1/100 of the actual configuration of Cave A and its surrounding was prepared (Figure 10). The model rock mass is 400 mm long, 250 mm high and 50 mm thick. The model material was a mixture of $BaSO_4$, ZnO and Vaseline oil, which were used in base-friction model tests.

The cavity was first excavated and its deformation to the excavation procedure was monitored. The opening was stable under static condition. Following the frequency response experiments under a base acceleration of 100gals, the model was subjected to horizontal shaking along the longitudinal axis of the cave A until the failure occurred. The frequency of the applied base acceleration was 5Hz and its amplitude was about 600 gals when the model with the cave failed. Figure 10a, b shows a shaking model experiment in relation to the effects of karstic caves beneath Gushikawa castle remains. Figure 10c shows the measured displacement in relation to the applied base acceleration. As noted from the figure, the elastic displacement is very small to be discernible and the displacement becomes very large during the failure stage suddenly.

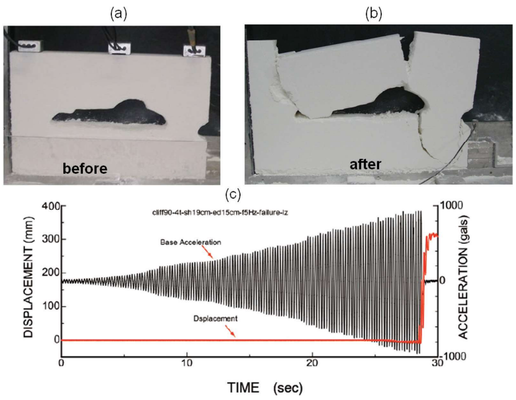

Figure 10. Views of Cave A before and after shaking and the measured response during shaking.

The cavity was filled with a very weak material (sponge), similar to that in actual conditions, to see the effect of the filling of the cavity. As in the previous case, the same procedure was followed and the model was subjected up to 1g, which was the maximum allowable capacity of the shaking table. Although the filling material was very weak, the opening remained stable compared to that in the unfilled state.

In addition to 2D and 3D static numerical analysis, a series of dynamic analyses were carried out (Geniş et al. 2009). The Gushikawa castle remains are approximately 120 km away from both Ryukyu Trench and Okinawa Trough. The area experienced a very strong earthquake with a magnitude of 7.2 on Feb. 27, 2010 (Aydan & Tokashiki 2010). The maximum ground accelerations nearby the castle remains ranged between 70–120 gals (0.07–0.12 g). Therefore, the consideration of dynamic condition is very important for the stability of Karstic caves even after filling the cavities.

The mesh used in 3D static analyses was used with the introduction of viscous boundary conditions following the static loading. The main purpose was to assess the stability of karstic caves in the natural state and filled state. The input waves were assumed to be horizontal and perpendicular to the longitudinal axis of the numerical mesh. Since there is no strong motion record for this area, a sinusoidal acceleration waves with amplitude of 0.3 g and a frequency of 2 Hz to simulate the worst scenario of dynamic loading and were used.

Figure 11 shows the plastic zone formation in the computational model for the non-filled state of caves under static and dynamic conditions. Unexpectedly, plastic zone development occurred at the boundaries and corners of the 3D model. If the attention is given to the vicinity of the karstic caves, it is easily noticed that the plastic zone formation is very extensive for both caves and the geometry of

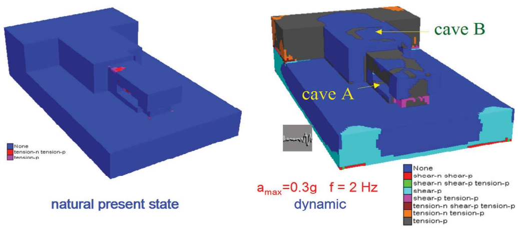

Figure 11. Plastic zone formation for static and dynamic conditions.

plastic zone implies how the total collapse of the caves would occur under dynamic conditions. The results indicate that Cave-A would fail by toppling towards the west side while Cave-B will collapse as a circular sinkhole (i.e. doline).

3.2 *Monitoring at nakagusuku castle and measured response during 2014 March 3 earthquake and its analysis by DFEM*

There is a continuous crack in Ryukyu limestone layer (about 20 m thick) at the south-east side of the Nakagusuku Castle Remains designated as World Heritage Site by UNESCO (Figure 13). The authorities are concerned with the stability of this part of the castle remains particularly during earthquakes as some part of the Katsuren Castle remains collapsed during the M7.2 2010 Okinawa earthquake. The authors established a long-term multi-parameter (displacement, acoustic emission, inclination, temperature, humidity, air pressure and accelerations) monitoring system (Figure 12). This system utilizes solar-power as the energy source for instruments and it is environmental friendly.

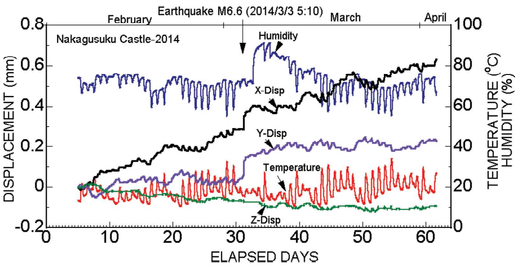

Figure 13. Preliminary monitoring results during February and March, 2014.

Table 1. Material properties used in DFEM analyses.

Material	λ MPa	μ MPa	γ MPa	c kN/m³	φ(°)	σ_t MPa
Limestone	900	900	25	–	–	–
Mudstone	400	400	22	–	–	–
Weathered Mudstone	300	100	20	–	–	–
Dis.-L	100	20	–	10	10	1
Dis.-V	0.02	0.02	–	10	10	1

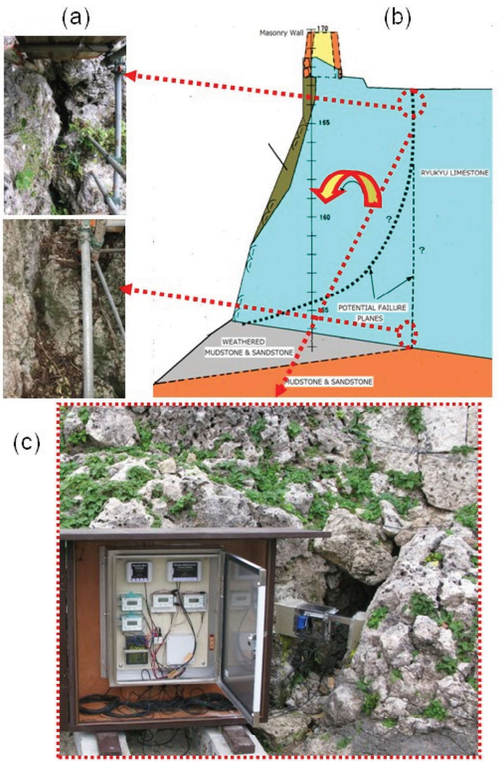

Figure 12. Views of monitoring location and instrumentation.

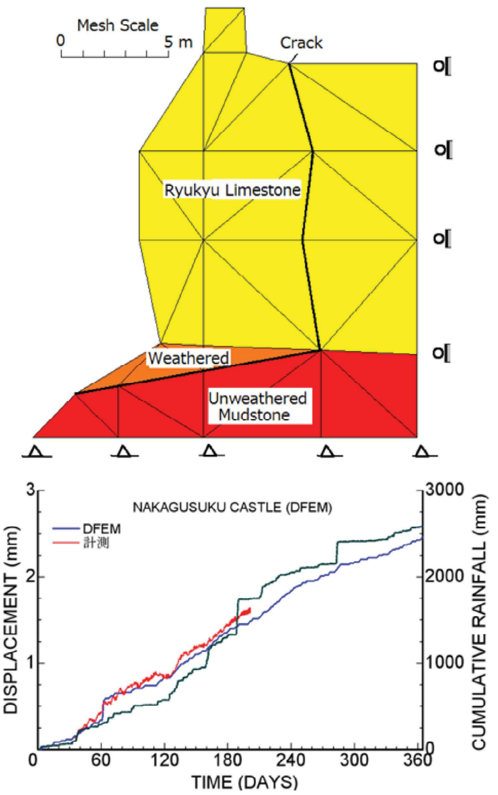

Figure 14. Mesh used DFEM analysis and comparison with measured responses.

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 (Figure 14a). 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 Figure 13.

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 14 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.

4 CONCLUSIONS

There are many historical stone masonry structures in Ryukyu Islands, in which Ryukyu limestone blocks are generally used. The static and dynamic stability of assessment of these historical structures can be done using dynamic limit equilibrium method and numerical techniques suitable for the structure dealt with. The analyses by the discrete finite element method of these historical structures as well as model testing and available other methods are found to be appropriate to assess the dynamic response and stability of masonry structures and natural monumental rock structures. Furthermore, the instrumentation of masonry structures is also of great value to assess as well as the validate the results of dynamic limit equilibrium and numerical methods.

ACKNOWLEDGEMENTS

The authors sincerely thank several organizations and individuals in Okinawa Prefecture, in particular, the Cultural Assets Departments of Itoman City, Naha City, Nakagusuku Village and Mahae Corporation for their financial assistance as well as providing case studies reported here. Dr. Y. Ohta and the former students of the authors at Tokai University and University of the Ryukyus for their support and help during experiments, analyses and in-situ monitoring.

REFERENCES

Aydan, Ö. 2016. Time dependency in rock mechanics and rock engineering. CRC Press, ISRM Book Series, p. Analysis of masonary structures by finite element method, *Proceedings of Prof. Dr. Rifat Yarar Symposium*, Istanbul, TDV, 141–150.

Aydan, Ö. 1998. Analysis of masonary structures by finite element method, *Proceedings of Prof. Dr. Rifat Yarar Symposium*, Istanbul, TDV, 141–150.

Aydan, Ö. Mamaghani, I.H.P & Kawamoto, T. 1996. Application of discrete finite element method (DFEM) to rock engineering structures. *NARMS'96*, 2039–2046.

Aydan, Ö. & Tokashiki, N. 2010. The Off-Okinawa Island earthquake of February 27, 2010, *JSCE-EEC*, http://www.jsce.or.jp/library/eq_repo/Vol3/14/20100227okinawa_report.pdf.

Aydan, Ö., Tokashiki, N., Shimizu, Y. & Mamaghani, I.H.P., 2001. A stability analysis of masonry walls by Discrete Finite Element Method (DFEM). *10th IACMAG Conference*, Austin.

Aydan, Ö., Ogura, Y., Daido, M. & Tokashiki, N., 2003. A model study on the seismic response and stability of masonary structures through shaking table tests, *Fifth National Conference on Earthquake Engineering*, Istanbul, Turkey, Paper No: AE-041(CD).

Aydan, Ö., Tokashiki, N. & Geniş, M., 2011. Stability assesment of Himeyuri monument and adjacent karstic cave, *Proc. of the KAYAMEK'2011-Xth Regional Rock Mechanics Symposium*, S. Kulaksız and E. Tuncay (eds.), Ankara, Turkey, 39–46.

Geniş, M., Tokashiki, N. & Aydan, Ö. 2009. The stability assessment of karstic caves beneath Gushikawa Castle remains (Japan), *EUROCK2009 ISRM Regional Sym.*, Dubrovnik,, 449–454.

Itasca, 2005. FLAC3D-Fast Lagrangian Analysis of Continua-User Manuel (dynamic option) (Version 2.1). *Itasca Consulting Group Inc.*, Minneapolis

Tokashiki, N. & Aydan, Ö. 2003. Characteristics of Ryukyu Limestone and its utilization as a building stone in historical and modern structures, *International Symposium on Industrial Minerals and Building Stones*, Istanbul, 311–318.

Tokashiki, N., Aydan, Ö., Daido, M. & Akagi, T. 2007. Experiments and analyses of seismic stability of masonry retaining walls, *Rock Mechs. Symp.*, *JSCE*, 115–120.