2019 Rock Dynamics Summit– Aydan et al. (eds)
© 2019 Taylor & Francis Group, London, ISBN 978-0-367-34783-3

A fundamental study on the foundations in Ryukyu Limestone Formation and the shear properties of interfaces and discontinuities under static and dynamic loading conditions

Y. Araki, T. Ito, J. Tomiyama, Y. Suda, K. Horiuchi, N. Tokashiki & Ö. Aydan
Department of Civil Engineering, University of the Ryukyus, Okinawa, Japan

Y. Shuri
Asahi Consultants Co., Urasoe, Okinawa, Japan

ABSTRACT: The Ryukyu limestone formation is not assumed to be a suitable load bearing foundation in Ryukyu Archipelago. The characteristics of Ryukyu limestone with various porosity under static and dynamic conditions have been investigated by the authors. Furthermore, the behavior of the interface between piles and Ryukyu limestone are tested using large-scale dynamic shear testing device. Some model piles founded on Ryukyu limestone are subjected to static and dynamic loads to check their deformation response and their load-bearing capacity. The authors will explain fundamental studies on foundations on Ryukyu Limestone Formation under static and dynamic loading conditions and present the outcomes of these studies and discuss their implications on bridge piles.

1 INTRODUCTION

Ryukyu limestone formation, which is broadly divided into coral limestone and sandy limestone, is widely distributed in Ryukyu Archipelago. As limestone is solvable due to percolating groundwater and accumulation of corals and as well broken pieces, the porosity of limestone is large. Furthermore, they may contain some large scale cavities due to combined action of groundwater and tectonic movements. Therefore, the Ryukyu limestone formation is considered to be not suitable as a foundation rock for large-scale engineering structures. When the thickness of the Ryukyu limestone formation is quite thick, it results in the non-economical foundation design. This is a serious engineering issue in Okinawa Prefecture, Japan and some fundamental studies are necessary to clarify whether it is really unsuitable or suitable as foundation rock. The authors investigate the characteristics of Ryukyu limestone with various porosity under static and dynamic conditions. The behavior of the interface between piles and Ryukyu limestone are tested using large-scale dynamic shear testing device. Furthermore, some model piles founded on Ryukyu limestone were subjected to static and dynamic loads to check their deformation response and their load-bearing capacity. In addition some analytical and numerical studies are proposed. The authors explain these fundamental studies on foundations on Ryukyu Limestone Formation under static and dynamic loading conditions and present the outcomes of these experimental studies and discuss their implications in foundation design.

2 CHARACTERISTICS OF RYUKYU LIMESTONE FORMATION

2.1 *Geological Characteristics*

The main islands of Ryukyu Archipelago are Okinawa, Amami-Oshima, Miyako, Ishigaki, Iriomote and Yonaguni. The islands are situated on Ryukyu arc bounded by Okinawa trough and Ryukyu trench. The environment is tropical. Ryukyu limestone is widely distributed in Ryukyu Archipelago. It is broadly defined as coral, gravely and sandy or sandy-gravel limestone. Geoengineering issues associated with Ryukyu limestone formation are cliff collapses, sinkholes due to karstic caves and their effect on super structures (Fig. 1).

Figure 1. Some examples of engineering problems associated with Ryukyu Limestone Formation.

2.2 *Physico-mechanical Characteristics of Ryukyu Limestone*

The mechanical properties of Ryukyu limestone have been investigated by Tokashiki (2010) and his colleagues (Tokashiki & Aydan, 2003, 2010) in details. Tokashiki (2010) utilized the stereology technique to evaluate the porosity of Ryukyu limestone and the shape of pores. This technique requires a number of slices of rock sample for the digitization and data processing to determine the porosity and the shape of pores. This is a quite cumbersome procedure.

A sample of Ryukyu limestone with a height of 100 mm and 50 mm in diameter was prepared and it was scanned using the inspeXio SMX-225CT FPD. Fig. 2 shows visual and scanned images of the Ryukyu limestone (Aydan et al. 2016). It is quite interesting to notice the porous structure of the sample can be easily visualized without any physical disturbance to the sample. Furthermore the shape, distribution and physical positions of pores in rock sample can be easily evaluated. For example, if such data is imported for some numerical simulations, the equivalent properties of porous rocks could be evaluated without any assumption of some models adopted in averaging techniques such as mixture theories, micromechanics, micro-structure models or homogenization technique. Fig. 3 shows a 3D visualization of porous structure of Ryukyu limestone and number of porosities with different volumes.

Figure 2. Comparison of actual and scanned images of a Ryukyu limestone sample.

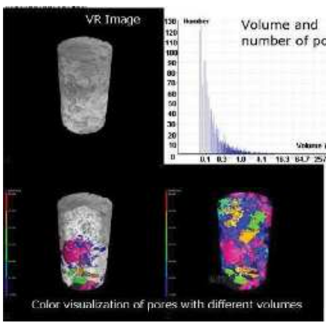

Figure 3. A 3D visualization of porosities in Ryukyu Limestone.

2.3 *Dynamic Mechanical Characteristics of Ryukyu Limestone*

In the experiments, coral limestone is tested under uniaxial compression and Brazilian shock tests. Figs. 4 and 5 show the force and acceleration responses of Ryukyu limestone samples. The strength of Ryukyu limestone depends upon the porosity and the static UCS ranges between 20.0 and 33.3 MPa. Similarly the Brazilian tensile strength of Ryukyu limestone depends upon the porosity and it ranges between 2.4 and 5.3 MPa. Fig. 6 compares the failure state under static and dynamic conditions.

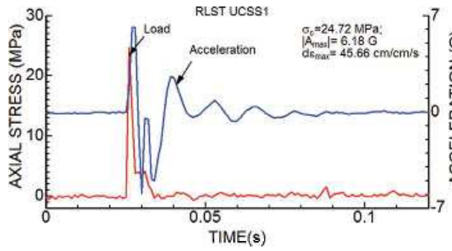

Figure 4. Axial stress and acceleration response of Ryukyu limestone sample under uniaxial compression shock test.

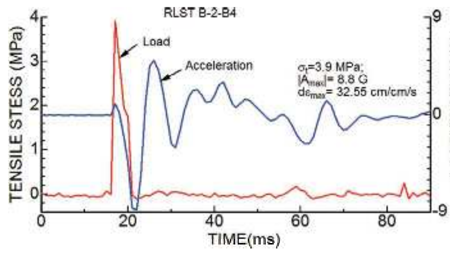

Figure 5. Axial stress and acceleration response of Ryukyu limestone sample under Brazilian shock test.

Table 1. Comparison of Static and Dynamics strength of Ryukyu limestone

Condition	Static (MPa)	Dynamic (MPa)
UCSS	20-33.3	24.72
BRS	2.4-5.3	3.90
Coral Finger-UCSS		27.94

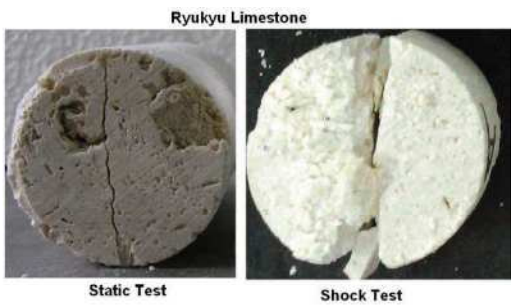

Figure 6. Comparison of fracturing of Ryukyu limestone samples under static and dynamic conditions.

2.4 *Direct Shear Tests on Ryukyu Limestone*

A direct shear is carried out to investigate the shear response of coral limestone stone with honeycomb-like structure (Fig. 7). Figs. 8 and 9 show the responses measured during the direct shear experiment. Once peak load exceeded, the deformation rate increases as noted from the figure.

2.5 *Tilting, Stick-slip and Cyclic Tests on Limestone discontinuities*

Tilting test technique is one of the cheapest techniques to determine the frictional properties of rock discontinuities and interfaces under different environmental conditions (Barton and Choubey, 1977; Aydan et al. 1995; Aydan 1998). This technique can be used to determine the apparent friction angle of discontinuities (rough or planar) under low stress levels. It definitely gives the maximum apparent friction angle, which would be one of the most important parameters to determine the shear strength criteria of rock discontinuities as well as various contacts. Therefore, the data for determining the parameters of the shear strength criteria for rock discontinuities should utilize both tilting test and direct shear experiment. Experimental results on saw-cut discontinuity planes of Ryukyu limestone samples are shown in Fig. 10, which shows responses measured during a tilting experiment on a saw-cut plane of Ryukyu-limestone. The static and dynamic friction coefficients of the interface were calculated from measured displacement response explained in previous section and they were estimated at 28.8-29.6° and 24.3-29.2° respectively.

A series of stick-slip experiments are carried out on the saw-cut discontinuities of Ryukyu Limestone. The peak (static) friction angle can be evaluated from the T/N response while the residual (kinetic) friction angle is obtained from the theoretical relation (Aydan et al. 2018). Fig. 11 show the stick-slip responses of discontinuity planes shown. The residual (kinetic) friction angle of saw-cut discontinuity plane of Ryukyu limestone obtained from stick-slip experiments are very close to those obtained from tilting experiments. Nevertheless, the kinetic or residual friction angle is generally lower than those obtained from the tilting experiments.

A multi-stage (multi-step) direct shear test on a saw-cut surface of sandy Ryukyu limestone sam-

Figure 7. A view of direct shear testing by OA-DSTM testing machine

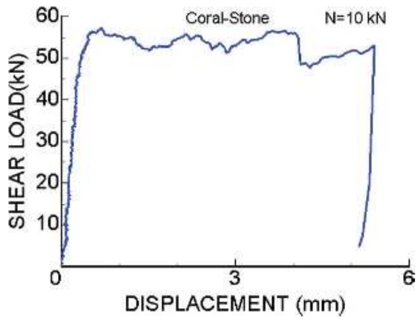

Figure 8. Shear displacement-shear load relation of coral-stone.

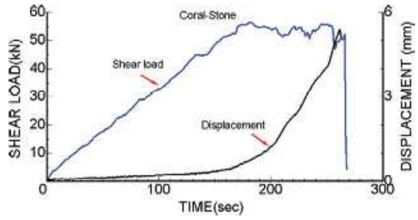

Figure 9. Shear displacement-shear load response of coral-stone

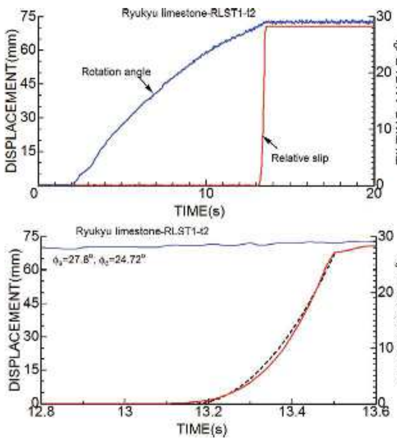

Figure 10. Responses of saw-cut discontinuity planes of Ryukyu limestone samples during a tilting test.

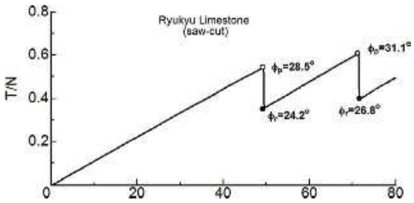

Figure 11. Stick-slip response of saw-cut plane of Ryukyu limestone

ple, which consist of two blocks with dimensions of 150x75x37.55mm, was varied out (Figs. 12 and 13). The initial normal load was about 17 kN and increases to 30, 40, 50, 60 and 70 kN during the experiment. Fig. 14 shows the shear displacement and shear load responses during the experiment. As noted from the figure, the relative slip occurs between blocks at a constant rate after each increase of normal and shear loads. This experiment is likely to yield shear strength of the interface two blocks under different normal stress levels. Fig. 14 shows the peak and residual levels of shear stress for each level of normal stress increment. Tilting tests were carried out on the same interface and the apparent friction angles ranged between 35.4 and 39.6 degrees. Tilting test results and direct shear tests are plotted in Fig. 15 together with shear strength envelopes using the shear strength failure criterion of Aydan (Aydan 2008; Aydan et al. 1966).

As noted from the figure, the friction angles obtained from tilting tests are very close to the initial part of the shear strength envelopes. However, the friction angle becomes smaller as the normal stress level increases. In other words, the friction angle obtained from tilting tests on saw-cut surfaces can not be equivalent to the basic friction angle of planar discontinuities and interfaces of rocks. The basic friction angle of the planar interface of sandy

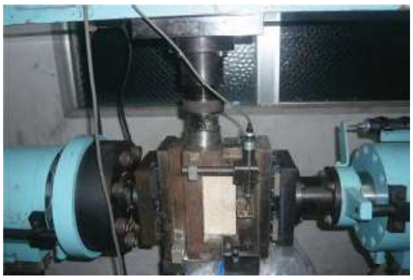

Figure 12. A view of direct shear test on a saw-cut discontinuity plane.

Figure 13. A view of a saw-cut discontinuity plane after a direct shear test.

limestone blocks is obtained as 27.5 degrees for the range of given normal stress levels.

A series of two-ways direct shear tests were carried out saw-cut discontinuity planes of Ryukyu limestone. Fig. 16 shows the normalized shear resistance (T/N) response of the saw-cut planes and acceleration during the two-ways shearing with ±15 mm forced displacement amplitude. As noted the acceleration response is quite different than that anticipated and it has a very irregular response with an amplitude less than 0.42g.

Fig. 17 shows the relative displacement-T/N relation. In the same figure, the trajectory of the first cycle is distinguished. It is quite interesting to note that the shear resistance of the discontinuity plane gradually changes after each cycle of shearing. At the end of the experiment, a thin powder is recognized on the discontinuity plane.

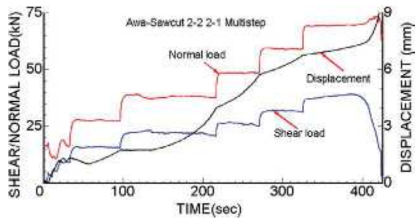

Figure 14. Shear stress-shear load response of the interface of sandy limestone blocks during the multi-stage(step) direct shear experiment.

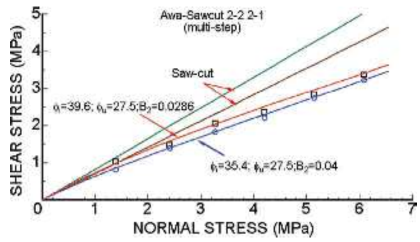

Figure 15. Comparison of shear strength envelope for the interface of sandy limestone blocks with experimental results from the multi-stage(step) direct shear experiment.

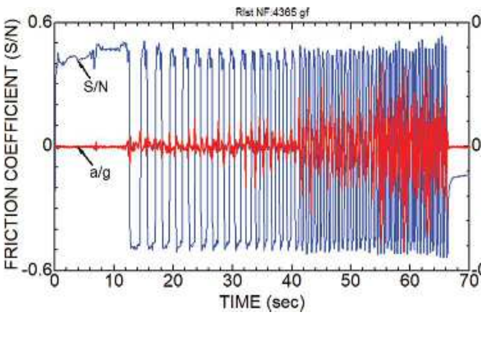

Figure 16. The response of the normalized S/N and acceleration response of a saw-cut plane during two shearing experiment.

3 EXAMPLES OF FOUNDATION DESIGN ON RYUKYU LIMESTONE FORMATION

The design of foundation on Ryukyu Limestone Formation (RLF) is always a major problem. Despite the general tendency to avoid foundation design on the RLF, there are some examples, in which the foundations are located in the RLF. These examples are Kouri Bridge (Fig. 18) and New Ishigaki Airport Protection structures (Fig. 19).

The foundations of the bridge along Gushikawa By-Pass roadway was designed to be having end-bearing on the phyllite formation below the Ryukyu limestone formation (Fig. 20). The distribution deformation and axial stress of the pile and the shear stress along the pile and surrounding ground was analyzed using the solution given by Aydan (2018) (Fig. 21). As noted from the figure, the applied load is not fully transferred to the tip of the pile at depth and it is only a small fraction of the total load. These result imply that the current concept of the design of pile foundation in Okinawa Prefecture requires substantial revision.

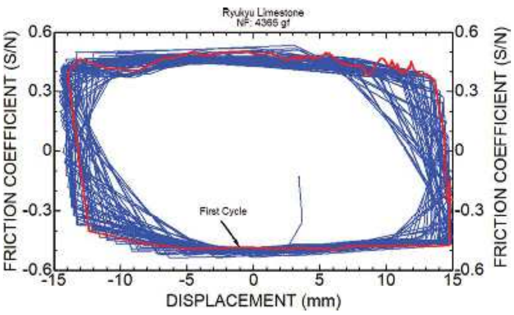

Figure 17. Shear response of a saw-cut discontinuity plane of Ryukyu limestone shown in Figure 18 in the space of relative displacement and T/N.

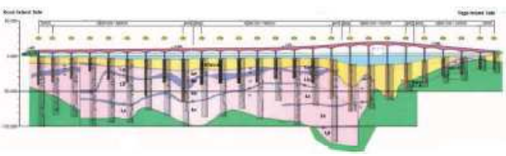

Figure 18. The design of bridge foundation piles of the Kouri Bridge.

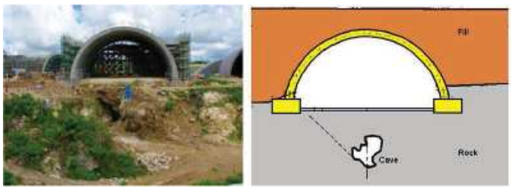

Figure 19. The design of arch protection structure on karstic caves at New Ishigaki Airport.

Figure 20. Stages of construction of piles and the bridge.

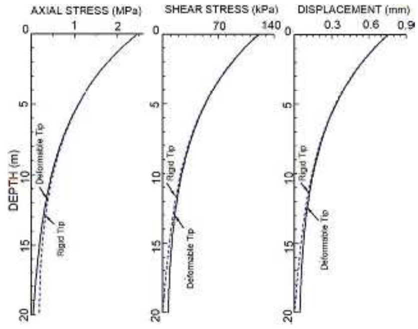

Figure 21. Distribution of axial and shear stresses and displacement with depth.

4 EXPERIMENTS ON BEARING CAPACITY FOUNDATIONS ON RYUKYU LIMESTONE FORMATION CONTAINING CAVITIES

4.1 *Unfilled Cavities*

The authors have performed laboratory experiments under static and dynamic conditions on the influence area above the caves (Fig. 22). Furthermore, bearing capacity experiments were performed on the limestone blocks obtained from the construction site. The influence line to estimate the effect of caves beneath foundations and structures is specified by taking a tangential line to the cavity with inclination of 45 degree in Japanese regulation. However, the experiments clearly showed that the regulation is not appropriate for evaluating the influence of cavities on the separation of discontinuities is not true and appropriate.

4.2 *Filled Cavities*

Some experiments were carried out to investigate the effect of backfilling on the bearing capacity of Ryukyu limestone formation. Fig. 23 compares the average strain stress relations for unfilled and pillars backfilled with granular and cohesive backfill materials. It is interesting to note that the bearing capacity of backfilled pillars is increased about 1.2-1.3 times compared with that of the unfilled sample at the same strain level. Furthermore, the behavior of backfilled pillars is elasto-plastic without any softening after the yielding of the pillar. When the limestone pillar is backfilled with NSK backfilling material, the overall strength of pillars greatly increased and the experiments were terminated in order to prevent the bursting of the acrylic cell resulting in undesirable accidents.

5 A PROPOSAL FOR FOUNDATION DESIGN ON RYUKYU LIMESTONE FORMATION

As pointed previously, there is high possibility of caves of different sizes in Ryukyu Limestone Formation (RLF). The existence of these caves may result in non-uniform settlement and/or collapse of foundations of the superstructures. For this reason, it is common to drill boreholes to a depth of rock layer such as Shimajiri formation or phyllite rock mass at each pier of the super structures. These boreholes can be used to check if there is any cave beneath the foundation. The spread foundation or very shallow foundations can be used if there is no cavity. If there is any cavity, the possibility of the backfilling should be explored. The filling of such caves is possible and limited area type backfilling may also be utilized. Besides these suggestion, there may be other alternatives as illustrated in Fig. 24.

Figure 22. Experiment on the effect caves on footing separation.

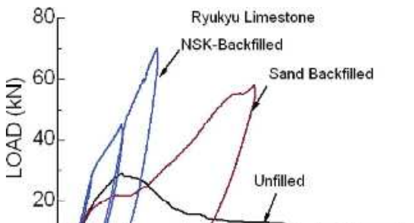

Figure 23. Comparison of strain-stress responses of unfilled pillar, backfilled pillars with granular and cohesive backfill materials during cyclic compression.

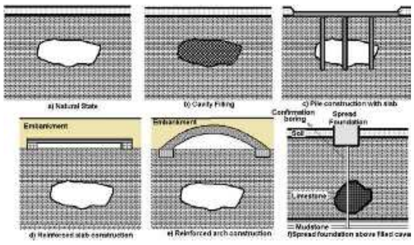

Figure 24. Various alternatives to deal cavities during the construction on Ryukyu Limestone Formation

6 CONCLUSIONS

The utilization of Ryukyu Limestone Formation (RLF) as the foundation rock of superstructures is explored and the characteristics of the RLF are presented and the applications of various methods for the characterization of the RLF are explained. If sufficient explorations and counter-measures are implemented at a given foundation location, it is possible to utilize the RLF as foundation rock. Therefore, the present design philosophy is not correct and it is resulting in uneconomical foundation design and it is overconservative.

REFERENCES

Aydan, Ö. (2018): Rock Reinforcement and Rock Support, CRC Press, ISRM Book Series, No.7, 473 pages.

Aydan, Ö. and Tokashiki, N. 2007. Some damage observations in Ryukyu Limestone Caves of Ishigaki and Miyako islands and their possible relations to the 1771 Meiwa Earthquake. Journal of The School of Marine Science and Technology, 5(1), pp. 23–39.

Aydan, Ö., N Tokashiki, M. Edahiro (2016). Utilization of X-Ray CT Scanning technique in Rock Mechanics Applications. ARMS2016, Bali.

Tokashiki, N., 2010. Study on the Engineering Properties of Ryukyu Limestone and the Evaluation of the Stability of its Rock Mass and Masonry Structures. PhD Thesis, Waseda University, Tokyo.

Tokashiki, N. and 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, pp. 311–318.

Tokashiki, N. and Ö. Aydan, 2010. The stability assessment of overhanging Ryukyu limestone cliffs with an emphasis on the evaluation of tensile strength of Rock Mass. Journal of Geotechnical Engineering, JSCE, Vol. 66, No. 2, 397–406.