2019 Rock Dynamics Summit– Aydan et al. (eds)
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An integrated study on the risk assessment of Abuchiragama karstic underground shelter (Okinawa, Japan) under static and dynamic conditions

H. Inoue
Nanjyou consultants, Haebaru-city, Okinawa, Japan

N. Tokashiki and Ö.Aydan
Department of Civil Engineering., University of the Ryukyus, Nishihara, Okinawa, Japan

ABSTRACT: Abuchiragama is karstic cave in Ryukyu limestone. There is a increasing tendency that ground water is seeping in from top of cave after rainfalls. For the safety of entrants, it is necessary to evaluate the stability of the cave. This study is concerned with the risk managment of this cave utilizing RMQR as a new evaluation method of the quality of rock mass, and the stability evaluation of the cave was carried out through an empirical method and analytic methods. It is understood that it is necessary to examine in details the areas accessible to entrants, in particular, the entrance and exit areas. These areas are now being investigated in details and we have been considering to review the counter-measures master plan for rehabilitation.

1 INTRODUCTION

Itokazu Abuchiragama karstic underground cave is in Nanjyo-city, in south part of Okinawa Island (Figure 1). This cave was used as underground shelter during the battle of Okinawa. Now this cave is used for peace education for trips of the schools, and the number of entrants is about 110 thousand people.

From around 2012, there is an increasing tendency that groundwater infiltrates into the cave from its top of cave after rainfalls. For safety of entrants, it was necessary to evaluate safety and stability of this cave.

We have conducted various investigations. These involves discontinuity surveying, monitoring the crack displacements, acoustic emission measurements and accelerations at ground surface and inside the cave during seismic events. RMQR proposed by Aydan et al. (2014) as a new rock mass classification system is used to assess the quality of rock mass surrounding the cave and the stability assessment of the cave was carried out using empirical method and analytic methods.

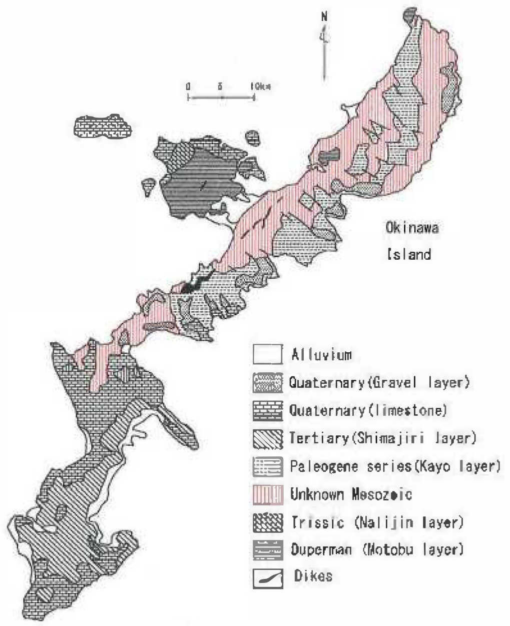

Figure 1. The geology of Okinawa Island (Okinawa Earth Science Society, 1997).

2 GEOLOGICAL OVERVIEW

Ryukyu limestone is relatively young formation formed during Pleistocene. This formation is widely distributed in middle south area of Okinawa island.

Abuchiragama is located within the west plateau of Ryukyu limestone formation. There are faults around this underground shelter, There is a high possibility that they played a role on the formation of the cave (Figure 2).

3 THE PRESENT SITUATION OF THE SHELTER

Abuchiragama cave is 200m long and its depth ranges between 6~17m from ground surface and its width is in between 12 and 30m.

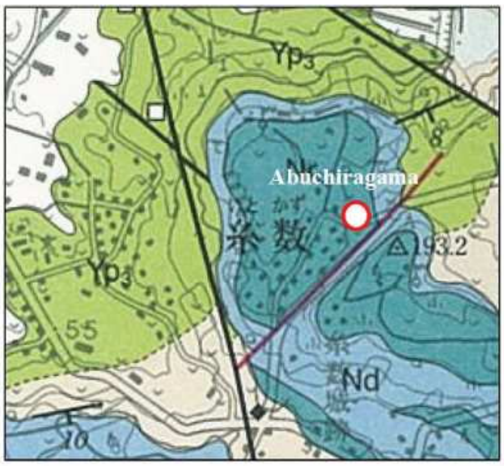

Figure 2. Close vicinity geology (National Institute of Advanced Industrial Science and Technology (2006)). Legend: Nr,Nd:Ryukyu limestone, Yp_3: Shimajiri Mudstone, Black Line: Fault

Figure 4. Status of the crown of the cave near exit (Area 7), note the movable block.

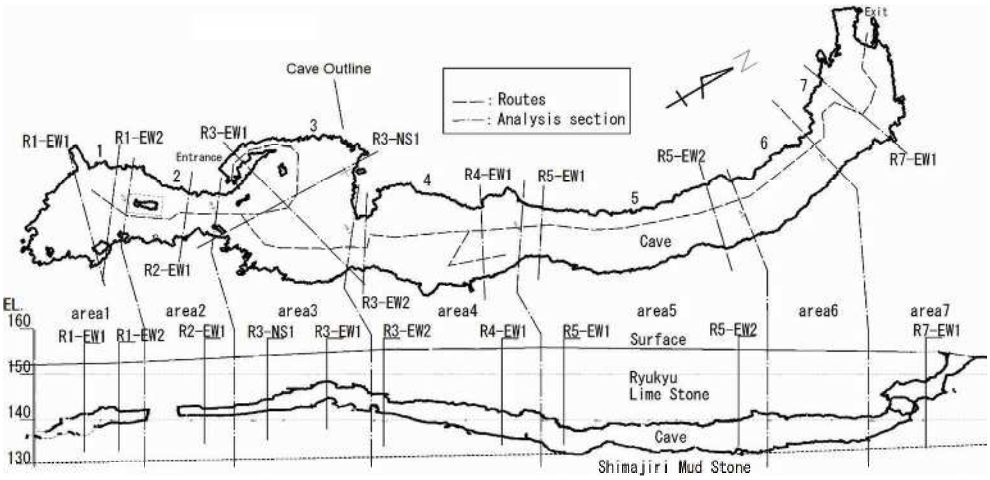

Figure 3. Areas in plan and cross section of the cave

Figure 5. Status of the top of the cave in Area 3.

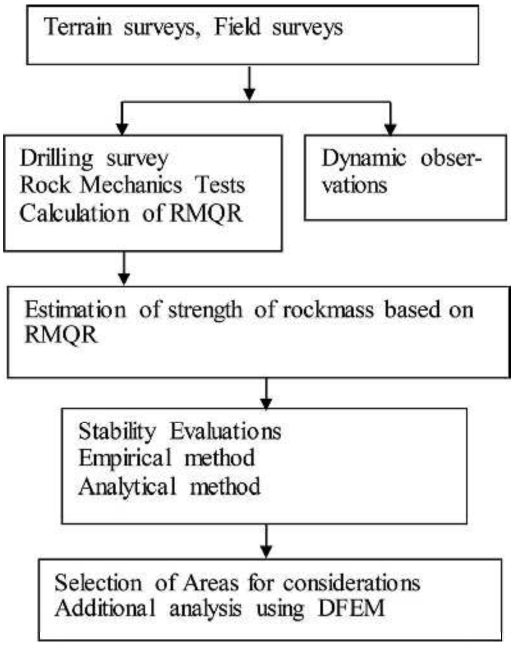

Figure 6. Flow chart of consideration

During wartime, almost all areas of this cave were used as shelter. For this reason, almost all areas of this cave had become routes for entrants.

To analyze, this cave was subdivided into 7 areas with the consideration of segmentation conditions such as shape, rock cover thickness etc. We have analyzed each area as illustrated in Figure 3. Some potentially unstable blocks were observed in the roof of the cave in Area 7.

4 FLOW CHART OF CONSIDERATIONS

We are currently conducting a series of studies. The method employed in this study has been already utilized in some projects such as "New Ishigaki Airport","Gushikawa Castle Remains", and "Himeyuri Peace Park". In each project, the existence of the caves is noted and they were considered in structural stability evaluations. The flow chart of this method is illustrated in Figure 6.

Discontinuity surveys were carried out through the cave. The investigations indicated that there are at least 3 discontinuity sets together with some random cross-joints. Figure 7 shows a stereo projection of discontinuities measured in Area 3.

Borings were drilled and the rock mass conditions were evaluated using RMQR rock classifications system as well as other rock mass classification systems (Figure 8). Rock samples have been prepared and the unit weight of rocks and elastic wave velocities were measured. The samples are used in uniaxial compression, Brazilian tensile tests. Figure 9 shows the variation of Brazilian tensile strength of samples with the ratio of porosity.

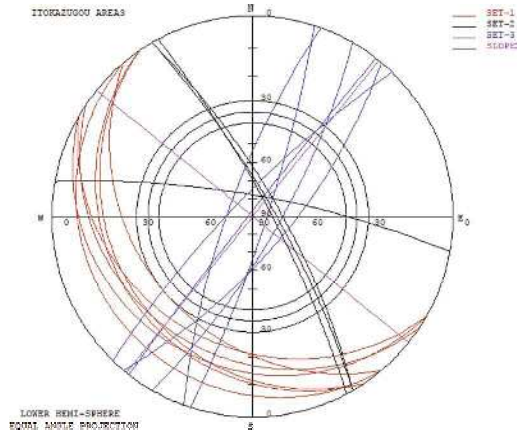

Figure 7. Stereo projection of discontinuities in Area 3.

Figure 8. Boring cores and their evaluation and sample selection.

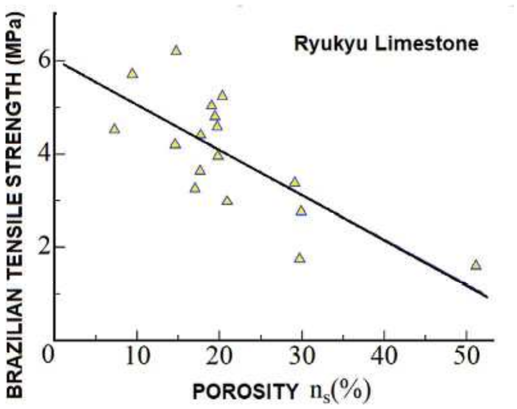

Figure 9. the variation of Brazilian tensile strength of Ryukyu limestone

5 STABILITY EVALUATION OF CAVE

5.1 *Empirical Evaluation Method*

Aydan (1989), Tokashiki (2011) and Aydan and Tokashiki (2011) developed some empirical and analytical methods to analyze the stability of natural caves. The rock mass conditions were evaluated using the RMR rock classification system. Aydan et al (2014) proposed a new rock mass classification which is named as Rock Mass Quality Rating (RMQR). This new rock classification system was utilized in this study to assess the state of the underground cave and the previously proposed method was extended to the use of RMQR together with further subdivision of stability conditions around the caves in view of the conditions observed in Abuchiragama cave. (Table 1, Figure 11). Meaning of H_f, H_r, B_s and B are shown to Figure 10. We plotted the width of cave and RMQR shown in Figure 11. R1 to R7 are section lines in Areas 1 to 7. As a result, we concluded that Area 3 and Area 7 need further detailed considerations

Table 1. State of stability classification (from Aydan 2018)

Category	State	$\frac{H_f}{H_r}$	$\frac{B_s}{B}$	Comments
I		0.0	0.0	Opening locally and globally stable
II		0.0-0.1	0.0	Some rock block falls from roof. Opening globally stable
III		0.1-0.3	0.0	Block falls from roof and sidewalls into the opening occur and the failure zone increases in size. Roof height is higher than opening width. The failure zone may increase in size with time.
IV		0.3-0.7	0.0	Considerable scale of falls and sliding of rock blocks from the roof and sidewall of openings occur and the failure zone larger in size. Roof height is much higher than opening width. The failure zone may increase reach ground surface in long-term
V		0.7-1.0	0.8-1.0	Failure zone reaches to ground surface and a small size crater develops at ground surface. The possibility of collapse zone may increase in size and shoulder may fall into opening in long-term
VI		>1.0	>1.0	Opening globally unstable. In other words, it is in a total collapse state. Deep Sinkhole appear on the ground surface.

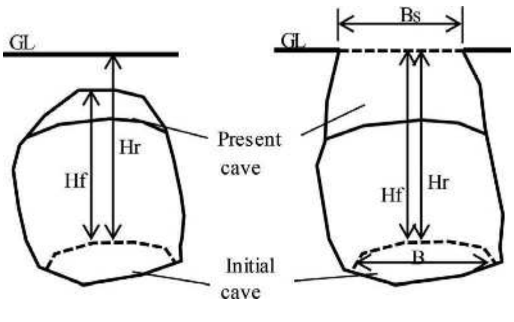

Figure 10. State of cave

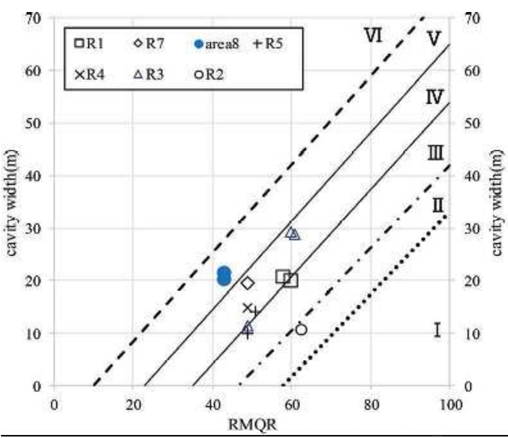

Figure 11. Comparison of stability categories of areas with estimations from the empirical method.

5.2 *Analytical Evaluation Method*

The rock mass strength for analytical stability evaluation method is necessary. In this study, RMQR system is used to estimate rock mass properties through the utilization of RMQR value and intact rock properties. The properties of rock mass is obtained from the Eq. (1) given below (Aydan et al. 2014).

$$\alpha = \alpha_0 - (\alpha_0 - \alpha_{100}) \frac{RMQR}{RMQR + \beta(100 - RMQR)} \quad (1)$$

The strength reduction was calculated by applying the RMQR values in Table 2 to Eq.(1). Calculation examples are given in Table 4.

Aydan (1989), Kawamoto et al. 1991, Tokashiki (2011) and Aydan and Tokashiki (2011) showed the following three patterns for stability of the roof of the cave (Figure 12). The following relationships are used to estimate the maximum width of the cave for the stability under no-support condition:

(Formula for simple beam and built-in beam)

Table 2. Results of empirical stability evaluations

Area	Section	Cavity width (m)	Value of RMQR	Stability Category
1	R1-EW1	20.8	58	IV
	R1-EW2	20.2	60	III
2	R2-EW1	10.5	63	II
3	R3-EW1	28.8	61	IV
	R3-EW2	29.3	60	IV
	R3-EW3	11.5	49	III
4	R4-EW1	15.0	49	IV
5	R5-EW1	10.0	49	III
	R5-EW2	14.3	51	III
7	R7-EW1	19.5	49	IV

Table 3. Values of parameters used in the Eq. (1)

Property (α)	α_0	α_{100}	β
Deformation modulus	0.0	1.0	6
Poisson's ratio	2.5	1.0	0.3
Uniaxial compressive strength	0.0	1.0	6
Tensile strength	0.0	1.0	6
Cohesion	0.0	1.0	6
Friction angle	0.3	1.0	1.0

Table 4. Example of calculation used for estimating rock mass strength using RMQR

Strength of Intact rock				
Uniaxial compressive strength	σ_{ci}	12.34	MPa	
Tensile strength	σ_{ti}	4.0	MPa	
Constants used in Eq. (1)				
	α_0	α_{100}	β	
Uniaxial compressive strength	0.0	1.0	6	
Tensile strength	0.0	1.0	6	
Strength of rock mass (RMQR Value is 61)				
Uniaxial compressive strength	σ_{cm}	2.55	MPa	
Tensile strength	σ_{tm}	0.83	MPa	

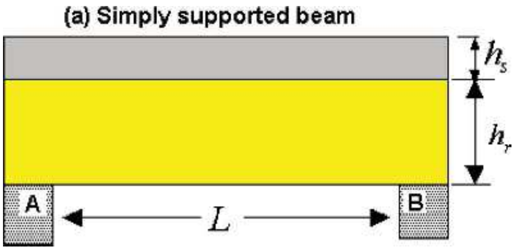

Figure 12. Models for assessing roof stability

$$\frac{L}{h_r} = \sqrt{\beta \frac{\sigma_t}{(\gamma_r h_r + \gamma_s h_s)}} \tag{2}$$

Simple beam:β=2/3, Built-in beam: β=2
(Formula of Arching model)

$$\frac{L}{h_r} = \sqrt{\beta \frac{\sigma_c}{(\gamma_r h_r + \gamma_s h_s)}} \tag{3}$$

In case of no crack: β=4/3

Eqs. (2) & (3) were applied to each section and the stability state were evaluated. An example of analyzed cross section used for evaluation is shown in Figure 13. The evaluation results are given in Table 5. As the roof situation is close to the built-in beam condition, the cave is stable in many section except Area 3 and Area 7. The estimations imply that cracking may occur. However, the arching model implies that the roof should be stable even in Area 3 and Area 7 under static conditions.

Table 5. Results of stability evaluation based on analytical method

Area	Section	Simple Beam	Built-in Beam	Arching Model
1	R1-EW1	Potential	OK	OK
	R1-EW2	Potential	OK	OK
2	R2-EW1	OK	OK	OK
3	R3-EW1	Potential	Potential	OK
	R3-EW2	Potential	Potential	OK
	R3-EW3	OK	OK	OK
4	R4-EW1	Potential	OK	OK
5	R5-EW1	OK	OK	OK
	R5-EW2	OK	OK	OK
7	R7-EW1	Potential	OK	OK

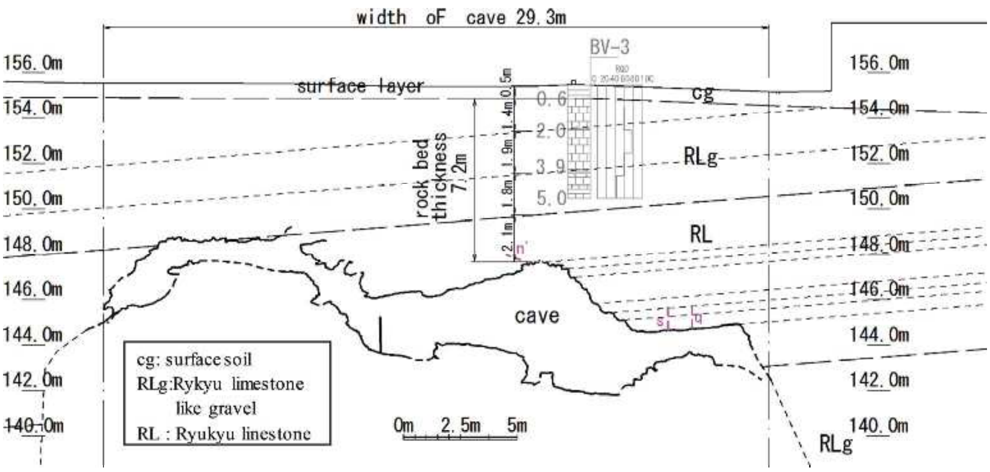

Figure 13. Analysis section for Stability evaluation, (R3-EW2)

Figure 14. Instrumentation for multi-parameter monitoring

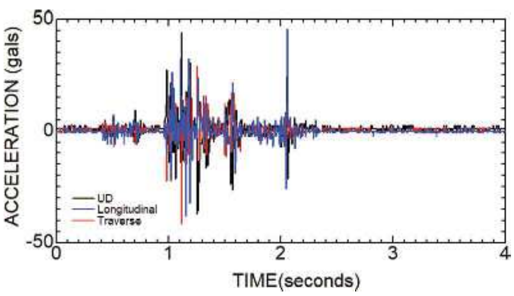

Figure 15. An acceleration record on ground surface on February 7, 2018.

6 MULTI-PARAMETER MONITORING

The long-term monitoring is essential for structures of great importance. Particularly for structures of this kind, it is very rare to see any monitoring worldwide. However, the monitoring studies in the Gushikawa Castle remains is probably the first attempt for such a purpose.

The multi-parameter monitoring of groundwater seepage into the cave, the crack displacements, acoustic emission measurements and accelerations at ground surface and inside the cave during seismic events has been initiated at the Abuchiragama cave since May 2017 (Figure 14). In addition some micro-tremor measurements were implemented inside and the surface of the underground shelter. Figure 15 shows an example of acceleration record on the ground surface taken on Feb. 7, 2018.

7 CONCLUSIONS

The following conclusions may be drawn from this study:

1. The stability category of Area 3 is estimated form the analytical method lower than that estimated from the empirical method.
2. It is estimated that the Area 3 should be stable if the arching model is valid. In other words, such a condition may be violated in case of large scale seismic events.
3. Further studies are necessary for Areas 3 and 7. Such studies are currently underway such as using the Discrete Finite Element Method (DFEM) (Aydan et al. 1996).

ACKNOWLEDGEMENTS

This work is carried out as a part of project with the consignment of the Nanjo City. We gratefully acknowledge the authorities of the Nanjo City for the permission to publish the content of the project in this conference.

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