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An experimental study on the dynamic stability of overhanging cliffs

K. Horiuchi & Ö. Aydan
Department of Civil Engineering, University of the Ryukyus, Okinawa, Japan

ABSTRACT: Overhanging rock cliffs may generally become unstable due to toe erosion resulting from the wave action. The critical erosion depth depends upon the height of cliff and the strength (tensile or shear) of the rock, and if the resulting stress state exceeds the strength of rock, it will collapse. Recently, it is reported that overhanging rock slopes may also fail during recent earthquakes. This experimental study was undertaken to investigate the stability of model rock cliffs under dynamic loading conditions in order to clarify the governing factors associated with their failure. The rock mass was modeled as continuum, layered, and blocky model. Shaking table (OA-ST1000X) has a size of 1 m × 1 m and the allowable maximum load is 100 kg under the conditions of maximum horizontal displacement of ±50 mm, maximum velocity of 0.56 m/s and maximum acceleration of 600 gals. The outcomes of the experimental studies are presented and discussed in this study. It is found that the failure modes of overhanging cliffs very much depend upon the number of discontinuity sets, tensile and shear strength of rock mass and their geometrical configuration.

1 INTRODUCTION

There are many cliffs with toe-erosion along shorelines of around the world and it may cause stability problems especially to historic structures and lighthouses. Such an example is the Gushikawa castle constructed on Ryukyu limestone cliffs. Sea waves, winds and percolating rain water are the main causes of toe-erosion leading to the failure. To prevent collapses, reinforcement for improving the stability of eroded cliffs using filling materials with the consideration of landscape has been introduced. numerous collapses of the overhanging cliffs have been reported due to earthquakes (Aydan 2013; Aydan and Amini, 2008; Aydan et al. 2012). In the vicinity of Japan, there are the four plates, namely "Eurasia Plate", "North American Plate", "Pacific Plate", "Philippine Sea Plate", interacting with each other in a complex manner (Figure 1). While Japan constitutes less than 1% of the world's area, earthquakes of about 10% of the world occurs in Japan. Considering the Philippine sea plate as an example, which is subducting in the northwest direction at a rate of 3-5 cm per year beneath the south east side of Ryukyu Archipelago. Also, on the continental side, there is a seabed topography called Okinawa trough. Following the formation of fractures the stability of the cliffs declines, and the occurrence of an earthquake may cause their collapse. But, there are few studies on the estimation of the collapse mechanism of the eroded cliffs during the earthquakes and the effect of discontinuity orientation and erosion on the collapse mode. It is necessary to examine the different failure form and the stability of rock cliffs depending on the discontinuous nature of rock mass at the time of the earthquakes. In this study, the failure modes of eroded cliffs are examined using rock mass models having different number of discontinuity sets, namely, continuum, layered and blocky. Then, the authors classified each failure mode into three categories based on strength and discontinuous nature of rock mass.

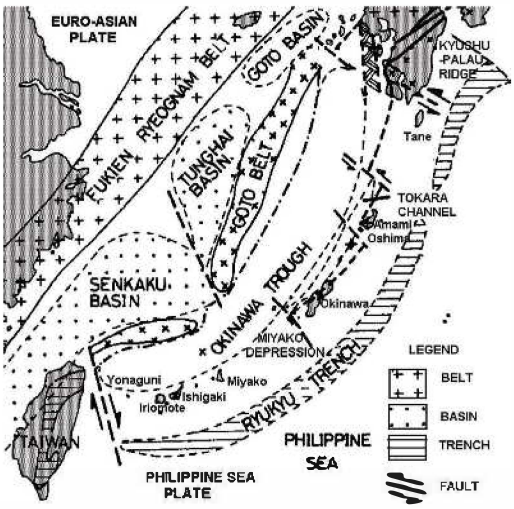


Figure 1. Ryukyu Islands and their tectonics (modified from Kizaki)

2 MATERIALS PROPERTY TEST

The model materials used in this study is in powder form obtained by mixing barium ($BaSO_4$), zinc oxide (ZnO) and Vaseline in a weight ratio of 70: 21: 9 and it can be formed into various

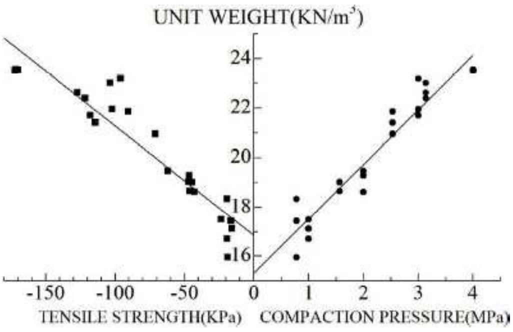


Figure 2. Relationship between tensile strength and compressive strength by unit volume weight.

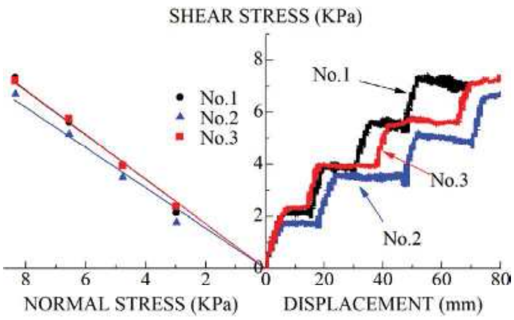


Figure 3. Shear characteristic of model materials.

shapes by compacting in a mold. The strength of the model block mostly depends on its unit weight and strength of the model block can be easily changed by varying the compaction force and it can return to its original powder form after model tests. In this study, two types of experiments were conducted to investigate the tensile properties of the model material and shear strength characteristics of interfaces between model materials. The cantilever test was carried to determine the tensile properties. Figure 2 shows the relationship between unit weight and tensile strength and compaction pressure. Experimental results confirmed that the unit volume the tensile strength increase are proportional to compressive strength. As the compaction pressure increases, compressive strength of the model material also increases. The shear test was used to obtain shearing characteristics of interfaces between blocks by gradually increasing normal load as 0 gf, 500 gf, 1000 gf, 1500 gf. Figure 3 shows the results of shear tests on interfaces between the blocks. The shear strength increases as the normal force increases.

Table 1. experimental condition.

	Acceleration(gal)	Frequency(Hz)
Sweep	50	3-50-3
Failure	0 - 400	5

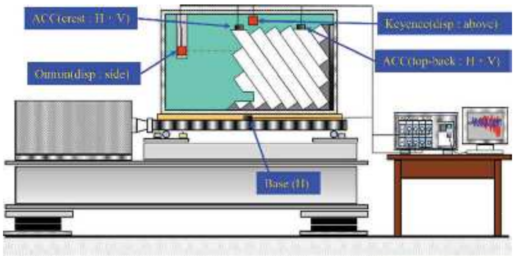


Figure 4. Illustration of the set-up of shaking table model tests.

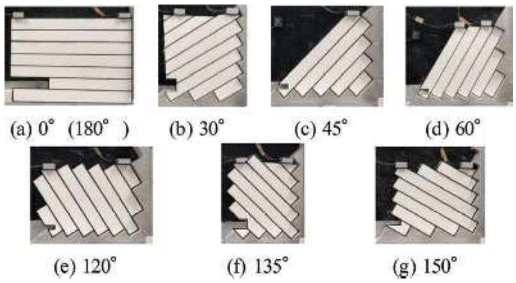


Figure 5. Layer model

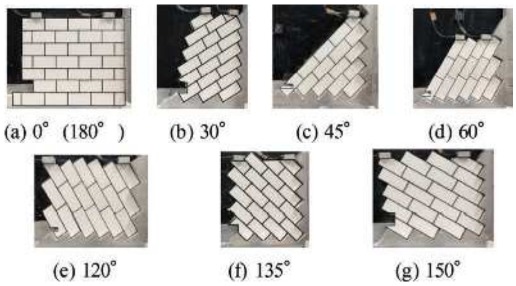
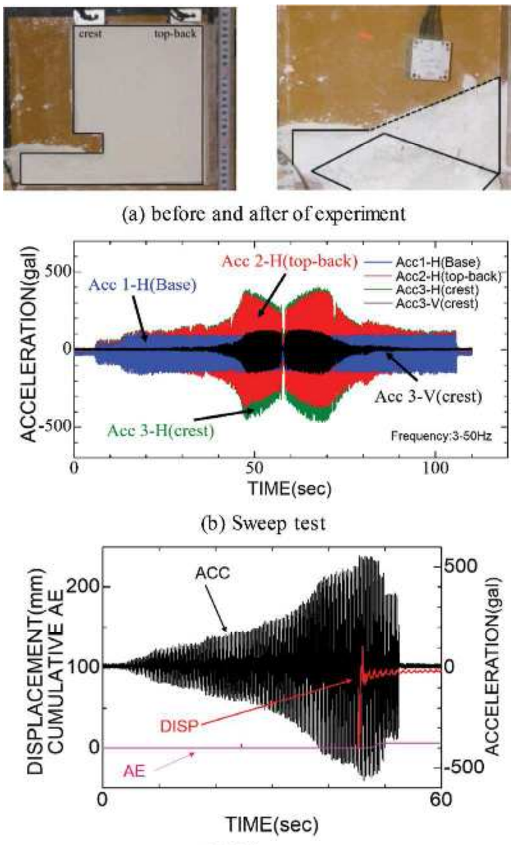


Figure 6. Blocky model

3 SHAKING TABLE TESTS

3.1 *Dynamic experiment method*

Two types of shaking table experiments were conducted, specifically, natural period characteristic test (Sweep test) and failure experiment. In some model experiments for layered and blocky rock mass models, FFT analyses were also performed. Experimental conditions are given in Table 1. In experiments, model blocks was laid into a model frame of 25 cm or 50 cm after the blocks were prepared under a compaction force of 2.5 tonf or 5 tonf respectively, and compaction was performed. The compaction pressure was selected on the assumption that the model itself didn't fail in a static state and could preserve its shape after molding. The model was subjected to vibration by the shaking table, and the acceleration and displacement responses were measured. Figure 4 shows the set-up of models and

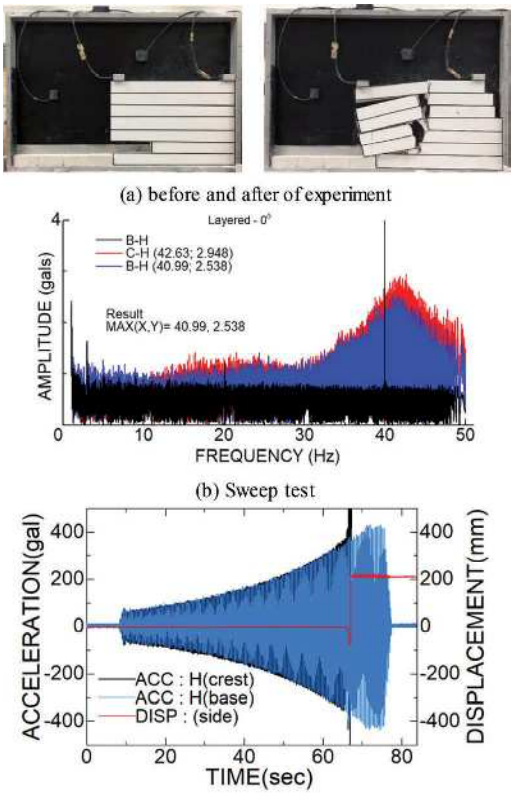


(a) before and after of experiment

(b) Sweep test

(c) failure test

Figure 7. Continuous model



(a) before and after of experiment

(b) Sweep test

(c) failure test

Figure 8. Layered model

instrumentation. We installed three accelerometers and two non-contact laser displacement transducers in the model of cliff. The model experiment of the eroded cliff was carried out three times. A model experiment is shown in Figure 5&6. As seen from the figures, the slope angle was 90 degrees (except for 45 degree and 60 degree). The erosion was introduced into the model and sweep test was first carried and results are shown in Figure 7 (b). Then, the model was subjected to shaking until failure under a chosen frequency 3-5Hz. The slope angle and erosion depth is chosen such a way that the model slope is stable under static condition and it may fail under dynamic conditions.

3.2 *Result of continuous model*

The collapse of continuum model entirely depends upon the strength of material constituting slope. The collapse of the continuum model may be due to tensile failure or combination of tensile and shear failure.

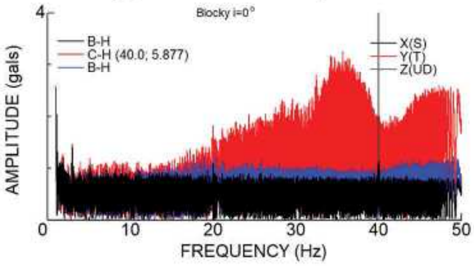
First a sweep test was carried out and it is found that the acceleration at the crest of the slopes was more than three times that on the shaking table. Regarding the acceleration response in the vertical direction, an amplification was observed in a certain frequency band.

Regarding the test resulting in the failure of the model slope, the results of the acceleration response, displacement and AE indicated that the model was greatly displaced when the acceleration response was around 500 gals. In addition, when the acceleration response at the crest of the slope was compared with that of the shaking table, it was about 1.5 times (Figure 7 (c)). From the above results, it was found that the crest of the slope shows larger acceleration response. The failure mode of the continuum cliff with toe erosion, a crack was initiated near the toe of the model slope, it was found that the collapse depended on the strength of the rock.

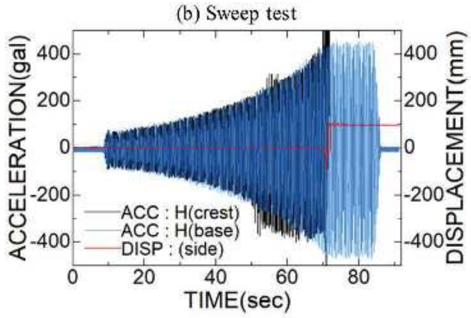
3.3 *Result of layered model*

The model experiment was conducted with a erosion depth being 50 mm. But, the model didn't collapse. As our purpose was to investigate the collapse mode, we increased the erosion depth of the model to 100 mm. Figure 8 show the experimental results before and after the layered model with toe erosion of 100 mm. The layer inclination of cliff model with toe

(a) before and after of experiment



(b) Sweep test



(c) failure test

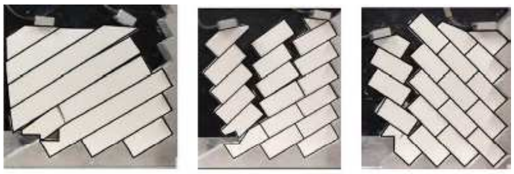
Figure 9. Blocky model

erosion was 0 degree and the failure occurred in the form of bending failure, which is just above the erosion tip. From the result of the acceleration response, it turned out that the model had collapsed at about 380 gals. There was almost no big difference regarding the amplitude of the acceleration at the failure in three experimental results. The movements was slightly different during the test, although the final collapse mode was same.

3.4 *Result of blocky model*

Although the layered model, did not collapse when the erosion depth was 50 mm, the blocky model collapsed when the erosion depth was 50 mm.

Figure 9 shows the views of the models before and after the experiment. For cliffs with toe erosion and 0 degree thoroughgoing discontinuity set, failure occurred near the vicinity of erosion tip and resulted in the toppling of blocks above a stepped failure surface. From the result of the acceleration response, it turned out that the model had collapsed at about 400 gals. There was almost no big difference regarding the amplitude of the acceleration at the failure in the three experimental results. The failure mode was slightly different during the test, but the final collapse mode was same.



(a) layered 30 degree | (b) blocky 30 degree | (c) blocky 135 degree

Figure 10.Example of flow model and received model

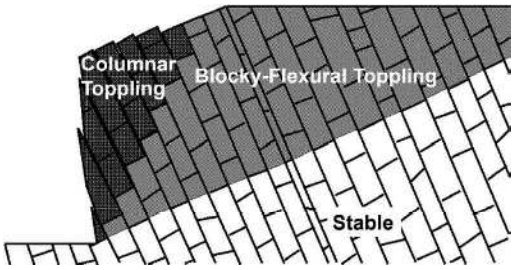


Figure 11.Blocky flexural toppling failure

(a) bending failure | (b) shearing failure

Figure 12.Special failure modes

3.5 *Evaluation of experimental results*

In this study, an investigation on the acceleration response and failure modes of the cliff models with toe erosion having different number of discontinuity sets was undertaken. From the comparison of experimental results, it may be stated that.

1. The blocky collapses when the erosion depth is less than of the layered model.
2. The results of acceleration response for three experiments showed almost the same result.

4 FAILURE MODES OF ERODED CLIFF

4.1 *Example of cliff failure after the experiments*

1. In the layered model, the model material itself was broken. However failure mode was affected by the discontinuities in blocky model.
2. The collapsed region in the blocky model collapses was larger than the layered model as the discontinuities of the rock mass has a large influence (Figure 10).

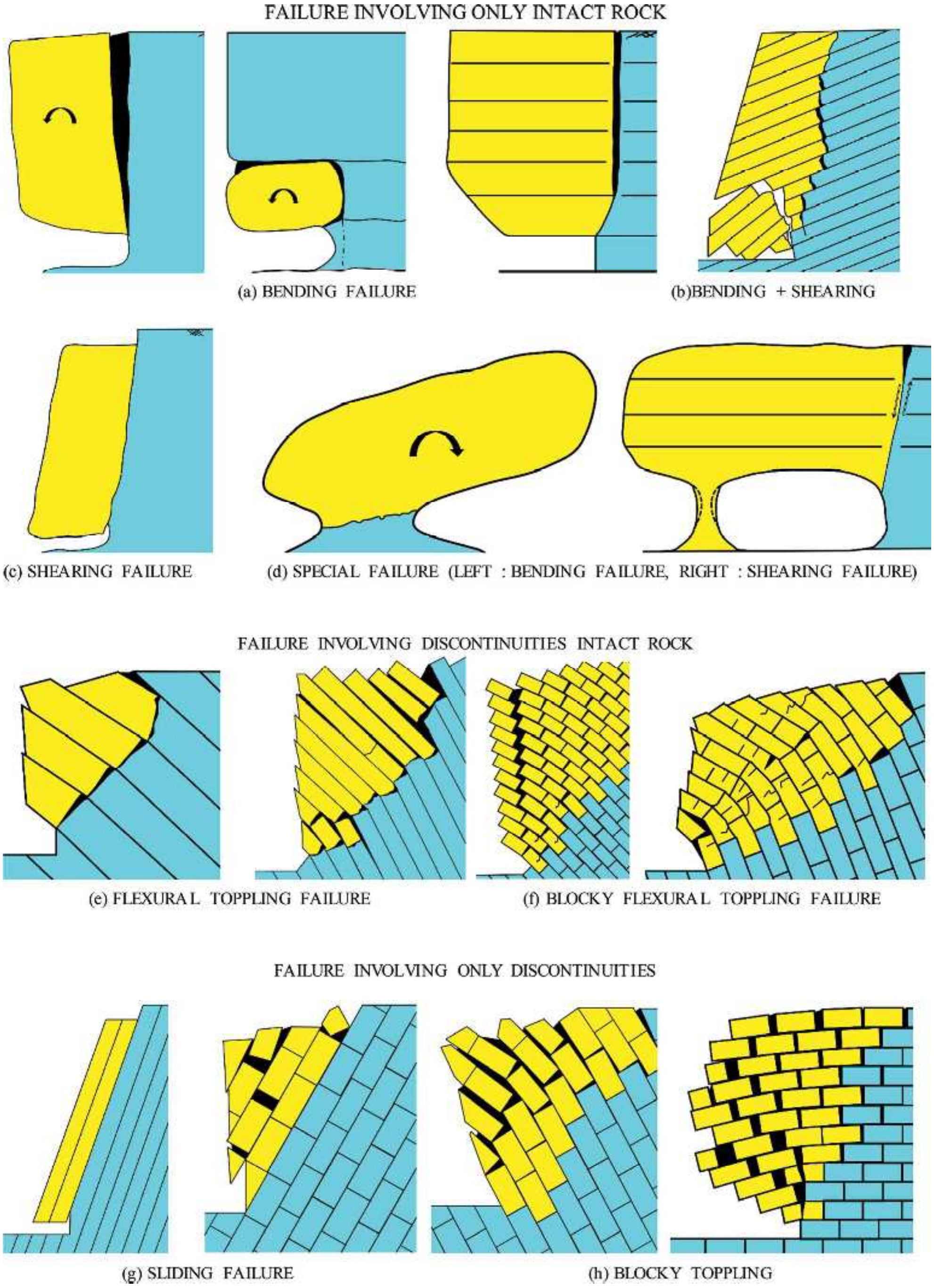


Figure 13. FAILURE MODE OF EROSION ROCK SLOPES

4.2 *Blocky flexural toppling failure*

Blocky flexural toppling failure is the failure of flexural failure of some of blocks while the others topple. (Figure 11). Blocky toppling failure related to purely to discontinuities. Flexural toppling failure caused by tensile stresses in layers of the rock mass (e.g. Aydan and Kawamoto, 1992).

4.3 *Proposal of failure modes of cliffs with erosion*

The authors have been surveying case histories of many cliffs with toe erosion in major islands of the Ryukyu Archipelago. From dynamic experiments and survey of cliffs (e.g. Aydan and Amini, 2009; Horiuchi et al. 2018; Tokashiki and Aydan 2010) the failure modes of the cliffs with toe erosion are classified as shown in Figure 13. The area shown in yellow in the figure corresponds to the area of actual collapse. The area shown in blue is in a stable state. This failure modes can be roughly categorized into three classes. The mechanism of detailed failure form is described in a study conducted by Aydan et al. (1989 a), b)) and Shimizu et al.

1. Failure involving only intact rock
   a) Bending failure
   b) Bending failure + Shear failure
   c) Shear failure
   d) Special failures (Figure 12)
2. Failure involving discontinuity and intact rock
   e) Flexural toppling failure
   f) Blocky flexural toppling failure
3. Failure involving only discontinuities
   g) Planar sliding
   h) Blocky toppling

5 CONCLUSIONS

In this study, the authors investigated dynamic stability of cliffs with toe erosion by varying discontinuity inclination and the number of discontinuity sets. The model material used in the experiment can be repeatedly used and it is most suitable for model tests of discontinuous rock slopes. In this experimental study, we also investigated the failure modes of cliffs with toe erosion as well as the acceleration response. The findings obtained in this research may be listed as.

1. The failure modes of the continuum, layered, blocky model cliffs are greatly affected by the number of discontinuity sets and their distributions.
2. It was difficult to compare the acceleration response of the model cliffs as the geometry of each model was different. In the future studies, we need to reconsider the model of the sea cliffs and the stability evaluation in relation to acceleration response.

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