Some considerations on the causes of cliff failures of Ryukyu Limestone in Ryukyu Archipelago

Ryukyu Takımadalarında Ryukyu Kireçtaşı Falezlerindeki Yenilmelerin Nedenleri Üzerine Bazı Görüşler

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ABSTRACT: The cliff failures occur due to toe erosion as well as seismic forces induced by earthquakes. However, the causes of cliff failures are not well understood and some researches are still necessary to clarify those causes so that software and hardware countermeasures can be taken. The causes of the cliff failures in Ryukyu Limestone formation in Ryukyu Archipelago are studied using very recent exploration tools such as drones, infrared imaging technique as well as experimental, analytical and numerical techniques. Furthermore, some photo-elasticity tests on cliffs using gelatin models and the results of these studies are presented and discussed. The results indicate that the observations, model experiments and computations provide some insight views to the stability issue of the cliffs.

Keywords: Static, dynamic, erosion, tensile strength, photo-elasticity


Anahtar Kelimeler: Statik, dinamik, erozyon, çekme dayanımı, foto-elastisite

1. INTRODUCTION

Overhanging rock cliffs occur due to the toe erosion of rock cliffs resulting from sea wave and wind forces, and chemical and physical weathering actions. The cliff failures also occurred due to seismic forces induced by recent damaging earthquakes (Aydan 2013, 2015). Nevertheless, the causes of cliff failures are not well understood and some researches are necessary in order to understand the causes so that software and hardware countermeasures could be undertaken.

In this study, the authors investigated the causes of the cliff failures in the Ryukyu Limestone in Ryukyu Archipelago, Japan, using very recent exploration tools such as drones, infrared imaging technique as well as experimental, analytical and numerical techniques. Figure 1 illustrates some examples of cliff failures observed in various islands along Ryukyu Archipelago.

Some shaking table experiments were carried out by changing the number and orientation of discontinuities for various depth of erosion. Some photo-elasticity experiments using gelatin models were also performed and stress changes during the failure process of the cliffs were observed. Numerical analyses of rock cliffs using Finite Element Method (FEM) were performed for observing the changes on the stress state at the top surface and in the vicinity of erosion tip of the cliff. The tensile strength of rock masses was evaluated using the stable and unstable cliffs and the bending theory. In addition, the effect of porosity of intact rock on the overall tensile strength of rock mass was taken into account in the rock mass property estimation based on Rock Mass Quality Rating (RMQR) System for evaluating the cliff failures. Finally, a recent cliff failure at Sesoko Island was analyzed using the various techniques explained in the first part of the paper.
2. MODEL MATERIALS

2.1. Breakable Model Materials

The model materials used in this study is in powder form obtained by mixing barium (BaSO₄), zinc oxide (ZnO) and Vaseline in a weight ratio of 70: 21: 9 and it can be formed into various 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 2a shows the relationship between unit weight and tensile strength and compaction pressure. Experimental results confirmed that the tensile strength and compressive strength increase in proportion to the increase of the unit weight of model material. Increase is proportional to compressive strength. As the compaction pressure increases, compressive strength of the model material also increases. The shear test was carried out to obtain shearing characteristics of interfaces between blocks by gradually increasing normal loads. Figure 2b shows the results of the shear tests on interfaces between the blocks. The shear strength increases as the normal force increases.

![Figure 2](image_url)

Figure 2. (a) Relationship between tensile and compressive strengths by unit volume weight, (b) shear characteristic of the model materials.
2.2. Photo-elastic Materials

In photo-elasticity tests, gelatin or polyurethane materials were used. Although it is very difficult to measure the properties of gelatin, the properties of polyurethane can be easily measured. Table 1 gives some material properties of gelatin and polyurethane materials.

Table 1. Physico-mechanical properties of photo-elastic model materials.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Unit weight (kN/m³)</th>
<th>Elastic Modulus (MPa)</th>
<th>Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gelatin</td>
<td>14.5</td>
<td>0.04-0.07</td>
<td>0.45</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>12.5</td>
<td>2.0</td>
<td>0.3-0.4</td>
</tr>
</tbody>
</table>

3. STATIC MODEL TESTS

3.1. Photo-elastic Tests

The method relies on the property of birefringence exhibited by certain transparent materials. Photo-elastic materials exhibit the property of birefringence, and the magnitude of the refractive indices at each point in the material is directly related to the state of stresses at that point when they are subjected to loading. In such materials, maximum shear stress and its orientation are obtained from analyzing the birefringence from a polariscope. The difference in the refractive indices leads to a relative phase retardation between the two components. A simple polariscope consists of a light source, polarizer, photo-elastic model, analyzer as illustrated in Figure 3a. Figure 3b shows a simple implementation of the concept utilizing a polariscope and digital camera with Figure 4 shows stress state in cliffs with different conditions and several failure stages of a cliff made of gelatin. It is interesting to notice largest shear stresses occur at the toe of the cliff while top part is subjected to tensile stresses (Aydan and Tokashiki, 2011; Tokashiki and Aydan, 2010, 2013; Horiuchi et al., 2018, 2019). Once tensile stress occurs, the crack propagates from the tip of tensile crack towards the tip of the erosion. It is very illustrative how the failure process takes place and stress changes occurs in photo-elastic tests.

![Figure 3a](image)

![Figure 3b](image)

(a) Basic concept

(b) Practical implementation

Figure 3. The principle of photo-elasticity testing and its implementation.

3.2. Base Friction Tests - Breakable Materials

Base friction model test was first contemplated by Erguvanlı and Goodman (1972). The principle of this model testing device based on the frictional resistance between the basal surface and the model, which is restricted in the direction of motion. Erguvanlı and Goodman (1972) used a flour and oil based material that permitted cracking within the model. In 1979, Egger (1979) presented an advanced base friction machine where a uniform pressure could be applied to increase the stresses on the model. Furthermore, Egger (1979) introduced a mixture of BaSO₄, ZnO and Vaseline. which can be compacted under different pressures to develop materials with different mechanical properties. Aydan et al. (1989) investigated failure modes of slopes made of breakable continuum, layered and blocky model materials and with/without toe erosion. Figure 5 illustrates examples of cliff failures with toe
erosion. It is interesting to note that most of failures occur due to flexural failure of continuum, layers or blocks although, shearing failure may occur in some cases (Tokashiki and Aydan, 2010). Nevertheless, the flexural failure is the dominant failure form.

![Stress distribution in stable and failing cliffs](image)

Figure 4. Stress distribution in stable and failing cliffs (model material: gelatin).

![Failure modes of model cliffs with toe erosion](image)

Figure 5. Examples of failure modes of model cliffs with toe erosion.

4. DYNAMIC TESTS

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, Fourier spectra analyses were also performed. In experiments, model blocks were laid into a model frame of 25 cm or 50 cm after the blocks were prepared under a compaction force of 2.5 tf, and compaction was performed. The compaction pressure was selected on the assumption that the model itself didn’t fail under a static condition 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 6 shows the set-up of models and instrumentation for layered and blocky rock mass 
slopes. We installed three accelerometers and two non-contact laser displacement transducers in the 
model of cliff.

Figure 6. Model slopes tested.

The model experiment of the eroded cliff was carried out three times. As seen from Figure 6, the slope 
angle was 90 degrees (except for 45 and 60 degrees). The erosion was introduced into the model and 
sweep test was first carried. Then, the model was subjected to shaking until failure under a chosen 
frequency 3-5Hz. The slope angle and erosion depth are chosen such a way that the model slope is 
stable under static condition and it may fail under dynamic conditions.

4.1. Continuum Cliff Models

The collapse of continuum model entirely depends upon the strength of material constituting slope 
(Figure 7). The collapse of the continuum model may be due to tensile failure or combination of 
tensile and shear failure. 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 involves a crack 
appeared at the ground surface just above the erosion tip of the toe of the model slope. However, it 
was found that the collapse depended on the strength of the rock.

Figure 7. Views of the cliff before and after shaking.

4.2. Cliff Models with Layered Rock Mass

Layered slopes with toe erosion shown in Figure 5a are tested. First the model experiment was 
conducted with an erosion depth being 50 mm. As the model didn’t collapse, the erosion depth was 
increased to 100 mm. Figure 8 shows the experimental results before and after the layered model with 
toe erosion of 100 mm. The layer inclination of cliff model with toe erosion was 0 degree and the 
failure occurred in the form of bending failure, which is just above the erosion tip. The movements 
were slightly different during the test, although the final collapse mode was same. However,
depending upon the inclination of the layers in relation to the cliff geometry, failures involving discontinuities or strength of layers and discontinuities may occur.

4.3. Cliff models with block rock mass

The blocky model collapsed when the erosion depth was 50 mm as the block size is about 100 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. The failure mode was slightly different during the test, but the final collapse mode was same. Depending upon the configuration of cliffs in relation to the distribution of discontinuities, failures may be due to through discontinuities or involving bot flexural strength of blocks and discontinuities.

4.4. General Characteristics of Cliff models

In this section, an investigation on the acceleration response and failure modes of the cliff models with toe erosion having different number of discontinuity sets was undertaken. Figure 10 shows several examples of failure modes of cliffs with layered and blocky rock mass. From the comparison of experimental results, it may be stated:

1) The blocky collapses when the erosion depth is less than of the layered model.
2) The results of acceleration levels to induce failure in blocky rock mass is much less than that for cliffs with layered rock mass.
3) Failure may depends involve the intact, intact rock and discontinuities and discontinuities only as pointed out by Aydan (1989), Aydan et al. (1989a, b) and Horiuchi et al. (2018, 2019).
4) The collapsed region in the blocky model collapses was larger than the layered model as the discontinuities of the rock mass have a large influence.
5. IN-SITU OBSERVATIONS

Tokashiki and Aydan (2010) investigated many cliffs in various islands of the Ryukyu Archipelago, Japan. Figure 11a shows the results of measurements of failed and stable Ryukyu limestone cliffs together with estimated stability bounds for different tensile strength of rock mass using the bending theory of cantilever beams. It is interesting to note that the in-situ tensile strength of rock mass should range between 0.25 and 1.0 MPa if the presented theoretical model is applicable. The tensile strength of the Ryukyu limestone generally varies between 2 and 4 MPa. The estimated in-situ tensile strength of rock mass is 0.06-0.25 times the tensile strength of intact rock. This comparison also has some important implications regarding the tensile strength of rock masses, which is often neglected in rock mechanics and rock engineering. The observational results together with computational results clearly indicate that rock masses in nature have tensile strength and some considerations must be given to how to evaluate it. Aydan et al. (2014) recently applied the new rock mass quality rating (RMQR) to the cliffs shown in Figure 11a and they inferred tensile strength of rock mass using the following formula:

\[
\frac{\sigma_{\text{tensile}}}{\sigma_{\text{int}}(\text{MPa})} = \frac{\text{RMQR}}{\text{RMQR} + \beta(100 - \text{RMQR})}
\]

where \( \beta \) is an empirical coefficient. Its value ranges between 3 and 9. Horiuchi et al. (2019) advanced Eq. (1) by taking into account the porosity of intact rock as given below:

\[
\frac{\sigma_{\text{tensile}}}{\sigma_{\text{int}}(\text{MPa})} = \frac{\text{RMQR}}{\text{RMQR} + \beta(100 - \text{RMQR})} \left(1 - \frac{n}{n + \alpha(100 - n)}\right)
\]

Eq. (2) is applied to the data of Figure 11a by varying Poisson's ratio. As noted from Figure 11b, the consideration of porosity can explain the scattering of data. It is recommended to use Eq. (2) if porosity of intact rock is available.
6. CONCLUSIONS

In this study, the authors assessed the stability of steep cliffs made of the Ryukyu limestone in Ryukyu Islands of Japan. The conclusions drawn from this study are as follows:

1) The severest condition regarding the bending stress at the outer most fiber of overhanging cliffs occurs when the overhanging cliff has rectangular shape and the value of the bending stress is much higher for the rectangular configuration than those for other configurations. Such overhanging cliff will fail immediately once the tensile stress exceeds the tensile strength of rock mass.

2) Tensile stresses in steep cliffs do occur. However, their value is unlikely to cause any tensile fracture in cliffs in view of the tensile strength of rock mass.

3) The utilization of drones is quite effective for site-investigations in view of safety and access easiness to difficult areas.

4) The RMQR value of the typical Ryukyu limestone cliffs ranges between 38 to 60 except fault or fracture zones.

5) The photo-elasticity experiments using gelatin models proved to be quite useful to visualize the stress state in cliffs and stress changes during the failure process.

6) The comparisons of the results of measurements of failed and stable Ryukyu limestone cliffs together with estimated stability bounds for different tensile strength of rock mass indicated that the in-situ tensile strength of the rock mass should range between 0.25 and 1.0 MPa.

The in-situ tensile strength of rock mass as can be estimated as a fraction of that of intact rocks from the empirical relation proposed by Aydan et al. (2014) with the consideration of porosity of intact rock (Eq. 2). The normalized form of the tensile strength of rock mass has the same form as those for the uniaxial compressive strength and elastic modulus of rock mass.

7. REFERENCES


