The assessment of dynamic stability of rock slopes with hexagonal jointing through shaking table tests and dynamic limiting equilibirum method (DLEM)

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ABSTRACT: The authors investigated the dynamic stability of rock slope consisting of hexagonal blocks through model tests on shaking table and evaluate their stability through dynamic limiting equilibrium method (DLEM). Experiments indicated that the failures may be toppling or sliding and, they may be of active or passive modes. Critical acceleration levels can be estimated from the limit equilibrium method if frictional properties of rock blocks and the geometry of model slopes together with appropriate consideration of failure modes.

Keywords: Hexagonal jointing, dynamic limiting equilibrium method, dynamic, static, shaking table, slope.

1 INTRODUCTION

Rock masses irrespective of its type contain discontinuities associated with their geological formation. The hexagonal jointing is common to extrusive rocks such as basalts and andesite as well as to some sedimentary rocks such as sandstone. In nature, rock masses consisting of hexagonal blocks receive great attention of ordinary people due to their beautiful geometrical patterns. they constitute some spectacular features, which often constitute geo-parks in many countries all over the World. Such structures are even observed in Mars.

In literature, there are very few studies on the mechanical behavior of rock mass models having hexagonal rock blocks and associated engineering structures (e.g. Aydan 2016, 2017; Aydan et al. 1989). There is a great concern on the both stability of slopes, underground openings and seepage and bearing capacity of rock formations having hexagonal joint sets in recent years. As the hexagonal discontinuity sets result in columnar structures, there is a big concern on rockfalls from steep rock slopes and tunnel portals.

This study is concerned with the dynamic stability of rock mass models having hexagonal discontinuity pattern. The dynamic stability of slopes of rock mass models consisting of hexagonal blocks was investigated through model tests on shaking table and they are analyzed using dynamic limit equilibrium method. The authors present the outcomes of these studies and discuss their implications in practice section describes the general layout of this paper template briefly.

2 EARTHQUAKE INDUCED FAILURES OF ROCK SLOPES WITH HEXAGONAL JOINTING

Earthquakes may induce failures of rock slopes (Aydan 2016, 2017). This issue is less studied in literature. As rock mass in nature contains numerous discontinuities, usually in the form of sets, the stability of such slopes depends upon the spatial orientations of discontinuity sets with respect to slope geometry, their continuity and their mechanical properties. As long as the rock material itself does not break up under induced state of stress, and two sets of discontinuity, whose strikes are parallel or nearly parallel to the axis of the slope, exist, the possible forms of slope instability are sliding failure, toppling failure and combined sliding and toppling failure. These instability forms may appear depending upon the discontinuity pattern, their inclination, frictional properties and the geometry of slopes. More general discussion on the stability of rock slopes is given in Aydan et al. (1989) and his follow-up publications. Observations on failure modes also indicated that the passive modes of failure forms can also occur in nature (Aydan 2016, 2017). Figure 1 shows some actual rock slope failure observed in 2008 Iwate-Miyagi, 2011 Christchurch, 2011 Mt. Fuji and 2016 Kumamoto earthquakes. Most of rock slopes failures are dominated by toppling or combined toppling and sliding modes.

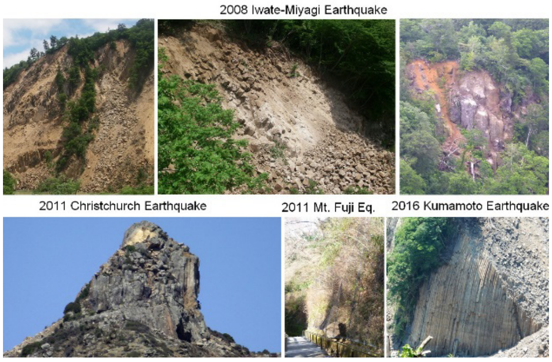


Figure 1. Views of earthquake induced rock slope failures having hexagonal discontinuity pattern.

Table 1. Physical and elastic constants of Aluminum.

Elastic Modulus (GPa)	68.0
Poisson's ratio	0.33
Unit weight (kN/mm^3)	26.89

Table 2. Frictional characteristics of aluminum block interfaces.

Test No	φ_s°	φ_d°
①	15.0	14.10
②	15.9	14.54
③	15.7	14.23

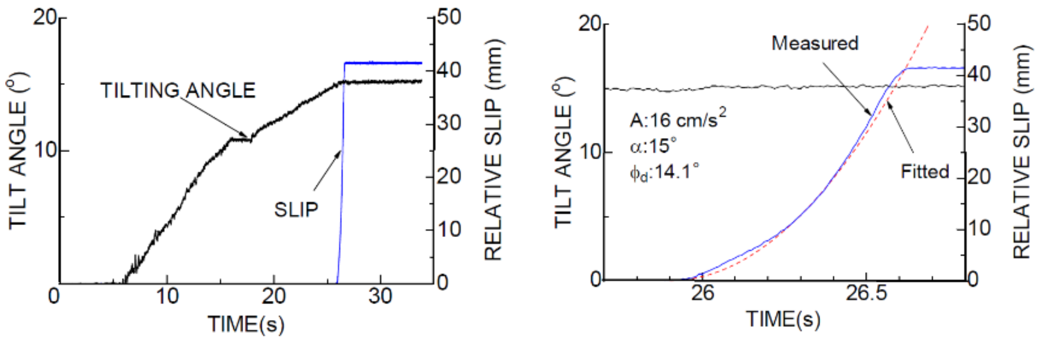


Figure 2. An example of tilting test and determination of kinetic friction angle.

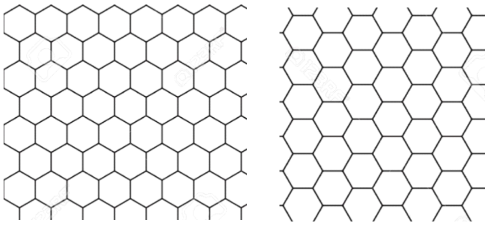
3 MODEL SLOPES

3.1 Model Materials and Their Frictional Properties

Aluminum hexagonal blocks were selected to create rock slope models. Blocks were 50mm long with side length of 6mm. The physical and mechanical properties of aluminum are given in Table 1. In these particular experiments, the blocks were selected such that they will remain elastic while the movements can take place in the form of separation and/or sliding along block interfaces. Therefore, the friction properties are necessary. As the height of slopes is selected to be about 250mm, any friction tests should consider this normal stress levels. Although direct shear tests are possible, the applicable normal stresses would be too high. Taking into account this fact, tilting tests were carried out on hexagonal aluminum blocks. In tests, the motion of blocks is also recorded using laser-transducers so that it was possible to determine both static and kinetic friction angles (Aydan 2017). Table 2 summarizes experimental results. As noted from the table, static friction angle ranges between 15 to 15.9 degrees while the kinetic (dynamic) friction angle ranges between 14.1 and 14.54 degrees. Fig. 2 shows an example of slip response of the block during a tilting experiment. Kinetic friction angle is determined from the measured slip response, which was described by Aydan (2017).

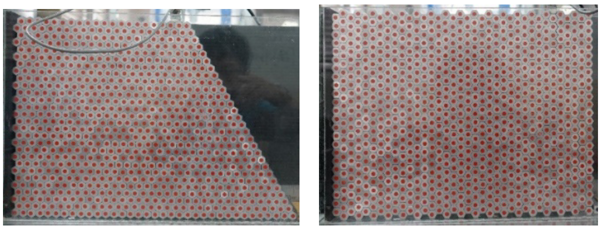
3.2 Discontinuity Pattern of Model Slopes

Fundamentally, the discontinuity patterns used in model slope tests are denoted as Pattern A and Pattern B as illustrated in Fig. 3. The rotation of Pattern-A results in Pattern-B. In other words, the variety of model slopes is quite restricted to two patterns. If the friction angle of block interfaces is less than 30 degrees, the slope angle cannot be greater than 60 degrees under gravitational conditional (Fig. 4(a). For Discontinuity Pattern-A, the anticipated slope failure modes would always be passive type. As for Discontinuity Pattern-B, it is possible to build-up slopes with an angle of 90 degrees (Figure 4(b) and the slope failure modes would be always active.



(a) Pattern A (30°) (b) Pattern B (60°)

Figure 3. Selected discontinuity Patterns.



(a) Discontinuity Pattern-A (b) Discontinuity Pattern-B

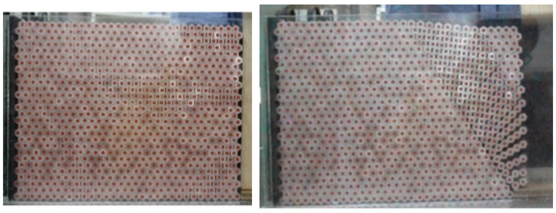
Figure 4. Views of model slopes.

4 MODEL SLOPE TESTS

4.1 Gravity Model Tests

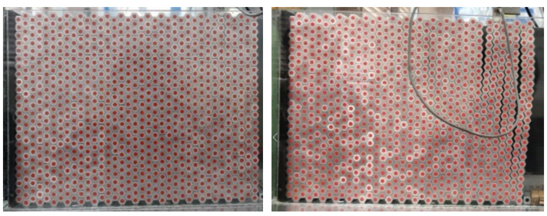
(a) Model Slopes with Discontinuity Pattern A

As pointed out in previous subsection, when the slope angle is greater than 60 degrees, the model slope would be unstable under gravitational loading. Fig. 5(a) shows the initial state of the model slope with a support while Fig. 5(b) shows the motion of failing slope after the removal of the support. The slope angle was 90 degrees. It is quite interesting to note that the blocks above the stable region fail like columnar toppling with some relative slip on the failure plane. Aydan et al. (1989) theoretically explained the reason why blocks above the failure plane constitute equivalent columns during the initial phase of failure. In other words, the failure can be classified as columnar toppling with base sliding.



(a) (b)

Figure 5. Views of the model slope with support (a) removal (b) of the support.



(a) Static state (b) failure during shaking

Figure 6. A view of the model slope before and after the removal of support.

(b) Model Slopes with Discontinuity Pattern B

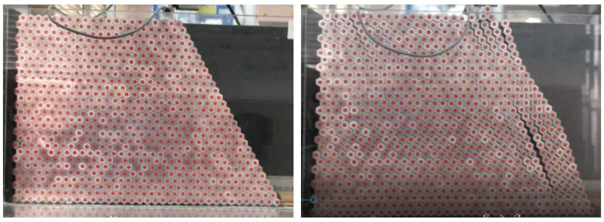
Next the stability of model slopes with Discontinuity Pattern B is investigated. The slope angle was 90 degrees. Figure 6(a) shows the slope after the removal of the support. As noted from the figure, the slope is stable. However, the column consisting of hexagonal blocks is anticipated to be quite vulnerable to failure under even slight vibration (24-40 gals) or slight tilting of the base in the range of 1.37–3.17 degrees inclination as seen from Figure 6(b), which shows the failing state explained next section.

4.2 *Shaking Table Tests*

For model slopes for each discontinuity pattern were subjected to shaking using the shaking table test device at the University of the Ryukyus. During experiments, the accelerations at the top of the model slope and on the shaking table and displacements at the slope crest were monitored simultaneously. Accelerations were recorded Tokyo Sokki 10G accelerometer and displacements were measured using the laser displacement transducers. The sampling was set at 10 ms and YOKOGAWA SL1000 Dynamic acquisition is utilized together with recordings on laptop computers. In addition, experiments were recorded on the high-speed camera. At least, three experiments were carried out for each discontinuity pattern. However, only one experiment for each discontinuity pattern is explained herein.

(a) Model Slopes with Discontinuity Pattern A

The slope angle was 60 degrees, which is the stable slope angle under static condition for this discontinuity pattern. Figure 7 shows views of the model slope before and during shaking. As noted from the figure, a columnar motion of the passive toppling mode is recognized. The column consisting hexagonal blocks tend to be in motion like an equivalent monolithic column. Figure 8 shows the base acceleration and displacement of the top of the slope. The columnar behavior is noted at the acceleration level of 720 gals and the model slope become totally unstable when the acceleration reached the level of 790 gals.



(a) (b)

Figure 7. Views of the model slope before shaking (a) and during shaking (b).

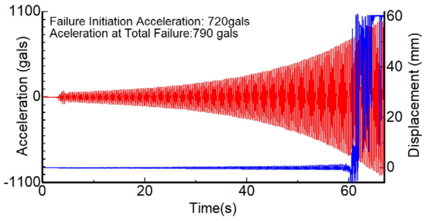


Figure 8. Recorded base acceleration and the response of the top of the model slope.

Discontinuity pattern may also fail in a mode, which may be categorized block buckling. As seen in Figure 9. This mode occurs when shaking intensity increases. The deformation pattern may indicate higher modes.

Figure 9. Buckling mode.

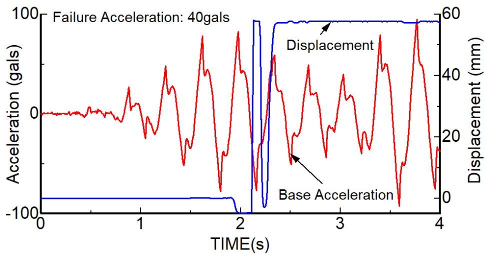


Figure 10. Recorded base acceleration and the response of the top of the model slope.

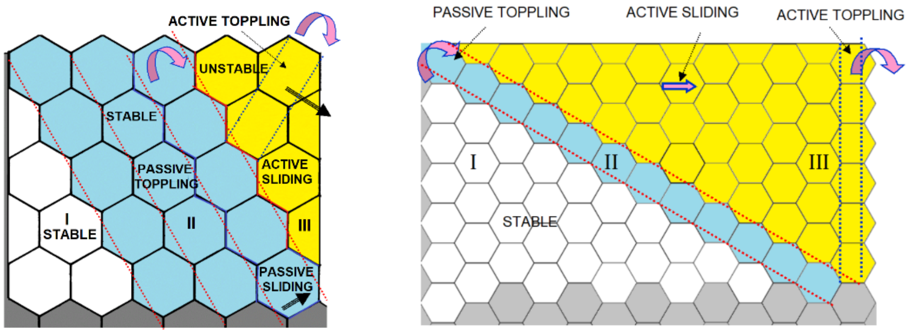
(b) Model Slopes with Discontinuity Pattern B

The slope angle was 90 degrees. As pointed out in the previous sub-section, the column consisting of hexagonal blocks is anticipated to be quite vulnerable to toppling failure under even very slight vibration (24-40 gals) or slight tilting of the base in the range of 1.37 - 3.17 degrees inclination. Figure 6a,b shows views of the model slope before and during shaking. As noted from the figure, a columnar motion of the active toppling mode is recognized as also noted in Figure 6(b). The column consisting hexagonal blocks above the plane inclined at an angle of 30 degrees tend to be in motion like equivalent monolithic columns. Figure 10 shows the base acceleration and displacement of the top of the slope. The columnar behavior is noted at the acceleration level of 20 gals and the model slope become totally unstable when the acceleration reached the level of 40 gals.

4.3 Discussion of Failure Modes in Shaking Table Model Tests

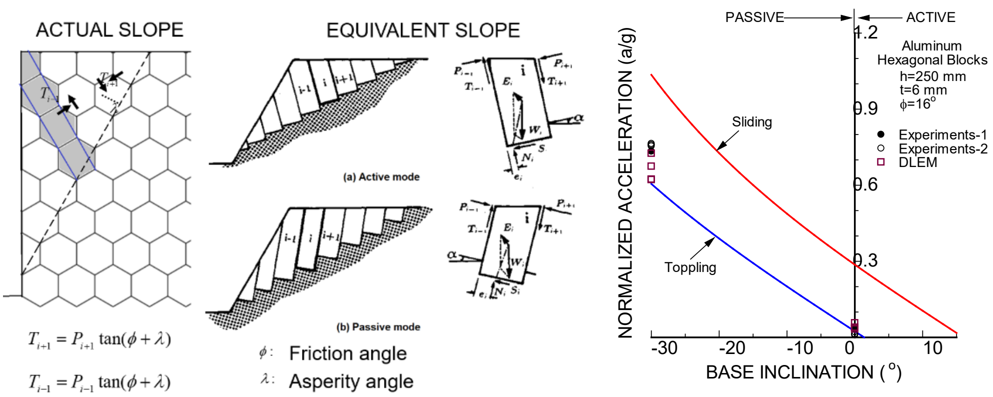
As for Discontinuity Pattern A, the failure regions within the slopes can be denoted as shown in Figure 11(a), depending upon the slope geometry and frictional characteristics of discontinuities. Region III is the first most likely failure form of the slope. The region denoted by III will fail in the active sliding mode and/or active toppling mode under gravity. If the slope angle such that the region III does not exist, the region denoted as II, can only fail in the form of passive toppling and/or passive sliding mode when the slope is subjected shaking. When slope height is relatively high, the passive toppling mode would be dominant. On the other hand, the passive sliding mode may be dominant depending upon the frictional properties of discontinuities and dimensions of hexagonal blocks with respect to slope geometry (Aydan et al. 1989, 2021; Aydan 2017). The stable denoted by Region I may also become unstable if the passive sliding mode is prevailing.

The failure regions within the slopes with Discontinuity Pattern B can be denoted as shown in Figure 11(b). Region III is fundamentally stable under gravity and it would become unstable first when the slope is subjected to shaking. The region denoted III will fail in the active sliding mode and/or active toppling mode under shaking (e.g. Aydan et al. 2021). The active toppling mode will be governed by the highest column of hexagonal blocks. If the slope angle such that the region III does not exist, the region denoted as II, can only fail in the form of passive toppling and/or passive sliding mode when the slope is subjected shaking. Although passive sliding mode is possible, the passive columnar toppling would be the prevailing failure mode. The stable denoted by Region I will remain stable as expected.



(a) Pattern A (b) Pattern B

Figure. 11. Possible failure modes of rock slopes with hexagonal discontinuity patterns.



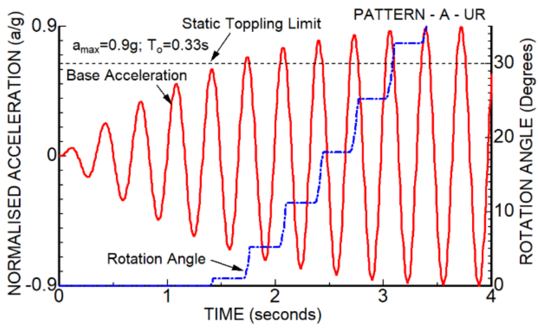
(a) (b)

Figure 12. (a) Mechanical modelling concept and (b) comparison of computational results with experimental methods

5 ANALYSIS OF EXPERIMENTS

Aydan et al. (2022) proposed a method to analyze the stability of slopes with hexagonal jointing under static and dynamic conditions. Although this method cannot be explained due to space limitation, this method was utilized to analyze the experiments described in the previous sections. The failure of slopes was first analyzed using the seismic coefficient method and computational results are compared with experimental results in Figure 12. The experimental results are with the bounding lines for sliding and toppling. However, the bound for toppling would be appropriate for practical applications.

The dynamic limiting equilibrium method developed by Aydan et al. (2022) is also utilized for the rotation/displacement response of the slopes and the computed results are shown in Figures 13 and 14 for an input wave form with 3 Hz as used in experiments. These computed results are quite similar to the experimental responses shown in Figures 8 and 10 for each respective pattern.



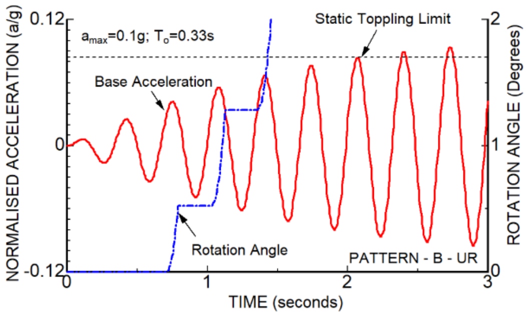


Figure 13. Rotation response of the model slope crest. Figure 14. Rotation response of the model slope crest.

6 CONCLUSIONS

The hexagonal discontinuity patterns are often observed in nature, particularly in extrusive volcanic rocks. Nevertheless, studies in rock mechanics and rock engineering is quite rare. First, a brief summary of rock masses with hexagonal discontinuity patterns is given and the possible mechanism of such discontinuity patterns is presented. A brief review of engineering problems is described. The results of these experiments are presented and their implications are discussed. And then the possible failure modes depending upon the discontinuity patterns are discussed. On the bases of theoretical formulations based on limiting equilibrium method (e.g., Aydan et al. 1989, 2021, 2022; Aydan 2017) and results of frictional properties and geometry of model slopes, the critical acceleration levels are estimated. Despite some limitations of the dynamic limiting equilibrium method, the results of estimations can be quite close to those of experimental results. Besides the limiting equilibrium method, it would be desirable to carry out some numerical analyses based on Discrete Finite Element Method (DFEM) and compare both experiments and those from limiting equilibrium method.

REFERENCES

Aydan, Ö. 2016: Large Rock Slope Failures Induced by Recent Earthquakes, *Rock Mech Rock Eng*, 2503-2524.

Aydan, Ö. 2017. *Rock Dynamics*, CRC Press, ISRM Book Series 3, 147-186.

Aydan, Ö., Shimizu, Y. and Ichikawa, Y. (1989): The effective failure modes and stability of slopes in rock mass with two discontinuity sets, *Rock Mechanics and Rock Engineering*, Vol. 22, 163-188.

Aydan, Ö., Tokashiki, N., Ito, T. and Murayama, Y., 2021, Dynamic stability of rock slopes with hexagonal discontinuity pattern (in Japanese with English abstract). 15th Japan Rock Mechanics Symposium, 453-458.

Aydan, Ö., Tokashiki, N., Ito, T., Murayama, Y., 2021. Dynamic stability of rock slopes with hexagonal discontinuity pattern. 11th Asian Rock Mechanics Symposium, ARMS11, Beijing. M150, 8p, 2021. IOP Conf. Series: Earth and Environmental Science 861, IOP Publishing

Aydan, Ö., Tokashiki, N., Ito, T., Murayama, Y., 2022. The applicability of dynamic limiting equilibrium method to slopes with hexagonal jointing. 48th Japan Rock Mechanics Symposium, Tokyo, JSCE, 103-108