Dynamic stability of rock slopes with hexagonal discontinuity pattern

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Abstract. Various regular discontinuity patterns are observed in rock masses and one of the common discontinuity patterns is hexagonal pattern, which is mostly observed in all extrusive volcanic rocks such as basalt, andesite, rhyolite and welded tuffs as well as in some sedimentary rocks subjected to desiccation or freezing-thawing processes. In this study, the authors investigate the dynamic stability of rock slope consisting of hexagonal blocks through model tests on shaking table. Experiments indicated that toppling or sliding failures, which may be of active or passive modes occur. Critical acceleration levels can be estimated from the limit equilibrium method with the consideration of results of frictional properties and geometry of model slopes.

Keywords: Rock Slope, Hexagonal Pattern, Dynamic Stability.

1. Introduction

Rock masses irrespective of its type contain discontinuities associated with their geological formation. In nature, rock masses consisting of hexagonal blocks receive great attention of ordinary people due to their beautiful geometrical patterns. These patterns are commonly observed in basic extrusive volcanic rocks such as basalt and andesite.

In literature, there are very few studies on the mechanical behavior of rock mass models having hexagonal rock blocks and associated engineering structures [1,2,3,4]. However, the rock masses having hexagonal discontinuity often observed in nature and they constitute some spectacular features, which often constitute geo-parks in many countries all over the World. Such structures are even observed in Mars (Fig. 1).

(a) Orhun (Central Asia) (b) Kelbecer(Azerbaijan) (c) Oma (Japan) (d) Basalt (Mars)

Fig. 1. Columnar jointing associated with lava flows on Earth and Mars

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. Fig. 2 shows some examples of engineering problems associated with hexagonal discontinuity sets.
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 limit equilibrium method. The authors present the outcomes of these studies and discuss their implications in practice.

2. Formation of Hexagonal Discontinuity patterns in Nature

The hexagonal jointing involves at least three discontinuity sets due to cooling of hot lava in plan. This discontinuity sets have a regular angular form and they intersect each other at angle of 120 degrees. The 4th discontinuity set perpendicular to cooling joints. The joints start to develop at the top surface of lava flow and also at the bottom surface. Nevertheless, the crack propagation near the top surface is much quicker than that at the lower surface of the lava flow. However, the morphology of cooling discontinuities is generally rough and they are generally open so that the percolation of ground water can easily takes place (Fig. 3a).

The lava intrusion may also occur as dykes or sills. As the adjacent rock mass is at lower temperature, cooling discontinuity sets also occur within the dykes. Figç 3b,c shows two examples of hexagonal discontinuity formation associated with basaltic lava intrusions in a Okumino dam site and along roadway near Urla Town.

It is also reported that similar type jointing is observed in sedimentary rocks, which undergo cyclic wetting and drying (Fig. 4a). These discontinuities are called desiccation cracks, which are sometimes wrongly called mud-cracks etc (Fig. 4b,c). In addition, similar cracks may occur in sedimentary rock subjected to freezing conditions.
Fig. 4. Examples of desiccation cracks in (a) sandstone (Iriomote, Japan) and (b,c) clay.

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.

Table 1. Physical and elastic constants of Aluminum

| Property                  | Value |
|---------------------------|-------|
| Elastic Modulus (GPa)     | 68.0  |
| Poisson’s ratio           | 0.33  |
| Unit weight (kN/mm^3)     | 26.89 |

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 [2]. 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. 4 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 [2].

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   |

Fig. 4. An example of tilting test and determination of kinetic friction angle

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. 5. 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. 6(a). For Discontinuity Pattern-A, the anticipated slope failure modes would always be passive type [2]. As for Discontinuity Pattern-B, it is possible to build-up slopes with an angle of 90 degrees (Figure 6(b) and the slope failure modes would be always active.

Fig. 5. Selected discontinuity Patterns

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

Fig. 5. Views of model slopes.

4. Model Slope Tests

4.1. Gravity Tests

4.1.1. 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. 7(a) shows the initial state of the model slope with a support while Fig. 7(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.

Fig. 6. Views of the model slope with support (a) and after removal of support (b)
4.1.2. Model Slopes with Discontinuity Pattern B

Next the stability of model slopes having Discontinuity Pattern B is investigated. The slope angle was 90 degrees. Fig. 8a 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 Fig. 8b, 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.

4.2.1. 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. Fig. 9 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. Fig. 10 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.
4.2.2. 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. Fig. 8a,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 Fig. 8(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. Fig. 11 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.

5. Methods of Stability Analyses and Comparisons

There are different techniques to analyze the stability of the model slopes described in the previous section. The simple yet most effective technique is to utilize the limiting equilibrium method together either pseudo-dynamic approach or pure dynamic approach [1,2,3]. Although there are also some numerical methods, the limiting equilibrium approach is selected, and its fundamentals are explained briefly.

5.1. Fundamentals

Aydan et al. [3] developed a two-dimensional dynamic limiting equilibrium method (DLEM) and extended to various conditions by considering both active and passive modes of sliding, toppling and combined toppling-sliding while modelling the region of failure consists of columns of rock blocks. The same model can be used for rock slopes having hexagonal discontinuity pattern with appropriate selection of effective width, height and inter-column shear resistance.
5.2. Applications and comparisons
For the both discontinuity patterns, the possible failure modes would depend upon the slope geometry and frictional characteristics of discontinuities and the columnar structure within failure regions of the slopes as shown in Fig. 12. For Discontinuity Pattern A with slope angle of 60°, the estimated acceleration level will be 981 gals for the friction angle of 15 degrees. The failure in tests was initiated at the level of 720 gals and the total failure occurred at 790 gals. The discrepancy is due to shock waves induced during shaking as well as block buckling mode. Although the details of the method can not be explained due to lack space in this study, the computed base acceleration would be 23.5 gals for active toppling and 262.9 gals for active sliding for Discontinuity Pattern B and slope angle of 90°. As the horizontal acceleration required for active toppling is much less than that for active sliding, the active toppling mode becomes dominant as expected.

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

Fig. 11. Possible failure modes of rock slopes with discontinuity patterns A and B.

6. Conclusions
Experiments indicated that toppling or sliding failures occur and the modes can be classified as active or passive. Critical acceleration levels associated with failures could be estimated from the limit equilibrium method with the consideration of results of frictional properties and geometry of model slopes and the results of theoretical estimations are 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).

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