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The dynamic response and stability of discontinuous rock slopes

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

Y. Ohta
Graduate School of Science & Technology, Tokai University, Shizuoka, Japan (Presently with Nuclear Energy Regulation Authority, Tokyo, Japan)

M. Amini
Department of Mining Engineering, Tehran University, Tehran, Iran

Y. Shimizu
Department of Civil Engineering, Meijo University, Nagoya, Japan

ABSTRACT: The dynamic response and stability of rock slopes during earthquakes are of great concern in rock engineering works such as highway, dam and nuclear power plant constructions. The main objectives of the study are to investigate the dynamic response of slopes and likely forms of instability of the slopes in relation to the number and orientation of discontinuity sets with respect to the slope geometry under various kinds of acceleration waves. The dynamic response of the model slopes were measured using accelerometers installed at various points in the slope. In the tests, various parameters such as the effect of the frequency and the amplitude of input acceleration waves are investigated in relation to discontinuity patterns and their inclinations and the slope geometry. Finally, the model slopes were forced to fail by increasing the amplitude of input acceleration waves and the forms of instability were investigated. In this study, the authors describe the results of the model tests on the dynamic response and stability of rock slopes and discuss their implications.

1 INTRODUCTION

The dynamic response and the stability of rock slopes associated with rock engineering works such as highway, dam and nuclear power plant constructions during earthquakes are of great concern. Fig. 1 shows some slope failure examples observed during recent earthquakes (e.g. Aydan 2016). As rock masses in nature generally have discontinuities due to various physical, chemical phenomena they underwent in the geologic past, there is a need to take into account the discontinuous nature of rock masses for evaluating the dynamic response and the stability of rock slopes.

An experimental study was undertaken to investigate the stability of rock-cut excavations during earthquakes. The main objectives of the study were to investigate the dynamic response and instability modes of the rock slopes in relation to the number and orientation of discontinuity sets with respect to the slope geometry under various kinds of acceleration waves. Blocks with two kinds of materials are used. The blocks with unbreakable material was intended to study the effects of disontinuities while the breakable blocks were intended to study the effect of block failure on the response and stability of discontinuous rock slopes. The results obtained from these experimental study on model rock slopes with various discontinuity sets are presented and discussed.

Figure 1. Examples of slope failures induced by earthquakes.

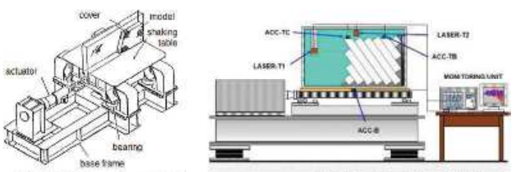
2 DEVICES AND MATERIALS

2.1 *Shaking Table Devices*

Two shaking test (ST) devices were used. The shaking table at Nagoya University(NU) was used for studying the response of models slopes for unbreakable material and the shaking table at University of the Ryukyus(UR) was used to study the response of models slopes with breakable material. Main features of the shaking table apparatusses are given

Table 1. Specifications of shaking tables

Parameters	NU Shaking Table	UR Shaking Table
Vibration Direction	Uni-axial	Uni-axial
Operation Method	Electro-oil servo	Magnetic
Table size	1300x1300	1000x1000
Load	30 kN	6 kN
Stroke	150 mm	100 mm
Amplitude	5G	0.6G
Wave Form	Harmonic, triangular, rectangular, random	Harmonic, triangular, rectangular, random



(a) NU-Shaking table (b) UR-Shaking Table

Figure 2. Illustration of shaking tables and intsrumentation.

in Table 1. Fig. 2 shows a sketches of the devices together with the model mounted upon and instrumentations. Slope models were two-dimensional and were mounted upon the table through metal frames. The metal frame at NU-ST was 1200 mm long and 800 mm high while it was 1000 mm long and 750 mm high at UR-ST. The frame width was 100 mm wide at two shaking table experiments. Acceleration responses of the slope at several locations and input waves were measured using the accelerometers.

2.2 *Model materials*

2.2.1 *Non-breakable materials*

Blocks with dimensions of 10 × 10 × 100 mm and 10 × 20 × 100 mm were made of wood and used to simulate the discontinuity sets in rock masses.

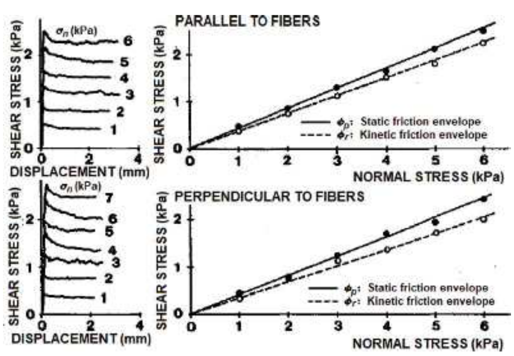


Figure 3. Shear tests on interfaces between wood blocks.

Direct shear tests were carried out on discontinuities between wood blocks and results together with shear strength envelopes are shown in Fig. 3.

2.2.2 *Breakable materials*

Breakable blocks are made of $BaSO_4$, ZnO and Vaseline oil, which is commonly used in base friction experiments (Aydan and Kawamoto, 1992). Properties of materials of blocks and layers are described in detail by Aydan and Amini (2009) and Egger (1983). Fig. 4 shows the variation of the strength of the model material with respect to compaction pressure. The material can be powderized and re-used after each experiment. The friction angle of interfaces between blocks are tested and shown in Fig. 5.

2.3 *Testing procedure*

The metal frames have some special attachments to generate different discontinuity patterns. The models were subjected to some selected forms of acceleration waves through a shaking table. The acceleration responses of model slopes were

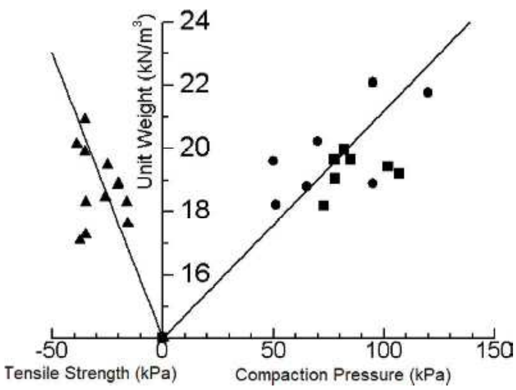


Figure 4. Variation of tensile strength of model material.

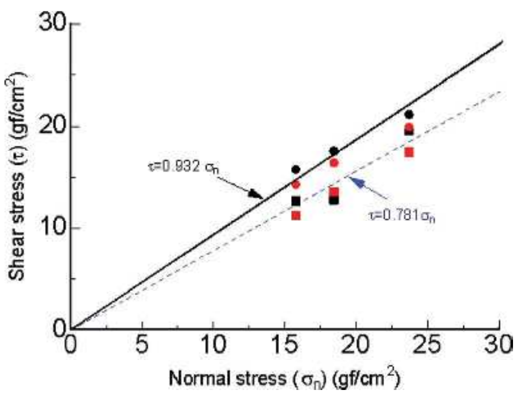


Figure 5. Shear tests on interfaces between breakable blocks.

measured using accelerometers installed at various points in the slope.

2.3.1 *Non-breakable blocks*
Model slopes were prepared by arranging wood blocks in various patterns to generate discontinuity sets with different orientations in space. Slope angles were 45, 63 and 90 degrees and the height and base width of model slopes were 800 mm and 1200 mm respectively. The intermittency angle ξ of cross joints were 0 and 45 degrees (Aydan et al. 1989) and one discontinuity set was always continuous as such sets in actual rock masses always do exist.

The inclination of the thoroughgoing (continuous) set was varied from 0 to 180 degrees by 15 degrees. At some inclinations, model slopes were statically unstable and at such inclinations no tests were done. Besides varying the inclination of the continuous set, the following cases were investigated:

CASE 1: Frequency was varied from 2.5 Hz to 50 Hz while the amplitude of the acceleration is kept at 50 or 100 gal.

CASE 2: The amplitude of the acceleration waves was varied until the failure of the slope occured, while keeping the frequency of the wave at 2.5 Hz.

2.3.2 *Breakable blocks*
The inclination of thoroughgoing discontinuity set was selected as 0, 45, 60, 90, 120, 135 and 180 degrees. Before forcing the models to failure in each test, vibration responses of some observation points in the slope were measured with the purpose of investigating the natural frequency of slopes and amplification through sweep tests with a frequency range between 3-40 Hz. Also, deflection of the slope surface was monitored by laser displacement transducers and acoustic emission sensors.

3 DYNAMIC RESPONSE AND STABILITY OF MODEL SLOPES

Various parameters such as the effect of the frequency and the amplitude of input acceleration waves are investigated in relation to discontinuity patterns and their inclinations and the slope geometry for the model slopes with non-breakable and breakable models. The model slopes were finaly forced to fail by increasing the amplitude of input acceleration waves and the forms of instability were investigated.

3.1 *Natural frequency of model slopes*

3.1.1 *Model slopes with non-breakable blocks*
Fig. 6 shows the amplification of waves measured at selected points in relation to the variation of input wave frequency The inclination of the throughgoing set for both discontinuity patterns

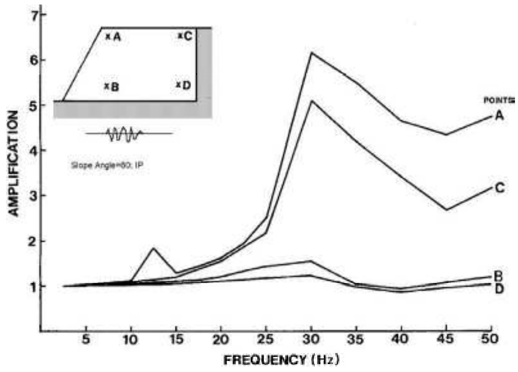


Figure 6. Variation of amplification with respect to frequency of model slopes and measurement locations.

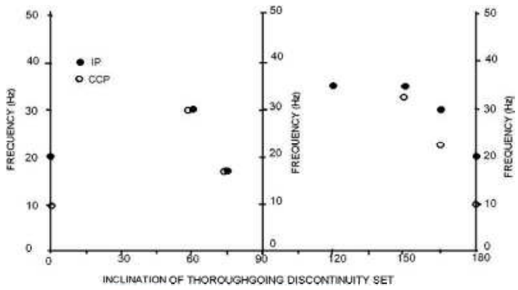


Figure 7. Variation of natural frequency of model slopes with respect to the inclination of thoroughgoing discontinuity set.

was 75 degrees.. The letter on each curve indicates the selected points within the model slopes. It is noted that if the natural frequency of the slopes exist, it varies with the spatial distributions of the sets and the structure of the mass.

In the followings, the frequency responses are discussed and compared for each respective inclination of the throughgoing discontinuity set for the point A (see Fig.6 for location) as shown in Fig. 7. The slope angle was 63 degrees in the sweep tests shown in Fig. 7. The results for each discontinuity set pattern are indicated in the figure for intermittent pattern as IP and for cross-continuous pattern as CCP.

Inclination 0: The natural frequency of the slope is 10 Hz for cross-continuous pattern and 20 Hz for intermittent pattern, respectively. Therefore, the natural frequencies of the slopes for intermittent pattern and cross-continuous pattern are different even the slope geometry and intact material are same. This may be related to the resulting slender columnar structure of the mass in the case of cross-continuous pattern.

Inclinations 15, 30, 45: The slopes for these inclination of the througoing set could not be tested as they were statically unstable for the slope angle of 60 degrees.

Inclination 60: From the figure, the natural frequencies for both patterns coincide and they have a value of 30 Hz. This may be attributed to the similarity of the structure of the mass for this inclination of the throughgoing discontinuity set.

Inclination 75: Natural frequences of the slopes for both patterns are almost same and it appears to have a value of 17.5 Hz. Similar reasoning as in the case of inclination of 60 can be stated for this case.

Inclination 90: No tests for this inclination could be made.

Inclination 120: Slopes having intermittent pattern were only tested as slopes having cross-continuous pattern could not be tested as they were statically unstable. For this inclination of the throughgoing set, the natural frequency of the slope has a value of 35 Hz.

Inclination 150: Natural frequencies of the slopes for both patterns are almost the same and it has a value of 35 Hz.

Inclination 165: The natural frequency of the slope is 22.5 Hz Hz for cross-continuous pattern and 30 Hz for intermittent pattern, respectively. In addition, the natural frequencies of the slopes for intermittent and cross-continuous pattern are different.

3.1.2 *Model slopes with breakable blocks*

Fundamentally, the vibration response of model slopes are quite similar to those of model slopes made with unbreakable blocks. Fig. 8(a) shows the input and measured wave forms at selected two points on the slope. The amplification of the vibration response is highest at the slope crest and the

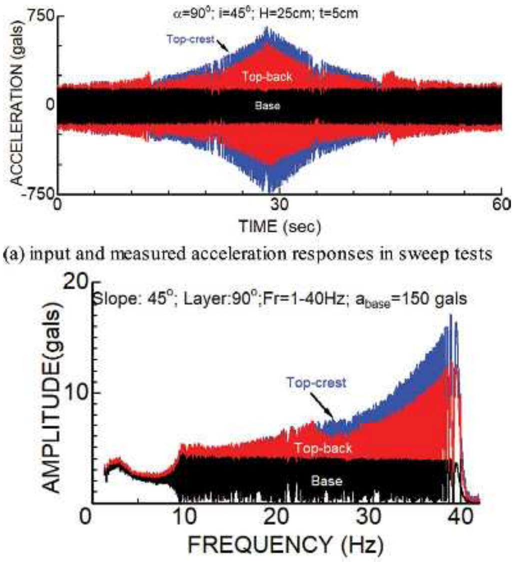


Figure 8. Acceleration responses of selected points on model slopes made with breakable blocks.

ampification at the top-back (ACC-TB) are a bit smaller than that at the slope crest as seen in Figure 8(b). From this figure, we can clearly state that amplification of the acceleration waves increases towards the slope (free) surfaces. In addition to this, the amplifications are larger at the top and have the maximum value at the crest of the slope (ACC-TC) as it was also noted in Figs. 6 and 7 for model slopes made with non-breakable blocks.

3.2 *Stability of model slopes: Failure tests*

When rock slopes are subjected to shaking, passive failure modes occur in addition to active modes (Aydan et al. 2009a,b, 2011; Aydan and Amini, 2009). Figs. 9 and 10 show examples of failures of some model slopes consisting of non-breakable and breakable blocks and/or layers. The experiments also show that flexural toppling failure of passive type occur when layers (60° or more) dip into valleyside.

The records of base acceleration and deflection of slope surface of the model are shown in Fig. 11 for a layer inclination of 90 degrees as an example. The acoustic emissions are also shown in the figure. Acoustic emissions starts to increase long before the displacement start to increase. This observation may also have an important implications for the monitoring of rock slopes. These responses were observed

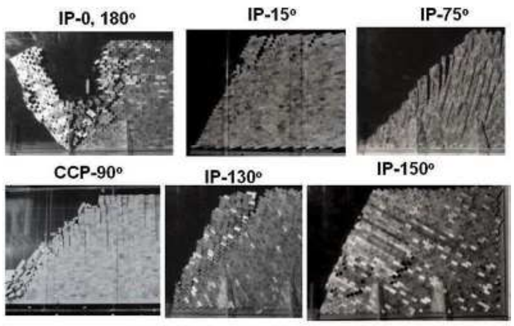


Figure 9. Failure modes of rock slope models with non-breakable material.

Figure 10. Failure modes of rock slope models with breakable material.

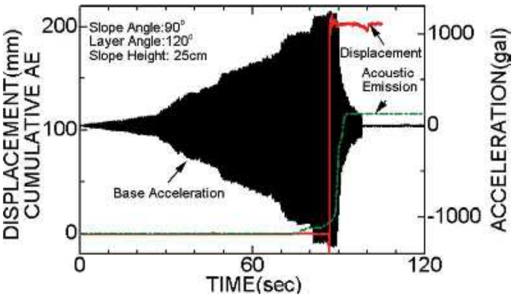


Figure 11. Acceleration, displacement and acoustic emission responses of a model slope.

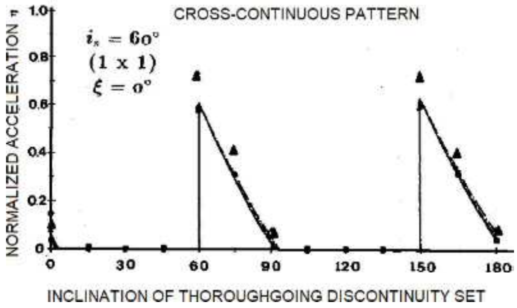


Figure 12. Comparison of theoretical estimations with experimental results (cross-continuous pattern).

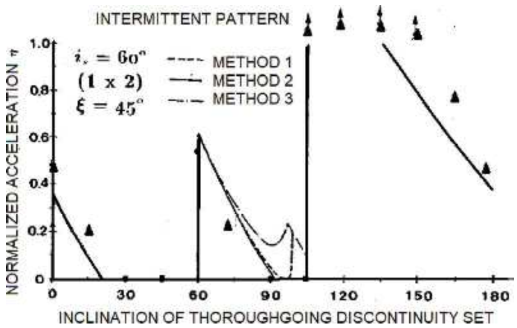


Figure 13. Comparison of theoretical estimations with experimental results (intermittent pattern).

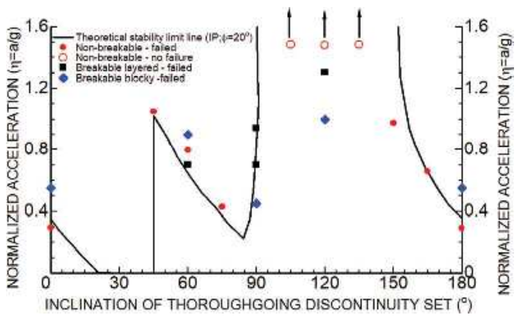


Figure 14. Comparison of theoretical estimations with experimental results (breakable layers and blocks).

in experiments on layered and blocky model slopes made with breakable blocks.

4 FAILURE MODES OF MODEL SLOPES

4.1 *Failure mode observations*

When the blocks of the mass are strong, failure modes involve only discontinuity sets (Aydan, 1989, 2015; Aydan et al. 1989, 1990). When failures involving only discontinuity sets, they are:

1. Sliding failure,
2. block toppling failure,
3. Combined toppling and sliding failure, and
4. Block buckling failure.

However, if the model slopes were made with breakable layers or blocks, flexural toppling or flexural block toppling failure are observed (Aydan and Kawamoto, 1992; Aydan et al. 2011; Aydan and Amini, 2009). All of the above failure forms were observed in our tests as seen in Figs. 9 and 10. These tests also showed that the above failure forms can also be subdivided into active and passive modes according to the vertical component of the displacement vectors with respect to that of the gravity.

4.2 *Analysis*

The authors developed a method of analysis for the stability of slopes under dynamic loadings using the limiting equilibrium concept. As the details of this method were described elsewhere (Aydan et al. 1989, 1991; Shimizu et al. 1986, 1988; Aydan and Kawamoto, 1992). Altough the method is not described herein, we compare the estimations by the method with the results of the tests. Figs. 12 and 13 show a comparison of the estimations by the method with the tests results for the slopes with an inclination of 60 degrees for both patterns. We note that predictions by the method are quite similar to the experimental results. However, the experimental results are above the predicted stable-unstable transition curves. This discrepancy is due to non-consideration of the amplification due to frequency content of the acceleration waves in the method as well as the inertial effects.

As explained in previous sections, model slopes are tested using breakable layers or blocks. The experimental results are plotted together with theoretical line computed for the stability of slopes having intermittent pattern and non-breakable material, which was published in a previous work by Shimizu et al. (1986). The theoretical line was computed for a slope with an inclination of 45 degrees and discontinuities to have a friction angle of 20 degrees. The stability line should act as a guideline for both layered and blocky rock mass with intermittent pattern for the upper limit of seismic resistance of the rock slopes. In other words, if the material constituting the slope fails, the slope will fail at lower acceleration levels. In accordance with this statement, the seismic resistance of the model slopes with breakable layers or blocks was either equal to theoretical lines or less than that. It should be noted that the friction angle for breakable material is much higher than the friction angle assumed in computations. Therefore, the resistance for sliding behaviour is expected to be higher than the theoretical line shown in Figure 14.

The model slopes indicated that flexural toppling or blocky toppling failure did occur. To analyse such failures, the methods proposed by Aydan and Kawamoto (1992) and Aydan et al. (1989) could be usefull. Aydan and Kawamoto (1992) have already proposed a method for analyzing the flexural toppling failure under dynamic loading condition and it can be easily used for active as well as passive mode of flexural toppling failure. Therefore, the available methods based on the bending theory of cantilever methods (i.e. Aydan and Kawamoto 1992; Amini et al. 2008) may be used for analyzing the experimental results in this study. Nevertheless, the most critical issue with these methods is how to designate the inclination of failure plane, above which layers are subjected to bending. Aydan and Kawamoto (1992) suggested the failure plane should be equal to the normal to layers for active flexural toppling failure and it was confirmed by experiments. The experiments presented in this study showed that inclination of the failure plane ranges between 0 and 15 degree above normal to discontinuities for active flexural toppling failure under dynamic condition. However, the inclination of the failure plane should be chosen through a minimization technique for the passive flexural toppling failure of rock slopes under dynamic condition.

5 CONCLUSIONS

The main objectives of the study were to investigate the dynamic response of the slopes and likely forms of instability of the slopes in relation to the number and orientation of discontinuity sets with respect to the slope geometry under various kinds of acceleration waves. In this particular study, some emphasis was put upon the effect of breakage of the layers/blocks used in creating model slopes.

The dynamic response of the model slopes were measured using accelerometers installed at various points in the slope. In the tests, various parameters such as the effect of the frequency and the amplitude of input acceleration waves are investigated in relation to discontinuity sets patterns and their inclinations and the slope geometry. Finally, the model slopes were forced to fail by increasing the magnitude of the input acceleration waves and their form of instability were investigated.

Test results show that slopes in discontinuous rock mass have a natural frequency, that depends largely upon the inclination of discontinuity sets rather than the properties of rock material. The failure modes slopes involving only discontinuities are:

1. sliding,
2. toppling and
3. combined sliding and toppling

However, each failure mode could be further subdivided to active mode and passive modes.

When layers or blocks constituting the model slopes are breakable under the induced stress state, some additional conclusions are as follow:

- If dip direction of layers discontinuities is approximately the same as that of the slope, the rock mass had a potential to fail in passive flexural toppling failure under dynamic condition.
- Flexural toppling failure under dynamic condition can also be classified into two modes: active and passive.
- As shown by Aydan and Amini (2009), experiments indicated that the required seismic coefficient is much higher for single column subjected to passive toppling as compared with that of columns subjected to active toppling.
- The experiments on model rock slopes also indicated that the required seismic coefficient is much higher for slopes subjected to passive toppling as compared with that of slopes subjected to active toppling.

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