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Technical Note

Application of the Distinct Element Method for Analysis of Toppling Observed on a Fissured Rock Slope

By

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1. Introduction

It is often difficult to examine the stability of fissured rock slopes. The Distinct Element Method (DEM) (Cundall, 1971, 1974) is one of the most suitable analytical methods for examining the stability of fissured rock slopes which are separated into many blocks with open joints. Although Cundall et al. (1975), Hocking (1978) and Voegele (1978) suggested with the results of their numerical analyses that DEM can be applied to the analysis of toppling of fissured rock slopes, the application of DEM to an actual case has not yet been reported. In this note, the authors describe observed toppling of a fissured rock slope and compare this to the results of DEM analysis on the phenomenon.

2. Geological Investigation

Toppling has been known for a long time and has been discussed by Talobre (1957), Ashby (1971) and other researchers. Now toppling is widely recognized as a type of slope movement (Varnes, 1978). De Freitas and Watters (1973) surveyed the structures formed by toppling at three sites in the British Isles and concluded that toppling is not unusual, can develop in a variety of rock types, and can encompass volumes from 10^2 m^3 to 10^9 m^3.

The authors found structures formed by toppling along a road constructed on a mountainside in Cretaceous rhyolitic welded tuff, about 10 km to the west of Mt. Ontake in the central part of Japan (Fig. 1). The welded tuff is highly jointed, and the joint attitudes were surveyed at the seven locations I to VII shown in Fig. 1. Orientation of joints longer than

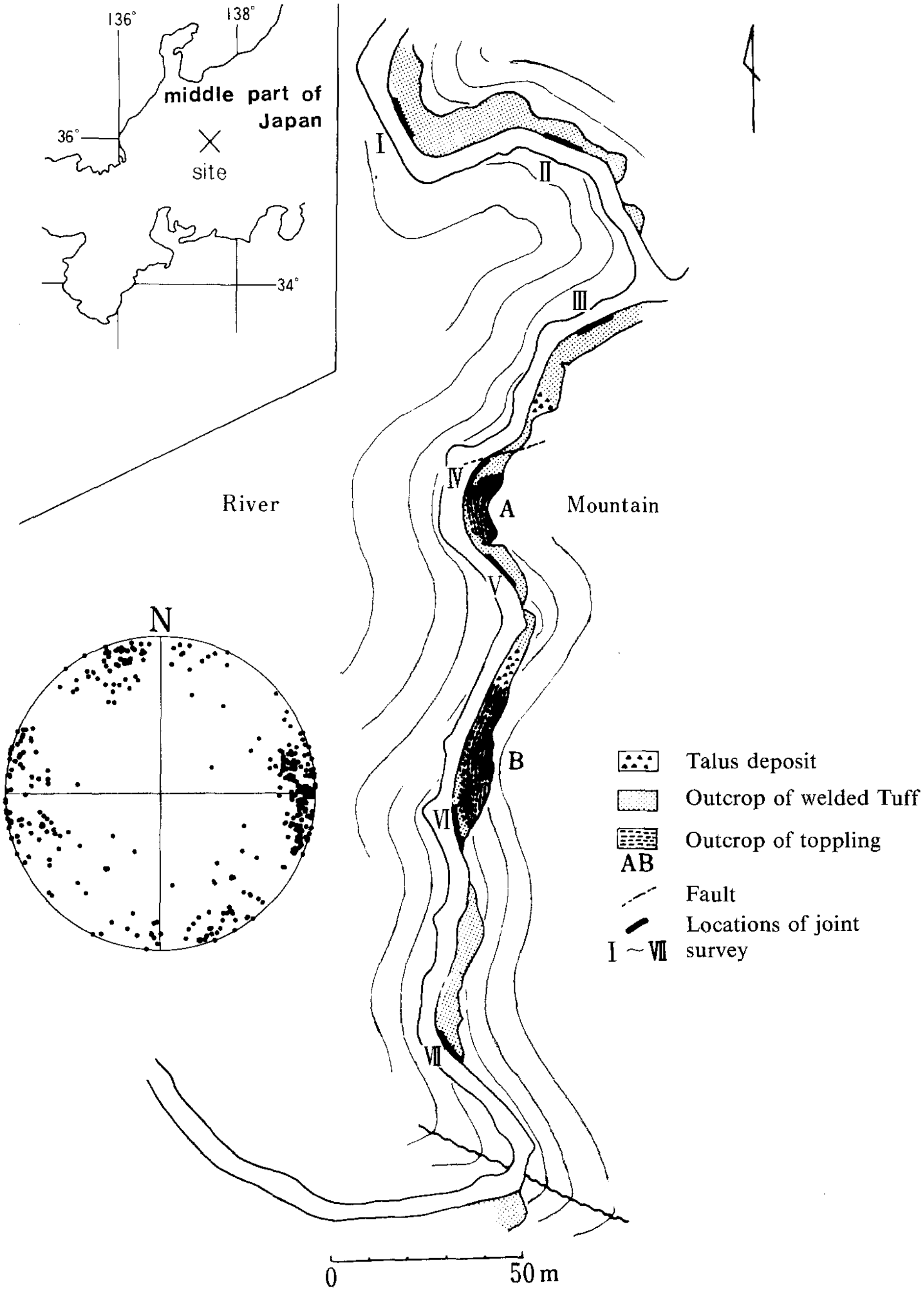

Fig. 1. Route map of the surveyed area, and the lower hemisphere of a Schmidt's net on which all poles of joints surveyed at the locations I to VII are projected

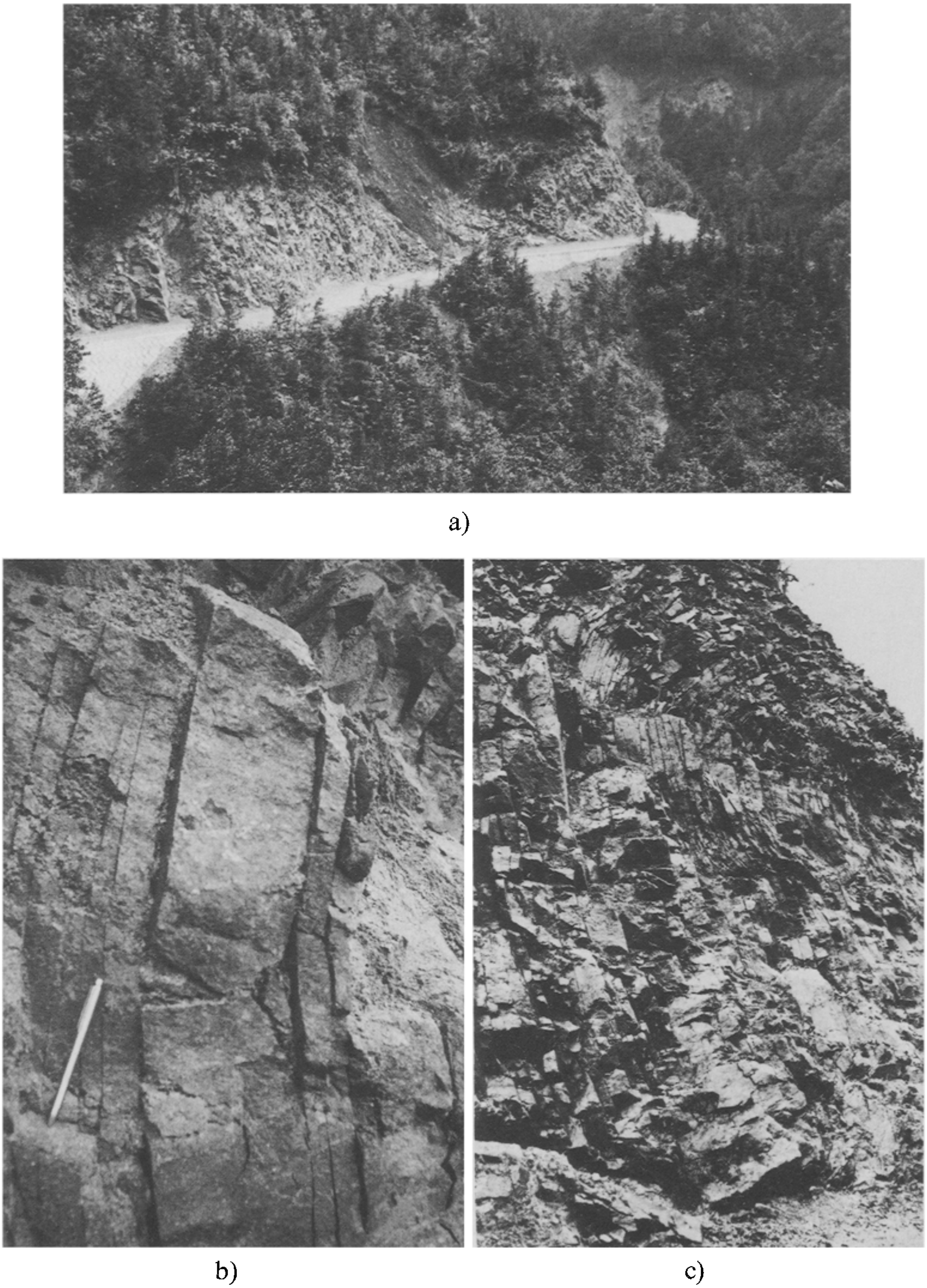

Fig. 2. Photographs of outcrop *A*.
(a) Distant view of outcrop *A* as seen from the north; (b) Failure of rock plates on a bending surface; (c) Close-up photograph of outcrop *A*, which shows the change of the structure from the base rock region through the weakly toppling region to the toppling region

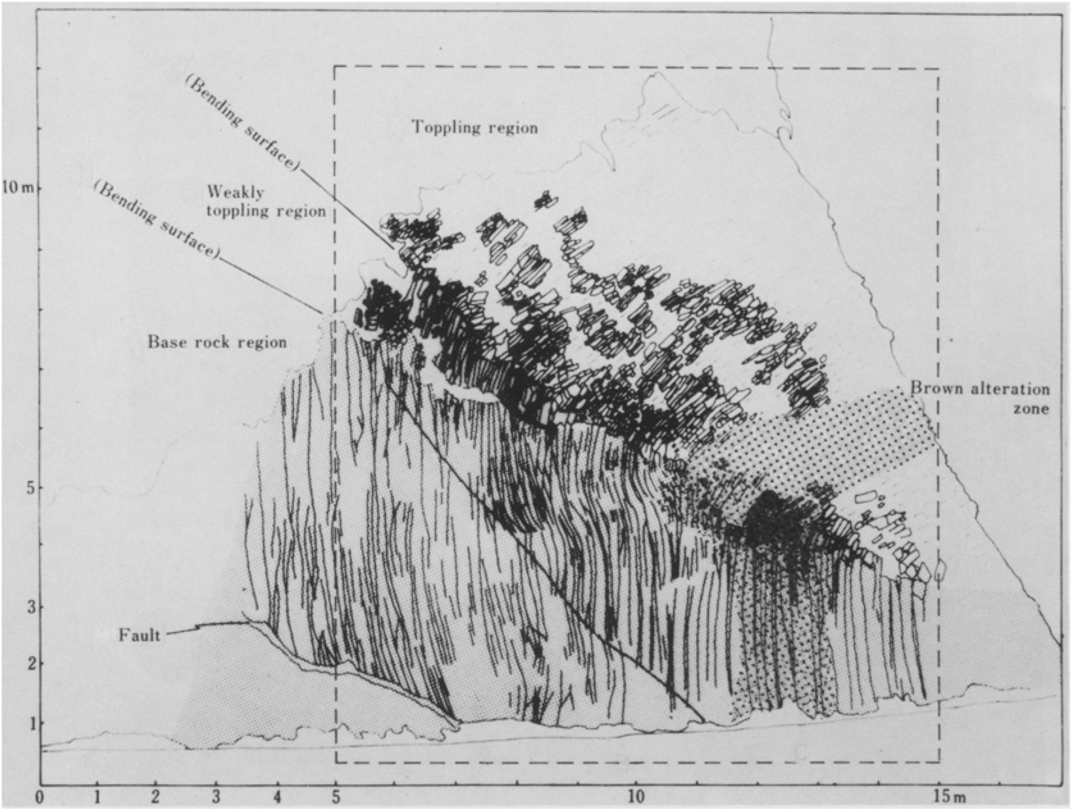

Fig. 3. Sketch of the east and west section of outcrop *A*. The area surrounded with a broken line is modelled in the DEM analysis

50 cm crossing a scan line 1 m above the road surface was measured. All poles of the measured joints are projected on a Schmidt's net shown in Fig. 1. The Schmidt's net of Fig. 1 shows that the welded tuff has two dominant joint sets: one trends north to south, and the other trends east-north-east to west-south-west. Both are dipping steeply from 60° to 90°, and the former joint set is more dominant than the latter.

The structures formed by toppling were found at the two outcrops *A* and *B* (Fig. 1) which have about the same structure. The structure of outcrop *A* can be observed more clearly than that of outcrop *B*, because the observed section of outcrop *A* trends east to west and is almost normal to the most dominant joint set trending north to south. Therefore, the structure of outcrop *A*, shown in the photographs in Fig. 2 and in the sketch in Fig. 3, is discussed in the following.

From Fig. 3, it is seen that the structure formed by toppling at outcrop *A* has the following features:

(1) Base rock region: In the lower part of the outcrop, we can find the base rock mass undisturbed but separated into plates from about 5 cm to

30 cm thick, almost vertical and with no open joints. About 80 % of the joints in this region trend north to south.

(2) Toppling region: In the upper part of the outcrop the rock mass is separated into plate rock segments by many open joints. The rock mass of this region has toppled downslope, and the originally vertical joints in the rock mass are inclined at angles of 40°—60° from the vertical.

(3) Weakly toppling region: Between the base rock region and the toppling region the rock mass has mostly closed joints. The rock mass of this region has toppled weakly downslope and the originally vertical joints are inclined at angles of 20°—30° from the vertical. (Fig. 2 (c) shows the change of the structure from the base rock region through the weakly toppling region to the toppling region.)

(4) Bending surfaces: There are two surfaces along which the rock plates are broken into plate segments and are bent downslope. One of the surfaces is situated between the base rock region and the weakly toppling region, and the other one is situated between the weakly toppling region and the toppling region. These surfaces are undulated and irregular, but they are nearly planar as a whole, inclined at an angle of about 25°. The two bending surfaces join and become one surface in the middle part and at the downward end of the outcrop. (Fig. 2 (b) shows the failure of rock plates on a bending surface.)

(5) Other geological features: In the lower part of the base rock region, there is a fault, 20 cm thick, with a gouge. Just above the toe of the outcrop, a brown alteration zone, 2 m thick, is found within the base rock region and the toppling region. However, neither the fault nor the alteration zone affect toppling in the outcrop.

The structure of outcrop *A* seems to have been formed near the free surface only due to toppling caused by gravity, and not by tectonic effects. This is so because only the upper (near surface) part of the slope is disturbed and inclined toward the valley. Also in the other neighbouring outcrops, similar structures formed by toppling are found near the free surface only, not in the base rock mass.

3. Distinct Element Method (DEM) Analysis

In DEM analysis, a fissured rock mass is treated as a rigid block assemblage, and the behaviour of the individual rigid blocks is under the control of Newton's second law. The solutions to the equations of motion are obtained through iterations over successive time steps. The DEM used in the following analysis is fundamentally the same as that of Cundall (1971, 1974).

Fig. 4 shows the DEM analysis results of the case shown in Fig. 3; (a), (b), (c) and (d) are the results at iteration numbers, 25, 3765, 5520 and 7530, respectively. Since the purpose of this DEM analysis is to know roughly the tendency of failure progress at outcrop A, only the area surrounded with a broken line in Fig. 3 is modelled. The spacing between joints in the

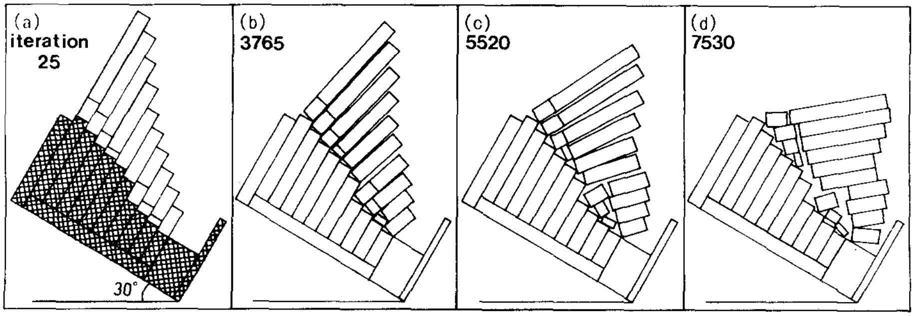

Fig. 4. DEM analysis results of the case shown in Fig. 3. The area surrounded with a broken line in Fig. 3 is modeled. The force used in the DEM analysis is assumed to be only the weight of the block elements themselves. The block elements shaded in Fig. 4 (a) are assumed to be fixed in the calculation. Figs. 4 (a), (b), (c) and (d) show the results at iteration numbers, 25, 3765, 5520 and 7530, respectively

model is assumed to be 1 m although they range from about 5 cm to 30 cm in the outcrop. The model is made up of ten rock plates of 1 m thickness set vertically; the ten rock plates in turn are divided into twenty-seven rigid blocks with stepped horizontal planes which represent the bending surfaces of the outcrop. The block elements shaded in Fig. 4 (a) are assumed to be fixed in the DEM calculation. In order to make the analysis simple, the force used in the DEM analysis is assumed to be only the weight of the block elements themselves, although, in the actual case, the force exerted from the neighbouring region above the toppling region probably also helps to topple the rock plates. To ensure that only the weight of the block elements can cause toppling, the base plane of the model is inclined at an angle of 30°.

Fig. 5 is obtained by rotating the base plane of Fig. 4 (d) horizontally. The comparison between Fig. 5 and Fig. 3 shows that toppling found in the results of the DEM analysis is consistent with the phenomena observed in the outcrop.

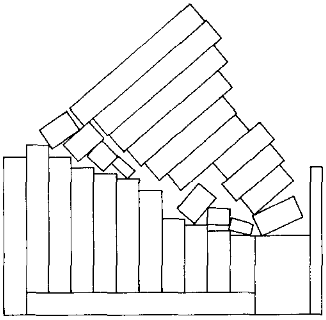

Fig. 5. Figure which is obtained by rotating the base plane of Fig. 4 (d) horizontally. The comparison between this figure and Fig. 3 shows that toppling found in the results of the DEM analysis is consistent with the phenomena observed in the outcrop

4. Discussion and Conclusions

In this note, a geological investigation of toppling observed on a fissured rock slope and the results of a DEM analysis on the phenomenon have been compared. Although real toppling of the slope probably takes a long time, the DEM analysis leads to similar results, and provides information on the geological process involved in the toppling.

Thus, we conclude that the DEM is a very helpful numerical method for examining the stability of a fissured rock slope, in particular one which is separated by many open joints and which may be regarded as a rigid block assemblage. In order to further develop the application of the DEM, additional engineering and geological efforts to compose a good DEM model from observations on outcrops are needed. Moreover, the engineers' subjective and intelligent interpretations of the results of the DEM analysis will always play an important role.

Acknowledgement

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