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Toppling Rock Slope Failures Examples of Analysis and Stabilization

By

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With 6 Figures

(Received February 22, 1980)

Summary — Zusammenfassung — Résumé

Toppling Rock Slope Failures — Examples of Analysis and Stabilization. Three case histories of toppling failures of rock slopes, and the methods used to ensure that failure did not disrupt operations below the slope, are described. The application of Goodman and Bray's limit equilibrium analysis of multi-block failures to these three slopes is demonstrated.

The first failure occurred in a 20 m high granite slope that was stabilized by removing the top 6 m and installing a number of tensioned rock anchors in the toe. The second failure occurred in a sequence of folded sandstone, shale and coal. This slide was too large to stabilize, so the movement rate was monitored while mining continued in the pit below until shortly before failure took place. In the third failure, the top 8 m of a single 12 m high toppling block was removed by blasting to prevent further rotational movement.

Kippvorgänge beim Bruch von Felsböschungen — Beispiele für die Berechnung und Stabilisierung. Es werden drei Fallstudien von Brüchen von Felsböschungen durch Kippen und die dabei angewendeten Sicherungsmethoden beschrieben. Die Anwendung der Grenzgleichgewichtsbetrachtung von Massenbewegungen, die durch Kippvorgänge ausgelöst wurden, nach Goodman and Bray, auf drei Felshänge wird gezeigt.

Der erste Bruch ereignete sich in einer 20 m hohen Böschung in Granit. Die Stabilisierung bestand in der Entfernung der obersten 6 m und der Einbringung von einigen Vorspannankern. Der zweite Bruch ereignete sich in einer Serie von gefalteten Sandsteinen, Schiefern und Kohlen. Da die Größe dieser Rutschung eine Stabilisierung unmöglich machte, wurden die Bewegungen genau registriert und der Abbau bis kurz vor dem eigentlichen Bruch fortgesetzt. Das dritte Beispiel ist ein einzelner 12 m hoher, kippender Block, dessen oberste 8 m weggesprengt wurde, um ein weiteres Kippen zu verhindern.

Défauts par chute de rampes rocheuses — Exemples des analyses et de stabilisation. Ce résumé décrit trois événements de rupture de pentes rocheuses et les méthodes de stabilisation utilisées. Dans ces trois cas l'auteur montre l'utilisation de l'analyse de la limite d'équilibre des masses rocheuses pour un mouvement de basculement selon Goodman et Bray.

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Le premier cas a eu lieu sur une rampe granitique de 20 m hauteur, laquelle a été stabilisée en 6 m de roche au sommet et en possant quelque d'ancrage au pied de la pente. La deuxième défaut s'a produit avec une séquence de roches de formation gréseuse, d'argile schisteuse et du charbon. Cette glissement a été trop grande pour être stabilisée, donc la raison de mouvement a été controlée au même temps qu'on travaillait dans le puit au dessous quelque temps avant que le défaut se produisse. Dans le troisième défaut les 8 m de sommet d'un seul bloc rocheux ont été dépilés par des méthodes explosifs pour prévenir ultérieur mouvements rotatives.

Introduction

Toppling failures can occur in slopes cut in rock with regularly spaced fractures which strike parallel to the slope, and dip into the face. This contrasts with sliding failures which occur when the geological structure dips out of the face [8]. Although the stability of toppling failures can be studied using numerical models [3, 4, 5] and physical models [1, 10], these analyses can be time consuming and the required facilities may not be readily available. However, Goodman and Bray's [6] limit equilibrium analysis for multi-block failures now permits the analysis of toppling failures, and the selection of appropriate stabilization measures, to be carried out more readily.

This paper describes three toppling failures and shows the stabilization measures which were applied in two cases. In the third case, movement was monitored with electronic distance measuring equipment while operations continued at the toe of the slide. The application of Goodman and Bray's analytical solution to these three examples is demonstrated, and the limitation of the technique in the design of slopes with a geological structure that could cause toppling, is discussed.

Mechanism of Toppling Failures

Toppling movement occurs in slopes where a regularly spaced set of joints or bedding planes strike parallel, or nearly parallel, to the slope face and dip at a steep angle into the face. This geological structure forms a series of tall, narrow slabs (Fig. 1). If the dimensions of a slab are such that its centre of gravity acts outside the base of the slab, then there is a potential for the slab to topple. This criteria is given by the relationship [6]:

$$y/\Delta x > \cot \alpha \text{ — toppling occurs,} \tag{1}$$

where: y = slab height,
Δx = slab width,
α = dip angle of base of slab.

Short slabs at the crest not meeting the criteria shown in Eq. (1), and that do not slide on the base, are stable (Fig. 1, slabs 6, 7), but longer slabs which topple (slabs 3, 4, 5) exert a thrust on the slab immediately below it on the slope. This thrust procedures a moment on the lower block which increases its tendency to topple, i. e. a "domino effect". However, it is constrained from toppling by the force transmitted upwards from the block below, and from the shear forces acting on its sides. As this motion progresses down the slope, the magnitude of the thrust from the upper slabs may be sufficient, near the toe, to cause short slabs, that do not meet the criteria shown in Eq. 1, to topple. However, where the thrust from the slabs

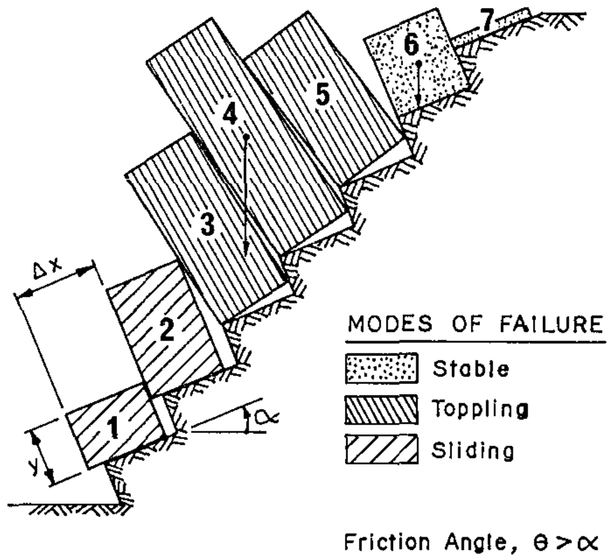

Fig. 1. Model for limit equilibrium analysis of toppling failure

above is sufficiently large that the ratio of the shear to normal forces on the base of the slab exceeds the friction angle of the base, then the slab will slide rather than topple (Fig. 1, slabs 1 and 2). Since the magnitude of the thrust is dependent upon the friction properties of the surfaces of the slabs as well as their dimensions, stability is governed both by the geometry of the slope and the rock properties. The analytical procedure is to define the dimensions of the slope, the geological structure, the rock properties, and the angle of the failure plane. The toppling and sliding characteristics of each slab are then examined in turn starting at the crest.

This mechanism has been clearly identified in a number of actual failures. It is also found that as movement continues, face-to-edge contact between slabs is converted to face-to-face contact and the friction coefficient required to prevent movement is sharply reduced. This may account for the progressive decrease in the measured rate of movement in the second example described in this paper. The mechanism assumes, of course, that the slope consists of discrete slabs which are free to rotate about the base. However, there will be cases where the slabs will tend to bend so that rotation will be restricted to some degree and the height of the columns will be difficult to determine precisely.

Examples of Toppling Failures

The following is a description of three toppling failures, and of the measures that were taken to ensure that failure did not disrupt operations beneath the slope.

Case Study 1: Toppling Failure in Jointed Granite

This failure occurred in a vertical, 20 m high slope in very strong granite above a railroad in Southwestern British Columbia. The rock contains three well defined joint sets which form an approximately orthogonal system of fractures (Fig. 2). The joint set striking perpendicular to the track and dipping at about 70 degrees to the south, formed a series of slabs, approximately 2.5 m thick, that toppled in a direction parallel to the track. The direction of movement was revealed by a 20 cm wide tension crack on

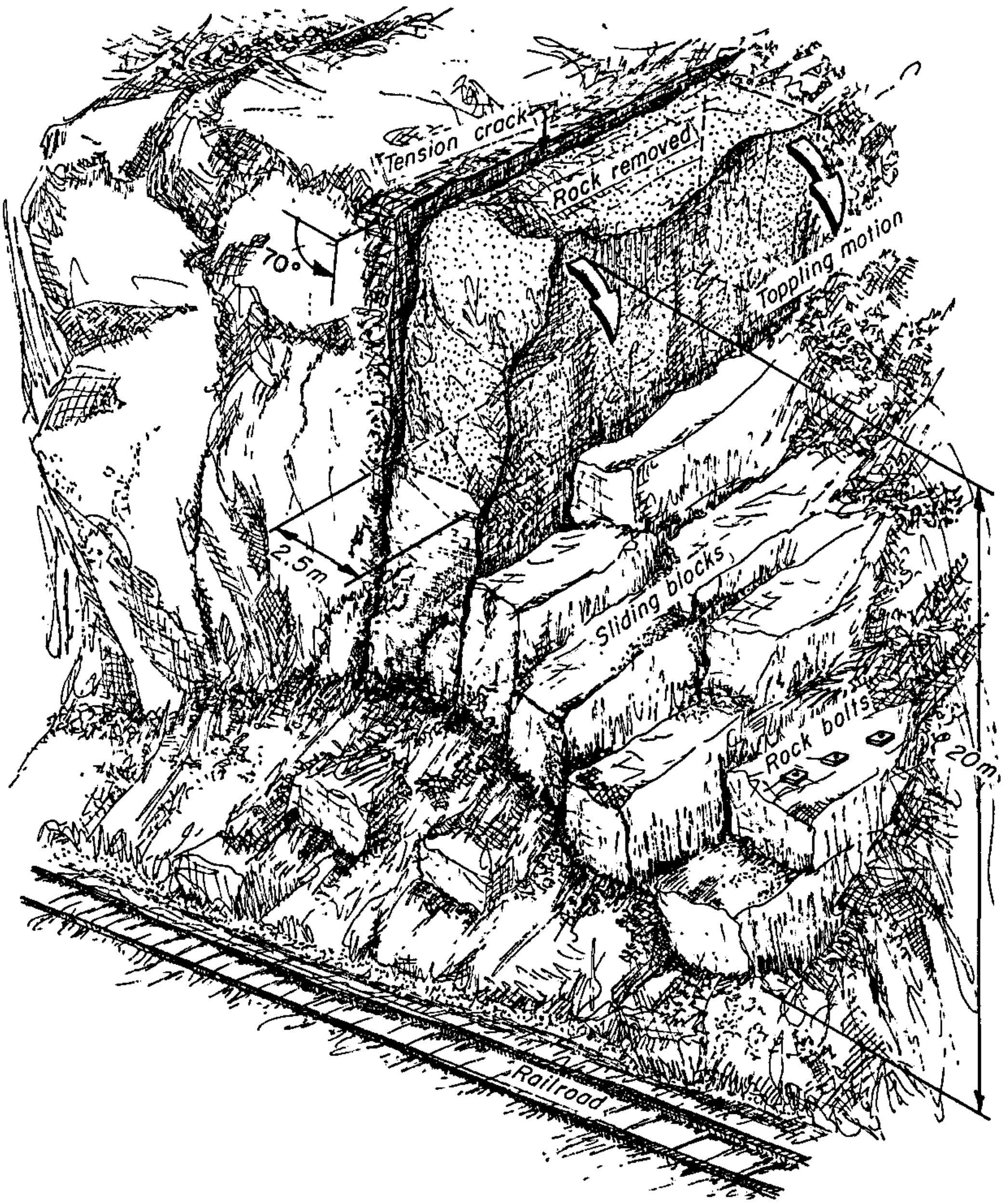

Fig. 2. Toppling failure in granite

the crest running at right angles to the main face. This rotational movement was sufficient to break intact rock on the vertical face, and to cause 2 m thick blocks at the toe of the slope to slide. The broken blocks on the face, which had volumes up to 3 m^3, were susceptible to failure during spring thaws and were a hazard to railroad traffic below.

The stabilization measure consisted of controlled blasting [2, 8] to remove the top 6 m of the toppling failure. Analysis showed that this would shorten the toppling columns sufficiently to prevent further rotational movement. Consequently, the thrust on the blocks at the toe would also be eliminated. As a further precaution, a number of tensioned rock anchors were installed in a block at the toe that had already moved about 15 cm, and which was partially supporting several blocks above it on the slope.

Case Study 2: Toppling Failure in Sandstone

This failure occurred at an open pit coal mine on the eastern foothills of the Rocky Mountains. The coal occurs in an interbedded sequence of shales, sandstones and coal which have undergone intense folding into a series of synclines and anticlines. On the south limb of an asymmetrical

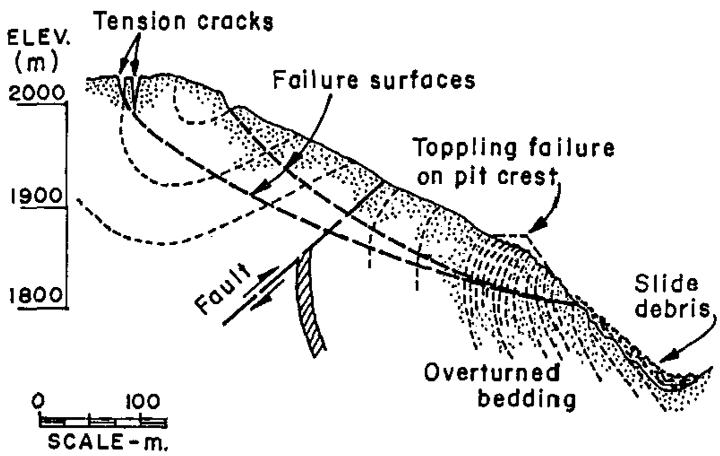

Fig. 3. Failure above open pit coal mine

syncline, the beds were overturned and dipped at about 70 degrees into the slope on the crest of the pit (Fig. 3). Since the bedding spacing was about 2 m to 3 m, the beds formed tall narrow slabs that underwent a toppling movement. This movement reduced support at the toe of the slope above so that eventually this upper slope started to move.

When the pit was 10 m deep after 7 months of mining, cracks were observed on the crest. By the time the pit was 20 m deep there were about six cracks on the crest, each 10 cm wide and 100 m long, which had opened as the overturned beds toppled towards the pit. Since the planned pit depth was 150 m, it was essential that some measure be undertaken to prevent the failure from disrupting operations in the pit.

It was decided that unloading the crest of the pit was not feasible because access for equipment was difficult, and the excavation would have undermined the toe of the slope above. Another alternative, the installation of tensioned rock anchors to stabilize the slide, would have taken too long to install, and would probably not have been economic because a large number of bolts would have been required in the highly broken rock. It was decided, therefore, to monitor movement of the crest of the pit to identify acceleration that would indicate deteriorating stability conditions [11]. If acceleration did occur, the pit would be cleared until either the movement slowed to a safe level, or a failure took place. If a failure did occur, the monitoring system would be re-established and the fallen rock removed when the movement rate showed that it was no longer hazardous to work in the pit.

The monitoring system consisted of tensioned wire extensometers across the tension cracks and reflector prism survey stations on the crest. The movement of the stations was monitored by measuring their distance from two stations on the other side of the pit with electronic distance measuring equipment. The vertical angle to each station was also measured. The surveying showed that the crest was moving almost horizontally, which is indicative of toppling movement. In sliding failures, the direction of movement tends to be parallel to the plane on which it is sliding. In the later stages of failure, considerable vertical movement occurred indicating that the toe had started to give way.

The failure can be divided into two phases. In the first phase, when the pit was 20 m deep and shovels were digging at the toe of the slide, periods of very rapid acceleration would occur, probably because key blocks were being removed. The rate of movement would decrease once mining

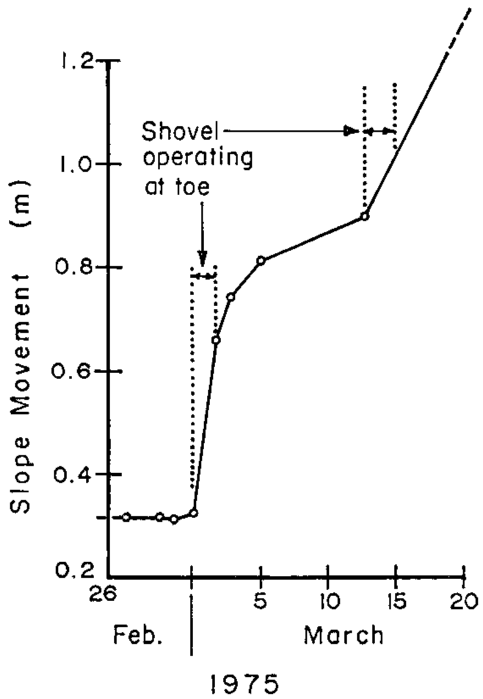

Fig. 4. Portion of slope movement curve of initial toppling failure

stopped (Fig. 4). After about six weeks of this carefully controlled mining operation, the bench was mined back to the design limit without a failure having taken place. At this time, the rate of movement had decreased to a few millimetres per day and continued to move at this rate or slower for the next year.

About 18 months after the first cracks had been observed on the pit crest, the slope started to accelerate and it was discovered that tension cracks had developed on the top of the mountain approximately 300 m above the pit bottom. It was inferred that the continued movement of the toppling failure had removed support from the toe of the upper slope, and this had triggered the upper slide.

The movement of the upper slope caused the beds on the crest of the pit to overturn further until a series of "sawtooth" blocks were formed (Fig. 5). Eventually the movement was sufficient to fracture the rock and

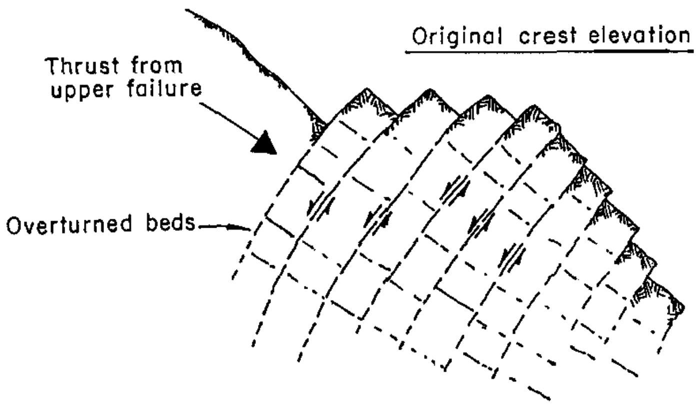

Fig. 5. "Sawtooth" formation on crest of pit

about 600,000 m^3 of material failed along the pit crest. Since monitoring had detected the accelerating movement, mining had been halted before conditions became hazardous and the failure caused no injuries.

Soon after the failure, the rate of movement again decreased. It is believed that on two occasions the decrease in the rate of movement was due to a drop in ground water pressure within the slope, as well as an increase in the resistance as deformation changed the edge-to-face contact between blocks to face-to-face contact.

Case Study 3: Toppling of a Single Block

The stability of this single toppling block is described by the criteria given in Eq. (1), which is similar to the analysis developed by John [9]. The major difference between this example and multi-block toppling failures, is that in this case stability was dependent upon slope geometry and geological structure, and was independent of rock properties.

This failure also occurred in Southwestern British Columbia, but the rock type in this case was a competent andesite with a much less clearly defined joint system than that in the granite described in the first case. This slope was approximately 120 m high and nearly vertical with a mainline railway at the toe of the slope. At the crest of the slope there were two vertical faults, about 10 m apart, and striking perpendicular to the slope face. Weathering of these two faults had produced an isolated 12 m high block with a slightly overhanging face (see Fig. 6). The shape of the block was partially determined by the orientation of the joint sets, one of which formed the face, and the other the base of the block.

Gradual weathering at the toe had undercut the block and as the width of the base (Δx) became smaller, the criteria of Eq. (1) was met and the block began to topple. This slow movement eventually opened a 1 m wide tension crack at the crest of the slope that extended to the full depth of the block. It is probable that, as the movement occurred, the rock at the toe of the block was overstressed and as the rock failed, support for the block was

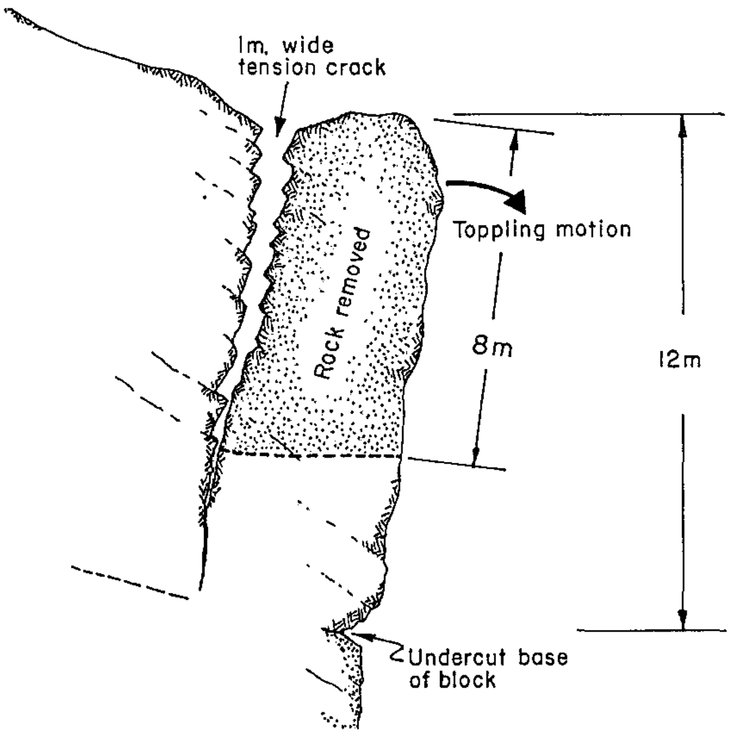

Fig. 6. Single toppling block

progressively removed. This movement could not be detected from the railroad level and it was only discovered when a close examination of the crest of the slope was made. This illustrates the difficulty of detecting toppling failures because there is usually little evidence of the failure at the toe.

It was decided that stabilization using rock bolts was impractical because of the great weight of the block and the difficulty of drilling across the open tension crack and then fully grouting the bolts. Consequently, controlled blasting was used to remove the top two-thirds of the block so that the remaining portion would not be liable to undergo further toppling. The blasting procedure was to drill vertical holes to a depth of 2.5 m on a spacing of approximately 0.6 m. The quantity of explosives was carefully controlled to ensure that the surrounding rock was not damaged. On completion of blasting, loose rock from the top and face of the block was removed by hand scaling.

Analysis of Toppling Failures

The stability of the three slopes described in this paper have been analyzed by Goodman and Bray's limit equilibrium techniques.

In the case of the granite slope, a friction angle of 47 degrees for both the sides and base of the slabs was required to achieve equilibrium. When the top 6 m of the slope had been removed the equilibrium friction angle had dropped to 34 degrees indicating a Factor of Safety of about 1.6.

Analysis of the toppling failure at the coal mine showed that a friction angle of 25 degrees on the sides and 42 degrees on the base of the blocks was required for equilibrium. These are appropriate values for shale and sandstone, respectively. Since the lower four blocks were on the point of sliding it can be seen that removal of the toe blocks by the shovel would have a detrimental effect on the stability of the slope.

For the single toppling block, it was estimated that the angle of the base was about 15 degrees which gives a value for $\cot \alpha$ of 3.7. The ratio of the height ($y = 12$) to the width ($\Delta x = 3.6$) of the block was originally about 3.7 and this was reduced to 1.3, significantly less than $\cot \alpha$, by removing the top 8 m of the block.

The analysis has been programed for a pocket calculator so that comparison of various stabilization measures can be carried out in the field. This enables decisions to be made as to whether a slope should be unloaded or bolted, and the extent of the required stabilization.

One modification that has been made to Goodman and Bray's original analysis has been to permit different friction coefficients to be used for the sides and base of the slabs. This was found to be necessary in the case of the coal mine where the base was sandstone, but shale with a much lower friction angle, formed the sides of the slabs. Another version of the analysis, incorporating ground water pressure within the slope, is also available [7].

Although this analysis is most useful in the analysis of existing slides, it has one drawback in its use as a design tool. This is, that the angle of the failure surface must be selected. The magnitude of this angle governs the height (y) of the slabs which in turn has a significant effect on their tendency to topple. The calculated stability condition of the slope is highly dependent upon the angle selected for the failure surface.

Conclusions

These three examples demonstrate how Goodman and Bray's analysis can be used to investigate the stability of toppling failures and to plan stabilization measures. These can be carried out rapidly and economically so permitting sensitivity analyses to be carried out to determine which factors have the greatest influence on stability. The successful results of the stabilization measures show that the analysis can be applied with confidence.

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