

Numerical modelling of toppling

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Evidence of large-scale toppling deformation has been reported in association with deep-seated landslides affecting mountain slopes along the Beaver River valley, Glacier National Park, British Columbia, Canada. A study has been undertaken to quantitatively investigate the relationship between the toppling mass movement process and the deep-seated landslides; specifically, whether the landslides represent a limiting condition of the toppling process. This is the first of two papers that describe the study. Methods of toppling analysis, including limit-equilibrium, finite-element, and distinct-element methods, are critically reviewed. The distinct-element method emerges as the best technique for modelling both block and flexural modes of toppling. The method is verified by modelling three examples of toppling: a theoretical block topple, a physical model of flexural toppling, and an engineered slope from the Brenda mine near Peachland, British Columbia. The results demonstrate that the Universal Distinct Element Code (UDEC) is capable of modelling both block and flexural types of toppling, that the toppling mass movement process limits to deep-seated planar as well as curvilinear landslides, and that other landforms such as obsequent scarps and grabens are a manifestation of the toppling process. The research reported here contributes to understanding of the deformation behaviour of engineered slopes and the evolution of natural slopes in rock masses containing pervasive discontinuities.

Key words: block toppling, flexural toppling, landslide, numerical modelling, distinct element, UDEC, sackung.

L'on a fait état d'évidence de déformation à grande échelle en basculement associée à des glissements profonds affectant les pentes montagneuses le long de la vallée de Beaver River, Glacier National Park, Colombie-Britannique. Une étude a été entreprise pour quantifier la relation entre le processus de basculement de masse et les glissements profonds, et plus spécifiquement, pour établir si les glissements représentent une condition limite du processus de basculement. Cet article est le premier de deux qui décrivent l'étude. Une revue critique des méthodes d'analyse incluant l'équilibre limite, les méthodes d'éléments finis et d'éléments distincts est présentée. La méthode d'éléments distincts ressort comme étant la meilleure technique pour modéliser tant le mode de basculement en bloc que le basculement en flexion. La méthode est vérifiée en modélisant trois exemples de basculement : le basculement théorique d'un bloc, un modèle physique de basculement en flexion, et une pente construite sur le site de la Brenda Mine près de Peachland, Colombie-Britannique. Les résultats démontrent que l'UDEC (Universal Distinct Element Code) peut modéliser les deux types de basculement de bloc et en flexion, que le processus du mouvement de basculement se limite aux glissements profonds planaires ou curvilignes, et que les autres formes topographiques telles que les escarpements plans et les grabens sont une manifestation du processus de basculement. La recherche décrite dans cet article contribue à la compréhension du comportement en déformation des pentes construites et l'évolution des pentes naturelles dans les masses rocheuses contenant de nombreuses discontinuités.

Mots clés : basculement en bloc, basculement en flexion, glissement, modélisation numérique, élément distinct, UDEC, dégradation.

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Introduction

Toppling is a mass-movement process characterized by the downslope overturning, either through rotation or flexure, of interacting blocks of rock. Slopes with well-developed discontinuities or a pervasive foliation dipping steeply into the slope and trending parallel or subparallel to the slope crest are generally considered susceptible.

Toppling can occur at all scales in all rock types (de Frietas and Watters 1973). The process commonly affects back-slopes of highway and railway cuts (Piteau *et al.* 1979; Brown *et al.* 1980; Wyllie 1980; Piteau and Martin 1981; Ishida *et al.* 1987), mine benches or mine slopes (Wyllie 1980; Piteau and Martin 1981; Piteau *et al.* 1981; Reid and Stewart 1986; Nieto 1987), and excavations for other engineered structures (Woodward 1988). The toppling process also affects natural slopes. De Frietas and Watters (1973) cited examples from England, Scotland, and Wales and speculated that the process is widespread. In the North American Cordillera, large-scale toppling in natural slopes

up to 800 m high has been described by Tabor (1971), Bovis (1982, 1990), and Evans (1987). Holmes and Jarvis (1985), who studied examples of toppling in Scotland, suggested a relationship between toppling and some forms of sackung, the large-scale gravitational deformation of a slope without a pervasive failure surface (Zischinsky 1966). Landforms associated with sackung have been shown by many authors to be widespread; among them, Beck (1968), Savage and Varnes (1987), and Radbruch-Hall *et al.* (1976).

The primary focus of toppling analysis has been the limit-equilibrium method proposed by Goodman and Bray (1976) for toppling deformation of small-scale engineered slopes (Wyllie 1980; Piteau *et al.* 1981; Piteau and Martin 1981; Teme and West 1983; Zambak 1983; Choquet and Tanon 1985). This technique is useful for examining the stability of small-scale topples that limit to a planar failure surface, but it has serious limitations for analysis of larger slopes (Brown 1982). As a result, large toppling failures have not been studied quantitatively, and their kinematic behaviour,

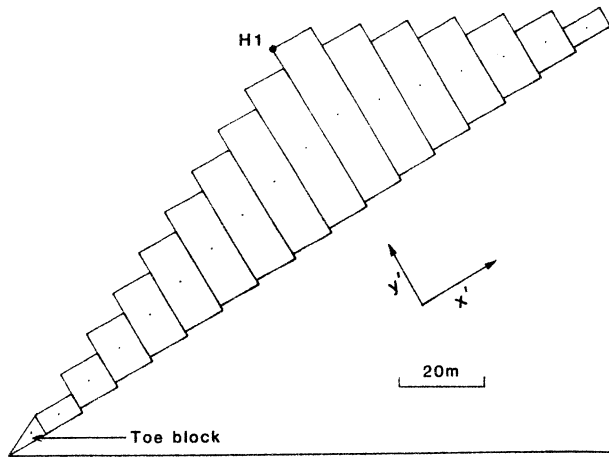


FIG. 1. Typical slope configuration used in limit-equilibrium method of analysis (after Goodman and Bray 1976) and geometry of UDEC block-toppling model.

morphology, and possible relationship to other mass-movement landforms such as sacking are poorly understood.

Pritchard *et al.* (1988) reported evidence of large-scale toppling deformation associated with deep-seated landslides in the Beaver River valley, Glacier National Park, British Columbia. Evidence cited included recent movement of obsequent scarps, overturned bedding, and visible rock mass dilation. These authors speculated that the deep-seated landslides represented a limiting condition of the toppling process.

A study has been undertaken in an attempt to verify this hypothesis. The results are reported in two parts. The limitations of available methods of analysis are discussed in this paper, and a new method of analysis that is suitable for modelling all types of toppling failures regardless of scale is proposed and verified using several examples. Use of this method to analyze the kinematics and morphology of one of several large landslides in the Beaver Valley is reported elsewhere (Pritchard and Savigny 1991).

Historical perspective

One of the first qualitative papers describing field examples of toppling failures was by de Frietas and Watters (1973). This paper was pivotal in persuading geotechnical engineers and geomorphologists to accept toppling as a significant and distinct mass-movement process and mode of failure. Goodman and Bray (1976) summarized the state of knowledge of toppling at the time, defined and discussed the basic types of topples, and described the limit-equilibrium method of analysis. The three basic types of toppling are flexural, block, and block-flexural. The deformation behaviour of slopes is often a mix of these generic types. The limit-equilibrium analysis, proposed by Goodman and Bray (1976), has become an accepted technique for predicting and analyzing block toppling (Choquet and Tanon 1985).

From the late 1970's to the present, work on toppling has dealt mainly with case histories, using both the limit-equilibrium (Wyllie 1980; Piteau and Martin 1981; Piteau *et al.* 1981) and the finite-element (Brown *et al.* 1980; Brown 1982; Evans *et al.* 1981) methods of analysis. Many papers discuss refinements to the limit-equilibrium technique or

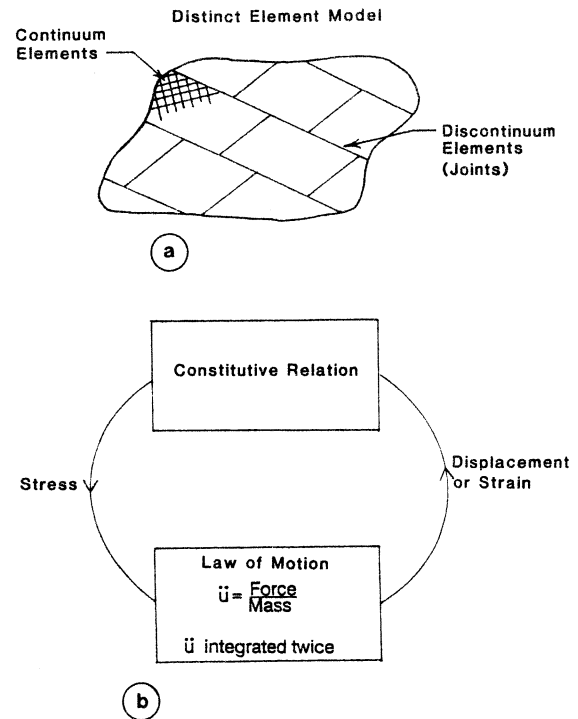


FIG. 2. (a) Nature of distinct-element model (after Itasca Consulting Group Inc. 1989). (b) Distinct-element model calculation cycle (after Cundall *et al.* 1977).

provide nomograms to facilitate its use (Wyllie 1980; Piteau and Martin 1981; Piteau *et al.* 1981; Teme and West 1981; Zambak 1983; Choquet and Tanon 1985). There are also several recent case histories that describe examples of large-scale toppling but do not attempt an analysis (Bovis 1982; Holmes and Jarvis 1985; Reid and Stewart 1986; Evans 1987). One post-1980 publication uses the distinct-element method to analyze a block toppling slope (Ishida *et al.* 1987).

Methods of analysis: usage and limitations

A detailed critical review of current methods of analysis for toppling is given by Pritchard (1989). The following is a brief summary.

Physical models

Some of the earliest modelling attempts utilized the friction table or tilt table. Ashby (1971), Soto (1974), and Whyte (1973) have examined block and block-flexural toppling, Kuykendall (1975) experimented with flexural-toppling models, and Hofman (1973) considered mixed modes of block-flexural and flexural toppling. Although these models contributed to the qualitative understanding of the toppling process, they lacked the ease, flexibility, and quantitative basis of other methods.

Limit-equilibrium method

The most popular analytical technique to predict whether a slope will topple is the limit-equilibrium method developed by Goodman and Bray (1976). The technique is described in detail by Hoek and Bray (1977) and Goodman and Bray (1976). This review is a brief summary of the method, concentrating on its capabilities and limitations.

The limit-equilibrium solution is formed by approximating the slope as a series of columns resting on a stepped base