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Stability analysis of slide-toe-toppling failure

Mehdi Amini*, Akbar Ardestani, Mohammad H. Khosravi

School of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

Toppling failure is a common mode of instability in layered and blocky rock slopes where rock blocks rotate about their toes and overturn. One of the most important types of toppling failure is slide-toe-toppling. In this failure, rock blocks at the toe of the slope are overturned by the pressure of sliding mass from the upper part of the slope. In the present study, this type of failure is examined through physical and theoretical modeling. The literature on toppling failures is reviewed briefly first and, then, the mechanism of slide-toe-toppling failure is described. To clarify the mechanism of the failure, a series of physical model tests is conducted under static condition by means of a new tilting table apparatus. Then, a theoretical approach is proposed based on limit equilibrium analysis and some new equations are developed for stability analysis of this type of failure. Finally, the results of physical modeling are compared with outcomes of proposed theoretical approach. This comparison shows a good agreement between the theoretical and experimental results.

1. Introduction

Toppling failure is a common instability in natural and excavated rock slopes. From the mechanism point of view, the toppling failures are classified as main and secondary (Goodman and Bray, 1976). In the main types of toppling failure (flexural, blocky and block-flexure), the primary cause of instability is weight of the rock mass. But, in the secondary types of toppling failure, rock mass is stimulated by some external factors. These types of failure are briefly described here. To understand the mechanism of blocky toppling failure, it is assumed that rock mass is composed of a set of dominant parallel discontinuities dipping steeply into the slope face and a set of cross-joints extended normal to the dominant discontinuities dividing the rock columns into a set of rock blocks. Under such condition, the rock blocks may slide along or turn over the natural cross-joins in their base; so their tensile strength has no significant effect on the stability of rock slope. Fig. 1-a shows a schematic diagram and a real case study of this instability. Another type of main toppling failure is flexural toppling. To understand the mechanism of this type of failure, it is assumed that a rock mass is only composed of a set of parallel persistent discontinuities dipping steeply into the slope face. As such, the rock mass behaves like a series of superimposed inclined continuous cantilever rock columns which are subjected to bending stresses. When bending tensile stress in the rock columns exceeds their tensile strength, they fail and topple downward. Fig. 1-b shows a schematic diagram of this instability and a photograph of such failure in a limestone quarry mine. In real case studies, the above-mentioned idealized failure mechanisms are not common. Natural toppling failures are mostly a combination of both blocky and flexural modes which can be generally termed as block-flexure toppling failure. If any of these failures is stimulated by some external factors, the result will be called a secondary toppling failure. Secondary toppling failures are quite diverse and many modes have been proposed for these failures. In Fig. 2, rock blocks at the toe of the slope are overturned by the pressure of sliding mass from the upper portion of the slope. This phenomenon is a combined failure known as slide-toe-toppling. In this paper, the mechanism of this failure is clarified through a series of physical model studies and a new flexible analytical approach is proposed.

2. Literature review

Failure due to overturning of natural rock blocks was first mentioned by Müller in 1968, after studying the instabilities near the Vaiont dam lake in Italy (Müller, 1968). In 1971, Ashby introduced a simple criterion for this type of failure and proposed the term “toppling” for it. From 1971 to 1976, toppling failure was the subject of a few scattered researches focused on numerical and physical modeling and real case studies (Cundall, 1971; De Freitas and Watters, 1973).

In 1976, Goodman and Bray classified the toppling failures into two categories: main (flexural, blocky and block-flexure) and secondary types and introduced a theoretical approach for the analysis of blocky mode. Later, several researchers tried to develop this approach into some design charts and computer programs to assess the failure (Hoek and Bray, 1977; Zanbak, 1984; Choquet and Tanon, 1985; Tatone and

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* Corresponding author at: School of Mining Engineering, College of Engineering, University of Tehran, Northern Kargar Street, Tehran, Iran.
E-mail addresses: mamini@ut.ac.ir (M. Amini), akbarardestani@ut.ac.ir (A. Ardestani), mh.khosravi@ut.ac.ir (M.H. Khosravi).

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List of symbols

σ_t	Tensile strength of rock blocks
UCS	Uniaxial compressive strength
γ	Unit weight
h	Average length of blocks or slices
z	Height of falling
t	Thickness of blocks
ψ_f	Dip of slope face
ψ_p	Dip of dominant discontinuities of rock mass or soil slices
ψ_t	Dip of overall failure plane of toppling failure
ψ_s	Dip of upper surface of the slope
ψ_b	Dip of normal to discontinuities
b	Distance between tensile crack and crown of slope
n	Number of rock block
m	Number of soil slice
H	Height of slope
f_R^j	Inter-slice normal force acting at the right side of slice “j”
f_L^j	Inter-slice normal force acting at the left side of slice “j”
N^j	Normal force acting at the base of slice “j”
S^j	Shear force acting at the base of slice “j”
ψ_R^j	Angle between f_R^j and normal to slice “j”
ψ_L^j	Angle between f_L^j and normal to slice “j”
h_R^j	Point of application of f_R^j with respect to base of slice “j”
h_L^j	Point of application of f_L^j with respect to base of slice “j”
ℓ^j	Point of application of N^j with respect to toe of slice “j”
ψ_a^j	Dip of base of slice “j” with respect to horizon
Δx^j	Thickness of slice “j”
ϕ_s	Internal friction angle of soil
c_s	Cohesive strength of soil
ϕ_{sb}	Interface friction angle between soil and rock masses
ϕ_b	Interface friction angle of base of rock blocks
c_b	Cohesive strength of base of rock blocks
ϕ_c	Interface friction angle between adjacent rock blocks
ϕ_i	Internal friction angle of intact rock
c_i	Cohesive strength of intact rock
κ	Constant coefficient
W	Weight of rock blocks
P	Inter-block normal force
Q	Inter-block shear force
y	Point of application of “P” with respect to base of block

Grasselli, 2010). Apart from the above mentioned researches, many other articles and reports can be found in the literature on the physical modeling, case study and theoretical and numerical analysis of blocky toppling failure, mostly based on the classification of Goodman and Bray (Wyllie and Mah, 2004; Pritchard and Savigny, 1990; Bobet, 1999; Sagaseta et al., 2001; Naresh et al., 2002; Xinbin et al., 2007; Brideau and Stead, 2010; Alejano et al., 2015; Smith, 2015).

The first comprehensive approach to analyze flexural toppling failure was introduced by Aydan and Kawamoto (1992) who managed to incorporate the effects of dynamic loads and underground water pressure into the analysis. In 2009, Amini et al. proposed a simple and direct method for analysis of the failure based on compatibility principles governing the behavior of cantilever beams (Amini et al., 2009). There was a good agreement between the results of this method and the results of existing physical modeling and case studies. Apart from these studies, this type of failure has been the subject of several articles in the

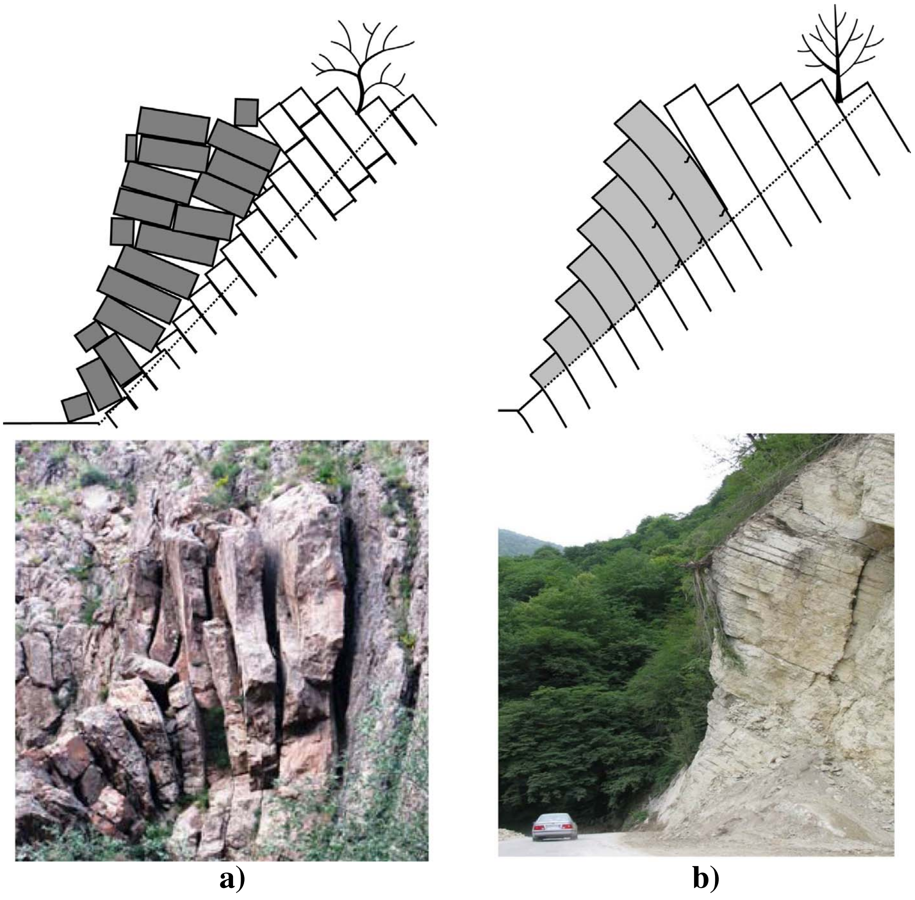

Fig. 1. Schematic diagrams and real case studies of main toppling failures: a) blocky; b) flexural.