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Block toppling stability in the case of rock blocks with rounded edges

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ABSTRACT

A characteristic feature of spheroidal weathering is the rounding of rock block edges, which affects the mechanical stability of slender rock blocks and, consequently, that of slopes prone to toppling. We analysed the influence of this erosion phenomenon on block toppling stability, first discussing the geological environments that produce this kind of phenomena and then reviewing classic limit equilibrium equations for block toppling that account for the role played by rounded edges. On the basis of this approach, it is clear that rounded edges do not greatly affect stability against sliding. However, since the equation to compute stability against toppling tends to overestimate the stability of slopes with round-edged slender blocks, we propose a modification that results in a more accurate estimation.

In physical model testing in the laboratory, we compared results for sharp-edge block models and artificially weathered rounded-edge blocks, confirming our formulated hypothesis and enabling us to explain the failure of sets of a small number of not-so-slender blocks. Fieldwork case studies confirm that rounded edges play a role in decreasing stability against toppling. We suggest that our proposed approach can be an appropriate tool to take this effect into account.

1. Introduction

Toppling failure mechanisms tend to occur in slopes in rock masses containing a discontinuity set striking more or less parallel to the slope and dipping towards it. Although slope instability failures associated with toppling are not easy to identify, detailed analyses have shown that this mechanism lies behind many problems identified in rock cuts (De Freitas and Waters, 1973; Sagaseta et al., 2001), open pit mine walls (Sjöberg, 1999; Martin, 1990) and natural slopes (Giraud et al., 1990; Cruden and Hu, 1994; Gischig et al., 2011). Sjöberg (1999) suggested that this type of failure mechanism seemed to be much more common than previously thought. A better understanding of toppling phenomena and its features would therefore be very useful in improving understanding, prediction and management of this type of instability.

Ashby (1971), in a seminal study, first documented the occurrence of toppling in rock, whereas Goodman and Bray (1976) made the first serious attempt to analyse this type of failure. More than a simple failure mechanism, in fact, toppling phenomena could be involved in a number of processes that negatively affect the stability of a slope. A simplified classification provided by Goodman and Bray (1976) referred to block toppling, flexural toppling and block-flexural toppling.

However, more complex phenomena that combine toppling with other basic failure modes (circular, planar or wedge failure) do occur and were described, among others, by Hoek and Bray (1974) and Wyllie and Mah (2004). These include failure mechanisms with toppling failure and circular failure in the upper and lower parts, respectively, like those described by Alejano et al. (2010) and Manera Bassa et al. (2014), or in the lower and upper parts, respectively, like those described by Mohtarami et al. (2014) and Stead et al. (2006). Other combinations of simpler mechanisms include sliding and toppling failure in the upper and lower parts, respectively (Cravero et al., 2003), or in the lower and upper parts, respectively (Gu and Huang, 2016; Coulthard et al., 2001). Even more complex failure phenomena involving toppling combined with two other mechanisms have been described in the literature (Böhme et al., 2013; León-Buendía et al., 2014).

Unlike other simpler failure mechanisms (e.g., planar or wedge failure), toppling tends to be controlled by many discontinuities with variable geometry, features and behaviour. It is therefore not surprising

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that our ability to accurately estimate the stability of these slopes is much more limited than for simple mechanisms.

Within this framework, we observed that blocks with rounded corners were more prone to toppling than blocks with sharp corners and a study explaining, quantifying and demonstrating this phenomenon in relation to a single block was reported in due course (Alejano et al., 2015). Here we describe an extension of that study that focuses on how rounded corners in blocks affect the stability of slopes prone to block toppling. This study can be considered an extrapolation of the Goodman and Bray (1976) approach to analysing the role played by round-edged blocks in stability.

Below we describe how the basic equations of the Goodman and Bray (1976) approach were modified to account for rounded corners and then the modified equations are applied to a number of analyses. We tested the validity of our approach by means of physical models and used the results to eventually explain how and why block toppling occurred in a moderately weathered granite rock formation in a mountain area of NW Spain.

2. Fundamentals

2.1. Analysis of a single block

Alejano et al. (2015) studied the influence of rounded corners on stability for a single rock block, indicating that, in the analytical solution for the factor of safety (FoS) against toppling of a single block with sharp edges (Eq. (1)), stability depends solely on the slenderness of the block for a given inclination of the base (α).

$$\mathrm{FoS} = \frac{M_{stab.}}{M_{overt.}} = \frac{W\cos\alpha^{\Delta x}/_{2}}{W\sin\alpha^{y_n}/_{2}} = \tan^{-1}\alpha\frac{\Delta x}{y_n} \tag{1}$$

This means that there is a critical inclination at which FoS = 1. The angle of failure can be physically observed in laboratory tilt tests, consisting of observing block behaviour on a progressively tilted surface.

The stability of blocks with rounded corners was analysed in different ways in Alejano et al. (2015): for specimens built by collating different pieces of the same rock, for artificially eroded blocks for which the radii of curvature were appropriately estimated and, finally, using a numerical approach and UDEC (Itasca, 2010). The analytical approach considered the radii of curvature of block corners by displacing the rotation axis and then calculating the moments in the computation of the FoS, as shown in Eq. (2) and Fig. 1:

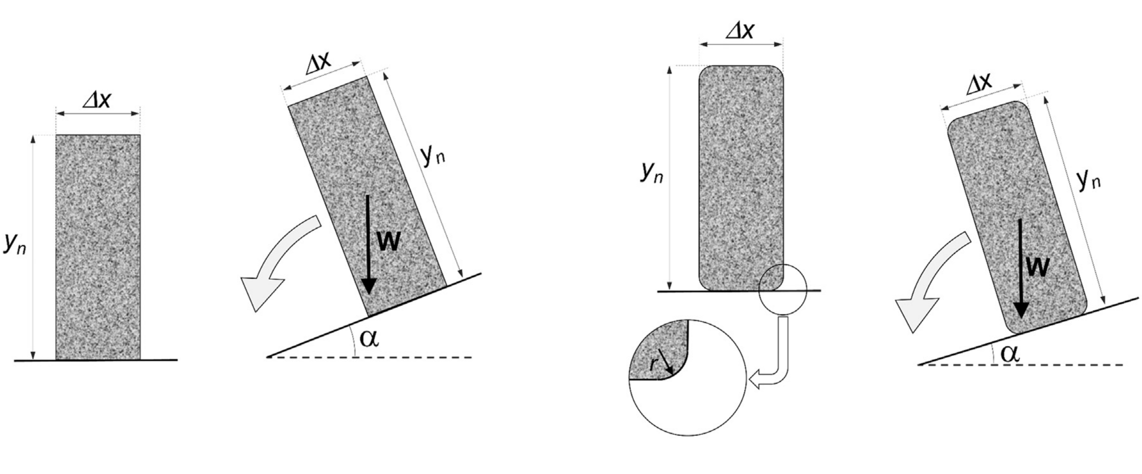
$$\mathrm{FoS} = \frac{M_{stab.}}{M_{overt.}} = \frac{W\cos\alpha\left(\frac{\Delta x}{2} - r\right)}{W\sin\alpha^{y_n}/_{2}} = \tan^{-1}\alpha\left(\frac{\Delta x - 2r}{y_n}\right) \tag{2}$$

2.2. Block toppling in rock slopes

In rock slopes, toppling involves the overturning of interacting columns or rock blocks around a fixed base (Goodman and Bray, 1976). This phenomenon usually happens when the strike of the rock mass joint sets (fault, stratification, etc.) and of the slope are the same and when another set dips steeply into the rock mass. The most frequent failures of this kind are classified by Goodman and Bray (1976) as block toppling, flexural toppling and block flexural toppling. These mechanisms, illustrated in Fig. 2, are briefly described below following Wyllie and Mah (2004).

Block toppling takes place in hard rock when individual blocks or columns are formed by two orthogonal joint sets, when the main set strikes parallel to the slope crest and dips steeply into the face. The upper blocks tend to topple and push forward on the short columns in the slope toe. Flexural toppling typically occurs in thinly bedded slate in which orthogonal jointing is not well developed; consequently, the basal plane is not as well defined as in block toppling. The general condition for flexural toppling is therefore when continuous columns of rock dipping steeply towards the slope break in flexure and tilt forward. Finally, block-flexural toppling is a complex mechanism characterized by pseudo-continuous flexure along long blocks that are divided by a number of cross-joints.

Cases of toppling have been widely reported in literature. Wyllie and Mah (2004) illustrated a case of pit-crest toppling that resulted in a circular failure in the upper slope. Hutchison et al. (2000), Coulthard et al. (2001) and Cravero et al. (2003) described complex failure mechanisms associated with toppling. Stead et al. (2006) reported and analysed a failure that occurred in the Delabole (UK) slate quarry that included toppling in the crest and circular failure in the lower part of the slope.



$$FoS = \frac{M_{stab}}{M_{overt}} = \frac{W\cos\alpha\,\frac{\Delta x}{2}}{W\sin\alpha\,\frac{y_n}{2}} = \tan^{-1}\alpha\,\frac{\Delta x}{y_n} \quad (1)$$

$$FoS = \frac{M_{stab}}{M_{overt}} = \frac{W\cos\alpha\left(\frac{\Delta x}{2} - r\right)}{W\sin\alpha\,\frac{y_n}{2}} = \tan^{-1}\alpha\,\frac{\Delta x - 2r}{y_n} \quad (2)$$

Fig. 1. Factor of safety for a single block with sharp edges (1) and rounded edges (2).