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Study of the stability against toppling of rock blocks with rounded edges based on analytical and experimental approaches

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ABSTRACT

Rounding of edges in rock blocks is a characteristic feature of spheroidal weathering. The objective of this paper is to examine the influence of edge rounding for rectangular prismatic blocks on the mechanical stability of the blocks against toppling at both laboratory and field scales. Equations for computing factors of safety against toppling and sliding for rectangular prismatic blocks resting on inclined surfaces are discussed first. The equations consider the situation of blocks with sharp edges and with assumed circular rounded edges. The analytical formulae show that rounding of the edges does not have influence on the factor of safety against sliding, but has influence on the factor of safety against toppling. In the latter case, the equations that do not account for rounding of the edges are shown to overpredict the stability conditions of the rock blocks against toppling. Results from a series of laboratory tests using a tilt table to estimate the factor of safety at the critical condition for toppling of blocks at laboratory scale are discussed next. The laboratory results show that for rock blocks with rounded edges produced by a process of abrasion in a slake durability machine, an overestimation of up to 30% or more for the factor of safety against toppling is expected when using classical stability formulae that disregard the curvature of the edges. Finally, stability analysis of large natural rock blocks in the field that show spheroidal weathering, confirm the overestimation of stability conditions predicted by the formulae that do not account for the rounding of the edges.

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1. Introduction

Spheroidal weathering, a particular form of chemical weathering, is a mode of rock block degradation that has been observed in different types of rock masses, including granites (Ollier, 1967; Sarracino and Prasad, 1989; Patino et al., 2003; Fletcher et al., 2006). For jointed rock masses defining prismatic blocks, spheroidal weathering produces an ongoing transformation of the originally sharp-edged prismatic blocks into blocks that display rounded edges. If the process of weathering continues indefinitely, boulders with ellipsoidal or spherical shapes are produced. This is illustrated in Fig. 1a, that shows spheroidal weathering occurring in three blocks (one of them toppled) in a granite outcrop of the formation known as *Lage* formation (Parga-Pondal, 1967), at Monte Pindo, near Santiago de Compostela, Galicia, Spain — see Fig. 1b. The process of spheroidal weathering is not constrained to specific granitic formations like the one shown in Fig. 1, but indeed it is rather a common and widespread feature of many granite landscapes in Spain and in many other countries (Twidale, 1982; Vidal-Romaní, 1989).

From an engineering geology point of view, the mechanisms of failure observed in hard jointed rock have been classified as being mainly of sliding and toppling types (see, for example, Hoek and Bray (1974), Wyllie and Mah (2004)). Sliding is the most common type of failure mechanism observed in jointed rock and comprises planar, wedge and circular failure (Giani, 1992). Even if slope failures associated to toppling are relatively uncommon, many authors have indicated that the toppling mechanism lies behind a good number of the problems they analyzed in rock cuts (De Freitas and Waters, 1973; Sagaseta et al., 2001), in open pit mine walls (Martin, 1990; Sjöberg, 1999; Alejano et al., 2010a) and in natural slopes (Giraud et al., 1990; Cruden and Hu, 1994; Gischig et al., 2011; Böhme et al., 2013). Also Sjöberg (1999) stated that rotational shear and deep seated toppling are the two typical failure modes in large open pit mines. Therefore a better understanding of toppling instability, even in its simplest form when comprising single blocks, is important to increase the understanding and so improve on the prediction and remediation of this type of instability in geotechnical applications. Also, it has to be mentioned that many authors have studied the problem of toppling of single blocks from an analytical perspective. Among those, one can mention the studies by Goodman and Bray (1976), Bray and Goodman (1981), Zanbak (1983)), and Sagaseta (1986) — these studies have been taken as a basis for the analytical developments to be presented in this paper.

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Fig. 1. a) Spheroidal weathering of blocks in the Lage formation. b) General view of the granite outcrop of the Lage formation at Monte Pindo, near Santiago de Compostela, Galicia, Spain.

With regard to the stability of sliding or toppling for a single rock block (e.g., the central block in Fig. 1a), and as it will be shown later in this paper, the sliding mechanism (e.g., the factor of safety of a rock block against sliding) is not affected by the occurrence of edge rounding in the rock blocks; on the contrary, the toppling mechanism is sensitive to the occurrence of the rounding of the block edges — although shown mathematically in this paper, this same observation has been made by other researchers in the past (see, for example, Muralha (2002); Brideau and Stead (2010); Segalini and Giani (2004); Alejano et al. (2010b)).

When analyzing stability of single rock blocks in outcrops like the one represented in Fig. 1a, the authors found that when the existing formulae to compute factor of safety against toppling for sharp-edged blocks are applied (e.g., the formulae presented in Hoek and Bray (1974); Wyllie and Mah (2004)), the stability conditions of the rock blocks tend to be always overestimated. This fact has motivated the developments presented in this study, which has as main objective the quantification of the influence of rounding of blocks (e.g., due to spheroidal weathering) on the stability conditions against toppling.

With this objective in mind, the authors have set up a basic laboratory scale testing program, which involved conducting tilt tests on mainly sharp-edged (artificially cut) rock blocks first, followed by similar tilt tests on manufactured and artificially weathered samples (generated by abrading rock samples in a slake durability testing machine), and comparing these results with existing formulae and extended formulae to account for the rounded edges. Thereafter, the authors have analyzed the stability of various blocks showing spheroidal weathering in the field, again, applying existing formulae and extended formulae. In all cases, as it will be described in this article, the extended formulae developed in this study more accurately predicted the stability conditions against toppling for blocks analyzed in the laboratory and in the field.

2. Toppling of blocks with sharp edges at laboratory scale

2.1. Analytical solution for stability against sliding and toppling

Before discussing the laboratory test work, the stability analysis of a rectangular prismatic block with sharp edges lying on an inclined frictional surface will be reviewed.

Fig. 2 represents the problem to be considered. A rectangular block of base width b and d (the latter in the direction perpendicular to the plane represented in Fig. 2) and height h, has a weight W and rests in static equilibrium on a frictional plane with inclination angle, α. The contact surface between block and inclined plane is assumed to be non-cohesive and frictional, with a friction angle ϕ.

With regard to stability against sliding, according to the principle of friction, the block will be in static equilibrium provided the shear force, S, parallel to the frictional surface and equal to $W\sin\alpha$, is less than the maximum shear force, S_{max}, that can be developed on the frictional surface (see Fig. 2a). Again, according to the principle of friction, this force

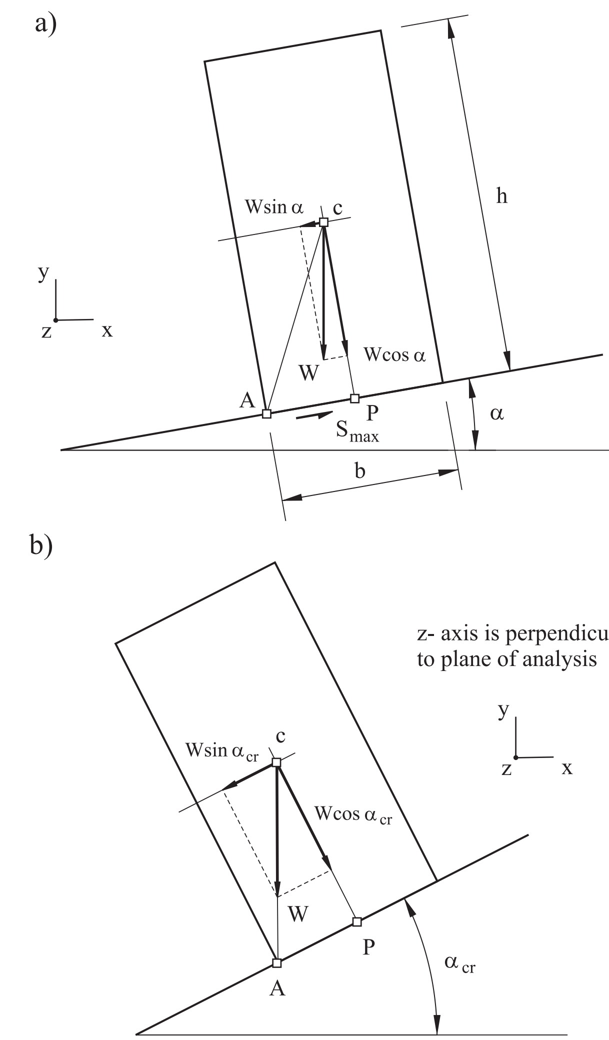

Fig. 2. a) Block with sharp edges resting on a frictional inclined plane. b) Critical angle of plane inclination for which the block is in limit equilibrium of toppling.