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Pseudo-static failure modes and yield accelerations in rock slopes

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ABSTRACT

Earthquake-induced landslide databases indicate that failure modes, observed in the field following earthquakes, include sliding, toppling, and slumping. Methods based on simplified, discrete, single block models are limited to rectangular blocks on a plane or wedge blocks that restrict the potential failure modes to sliding or toppling. This paper expands the geometry assumptions so that additional failure modes will be kinematically admissible. A simple, yet broadly applicable, two-dimensional (2D) single block framework is introduced that does not restrict the geometry to orthogonal fracture sets. This framework allows for the slumping failure mode to naturally occur and can identify a new failure mode, confined toppling. Using simple failure mode charts, this framework can be easily applied to a wide range of analysis and design applications. In addition to the identification of new failure modes, seismic yield acceleration equations are presented for all four modes of failure: sliding, toppling, slumping, and confined toppling. The equations for slumping and confined toppling are derived for the first time. Although the model may be simple in its formulation and implementation, it is quite powerful, allowing for significant implications to be developed. Complex shaped blocks can be easily evaluated knowing just their centers of mass and contact points with supporting fractures. The failure mode of a discrete rock block is shown to be independent of the primary fracture inclination on which the block rests upon and the scale of the block itself. Seismic failure modes are demonstrated to be different from those induced by static forces alone and can even change modes depending on the amount of displacement during the ground motion. In addition, it is shown that the characteristics of an earthquake ground motion acting on these blocks in combination with geometric variability can influence the abundance of failure types observed in the field. Finally, an example mode and yield acceleration evaluation of Alaskan rock slope is presented.

1. Introduction

Rock slope failures contribute to the economic and human losses that occur during seismic events throughout the world. Accounts of these often spectacular events have been well-described in the literature e.g.[1–9]. Earthquake-induced landslide databases by Keefer[10], Rodríguez et al.[11], and Keefer[12] identify rock-slope failures, which often occur from sliding, toppling, and slumping, as among the most abundant mass wasting events. Analytical techniques to assess these failures can generally be categorized as simple or complex. Simple techniques consist of empirical decision charts[13] and sliding/toppling block models[14] while the complex techniques involve site-specific, dynamic numerical models Bhasin and Kaynia[15]. Simplified, discrete, rigid block analysis models are commonly used to evaluate the stability behavior of rock slopes and determine the factor of safety against failure Hoek and Bray[16], Aydan et al.[17], Yagoda-Biran and Hatzor[14]. A limitation common to most of these models is that the geometry of the rock blocks is defined by orthogonal discontinuities, which restricts the potential failure modes to sliding and toppling. However, it is clear that a wide range of block shapes are found in nature, including parallelograms Fityus et al.[18], Aydan et al.[19].

In this paper, we present a simple, yet broadly applicable, two-dimensional (2D) single block framework for the seismic evaluation of discrete rock blocks. Geometry assumptions are less restrictive such that a wide range of commonly observed failure modes, including sliding, toppling, and slumping, will be kinematically admissible. In addition, the formulation identifies a new mode of failure termed *confined toppling that is related to toppling but has a higher, complex yield acceleration. With this framework, complex shaped blocks can be easily evaluated knowing only their centers of mass and contact points with supporting*

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discontinuities. The framework was used to develop a simple failure mode chart, which allows it to be easily applied in analysis and design applications. The formulation also allows for the calculation of the corresponding pseudo-static accelerations that lead to the initiation of block motion. Seismic yield acceleration equations are presented for all four modes of failure and derived for the first time for slumping and confined toppling.

Application of the model shows that the failure mode of discrete rock blocks is independent of the primary fracture inclination on which the block rests upon and the scale of the block itself. Seismic failure modes are demonstrated to be different from those induced by static forces alone and can even change modes depending on the amount of block displacement during the ground motion. We conclude by presenting, an example evaluation of mode and yield acceleration for an Alaskan rock slope.

2. Background

2.1. Failure modes

Goodman and Kieffer[20] describes failure modes in rock slopes span a range of styles including: erosion, ravelling, block sliding, wedge sliding, rock slumping, toppling, slide toe toppling, slide head toppling, slide base toppling, block torsion, sheet failure, rock bridge cracking, slide base rupture, buckling, kink band slumping, soil-type slumping, and rock bursting. These modes are often grouped into simplified categories such as sliding, toppling, and slumping that can be easily evaluated for stability. Experiments by Aydan et al.[17] simulating discontinuous rock slopes found that multiple blocks may act together to fail in these basic modes.

These simplified failure modes are distinguished by the mechanics of their motion. Sliding failures consist of purely translational motion characterized by the frictional and geometric properties of a slide surface and can occur on one or more of these surfaces. Toppling failures consist of purely rotational motion. The rotation point is commonly located at the toe of a rock block but need not be so. Slumping failures consist of both translational and rotational motion, with the rotational component resulting in backwards (i.e. opposite direction of toppling) rotation.

2.2. Stability analysis

For seismic stability, rock slopes can be evaluated using simplified failure charts based on rectangular-shaped blocks such as that developed by Yagoda-Biran and Hatzor[14] or site-specific numerical analyses.[21,22,15,23,24] The design charts most commonly used to assess single block failure modes are restricted to blocks formed by orthogonal joint sets (i.e. rectangles). These charts were developed to delineate boundaries between statically stable and unstable, rectangular blocks under gravitational and seismic loading. A review of these charts is presented by Yagoda-Biran and Hatzor[14] and briefly summarized here. Ashby[25] and Hoek and Bray[16] presented the first charts that established static limit equilibrium failure modes. They also identified dynamic behavior when the block is in motion relative to the fracture. The dynamic motion represented the scenario where a block would begin motion in a statically unstable condition or whose fractures undergo rapid strength loss. Bray and Goodman[26] revised these charts based on DEM modeling by Voegele[27] that indicated the sliding and sliding & toppling boundary should be modified based on the effects of the inertial forces. The dynamic behavior boundaries were again modified by Sagaseta[28] to reflect the appropriate application of inertial forces. Tokashiki et al.[29] further evaluated the dynamic motion of a parallelogram-shaped blocks. However, the focus of this paper is on the initiation of motion of statically stable blocks by seismic forces, thus dynamic modes are not further considered here.

Given the static loading limitation, Yagoda-Biran and Hatzor[14] showed that the seismic inertial force could be represented as an additional slope angle to the static charts thus expanding the charts applicability to include earthquake loading. The slope angle is effectively increased by the angle formed by the inertial force acting on the block relative to vertical. A hybrid chart delineating the pseudo-static limit equilibrium boundary for rectangular blocks was defined using this increased angle. Despite this advancement, this seismic failure chart still possess the primary assumption of earlier work: namely, it is applicable only to rectangular rock blocks.

The slumping failure mode was evaluated by Kieffer[30]. He described an analytical method to determine both static and seismic factors of safety for blocks that are parallelogram in shape and require a second discontinuity to provide static stability. While this advanced the evaluation of rock block failure modes, the implementation of this model was limited to factor of safety evaluations and assumed the slumping mode of failure in advance. Tonon[31] introduced a model that can evaluate complex block geometries and does not restrict potential failure modes. This model requires a block-by-block evaluation and is applicable to problems with a quick reduction in strength rather than rapid or seismic loading.

3. Geometry

3.1. Fractured rock slopes

The formation of a discontinuity within a rock slope is the result of complex tectonic and weathering processes. A primary concern of rock slope engineers is the geometry and condition of the discontinuities which strongly influences failure mode. Discontinuities from discrete rock blocks can interact and create complex, emergent behavior[17,32] or can fail as individual blocks. Studies of recent earthquakes in Pakistan and New Zealand have shown that failure of individual blocks can be catastrophic, imparting significant damage to the built environment and directly result in loss of life.[6,33] It is the individual block failures that is the focus of this paper.

3.2. Discrete rock blocks

Rock block geometries are defined by intersecting discontinuities within a rock mass. In some cases these fracture networks create orthogonal intersections that form rectangular blocks. However, for the more common scenarios where fractures intersect each other at other angles, additional block geometries become possible. For example, Fig. 1 shows slopes containing two predominate fracture sets. These figures depict slopes with a daylighting base fracture set dipping out of the slope while the back fracture set is oriented close to vertical. The

Fig. 1. Discontinuous rock slope damaged by the 2007 Pisco, Peru Earthquake.