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Research Paper

Investigating the role of kinematics and damage in the failure of rock slopes

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ABSTRACT

Recent developments in numerical codes provide an important tool for modeling brittle fracture associated with the failure of rock slopes. This is particularly important in simulation of rock slopes that may initially appear kinematically stable but if brittle fracture is considered within the model, stress-induced release surfaces may cause slope failure. This paper investigates the inter-relation between kinematics, failure surface geometry and damage leading to the failure of high rock slopes using a three-dimensional lattice-spring code. Two new methods are introduced to quantify damage in our numerical simulations. In the first method, an "ellipsoid of damage" is defined to encompass newly created cracks within a given rock Slope Model. Geometrical characteristics of the ellipsoid including volume, length and orientation of its axes allow quantification of damage within a model. In the second method, damage is quantified using "damage intensity" parameters, D_{21} and D_{32}. In this method damage is defined as the ratio of total length/area of the newly created cracks within the model to the sampling area/volume. The combined use of these two approaches allows a quantitative description of the intensity and extent of damage development within the rock Slope Models. Our numerical simulation results highlight a strong relationship between kinematics, failure surface geometry and damage in the failure of high rock slopes.

1. Brittle fracture in rock slopes

As large open pit slopes reach greater depths, it is becoming increasingly necessary to investigate non-conventional rock slope failure mechanisms. In massive brittle rock slopes, both natural and engineered (e.g. open pit mines), potential failure surfaces are often assumed to be comprised of intersecting, fully persistent features providing complete kinematic release for the failure to occur [1]. However, this is not the case for most slopes where a certain percentage of rock bridges are present along the discontinuity, which increases the stability; ignoring their existence may lead to conservative slope design.

Many authors have demonstrated the importance of intact rock bridges on the stability of slopes [2–8]. Tuckey et al. [9] state that the range of rock bridge percentages observed in the field or assumed in modeling studies in the published literature has varied between 0.2% and 45%. Martin [10] and Elmo et al. [11] have shown that for slopes greater than 300 m high in moderately hard rock, less than 10% rock bridges generally provides sufficient resistance along a prospective failure surface. Diederichs [12] reported that even when intact rock bridges occupy only a very small percentage of the discontinuity coplanar area, they may provide internal self-supporting load carrying capacity equivalent to artificial slope reinforcement systems (i.e. bolts or cables). Tuckey et al. [9] divided the theoretical models for incorporating intact rock bridges into two categories: (1) models that consider "in-plane" rock bridges and (2) models that incorporate non-coplanar or "out-of-plane" rock bridges (Fig. 1). In-plane rock bridges are represented by "patches" of intact rock along a theoretical fully-persistent discontinuity plane or failure surface [13] (Fig. 1a). Havaej et al. [14] studied the influence of in-plane rock bridges on stability of pentahedral wedges. In their results, 2% rock bridge content was sufficient to stabilize an unstable pentahedral rock slope wedge. Out-of-plane rock bridges on the other hand can be described as the intact rock that separates non-coplanar discontinuity tips within a volume of rock mass [9] (Fig. 1b). Identification of this type of rock bridge, however, can become very uncertain with increase in number of fractures. The assumption of through-going fully persistent discontinuities is often the result of the difficulty in obtaining persistence measurements and the limitations of current

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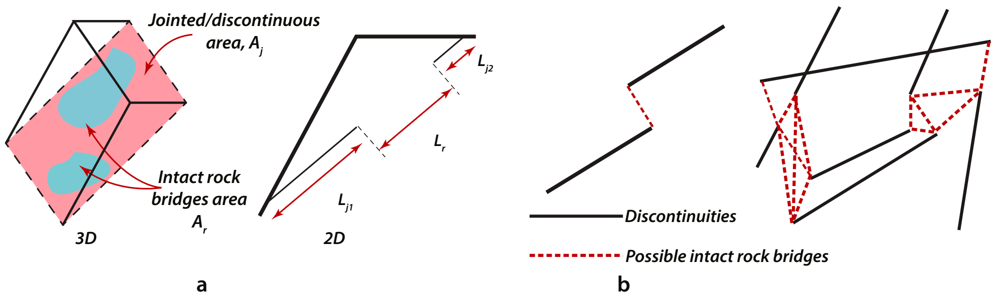

Fig. 1. (a) In-plane rock bridges and (b) out-of-plane rock bridges [9].

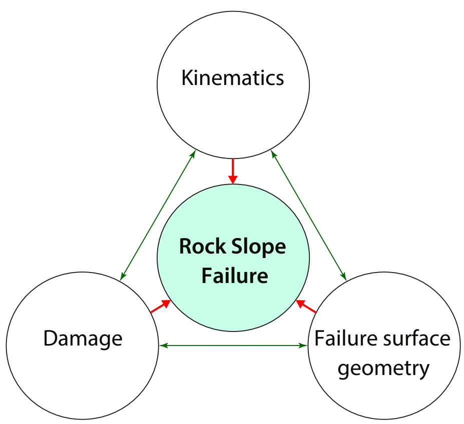

Fig. 2. Diagram illustrating the inter-relationship between kinematics, failure surface geometry and damage during failure of rock slopes.

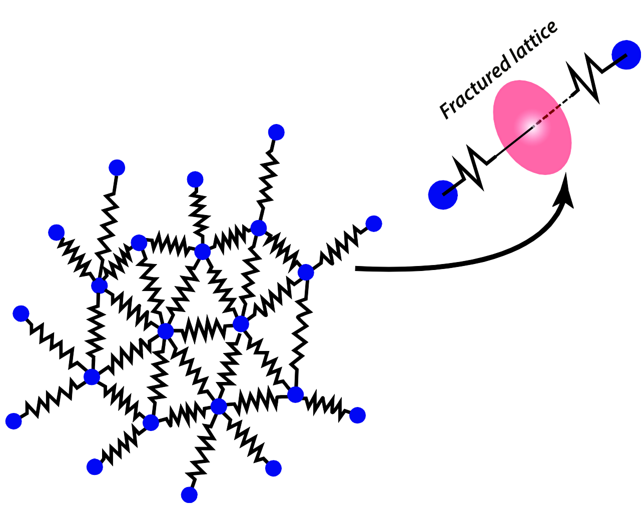

Fig. 3. The lattice-spring model used in the Slope Model code consisting of nodes and springs [31].

numerical modeling codes, which usually assume fully persistent discontinuities [15]. Although this assumption may often be appropriate for bench scale stability analysis, it becomes increasingly non-conservative as the scale of the slope increases.

High stress concentrations can potentially influence the strength of the rock mass through fracture initiation, propagation and coalescence. This generation of new fractures has been observed over a wide variety of scales ranging from shearing of joint roughness to development of failure surfaces and toe breakout [16]. As a result, it is necessary to investigate

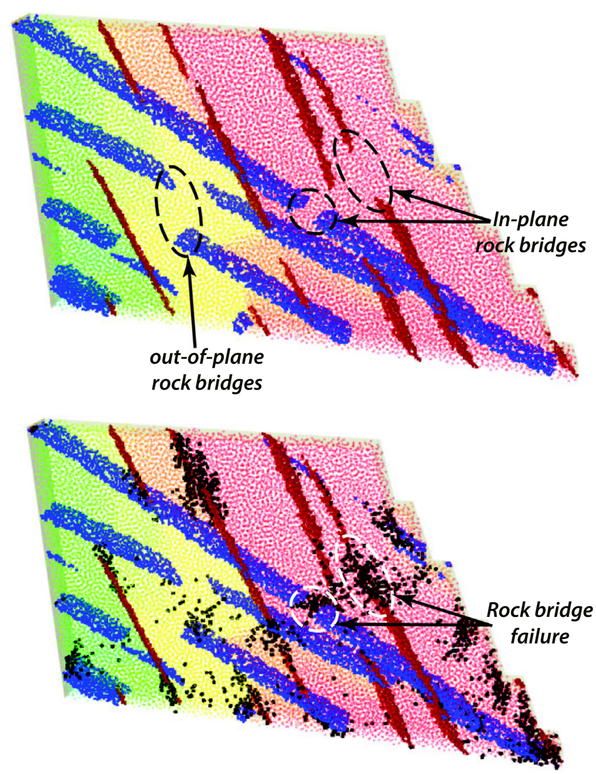

Fig. 4. Slope failure through fracture of intact rock bridges modeled with Slope Model; black dots indicate stress-induced cracks [33].

non-conventional rock slope failure mechanisms for large scale slope problems [17]. This includes the consideration of complex failure mechanisms, whereby failure involves several failure modes including sliding along the major geological discontinuities, step-path failure and circular or quasi-circular failure paths through the intact rock. Stead et al. [18] emphasized the need for incorporating the principles of fracture mechanics and the roles of damage, energy, fatigue and time dependent failure into rock slope analysis. To study the stability of high rock slopes, it is therefore necessary to consider the interaction between existing discontinuities and intact rock, while allowing for potential brittle rock failure. Limit equilibrium solutions consider an apparent cohesion in Mohr–Coulomb theory to account for intact rock bridges along the shear surface, and an apparent friction angle to account for the fact that some inclinations of potential failure have much lower strengths than others [19]. These solutions have been combined with probabilistic Monte Carlo methods to identify critical step paths [20]; however, they cannot represent the complex way in which localized failure propagates by fracture of rock bridges; nor do they account for scale effects.