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Technical Note

A new approach to kinematic analysis of stress-induced structural slope instability

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A R T I C L E I N F O

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A B S T R A C T

The compressive stress trajectory in a slope is parallel to the slope face. In a benched slope the compressive stress trajectory approximates the down-dip line of the overall slope. In steep, high slopes where compressive stress magnitude is high, slope-parallel compressive stress can play a major role in controlling instability related to movement on geological structures such as bedding, foliation and joints. A stereographic approach can be used for kinematic analysis of stress-induced structural instability. The proposed stereographic approach is based on identification of structural orientations relative to the local stress trajectories. Structures oriented obliquely to the principal compressive stress in a slope can become unstable leading to sliding and toppling mechanisms which can differ in orientation from those recognised in conventional gravity-based kinematic analysis.

1. Introduction

Kinematic analysis involves assessing the potential for movement to occur on structures within a rock mass. The assessment is conducted with the use of a stereonet as a graphical tool for representing three-dimensional orientations (Wyllie and Mah, 2004). The stereonet is used to identify the range of planar orientations (represented as poles) that are susceptible to specific mechanisms of structural instability. While rock slope instability often involves multiple mechanisms (Brideau et al., 2007; Alejano et al., 2010), two common mechanisms are planar sliding and toppling. Mechanisms involving multiple surfaces are referred to as wedge mechanisms and are not considered in this paper.

The envelope of poles susceptible to planar sliding is defined by the daylighting window, the friction circle and the strike range, commonly taken (Norrish and Wyllie, 1996) as ±20° for sliding (Fig. 1A). The envelope of poles susceptible to toppling is defined by the outer edge of the stereonet (representing poles to vertical planes on the basis that toppling structure must dip into the face), the friction angle relative to the slope angle and the strike range, taken to be ±10° (Goodman and Bray, 1976; Wyllie and Mah, 2004), ±20° (Norrish and Wyllie, 1996) or ±30° (Goodman, 1980) (Fig. 1A). Maurenbrecher and Hack (2007) discuss the three-dimensional aspects of the selection of appropriate strike ranges.

The friction angle limit for toppling is based on the maximum principal compressive stress (σ_1) in the slope being parallel to the slope face (Goodman and Bray, 1976). The vertical plane limit to toppling is based on the requirement for the weight force to lie beyond the basal extent of the block (block toppling; Goodman and Bray, 1976). Cruden (1989) showed that where a specific basal surface was not present (flexural toppling) the toppling susceptibility field could be extended a further 10° beyond vertical to include structures dipping steeply with the slope.

The kinematic mechanism envelopes described above are used to screen data to assess the potential for structural slope instability for a range of slope orientations and slope angles. Stereographic kinematic analysis of an example data set of structural poles shows a slope oriented northward at 50° having only a low to moderate susceptibility to planar sliding and a low susceptibility to toppling (Fig. 1B). The data contains two major peaks which both have similar strike to the slope but one is dipping too shallowly for the friction angle and the other is dipping too steeply to daylight on the slope (Fig. 1B).

This paper contends that the implications of the maximum principal compressive stress (σ_1) being parallel to the slope face have not been fully examined or incorporated into kinematic analysis methods for planar sliding and toppling rock slope instability mechanisms.

2. Stress trajectories in slopes

A stress trajectory is a line representing the orientation of a principal stress, the maximum principal compressive stress (σ_1) being of most interest. Stress trajectories, together with contoured stress magnitudes, provide a simple representation of stress in a slope. The orientation of a stress trajectory will depend on the remote stresses and any local disturbances to the stress field such as the shape of a slope or excavation (Jaeger et al., 2007).

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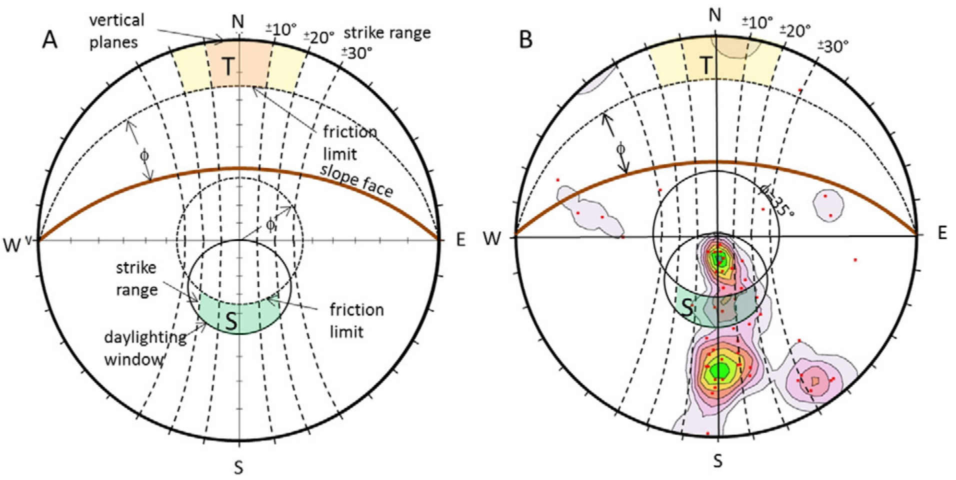

Fig. 1. (A) Equal angle lower hemisphere stereograph illustrating the gravity-driven kinematic analysis for sliding (S) and toppling (T) mechanisms. (B) Example structural orientation data showing low to moderate sliding potential and low toppling potential.

The redistribution of the orientation and magnitude of stress around open pit slopes has been shown by field observation and modelling (e.g. Myrvang et al., 1993; Stacey et al., 2003). Franz et al. (2007, p. 635) observed that in distinct element numerical modelling that "slopes with a height of 500 m or more, the slope stress state causes structure slip to occur even if their dip angle is smaller than or equal to the structure friction angle, which is unexpected if general assumptions of limit equilibrium approaches are taken into consideration".

Finite element models of stress trajectories in slopes readily show that, near the slope face, the principal compressive stress directions are approximately parallel to the overall slope, typically following the down-dip line of the slope (Fig. 2A). This relationship also applies behind the de-stressed zone of the benches of an excavated benched slope (Fig. 2B & C). In the examples given in Fig. 2, the zone of stress parallelism extends tens of metres into the slope and progressively rotates to the remote stress orientations.

The orientation of structural weaknesses, such as faults, joints, bedding and foliation, is a major influence on the stability of rock slopes. In the unloaded parts of benches, the critical orientation of structures is typically considered with respect to gravity. In a smooth natural slope and behind a benched slope the structural orientations must be considered with respect to the local stress trajectory. In this zone the maximum principal compressive stress (σ_1) is approximately parallel to the slope, in a two dimensional cross-section. The zone of stress parallelism can extend tens of metres into the slope, as indicated in Fig. 2.

For any given stress trajectory it is possible to infer the potential for shearing on two surfaces with opposite shear sense (Fig. 3). According to the Coulomb failure criterion (Jaeger et al., 2007) and confirmed experimentally (Rudnicki and Rice, 1975), the angular relationship between the stress trajectory and a shear structure is:

$$\theta = 45^{\circ} - \phi/2 \qquad (1)$$

where θ is the angle between σ_1 and the orientation most susceptible to sliding and ϕ is the friction angle of the sliding surface. It is noted that this equation describes the orientation of newly formed shear structures. If an existing discontinuity or planar weakness lies near this orientation it may be preferentially activated by the stress field.

3. Representation on stereographs

The relationship between orientations of structures and the stress trajectory can be assessed on a stereograph using the down-dip line of the slope as a surrogate for the maximum principal compressive stress direction (Fig. 4A). A ± 20° strike range is shown for reference, however, the role of strike range is not being considered in this paper. It is intended that the stereographic representation shown in Fig. 4 be used as a screening tool for potential stress-induced instability in the same way as gravity-induced kinematic assessment is conducted (Fig. 1). An example set of structural data (same as shown in Fig. 1B) is shown on the stress-induced kinematic analysis stereonet (Fig. 4B). It is observed that one of the main structure populations lies in the envelope for stress-induced sliding (Fig. 4B, S). This sliding envelope includes structures dipping at less than the friction angle because the driving force is delivered by stress parallel to the slope not directly by the vertical acceleration due to gravity on individual blocks. In the example shown, the stress-induced toppling envelope shows that more structures are present than for the gravity toppling envelope (Fig. 4B, T).

As with conventional stereographic kinematic analysis, it is necessary to adjust the stereographic envelopes to match the relevant slope angle, slope direction and frictional characteristics of the rock mass discontinuities.

4. Discussion

The stress-induced structural deformations discussed in this paper are expected to mainly occur in relatively steep and/or high slopes or open pit walls where high stress magnitudes occur. In particular, slopes where the height and steepness are sufficient to produce stresses comparable to the rock mass strength. It is inferred that stress within a slope could induce movement on structures within the rock mass with orientations most susceptible to sliding (Fig. 5A). The presence of stress parallel to the slope face has been emphasised but the principle also applies to other stress orientations that may occur. Consequently, it is not essential that structures daylight in the slope face for movement to be initiated. This internal stress-induced deformation would be observed at surface as a bulging of the slope. Rock slopes which contain structural weakness oriented in one or both of the local critical orientations will be expected to undergo plastic yield at a lower threshold than other rock masses. A structural weakness only needs to be approximately aligned with the critical directions to have an increased likelihood of being activated. The result may be complex mechanisms of structural instability. In a 'heavily jointed rock mass' comprising three, four or more sets and/or random discontinuities, the rock mass approaches an isotropic condition in which rock mass strength, rather than individual structure kinematics, is the dominant failure mechanism (Hoek and Brown, 1997, p. 1169). Within such a rock mass it is