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Technical Note

Distinguishing between single and double plane sliding of tetrahedral wedges using the circle method

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ABSTRACT

A tetrahedral wedge of rock can slide on one or both of the bounding discontinuity surfaces. The test to identify these two mechanisms can be performed on a stereograph based on the orientation of the two discontinuities, their line of intersection and the slope face. An alternative stereographic method involves identifying the great circle, known as a π-circle, linking the discontinuity poles and comparing this plane with the slope face orientation. A kinematically feasible wedge is double plane sliding unless the following two criteria are met. 1) One of the poles is within the daylight envelope for the slope face and 2) that pole lies between the dip direction of the π-circle and the direction opposite to the slope direction of the excavation face. These criteria are readily observable on a stereograph. The boundaries for poles capable of forming single and double plane sliding wedges in combination with another pole can be marked as zones on the stereograph.

1. Introduction

Rock slope stability is highly dependent on the orientation of the discontinuities within the rock mass. In particular, the presence of discontinuities in orientations that in combination can form tetrahedral wedges of rock in excavated faces (Hoek and Bray, 1981; Wyllie and Mah, 2004). Analysis of wedge stability can be conducted by limit-equilibrium and finite element methods (Wang et al., 2004) and can incorporate a range of aspects including dynamic effects (Kumsar et al., 2000), dilatancy (Wang and Yin, 2002) and probability (Jimenez-Rodriguez and Sitar, 2007). However, the stability analysis must be preceded by an assessment of the kinematics of mechanisms requiring further analysis. A tetrahedral wedge of rock can potentially slide on one or both of the discontinuity surfaces that form its base and the stability analysis required for each mechanism differs (Hocking, 1976; Öcal and Özgenoğlu, 1997). Kinematic analysis is typically initially conducted graphically using the stereographic system (Lucas, 1980; Priest, 1985; Lisle, 2004, Lisle and Leyshon, 2004). The geometric relations of planes can be solved analytically however, graphic representations such as the stereograph remain important for presenting results and as a tool for performing rapid assessment of field data. The conventional method of kinematic analysis involves an assessment of the orientation of the intersections of pairs of discontinuity planes (Markland, 1972; Goodman, 1980; Hudson and Harrison, 1997). An alternative method of kinematic analysis involves an assessment of the orientation of great circles linking pairs of discontinuity poles relative to the daylight window of the slope (Smith, 2016). These two methods will be referred to here as the intersection method and circle method, respectively. This paper presents the use of the circle method to differentiate single plane sliding and double plane sliding and assess their kinematic feasible wedges.

2. Methodology

The circle method, or π-circle method, of kinematic analysis of potential sliding wedges involves plotting stereographic great circles through pairs of discontinuity poles and comparing the great circle to the daylight envelope for the slope (Fig. 1A). If the π-circle passes through from one half of the daylight envelope to the other half without intersecting the friction circle, the wedge is kinematically feasible (Smith, 2016). To identify the potential for single plane sliding or double plane sliding to occur, the first criteria to consider is whether either pole lies within the daylight envelope for that slope face. If neither pole lies within the daylight envelope then single plane sliding is not possible. If one or both poles lie within the daylight envelope then the circle method can be further used to distinguish the mechanism of sliding. When a π-circle is constructed through the two poles it will be observed that the dip direction of the π-circle will be either opposite to the direction of the slope face or oriented in the same quadrant as one of the poles. The sector between the dip direction of the π-circle and the horizontal direction opposite to the slope face direction defines the range in which a single plane sliding pole can lie (Fig. 1). If a pole within the daylight envelope also lies within the single plane sliding range (as defined by the π-circle formed with another pole) then it forms a kinematically

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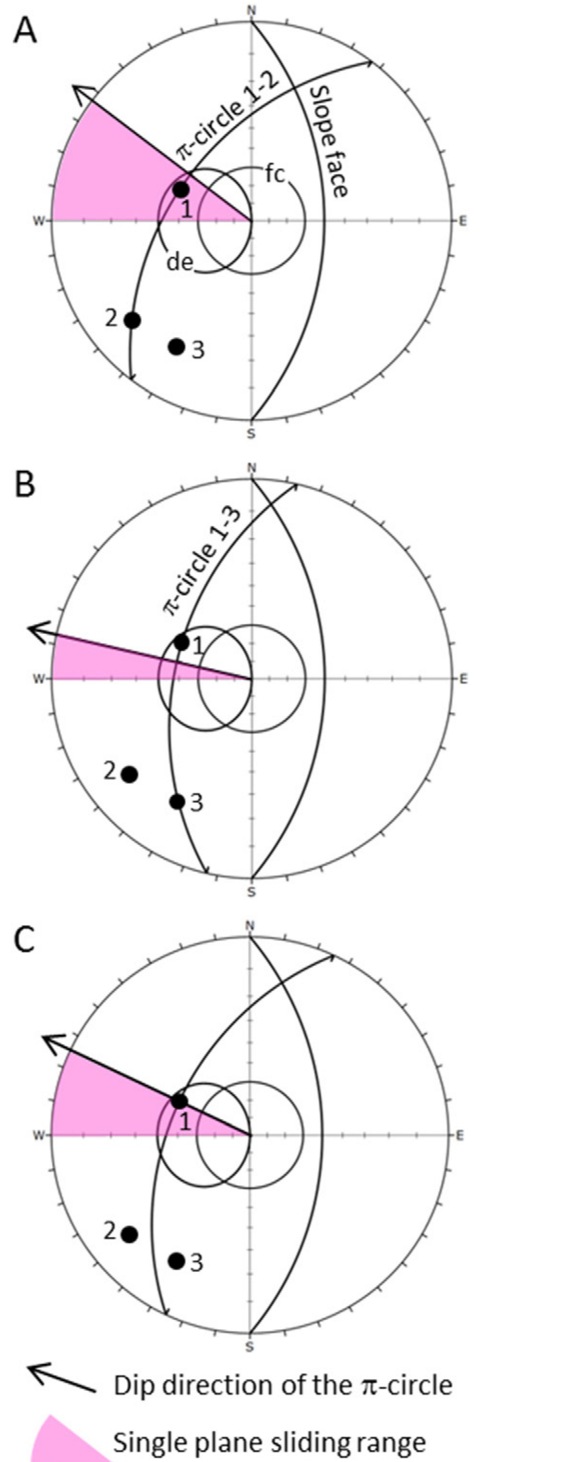

Fig. 1. The circle method for identifying wedges with single plane sliding versus double plane sliding. (A) Poles 1 and 2 combine to form a single plane wedge sliding on plane 1 (fc = friction angle circle, de = daylight envelope). (B) Poles 1 and 3 combine to form a double plane sliding wedge. (C) The boundary between poles forming single and double plane sliding mechanisms in conjunction with pole 1 is defined by the great circle (π-circle) having a down-dip line coinciding with pole 1. Equal angle, lower hemisphere stereograph. Friction angle is 30° and slope face angle is 50° toward east.

feasible single plane sliding wedge surface (Fig. 1A). If the pole is outside the single plane sliding range then the mechanism would be double plane wedge sliding (Fig. 1B). The boundary case is where the down-dip line of the π-circle coincides with a pole (Fig. 1C). Therefore, there is no fixed boundary between poles for single plane and double plane sliding, but a boundary that varies for each pair of wedge-forming poles.

It has been established that a wide range of pairs of planar orientations can intersect in such a way that the intersection occurs in the intersection envelope on a stereograph (Hudson and Harrison, 1997). For a pole to be part of a wedge-forming pair of poles it must lie in a defined part of the stereograph relative to the slope (Smith, 2016). For practical purposes it is logical to focus consideration on pairs of poles which both dip outward from the slope face and each having opposing apparent dips relative to the slope face. For example, wedges of most practical significance for an east-dipping slope face would be formed by two poles both of which are in the hemisphere on the western side (outward dipping) of the stereograph with one pole located in the northern half (left apparent dip, Fig. 2A) and the other pole located in the southern half of the stereograph (right apparent dip, Fig. 2A). The orientation of such poles will determine the shape and sliding mechanism of the wedge, which can potentially form in the slope face (Fig. 2B). The shape of the wedge is observed from the angle between the poles along the π-circle (75° in Fig. 2A) which is the supplement of the angle between the planes defining the wedge (105° in Fig. 2B). If one pole is selected for consideration various limitations can be set for the orientation of the other pole which could potentially combine to form a wedge.

There are five planes of particular importance to the formation of specific types of wedge in combination with a given pole 'P_1'. One of the planes is the limit to poles capable of being part of a feasible wedge (Fig. 2A). That plane is designated as A–B. The four other planes, which all pass through pole P_1, will be designated as plane B–C, plane C–D, plane D–E and plane D/E–F (Fig. 2C). Plane B–C is the plane (great circle) passing through the pole to the slope face (which is also the outermost point on the daylight envelope). Plane C–D has a down-dip line which coincides with pole P_1. Plane D–E is the plane with the same strike as the slope face. Plane D/E–F is tangential to the friction circle. Given an individual discontinuity plane and a slope face it is useful to consider what discontinuity orientations could combine with the first discontinuity to form a wedge and determine what would be the shape and sliding mechanism of that wedge (Fig. 2D).

Based on the planes defined above, six zones can be defined on the stereograph relative to an individual pole and a given slope face. The six zones are designated A to F (Fig. 3). Zone A represents all poles that do not have potential on their own to form a wedge, and therefore, need not be considered further. Zone B represents poles that would form a π-circle intersecting the daylight envelope on one side of the vertical plane perpendicular to the slope. Poles in this zone cannot form a kinematically feasible wedge with pole P_1. Zone C represents poles that can form kinematically feasible wedges which would undergo single plane sliding on the plane represented by pole P_1. Zone D represents poles that can form kinematically feasible wedges which would undergo double plane sliding on the intersection with the plane represented by pole P_1. Zone E is limited to the daylight envelope and represents poles that can form a wedge feasible for double plane sliding or single plane sliding on that plane (depending on the location of the pole relative to the single plane sliding range defined in Fig. 1). Zone F represents poles that form a π-circle that intersects the friction angle and therefore cannot form mechanically feasible wedges with pole P_1. The existence and extent of each of these zones will vary according to the location of pole P_1 (Fig. 3A–D).

3. Conclusions

The shape, kinematics and mechanics of a tetrahedral wedge exposed on a slope face cannot be fully represented by the orientation of the line of intersection alone but also depends on the orientation of each of the discontinuities bounding the wedge. The circle method provides a way of retaining information relating the two planes forming the