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Characterization of bi-planar and ploughing failure mechanisms in footwall slopes using numerical modelling

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ABSTRACT

Footwall slopes refer to unbenched rock slopes in which the slope face is parallel to a set of persistent discontinuities (e.g. bedding planes, foliation, faults). These are commonly encountered in weak, thinly bedded, orthogonally jointed, sedimentary rock sequences. Common failure mechanisms include bi-planar failures where shallow dipping crosscutting structures daylight near the slope toe, enabling sliding to occur along steep dipping bedding planes. In the absence of crosscutting structures, failure occurs through deformation and rock mass yielding involving the formation of inter block shear and toe breakout surfaces. Because of the complexity of the toe breakout mechanism, evaluation methods are not well understood. An improved understanding of the failure mechanism, the role of adverse discontinuities, and characterization of the discontinuity, intact rock and rock mass strength properties are key for a successful footwall stability analysis. This paper investigates the development of the inter block shear and toe breakout surfaces with three approaches: i) continuum-based frictional plasticity theory; ii) discontinuum-based distinct-element modelling with Voronoi tessellation using the commercial software UDEC; and iii) hybrid continuum/discontinuum finite-/discrete-element brittle fracture modelling using the commercial software ELFEN. Numerical simulations using ELFEN and UDEC demonstrated a good agreement with frictional plasticity theory. Ploughing failure of footwall slopes is also evaluated, specifically the influence of cross-cutting discontinuity dip angle relative to the slope face. The effects of different geometrical parameters (e.g., slope angle and depth/height ratio) on bi-planar and ploughing failure are assessed using a sensitivity analysis approach. A “Damage Intensity” parameter is introduced and used to quantify damage in the numerical simulations using ELFEN.

1. Introduction

In the surface mining of metallurgical coal, where the strata have undergone tectonic folding, slopes are often excavated parallel to the strata dip in synclinal and anticlinal structures forming extensive, high and unbenched footwall slopes (Stead and Eberhardt, 1997). Footwall slopes, also referred to as dip slopes, are encountered in other mine and engineered slopes (e.g., road cuts) where instability is structurally controlled, typically by a joint set, fault or weak zone parallel or subparallel to the slope (Konietzky, 2004; Fisher, 2009; Alejano et al., 2011). These authors classify the most commonly encountered footwall failure mechanisms into fully and partially joint-controlled (or rock mass-controlled in the case of the latter) and describe limit equilibrium and numerical approaches for obtaining the factor of safety of bi-planar and ploughing failures. In fully joint-controlled failure mechanisms, stability is primarily governed by the strength of the discontinuities. In the absence of fully persistent discontinuities enabling kinematic release, a more complex failure can occur through sliding along the major geological discontinuities, step-path failure and shearing through intact rock (i.e., rock mass failure).

Hawley et al. (1986) studied the failure modes in western Canadian surface mines and developed limit equilibrium analysis techniques for different modes of failure. Stead and Eberhardt (1997) also reviewed the different failure modes in surface coal mine footwall slopes, discussing the key factors that affect their stability. Based on the analysis of footwall slopes at the Quintette Coal Mine in northern British Columbia and Westfield Opencast Coal Mine in the UK, they introduced a numerical approach to analyse different footwall failure modes using continuum (finite difference) and discontinuum (distinct element) methods. Fisher and Eberhardt (2007) carried out similar distinct-element modelling together with limit equilibrium analyses to provide practical recommendations for the stability evaluation of footwall slopes. Tannant and LeBreton (2007) surveyed a steep footwall slope at Grande Cache coal mine using terrestrial photogrammetry before and after its failure to investigate slope deformation and ultimate failure

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mechanisms. They conducted simple force equilibrium analyses to back-analyse the shear strength properties of the slip surface. Bahrani and Tannant (2011) also investigated this failure. They used photogrammetry to generate failure surface roughness profiles to calculate the dilational component of the shear strength of the failure surface.

Based on these earlier studies, it is clear that the stability of footwall slopes is mainly controlled by the shear strength of the dominant, slope parallel discontinuities upon which sliding may occur. However, because these discontinuities are parallel to the slope and do not 'daylight' in the slope face, they are not considered in a simple planar/wedge kinematic evaluation such as that provided by Hoek and Bray (1981). Nevertheless, failure may still develop depending on the orientation of other cross-cutting discontinuities and rock mass shear strength, and involve bi-planar, buckling, ploughing and step-path failure modes (Stead and Eberhardt, 1997). Thus, to study the stability of high footwall slopes, it is necessary to consider the interaction between existing discontinuities (e.g. bedding planes and cross-cutting joints), intact rock bridges and rock mass strength. Development in sophisticated numerical codes and increasing computing power has made it possible to consider the complex interaction between intact rock, discontinuities, in situ stress, groundwater, dynamic loads, etc. In this study, analytical and advanced numerical modelling approaches are used to investigate the role of brittle fracturing in the development of bi-planar and ploughing failure modes in footwall slopes.

2. Bi-planar failure of footwall slopes

Bi-planar failure occurs when a rock mass slides sub-parallel along persistent discontinuities, such as a bedding plane or fault, with kinematic release enabled through shearing along a secondary shallow dipping discontinuity dipping out of the slope face (Figure 1). A review of the geotechnical literature suggests that bi-planar footwall slope failures are most prevalent in weaker, bedded sedimentary rock sequences (e.g., flysch). Footwall slopes are often associated with anticlines, synclines, and homoclines. Although less common, footwall slopes may also form where faults, shears, or lithologic boundaries occur parallel to an excavated slope. A good example is that presented by Behrens da Franca (1997). He completed a detailed back analysis of a mine slope that was excavated exposing a soft hematite layer with a deposit of itabirite located approximately 30 m behind and parallel to the slope face. At the contact of the hematite and itabirite, there was a thin layer of soft itabirite or leached iron formation which acted as the slope parallel sliding surface causing failure. Bi-planar failures have been reported for natural slopes (e.g. Chen, 1992; Eberhardt et al., 2005). These can develop due to weathering of weaker shale beds or other factors that contribute to progressive failure.

2.1. Different modes of bi-planar failure

Stead and Eberhardt (1997) illustrated variations of bi-planar failure mechanism based on a survey of UK footwall failures and a review of the relevant literature:

2.1.1. Sliding on bedding planes and a basal surface with active/passive zones

The most common mode of bi-planar failure forms when a low angle daylighting thrust plane or cross-cutting joint forms a basal release surface (Stead and Eberhardt, 1997). This type of failure involves an active–passive wedge failure mechanism. Fig. 2 schematically shows a bi-planar failure and location of the active and passive blocks, separated by a Prandtl wedge transition zone. Kvapil and Clews (1979) describe this transition zone as being characterized by severe fracturing and secondary shearing of the rock mass as the forces are transmitted from the active to passive block. This may be observed as large transverse displacements (or inter block shearing) and bulging of the rock mass within the transition zone. In contrast, very little rock mass deformation occurs in the active zone. The majority of the deformation is concentrated along the slope-parallel sliding surface that serves as the release surface in the upper part of the slope. Likewise, there is minimal disturbance of the rock mass within the passive zone, although more than in the active zone. Clearly the rock mass strength within the Prandtl wedge and at the slope toe has an important influence on the amount of movement and ultimately the stability of the rock slope. The strength along the rupture surface in the upper slope is also important as it controls the amount of driving force transmitted to the Prandtl wedge and passive zone below. Stead and Eberhardt (1997) highlighted the work undertaken by Brawner et al. (1971) in which they recognized and proposed methods of analysis for bi-planar failures involving bedding and low angle basal surfaces. They derived stability charts for estimating the allowable footwall slope height as a function of geometrical characteristics of the slope; e.g., bedding angle, bedding thickness, cross-cutting joint orientation, and bedding/joint friction angle.

2.1.2. Persistent basal surface and inter block shear surface

The simplest toe breakout and inter block shearing mechanism involves sliding along the slope parallel sliding surface with a

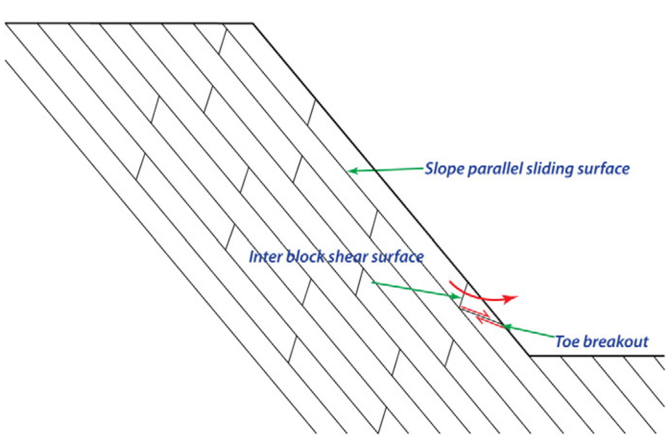

Fig. 1. Bi-planar failure of footwall slopes.

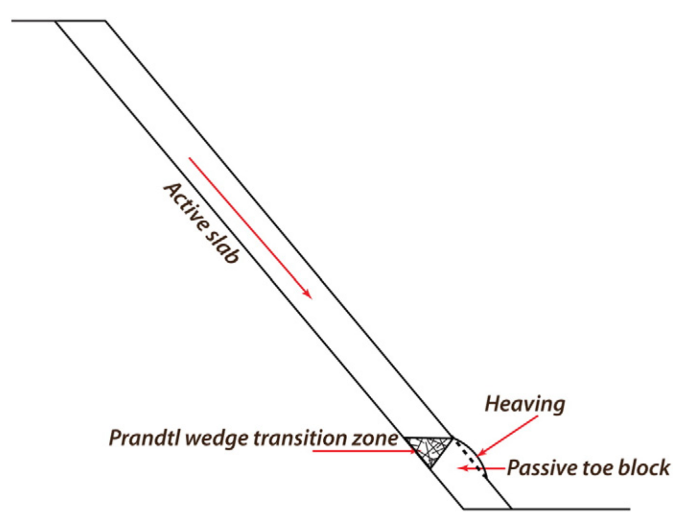

Fig. 2. Location of the Prandtl wedge in a bi-planar footwall failure (modified after Stead and Eberhardt (1997)).