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Cohesion and suction induced hang-up in ore passes

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ABSTRACT

This paper addresses the problem of hang-up in ore passes. A hang-up in a plane ore pass is analysed using the methods of discontinuous stress and velocity fields. The system consisting of broken ore material and a stiff ore pass wall is idealised as a plastic-rigid continuum satisfying the Mohr-Coulomb failure criterion and an associated flow rule. The influence of moisture in the ore, and its associated suction, is accounted for using the effective stress concept for unsaturated geomaterials. A simple failure mechanism consisting of three rigid blocks is assumed which is consistent with a bursting failure type and with the existence of a compressive arch underneath the hang-up section. Stress equilibrium and kinematic restrictions enable the derivation of simple algebraic expressions governing the stability of a hang-up. The separate influences of suction and cohesion are evident in the derived expressions. The paper then applies the derived expressions to a hang-up problem. Strength properties of an ore are determined experimentally using triaxial tests. The way water is retained in the ore is described using its fractal characteristics. It is shown how the ore pass size for hang-up instability is strongly dependant on moisture content and suction. An increase in suction increases the minimum ore pass dimension needed to avoid hang-up formation.

1. Introduction

The phenomenon of hang-up in an ore pass is of interest to underground mine operators as it may lead to loss of productivity and a heavy financial cost to clear them. There are two types of hang-up. One type is governed by the ratio D/d, where D is the ore pass width and d is a characteristic dimension of the ore, usually the size of the largest ore fragments, and is referred to as an interlocking hang-up.[1–3] The other type forms as a result of sticky, fine particles adhering to each other and the ore pass wall and depends primarily on the cohesion of the ore material and its moisture content.[4] Ore materials generally contain particles ranging in size from one or two meters to just a few micrometers in diameter. Ore segregates during handling, tipping and flow through an ore pass. It is the fine component of the ore material which builds up on the ore pass walls and causes hang-up (Fig. 1). This is exacerbated by moisture in the fine component as the moisture induces a suction increasing its strength and the possibility of hang-up formation. Suction and cohesion induced hang-ups are problematic. They are more difficult to dislodge with explosives than interlocking hang-ups.[5] There is also a risk of mud rushes[6] when water is introduced to lower suction and release the hang-up.

There have been related studies on a range of blockage and arching problems in ore passes and hoppers. Amongst the first were Jenike[1] and Kvapil [2] which involved small scale experiments focussing on blockage at narrow discharge zones. Others involved analytical and numerical work[1,7–13] and experiments.[14–16] However, hang-ups are formed by different mechanisms to blockages[17] as they develop in the flowing zone where the ore pass is wider and approximately constant. Research has used empirical and numerical methods to study the influences of ore pass geometry and ore properties on the frequency of hang-ups,[17–19] but there has been no mechanistic analyses of the hang-up problem. This paper addresses this knowledge gap.

In this paper the hang-up problem is solved analytically using the methods of discontinuous stress and velocity fields. These analytical techniques were developed from the theory of perfect plasticity and have been applied successfully to soils, concrete and powder.[20–22] They are suitable for the ore hang-up problem because the system consisting of broken ore material passing through a stiff walled ore pass can be idealised as a plastic-rigid continuum. This greatly simplifies analysis. The versatility of the analysis is demonstrated by adapting a simple hang-up failure mechanism to plane vertical and inclined ore passes. Although

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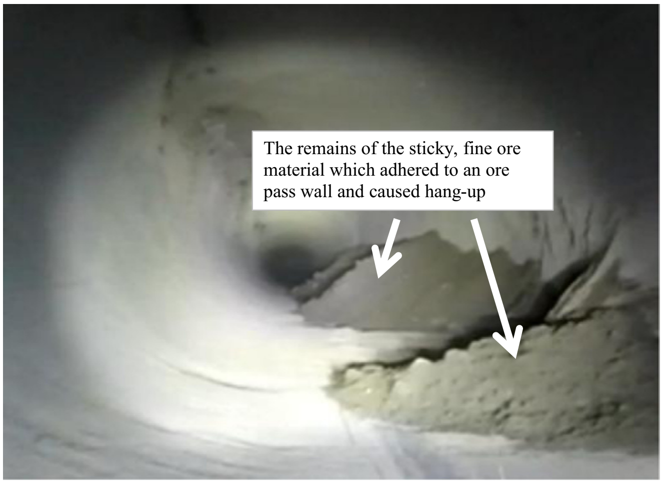

Fig. 1. The photograph shows the inside of an ore pass (looking down) once a hang-up had been dislodged by intervention. The remains of the sticky, fine particles which adhered to the ore pass wall are clearly visible. The ore pass is circular in section with a diameter of 2.8 m and is inclined at 70° above the horizontal. The ore contains particles as large as 1.2 m, although larger particles do not adhere to the ore pass wall so they are not present in the photo.

three dimensional ore passes are not considered, for example those which are square, circular or rectangular in section, some comments are given later on how the results derived here may be applied to them. The influence of geometry is revealed through closed form expressions for a normalised pressure ratio representing a limiting condition when hang-up occurs. The influence of ore self weight can also be studied, for which simple equations are also presented, although it will not be the focus of this paper. The analysis also shows a significant influence of the ratio L/D on the stability of ore hang-up, where L is the hang-up length. Hang-ups inclined slightly and moderately above the horizontal are found to be stable. This indicates that it may be more difficult to clear them compared to hang-ups in vertical or near vertical ore passes.

Critical to the stability of an arch, and therefore hang-up, are the cohesion of the ore material and its moisture content. The paper includes a suction influence in addition to a cohesion influence in the governing mechanics. It is demonstrated how suction can be used in a definition of the effective stress and shear strength and then appear in the governing equations.

In the paper strength and suction properties for a real ore material are obtained using results of triaxial compression test performed at different moisture contents. The measured relationship between moisture content and suction is also presented and proves to be important when quantifying the contribution of suction to strength.

The paper then applies the equations which govern hang-up using the determined ore properties. A hang-up example is detailed, which is similar to hang-up problems that underground mine operators face.

2. Analysis

2.1. Effective stress and shear strength for unsaturated geomaterials

An effective stress for saturated soils was defined by Terzaghi[23] as:

$$\sigma' = \sigma - u_{\mathrm{w}} \tag{1}$$

where $\sigma' \equiv$ effective stress, $\sigma \equiv$ total stress and $u_w \equiv$ pore water pressure. For unsaturated soils and other geomaterials, Bishop[24] proposed an extension of Terzaghi's effective stress as:

$$\sigma' = (\sigma - u_{\mathrm{a}}) + \chi(u_{\mathrm{a}} - u_{\mathrm{w}}) = \sigma_{\mathrm{net}} + \chi s \tag{2}$$

where $u_{\mathrm{a}} \equiv$ pore air pressure, $\chi \equiv$ effective stress parameter, $\sigma - u_{\mathrm{a}} = \sigma_{\mathrm{net}} \equiv$ net stress (i.e. total stress in excess of pore air pressure) and $u_{\mathrm{a}} - u_{\mathrm{w}} = s \equiv$ suction. Bishop[25] suggested that χ depends on many factors including degree of saturation (S_r), s, whether the material is undergoing drying or wetting and stress history. χ attains a value of 1 for saturated conditions and 0 for dry conditions. A prime indicates that the stress is effective.

For simplicity it is assumed that the ore's strength can be defined by the Mohr-Coulomb failure criterion, in which friction angle (φ') and cohesion (c') are independent of s, meaning the same values apply to saturated, dry and unsaturated conditions. There is experimental evidence showing this to be a reasonable approximation.[26–28] The shear strength (τ) is then expressed as:

$$\tau = c' + \sigma' \tan\varphi' = c' + (\sigma_{\mathrm{net}} + \chi s)\tan\varphi' \tag{3}$$

For simplicity it is also assumed that the product χs, representing the contribution of suction to the effective stress, is constant. It will be shown later in the paper that these are reasonable assumptions.

2.2. Discontinuous stress and velocity fields

Prager[29] stated that discontinuous stress and velocity fields are useful for approximating the load causing the initial plastic deformation of a material. This load is referred to as the limit load in this paper. Hill,[30] Green,[31] Green,[32] Shield and Drucker[33] developed techniques for constructing discontinuous stress and velocity fields and used them to calculate the limit loads for various problems. In particular, Drescher[12] utilised discontinuous velocity fields to approximate the stress distributions on hopper and bin walls. Despite similar features between the problems analysed by Drescher[12] and that considered here there have been no attempts to extend these analyses to the hang-up problem in an ore pass.

In constructing a discontinuous stress field the conditions of stress equilibrium, Mohr-Coulomb yield and imposed boundary tractions can be met by inserting stress discontinuities in the ore body. Normal stresses acting on the plane perpendicular to a discontinuity are allowed to undergo a finite jump (Fig. 2(a)). One advantage of this approach is that a stress solution to a given problem can be approximated and graphically illustrated using simple Mohr's circle plots. As the number of discontinuities increase and their curvature fine-tuned the approximate solutions approach the analytical solutions obtained by the method of stress characteristics.[21]

In constructing a discontinuous velocity field the infinitesimal strain-displacement relations and boundary kinematics can be fulfilled by inserting velocity discontinuities in the ore body. As the hang-up of ore is a static problem a velocity discontinuity can also be referred to as a displacement increment discontinuity. For dilative materials in drained loading separation occurs at the discontinuity and the displacement undergoes a finite jump (Fig. 2 (b)).[34] The method of velocity discontinuity has many appealing features. For example, the locations of velocity discontinuities can be predicted from the initial flow patterns (i. e. rupture patterns) observed in experiments.[35–38] For materials obeying the associated flow rule, an upper bound (or lower bound, depending on the directions of displacement increment and external force) to the limit load can be found by equating the internal work dissipated to the external work input.

To calculate the work dissipated in a hang-up section a dissipation function has to be defined. It is assumed in this paper that the ore material is unsaturated and obeys an associated flow rule