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A coupled flow-stress-damage model for groundwater outbursts from an underlying aquifer into mining excavations

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Abstract

Uncontrolled groundwater outbursts from underlying limestone aquifers into mining excavations present a significant safety challenge for underground coal mining in China. Although these mining hazards have been known for decades, the mechanism for groundwater outbursts remains elusive. A fully coupled flow-stress-damage model is presented to simulate the progressive development of fractures and the associated groundwater flow under incremental loading conditions resulting from mining processes. The model is based on classical theories of porous media flow and damage mechanics and importantly links changes in permeability with the accumulation of damage in following the complete stress–strain process. This coupled flow-stress-damage model is applied to examine the influence of mining advance on the initiation, extension, and evolution of an outburst conduit as it develops adjacent to the mine panel. Fractures are shown to initiate both from the wings of the excavation in shear, and from the center of the floor span, in extension. The growth of the extensile fractures is stunted by the presence of a high stress abutment, but the wing fractures extend, with one fracture becoming dominant. As the dominant fracture develops into the underlying over-pressured zone, water pressures transmitted along the now-open conduit reduce effective stresses and develop rapid heave displacements within the floor. The result is a groundwater outburst. The modeling is tuned to the results of laboratory experiments and follows the evolution of a viable outburst path. Observations corroborate with field measurements of permeability pre- and post-mining and are strong indicators of the veracity of the approach.

Keywords: Underground coal mining; Groundwater outbursts; Flow-stress-damage model; Permeability evolution; Rock failure

1. Introduction

In China, a number of coal deposits are located above karst aquifers which contain large volumes of water. Groundwater under high pressure can breach the underburden around active mine panels, and burst into active mining excavations. For the last few decades, catastrophic inrushes of groundwater have comprised a significant and safety challenge for underground coal mining in China [1,2]. The improving safety when mining above ubiquitous over-pressured karst aquifers is a common concern of both mine operators and researchers.

1.1. Statement of the problem

It is of vital importance to know when, where, and how groundwater outbursts develop during mining processes [2–5]. Rock is a heterogeneous geological material which contains natural weakness at various scales. When rock is subjected to mechanical loading, these pre-existing weaknesses can close, open, extend or induce new fractures, which can in turn change the structure of the rock and alter its fluid flow properties. Accordingly, when mining excavations are made, the re-distribution of the stress field leads to the initiation and growth of cracks, and potentially creates a highly permeable damage zone around these excavations. This damage zone creates a pathway for water flow, reduces effective stresses close to the excavation, which in turn may further extend and dilate fractures that

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Nomenclature

D	damage variable (dimensionless)
E	damaged Young's modulus (Pa)
E_0	undamaged Young's modulus (Pa)
f_c	uniaxial compressive strength (Pa)
f_{cr}	residual uniaxial compressive strength (Pa)
f_t	uniaxial tensile strength (Pa)
f_{tr}	residual uniaxial tensile strength (Pa)
F_i	body force (N/m^3)
G	shear modulus (Pa)
k	intrinsic permeability (m^2)
k_0	intrinsic permeability tensor at zero stress (m^2)
m	homogeneity index (dimensionless)
p	pore fluid pressure (Pa)
s	property of element (such as strength or elastic modulus)
s_0	mean of property of element
u_i	displacement vector of solid skeleton (m)

Greek symbols

α	pore-pressure coefficient (dimensionless)
β	coupling coefficient (Pa^{-1})
ε_{ij}	total strain tensor (dimensionless)
ε_{t0}	strain at the peak tensile stress (dimensionless)
ε_{tu}	ultimate tensile strain (dimensionless)
ϕ	internal friction angle (°)
η	residual strength coefficient (dimensionless)
λ	Lamé's constants (Pa)
σ_{ij}	stress tensor (Pa)
σ'_{ij}	effective stress tensor (Pa)
σ_1, σ_2, σ_3,	the first, second and third principal stresses (Pa)
σ_{ii}	average stress (Pa)
ξ	permeability increase factor (dimensionless)

Special symbols

$\nabla \cdot \mathbf{A}$	divergence of a vector ($= \operatorname{div} \mathbf{A}$)
∇A	gradient of a scalar ($= \operatorname{grad} A$)
$\nabla \mathbf{A}$	gradient of a vector ($= \operatorname{grad} \mathbf{A}$)

comprise the damage zone. This reinforcing feedback may either self-arrest, or ultimately accelerate towards an inrush event. Understanding key interactions of this coupled flow-stress-damage behavior are a key component in mitigating the occurrence and effects of outbursts. Although this phenomenon has been known for decades, the contributing mechanisms remain elusive. This knowledge gap has limited our ability to address this crucial issue for safer mining, and defines the objective of this study.

1.2. Previous studies

A number of theoretical models [6–10] have been presented to analyze changes in rock mass permeability that result from excavation-induced deformations. These include relationships between deformations of floor strata and permeability [11] using coupled fluid flow and solid deformation, and have evolved to incorporate complex constitutive laws [3,4] capable of following the outburst process. These studies of fracture behavior and extent during double face mining above a confined aquifer [3,4] have been extended to examine retarded outburst along pre-existing faults [5]. These include consideration of fault extension and weakening [5], and stress redistribution and strata failure [2] which in turn promote permeability enhancement. These studies have variously used field observations [2–5], numerical modeling [3–5], and physical analogs [2]. Although these theoretical models and numerical investigations have contributed significantly to our scientific understanding of groundwater outbursts, crucial questions of when, where and how these events may develop during mining remain unanswered.

Rock mass permeability is known to be strongly stress- and stress-history dependent. The growth of micro-cracks, together with the accumulation of inelastic strain, occurs in brittle rock when it is subjected to differential stress. As cracks grow, coalesce, and interconnect, permeability is significantly altered, and usually increases [12]. This behavior is a consequence of dilatancy and may endure to 80% of peak strength [13]. In many references [14–18], the permeability increase during the formation of compaction band is reported. Wang and Park [3] considered permeability enhancement the key mechanism promoting groundwater outburst in the floor. Therefore, it is crucial to consider changes in permeability that result from rock failure, especially in the strain softening regime of brittle failure. Combined ultrasonic and permeability measurements on rock salt [19] have illustrated the linkage between mechanical damage and transport properties in an analog to brittle failure—cumulative damage initiates dilatancy, that in turn enhances permeability. Changes in permeability that result from deviatoric loading of granite may be as large as two to three orders of magnitude [20]. Such changes have also been recorded adjacent to underground excavations in rock where changes in permeability result from the evolution of the damage zone [12,21].

Finite element, boundary element, finite difference, and discrete element methods, have all been applied to simulate the damage behavior of rocks or rock masses. Jeffrey [22] used a discrete crack model to study the hydraulic