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3D topographic stress perturbations and implications for ground control in underground coal mines

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ABSTRACT

It is well known that the perturbed stress field beneath valleys can result in roof instabilities in shallow underground coal and stone mines. Quantitatively predicting the magnitude of these stress perturbations, particularly beneath complicated three-dimensional (3D) topography, has not become commonplace in mine planning, perhaps due to the complexity and time-consuming nature of the problem. Here we utilize 3D digital elevation models and the 3D boundary element method (BEM) approach to efficiently calculate the pre-mining topographically perturbed stress field in the vicinity of the Carroll Hollow coal mine in eastern Ohio. We find that regions of elevated compressive stress in the mine correspond to areas in which cutter roof failure is a common source of roof instability. Furthermore, both the magnitude and inclination of the principal stresses calculated from the 3D topographic BEM model are found to be consistent with observed failure distributions within the mine. We propose that the approach outlined in this study can be efficiently applied to the mine planning process in order to mitigate or avoid potentially hazardous mining conditions.

1. Introduction

Of the 77 reported fatalities in underground coal mines nationwide from 2007 to 2011, 26 resulted from roof or rib falls [1]. Furthermore, Moebs and Stateham [2] reported that as many as 90% of roof falls in underground mines in the Appalachian Basin occurred in mines beneath stream valleys [2]. While this is a difficult number to confirm, Molinda et al. [3] mapped roof failures in five mines in Pennsylvania and found that 52% of roof failures occurred directly beneath valley bottoms, whereas fewer than 10% of roof falls occurred beneath hills. The same study indicated that valley shape is also an important factor, and risk of roof failure beneath broad valleys is generally greater than beneath sharp v-shaped valleys [3]. The cause of increased roof failure rate beneath valleys has many potential sources, including (1) magnification of the horizontal compressive normal stress and (2) long-term degradation of roof rocks due to fracture and fluid infiltration; however all of these potential sources are directly related to a perturbation in the regional stress field associated with uneven topography. The general relationship between stream valleys and roof instability has been recognized for quite some time [2–5]; however surface topography has not commonly been taken into account quantitatively when planning underground excavations.

Roof stability in underground mines is controlled by the quality and thickness of the rock layers which encase the excavation, the geometry of the excavation, the stress state around the mine excavation, and the presence of pre-existing geologic structures such as joints, faults, and channel sand deposits. Mechanisms of roof instability can be divided into geologic and stress-related mechanisms as well as post-mining degradation of the roof rock due to exposure to fluids. For shallow coal and stone mines, stress-related mechanisms are principally controlled by the greatest horizontal compressive stress, σ_H, in layered sedimentary rocks [6]. Because topography perturbs the stress field in the near surface, particularly where the depth is of the same order of magnitude as the topographic relief, the magnitude and orientation of σ_H, and other stress tensor components, can be extremely heterogeneous throughout the mine; yet no efficient method has been developed to calculate its distribution during the mine planning phase. However, given some basic observations, the state of stress acting on a target layer (coal seam, limestone, etc.) can be

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predicted with significant confidence *a priori*. Here we study the heterogeneous stress field induced at the scale of an individual mine by modeling the interaction of topography and tectonic stresses using the three-dimensional (3D) boundary element method (BEM) code *Poly3D*. The computed stress fields are evaluated in terms of mapped roof failure mechanisms throughout the mine. The results suggest that the computed stress field accurately represents the state of stress acting on the coal seam before creation of the excavations. Therefore, the approach outlined in this manuscript represents a potentially powerful, efficient means to optimize mine planning in order to minimize potential risks related to stress-related roof failure mechanisms.

2. Previous work

Molinda and Mark [6] listed several factors which commonly result in unplanned roof failures in underground coal mines, including geologic heterogeneities, moisture degradation of the roof rocks, extreme loading conditions, multiple seam mining, and inadequate support. A number of roof fall types, including stack-rock delamination, cutter roof, and spalling roof are typically attributed to large magnitudes of “horizontal stress”, the component of normal stress acting parallel to the roof strata [6,7]. Layer–parallel loading leads to buckling of the stratigraphic roof layers. Furthermore, moisture degradation can be enhanced in areas of large horizontal stress due to damage and increased permeability in roof layers, and unstable conditions around geologic defects can likewise be exacerbated by magnified horizontal stress.

The study of the mechanics of failure in undermined strata has been a topic quantitative research for some time. Bucky [8] pioneered the use of a centrifuge to build scale mechanical models of underground openings in stratified rock, and Bucky and Taborelli [9] showed that fractures formed at the mid-span of roof layers are the dominant mechanism of failure under gravitational loading conditions. Evans [10] developed a “Voussoir Beam” model, in which an arched and cracked elastic beam is confined between abutments, to study the failure mechanisms of rock crushing of roof strata at abutments or midspan, buckling of the beam and tensile failure of the beam at midspan, and sliding of the beam at abutments. Many more recent researchers have studied and improved Evans' Voussoir Beam approach in recent years [11–13]; however the model is ultimately two dimensional, and therefore limited in its applicability to complicated mine geometries such as room and pillar mines where stress perturbations associated with adjacent rooms are prone to mechanical interaction. Furthermore, the Voussoir Beam model is difficult to apply successfully where the 3D state of stress is heterogeneous and/or anisotropic.

A significant amount of work across the fields of geology and engineering has shed a great deal of light on the multi-scale nature of the state of stress in the earth's crust. The state of stress in the earth's crust is heterogeneous and anisotropic; yet at the global (crustal) scale, the directions and magnitudes of principal stresses are remarkably systematic, and stress trajectories are largely related to tectonic processes [14–17] (Fig. 1A). For example, in the northeastern United States, the maximum principal horizontal stress (σ_H) follows a NE–SW trend, and in the Appalachian Plateau in eastern Ohio, the location of the current study, σ_H trends approximately N60°E (Fig. 1A). At the regional scale, however, the state of stress may be highly heterogeneous, affected by geologic structures such as faults, and, near the earth's surface, by irregular topography (Fig. 1B). Given that many underground mine workings in the Appalachian Basin region are at depths less than a few hundred meters, stress perturbations at this scale due to topography are of immense importance, as such perturbations may decrease (or increase) the stability of mine workings. Furthermore, once the excavation is introduced in this already heterogeneous stress field, the local stress field is further perturbed (Fig. 1C).

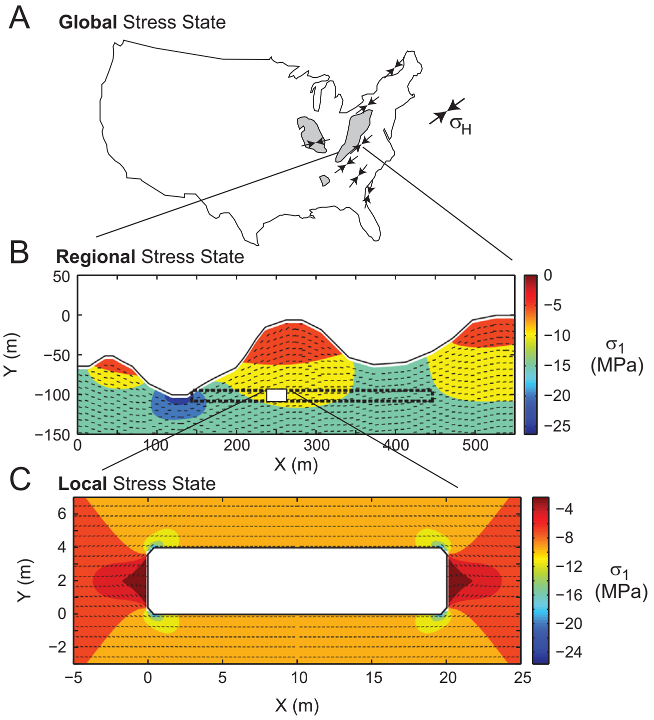

Fig. 1. Nature of the (A) global, (B) regional, and (C) local excavation-scale states of stress. (A) is shown in map view while (B) and (C) are vertical cross-sections.

The importance of topographic effects on subsurface stress has been recognized for some time. Unfortunately, however, perhaps due to the complex nature of the problem, quantitative assessments of the increased risk associated with mining under stream valleys are not customarily made. Empirical estimates of the stress effects of stream valleys [4] have focused on shape factors of the overlying valley, as well as the ratio of excavation depth to total surface relief as critical parameters in the estimation of stability risk; however it is difficult to incorporate the far-field tectonic stress state in such models, as this component of the stress field is independent of local factors such as topography. A number of workers have utilized the method of conformal mapping pioneered by Muskhelishvilli [12] to derive exact closed-form solutions for the elastic stress fields beneath slopes under different loading conditions [18–21]. While such solutions produce quick estimates of subsurface stresses, they are limited to simple idealized topographic shapes. Pan and co-workers [22–25] were able to develop a semi-analytical approach by combining the conformal mapping and the integral equation methods. Under gravitational stress only, they found that beneath irregular, asymmetric valleys and ridges, there can be several locations of local stress maxima and minima which could be potential locations of rock failure [22,24]. They also showed that under a horizontal tectonic stress, the compressive stress on the bottom of the valley could be several times larger (more compressive) than the applied tectonic stress. They further showed that, under combined gravitational and tectonic stresses, a stress concentration could also exist on the shoulder of the ridge [25]. They concluded that the topographically perturbed stress field depended strongly on the depth of the valley, the rock elastic properties, and the orientation of the rock strata [23]. For transversely isotropic rocks for which the plane of anisotropy is horizontal, as is the case for flat-lying sedimentary rocks, the increase of the horizontal compressive stress relative to the background global value can be considerably greater than for the isotropic case. A preliminary application of such findings is on the optimal selection of unlined pressure tunnel alignment [26].