



Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Technical Note

Validation of critical strain technique for assessing stability of coal mine intersections and its potential for development of roof control plans

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ARTICLE INFO

Article history:

Received 11 July 2017

Received in revised form

19 October 2017

Accepted 23 October 2017

Available online 31 January 2018

Keywords:

Roof support

Critical strain approach

Numerical modeling

ABSTRACT

Both room-and-pillar and longwall mining systems develop underground excavations whose stability must be ensured over their entire service life. Even though rock bolts have been extensively used as a support element in US coal mines for about 40 years, limited research has been conducted in quantifying its composite reinforcement effects. Recently, the authors suggested an approach to quantify the reinforcement effect of roof supports over a designated area based on critical failure strains in tension, compression and shear. This paper validates the critical strain technique (CST) using a case study and justifies the magnitude of selected critical strain by corroborating with the US roof fall statistics. Intersections are vulnerable to failure due to the larger exposed roof span and associated stress concentrations. Through numerical application of the CST to a case study, it was demonstrated that modifying the opening orientation and installing reinforcement at critical locations can help to improve the overall stability of intersections.

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1. Introduction

Longwall and partial extraction room-and-pillar techniques are the two major mining methods employed in the US coal mines. Both systems develop 3-way and 4-way intersections during mine development and coal extraction. Thirty percent of the fatal injuries occurred at intersections, of which 68% occurred at 4-way intersections while only 32% occurred at 3-way intersections (Abbasi, 2010). This increased frequency of accidents at 4-way intersections was primarily due to the greater effective roof span. Studies conducted on rock falls (fatal and non-fatal injuries) in the US by Spearing and Mueller (2008) and Chugh and Kollipara (2009) revealed that about 70–75% of rock falls occurred at intersections.

Since an intersection represents a three-dimensional (3D) problem, early closed-form solutions using plate theory for stress distribution around an intersection were simplistic (elastic, homogeneous rock mass). It is only in the last two decades, since the development of numerical modeling techniques, that researchers have attempted to develop a more scientific understanding of stress distribution under realistic conditions such as nonhomogeneous

and nonlinear rock mass behavior, sequential development of intersection (Abbasi, 2010), and incorporation of turned corner on one or more pillars around an intersection. Field studies by Hanna et al. (1986) and Hanna and Conover (1988) in the Illinois Basin provided data on bed separations and displacements around intersections. However, limited research has been done on designing roof support plans that would improve the stability of intersections.

The primary hypothesis of the context is that appropriate selection of primary and/or secondary supports and their spatial distribution can improve the stability of intersections. An important associated research issue is to assess the effectiveness of a particular roof support plan. One can use a stress-based approach, as has been done by several authors (e.g. Gale et al., 2004; Esterhuizen, 2012), but it suggests that using a stress-based approach in nonlinear behavior zones may not provide realistic estimates of failed zones and support requirements. Therefore, there is a need for a better understanding of stress and strain distributions around an intersection, zones of failure based on appropriate deformation-based failure criteria and its use to improve support plans around intersections.

Rock bolts have been extensively used as a primary support element in coal mines in the US for about 40 years. Typical cost of roof control constitutes about 7–20% of the production cost depending upon site-specific geo-mining conditions. The authors think that one of the primary reasons is the lack of scientific basis in

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

the design of roof control plans. Most of the currently practiced bolting layouts were developed based on field experience rather than on scientific basis. Therefore, it would be a contribution to develop an approach that can identify critical areas of instability around an intersection and assess the efficiency of a roof control plan in terms of support installation time and capability. These critical zones can be supplemented with appropriate reinforcement elements to come up with scientifically sound roof control plans that will be capable of controlling rock mass deformations around an intersection.

Recently, Chugh and Sinha (2015) suggested an approach to quantify the reinforcement effect of a roof support plan over a designated area. It employs analyzing zones of the critical tensile ($\epsilon > 0.5 \times 10^{-3}$), compressive ($\epsilon < -1 \times 10^{-3}$) and shear ($\gamma < -0.5 \times 10^{-3}$ and $\gamma > 0.5 \times 10^{-3}$) strains in the immediate roof before and after installation of supports. The analytical approach computes three separate reinforcement factors: reinforcement against tensile strains (RFT), compressive strains (RFC) and shear strains (RFSS) for immediate roof, coal pillar and immediate floor strata. Another study by Sinha and Chugh (2015) compared the Mine Safety and Health Administration (MSHA) approved roof support plans for 150 m and 80 m depth mines using the above approach. Since some of the previous relevant researches have been summarized in Chugh and Sinha (2015), it is not included here.

This study is a continuation of the authors' efforts to understand the stress and strain distributions around an intersection and improve its stability through cut sequence, reorienting the entries (with respect to pre-mining stress field) and bolt reinforcement. The goals of this paper are two-folds: (i) Validate the critical strain technique (CST) through comparison against published coal mine accident statistics, and (ii) Demonstrate the capability of this approach in improving the intersection stability through application to a case study.

2. Critical strain technique for assessing stability of intersections and reinforcement factors due to bolting

The CST is based on the assumption that immediate roof stratum over an excavation acts as a beam or a plate resting on elastic or inelastic foundations and is subjected to uniform or nonuniform loading from strata above. The loading results in a bending curve that has at each point vertical and horizontal displacements, slope, curvature and horizontal strains; the last two are mathematically correlated.

A typical deflection curve of immediate roof over an excavation would have associated curvature and horizontal strains at each point and would be expected to be different with and without roof supports. It is further known that failure of the immediate roof stratum will initiate due to tensile, compressive, or shear strain when the critical strain values are exceeded. This analytical approach can compute three separate reinforcement factors due to roof support: RFT, RFC and RFSS. Areas of immediate roof in a specified region that exceed critical tensile, compressive, or shear strain before and after bolting can be compared to compute the respective reinforcement factor. The critical value of tensile and shear strains used is 0.5×10^{-3} although a different value could be used. The critical value of compressive strain used is 10^{-3} (Sinha and Chugh, 2015).

The following example shows how reinforcement factors can be computed from the number of critically strained elements in numerical models. Table 1 lists the critical strain areas (number of elements can be related to the area by multiplying with the dimension of model elements; here, the area is listed) for two hypothetical cases: Case I (no support) and Case II (with roof support plan) over an arbitrary region UVWX, where U, V, W and X are the

Table 1
Critical strain areas in an arbitrary region UVWX.

Case	Failure type ^a	Critical strain area (m ²)		
		ϵ_{xx}	ϵ_{yy}	γ_{xy}
No bolt (1)	Tensile	9	0	69
	Compressive	64	13	74
Roof support plan (2)	Tensile	6	0	64
	Compressive	55	13	68

^a Compressive: exceeding lower critical strain bound; Tensile: exceeding upper critical strain bound.

vertices of the region. From the table, the following results can be computed: (i) Area of critical compressive strains in X-direction is reduced from 64 m² to 55 m², therefore, $RFC = (64 - 55)/64 \approx 14\%$; (ii) Critical tensile strains area in X-direction is reduced from 9 m² to 6 m², thus $RFT = (9 - 6)/9 \approx 33.3\%$, and (iii) Critical shear strain area is reduced from 69 m² to 64 m² yielding $RFSS = (69 - 64)/69 \approx 7.2\%$. For further details on application of CST, the reader can refer to Chugh and Sinha (2015).

The critical strain values are related to discontinuities rather than for intact rock. Field data on critical strains in underground mines that result in rock mass failure initiation are not available. Therefore, available field data on ground deformations that result in structural damage due to mine subsidence were considered logical for use (Baker, 1974). Further analyses were attempted to assess the suitability of the above values.

2.1. Validation of the critical strain technique based on the US roof fall statistics

A quarter model was developed for an idealized intersection (without turning corner) following the lithological sequence and modeling procedures detailed later in Section 3.1. Three regions, as specified in Fig. 1, were selected for the analysis. Each region was subdivided into volumetric elements of the size 0.25 m \times 0.25 m \times 0.1 m. The regions extend through the entire height of the coal seam and immediate roof strata (medium gray shale). The rationale behind incorporating coal in the analysis is that the failure may occur in the coal, roof or floor strata as part of the pillar system. Since coal is the weakest link in the system, it is typically involved in the failure process. The critical strain limits used for analysis are 10^{-3} for compressive strain, 0.5×10^{-3} for tensile strain, and 0.5×10^{-3} for shear strain.

Within the defined 3D volume, elements exceeding critical strains were counted for coal and roof strata separately, while the floor layer was ignored in these preliminary analyses. Table 2 shows the values obtained through this procedure. Since the dimensions of the elements are equal in the roof and coal lithologies, additive rule can be applied. Table 3 illustrates the net possibility of failure initiation in different modes for intersection corner, entry along X-direction and entry along Y-direction. The critical strain values provide an indication of failure initiation. It must be mentioned here that the effect of stress redistribution after failure initiation is not considered.

The formulae used for determination of net failure possibility at corner and entry are: (a) Intersection corner: Four times the summation of failure initiation possibility in each failure mode, and (b) Entry: Two times the summation of failure initiation possibility in each failure mode. The factors 4 and 2 have been used since the initiation of failure can occur at four points in an intersection and at two points in an entry. The ratio of net failure initiation possibility in entries to the net failure possibility at corners was compared with US roof fall statistics. For values presented here, the calculations are as follows:

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