The Effect of Discontinuities Characteristics on Coal Mine Stability and Sustainability: A Rock Fall Prediction Approach

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ABSTRACT

Rock fall related accidents continue to occur in coal mines, although artificial support mechanisms have been used extensively [1]. Roof stability is primarily determined in many underground mines by a limited number of methods that often resort to subjective criteria. It is argued in this paper that stability conditions of mine roof strata, as a key factor in coal mines, must be determined by a survey which proactively investigates fundamental aspects.

Failure of rock around the opening happens as a result of both high rock stress conditions and the presence of structural discontinuities. The properties of such discontinuities affect the engineering behavior of rock masses causing wedges or blocks to fall from the roof or slide out of the walls [2]. A practical rule-based approach to assess the risk of a roof fall is proposed in the paper. The method is based on the analysis of structural data and the geometry and stability of wedges in underground coal mines. In this regard, an accident causing a huge collapse in a coal mine leading to four fatalities is illustrated by way of a case study. A comprehensive investigation of the hanging wall has been gathered through a systematic collection of evidence. The investigation results are then analyzed, and an interpretation of the evidence gathered is provided.

For this purpose, horizontal and vertical profiles are prepared by geophysical methods to define the falling zone and its boundaries. The collapse is then modeled by the use of sophisticated computer programs in order to identify the causes of the accident and hence recommend corrective actions to prevent or minimize reoccurrence probability of similar accidents. The corrective measures are placed into a rule-based framework for the benefit of the mine operators.

INTRODUCTION

Roof rock failure has generally been the most dangerous hazard for underground coal mining in the world. Failure of rock around shallow coal mine openings often results from loosening of blocks of rock on the weakened planes under the influence of gravity. This condition is not typically seen in large deep coal mines. There are a number of differences between large mechanized mines and small mines related to ground control [3].

Many small coal mines have relatively strong roof rocks, but the presence of discontinuities results in the potential danger of falling roof blocks or even a large-scale collapse. The strength of roof rocks varies widely depending both on the rock type and on planes of weakness present within it [3].

The strength of a discontinuity plane can vary considerably. The boundary between two surfaces of the discontinuity is a ‘shear’ zone and this has little or no strength and as a result, underground mining may induce unstable shear failure along geological discontinuities [3].

The major proportion of developing countries’ coal is excavated through artisanal methods in small-scale mines, where roof stability is often not studied thoroughly. For example, structural instabilities tend to be ignored while properties of such discontinuities affect the engineering behavior of rock masses. Determining the active structural discontinuities that led to the fall of wedges or blocks from the roof, or sliding out of the walls of the mine opening, is a difficult technical task that is related to mapping and modeling discontinuities.

Roof Rock Failure

Fall of roof blocks bounded by planes of weakness can occur with little warning and is the cause of serious accidents in apparently good roof conditions.

There are many lessons to be learned from almost every roof fall accident, but generally the factors contributing to the accident are not clear; thus, much of the evidence is almost fully destroyed in a huge collapse such as the collapse of a hanging wall [4].

Roof rock failure in small mines may take the various forms from tiny cracks in immediate roof to a large scale movement of blocks of rock that extend up to the shear zone which could be tens of meters above the roof horizon. The weight of the failing zone could therefore vary from a few kilograms to as much as hundreds of tones, that far exceeds the support capacity of typical small mine systems.

Discontinuities in Coal Strata

A discontinuity is defined as a separation in an intact rock where two of its dimensions are several orders greater than the third dimension. Geometric and mechanical characterizations of rock discontinuities are important in the modeling process.

Coal strata contain discontinuities of various types, which control the strength of the rock coal seam. The discontinuities of coal and its surrounding rock are largely divided into two types; firstly, discontinuities occurring post-peat accumulation (faults, joints, cleats, etc.), and secondly, discontinuities occurring concurrently with peat accumulation (bedding planes, slickensides, etc.). In fact, they are rarely homogenous and isotropic in most continuum mechanics theories [5, 6].

Coal strata include generally, in descending order of strength (UCS), limestone (6,000-32,000 psi), sandstone (2,000-21,000 psi), siltstone (2,000-19,000 psi), and shale (<1,000-16,000 psi). Mudstone or claystone are similar to shale without the laminations. This order of strength is correct only when there are no discontinuous features such as bedding separations or fractures in the rock strata [6].

UNWEDGE SOFTWARE

A numerical modeling method is required which can model the presence of discontinuities as well as the failure mechanism of the coal material. UNWEDGE is a computer software program that calculates the possible wedges that can form around the excavation by the intersection of the three discontinuity planes of the excavation [7]. Wedge geometry (orientation) and the strength characteristics of discontinuity planes (discontinuities shear strength) that create the wedge and stresses within the coal bed affect the wedge stability. In using the software the following observations are warranted:

i. The orientations of three distinct discontinuities may be defined by their respective geophysics profiles. Wedges are considered tetrahedral, and the three discontinuity planes make up three sides of the tetrahedron. The fourth side is formed by the excavation boundary;
ii. The stope axis orientation is defined by the trend / plunge of the stope axis. In general, for any excavation orientation, the opening section is always a cross section perpendicular to the trend / plunge of the excavation axis;
iii. The shear strength of the discontinuities that separate the blocks controls stability of the system of individual rock blocks. Shear strength of the discontinuities are analyzed by the Mohr-Coulomb method ($\tau = c + \sigma_n \tan\varphi$) in the project. Where τ is the shear strength of the discontinuity, c is the cohesion, σ_n is the normal stress, and φ is the friction angle of the discontinuity plane. Shear strength is computed based on the normal stress acting on each discontinuity plane. The normal stress is computed based on the active and passive normal forces computed on the discontinuity planes; and
iv. The influence of water pressure on the stability of a wedge may be important in some cases, but since underground stopes are usually free-draining the water pressure is assumed zero.

Case study: Roof fall accident in Eshkeli coal mine

Eshkeli coal mine is located in Iran (Figure 1). The geological formation of the mine belongs to the middle Jurassic period. The lithology of the formation includes sandstone, siltstone, mudstone, and coal. The proven reserve has been estimated at 3 million tons of coal. The mine's region has been tectonized by tectonic processes and 11 main faults have been identified, and the average thickness and dip of the coal bed are 3 m and 35° respectively in the mine. The mine has 4 levels from 2,300 m to 1,900 m.

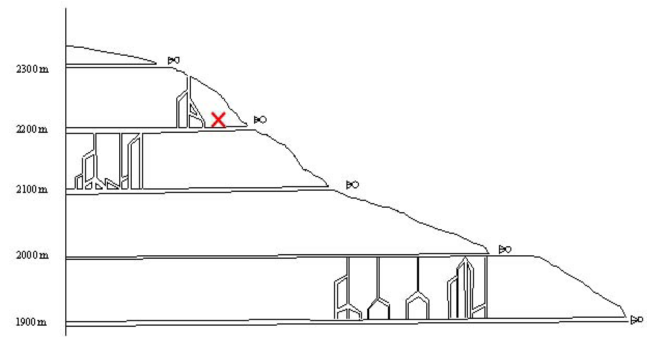

Figure 1. Sketch of Eshkeli coal mine (×: accident place).

The region's topography is rough and many hills and valleys are in the region, as shown in Figure 2.

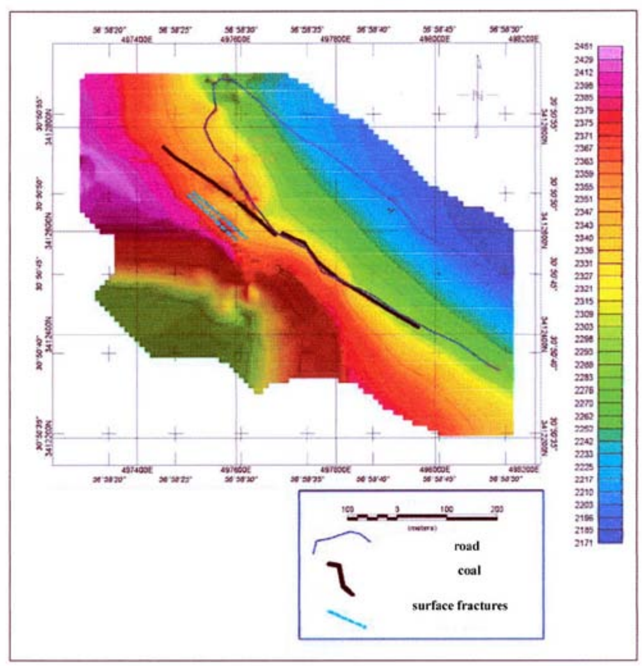

Figure 2. Topography map of the mine region.

A huge collapse occurred on 14 December 2010 at 11:30 while miners were installing the support system in the mine. All of the workers / miners (in four mining operations) that were at the location of the collapse (*stope 103*) were killed, and their bodies were retrieved four months later after drilling a rescue tunnel. The failure was so severe that it caused some cracks on the earth (Figure 3). A sketch of the collapsed stope (stope 103) (level 1 of the mine) is shown in Figure 4.

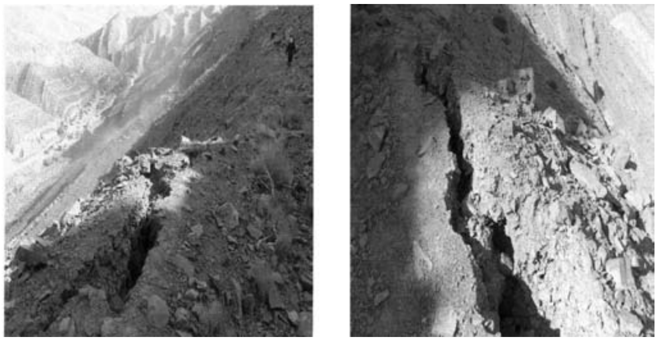

Figure 3. The cracks that were displayed on surface of failure zone.

Figure 4. The collapsed stope (stope 103).

The green lines show the collapsed part of the stope, and 8.95 m of stope length (26.82 m) was covered by the debris of the failure. The yielding steel sets that supported the haulage tunnel that was on level 2200 m (see Figure 1) were affected by the failure and they were compacted as much as 30 cm, and the struts were also deformed relatively (Figure 5).

Not all coal beds are suitable for mechanized mining such as longwall or room-and-pillar methods. The method of mining in

Figure 5. The displacement in the yielding steel sets and deformation in struts on the beneath level of the fractural zone (level 2200 m).

Eshkeli is stull stoping, which is generally used in small-scale coal mining in developing countries. The method follows characteristics such as flexibility, adaptability, and low capital, which other methods cannot easily match. The method applies to thin and steep coal beds with weak hanging and foot walls. Ground control is accomplished by timbering (wooden square-set) between the foot and hanging wall or backfilling with waste for a large stope. The minimum requirements are a haulage drift and crosscut to the stoping area. Two raise between levels are also drilled for access and ventilation [8]. Geometry of the stope is defined in Table 1.

Table 1. The geometry of stope.

Length	26.82 m
Width	4.5 m
Height	3 m
Dip	35°
Dip direction	69.5°

Geophysics in ground fall detection

Most ground fall incidents could be prevented by the use of available technologies. Geophysics in ground control refers to the detection of underground geological anomalies and assessment of rock strength and monitoring of opening stability (Hatherly, 2006) [6]. Several geophysical methods are available for locating discontinuities. Seismic, electrical resistivity and magnetic methods are applied to detect geological discontinuities in ground control operation. Geophysical methods do not measure discontinuities directly, but simply measure the changes in the potential fields caused by the changes in the geophysical properties for their presence. Geophysical data are usually displayed in the form of a contour map, but their interpretation is often made on profiles. The discontinuities are located by the interpretation of the natural geological boundaries at depth even if they are not outcropping at the surface [10].

Structural analyses of post-collapse geophysical information, obtained through electric and magnetic surveys assist mining accident investigators in understanding why and how the collapse occurred.

The magnetic method involves the measurement of the earth's magnetic fields' intensity by a magnetometer. In detailed magnetic surveys, a magnetic anomaly is usually related to a smaller magnitude that may be associated with the presence of fractural strata in joint zone or fault planes. In contrast, discontinuities may show up a higher magnitude as they were filled by magnetic material such as ferruginous cement.

Magnetic lineaments were found by magnetic method and are shown in Figure 6, which depicts geophysics' horizontal profile. The two main separate faults that affected the failure zone are shown as 1, 2 discontinuities in Figure 6, where the location of the collapsed stope is shown by the yellow circle. The third discontinuity was not uncovered by the magnetic method, so the resistivity method was applied as the additional measurement.

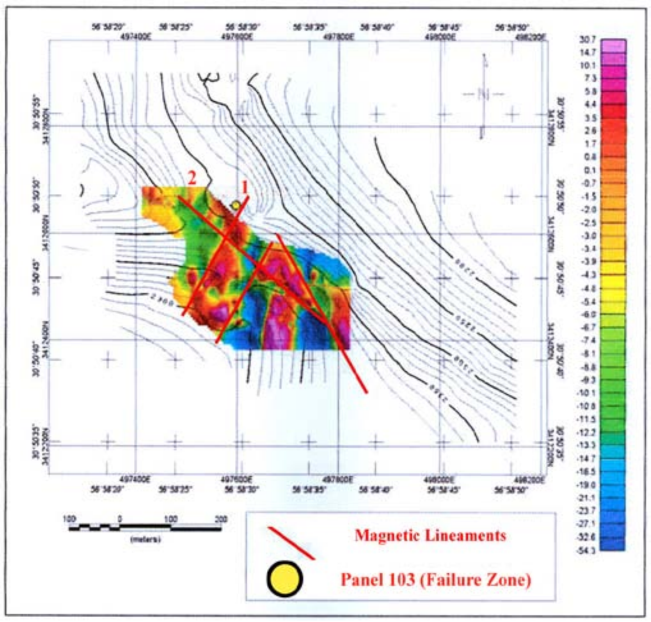

Figure 6. Magnetic horizontal profile.

In the resistivity method, an electrical current is applied into the ground by current electrodes, and the resulting potential distribution in the ground is mapped by two potential electrodes. Electrical conductivity is governed by the earth's crust material properties (density, permeability, porosity, and etc.). Coal has much higher relative conductivity than discontinuities, where a fracture or a failure zone increases the volume of porosity and consequently the electrical resistivity [9].

The vertical profile of the failure zone is shown in Figure 7. Failure zone started from the level of 2355 m (Figure 7), and the height between top and bottom of the failure zone is estimated as 20 m (from 2375 to 2355) and extended to the level of 2200 m, where there was the coal bed. Thus, this coal bed acted as a weakness plane or discontinuity.

Bed separation and failure can occur along the bedding planes in stratified deposits, especially when the thickness of the coal seam is not uniform. It is, therefore, possible that coal bed released from the hanging wall. In the present case study, the thickness of the coal bed fluctuated vastly between the level of 2300 m and 2200 m inthe mine. The changes in thickness are shown in Figure 8 (from 2.80 to 1.29 to 0.45 or 2.50 to1.40 to 0.42 m) [9].

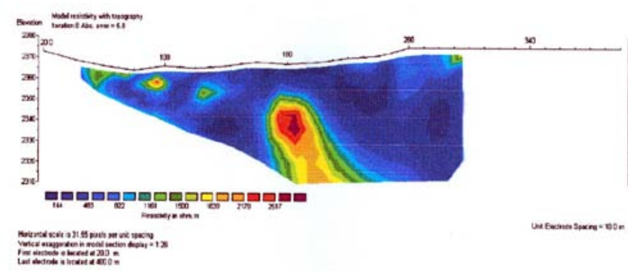

Figure 7. Electrical resistivity vertical profile.

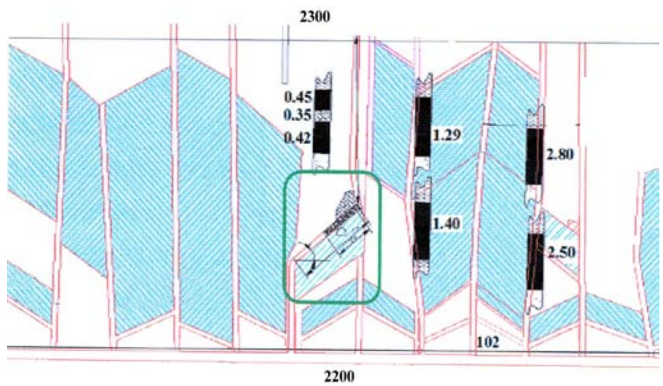

Figure 8. The section of changes in thickness of coal bed.

Discontinuity orientation describes the attitude of the discontinuity in space. A discontinuity's orientation is the most important property in opening stability and is uniquely described by its dip and dip direction angles. The type and orientation of the discontinuities are defined in Table 2.

Table 2. Dip and dip direction angles of discontinuities.

Plane	Type	Dip	Dip direction
1	Fault	62°	32°
2	Fault	35°	126°
3	Bedding Plane	35°	122°

Assuming C=0 and φ=26.5° for all discontinuities.

Stability analyses

Failures consist of brittle spalling and slabbing in a massive rock mass with few discontinuities, to a more ductile type of failure for heavily jointed rock masses under high stress levels in deep underground mines, and are largely structurally controlled under low stress levels in shallow underground mines where wedges or blocks falling from the roof or sliding out of the walls of the openings. The discontinuities were a primary cause of the Eshkeli shallow underground mine collapse and therefore the wedges analysis is appropriate in this case.

After, collecting evidence systematically in a rock fall accident by geophysical surveys, all of the evidence should be interpreted thoroughly, to prevent or minimize the probability of reoccurrence of similar accidents in the other parts of the mine.

A full screen stereographic projection of the discontinuities orientations and stope axis are shown on the stereonet Figure 9.

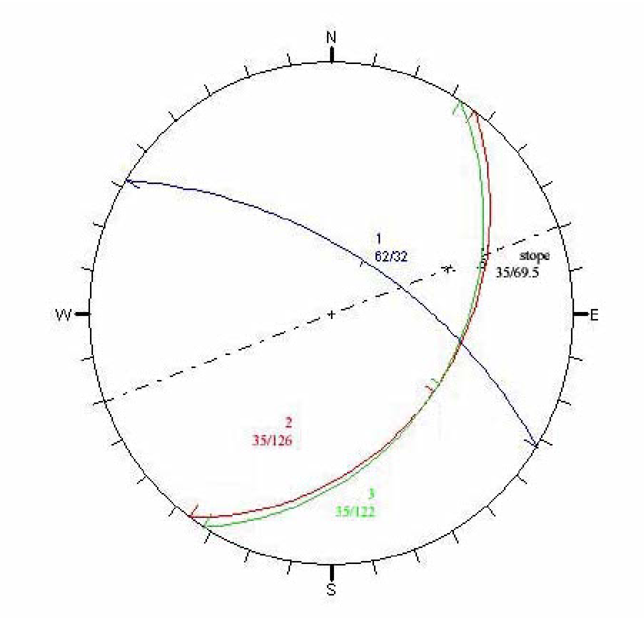

Figure 9. Stereographic projection of the discontinuities orientations and stope axis.

Workers are directly exposed to potentially unstable ground in the stope in traditional underground mining methods such as stull stoping. The stability design must be strict and as perfect as possible as a safety issue in artisanal small-scale mines. Determine the maximum sized wedges that can be formed in roof and sidewalls of the stope 103 by the given discontinuities are shown in Figure 10.

Two perimeter wedges are made by discontinuities, wedge #1 (upper left wedge) and wedge #2 (lower right wedge). In this case, wedge #1 has been scaled by the discontinuity 3 (bedding plane), and its volume and shear force are estimated 267 $m^3$and 230 tones respectively while wedge #2 is stable completely. The occupational accident in stope 103 is a result of falling wedge#1.

CONCLUSIONS

This study shows that structural discontinuities caused the sudden collapse of a massive hanging wall, which had never been foreseen during the design stage of the operation. It is unlikely that detailed information on rock properties and geological discontinuities will be available in small underground coal mines. Joint mapping through typical scan line techniques is an inappropriate technique for obtaining data on the nature of discontinuities in coal and more efficient technique like geophysical surveys is necessary in some cases.

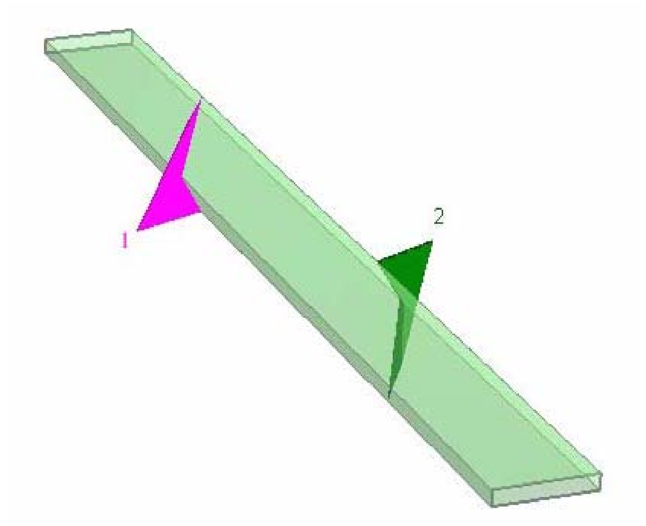

Figure 10. Perspective view of the stope and its wedges.

Coal is often well bedded and, as such, the intensity of layering in coal may be much greater than that of any of the other discontinuities. Thus, with regard to excavation stability, layering and control of this structure may require additional ground support and must be conducted very carefully.

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