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Assessment of excavation damaged zone around roadways under dynamic pressure induced by an active mining process

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ABSTRACT

This study presents an investigation of the excavation damaged zone (EDZ) around roadways under dynamic pressure during longwall mining. Based on their geological conditions, a total of fourteen typical roadways (seven roadways under dynamic pressure, seven roadways under static pressure) in Daxing Coal Mine, Liaoning Province, China, were selected to investigate the characteristics of their EDZ under both dynamic and static pressure with Borehole Camera Detection and Nonmetallic Ultrasonic Detection techniques. The results of the investigation indicate that the EDZ width around roadways under dynamic pressure was larger than those under static pressure due to mining-induced disturbance and the effect of unstable overlying rocks in adjacent goaf. The existence of faults and other adverse geological conditions can also contribute to the expansion of EDZs. The findings were incorporated in designing a more appropriate roadway support system. If the width of EDZ is larger than the bolt length, then the employment of bolts alone will not be sufficient to maintain roadway stability. Reinforcement with cables must be added to the support system. The reason is that cables have an overhanging effect and can be anchored in the excavation influenced zone (EIZ) which is adjacent to the EDZ in stable surrounding rock masses. The installation of cables could increase the volume of stable strata participating in the support system.

1. Introduction

An excavation damaged zone (EDZ) which is formed around man-made openings in civil engineering or underground coal mining is defined as the region beyond the excavation boundary where the physical, mechanical and hydraulic properties of the rock mass have been significantly affected as the results of the excavation and redistribution of stresses [1–3]. Fracturing, redistribution of in-situ stress and rearrangement of rock structures will occur in the EDZ which could form a permeable pathway for groundwater flow, reduce the stability of surrounding rock masses and raise the safety concern of underground opening support. Therefore, assessment and characterization of the EDZ in underground coal mines is a major issue for roadway support system design and long-term mine safety and productivity. For instance, based on the extent of the EDZ in surrounding rock masses, the length of cables or bolts should be appropriately designed in the support system.

Numerous studies have been conducted to obtain a comprehensive understanding of evaluation and characterization of the EDZ. Firstly, the assessment and evaluation of the EDZ must take into account the mechanical and physical properties of the surrounding rock masses as the type of rock involved plays a significant role in the size of EDZ. Based on this idea, Tsang and Bernier [1] presented a number of studies that involved a synthesis of the ideas to identify the formation processes, parameters, and long-term safety state of the EDZ in four types of geomaterials: crystalline rock, rock salt, and indurated and plastic claystones. Some valuable scientific conclusions obtained from their studies suggested that the experimental observation or field tests were required to evaluate the EDZ. Although some theoretical studies of the design and construction of deep underground nuclear waste repositories were presented, no experimental studies were performed until the 1980s when the Macro-permeability Test [4] and Buffer-Mass Test [5,6] were used to investigate the EDZ in fractured granite at the Stripa Mine in Sweden. The results from these studies showed a relationship between the extent of the EDZ and reduction in permeability of

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surrounding rock masses. Since these experiments at Stripa, more experimental studies on the damaged zone have been performed at USA, Canada, Switzerland and Japan [7]. In 2001, Schuster [8] pointed out that the seismic investigation was an effective method and could offer a fast and simple way to measure the EDZ. His study was performed by observing the distribution of seismic wave in 4 m boreholes drilled in opalinus clay. The results of this work revealed that these distributions could be analyzed to evaluate the extent of the EDZ in surrounding rock masses where the seismic parameters were disturbed. A similar study was conducted by Malmgren [9] in a coal mine in Sweden using seismic measurement techniques. His research suggested that the EDZ around an excavation could significantly affect the overall performance of the excavation and the general safety of personnel and equipment. In 2012, Li et al. [10] presented experimental studies of fracture evolution within the EDZ by the borehole image method with a digital panoramic borehole camera installed in the surrounding rock masses. In Li's study, the processes of fracture initiation, propagation and closure were observed in the EDZ. The results of this study showed that the Borehole Camera Detection was also an intuitive and an effective method to evaluate the characterization of the EDZ.

Although these approaches mentioned above are important approaches to evaluate the EDZ, they cannot be effectively used to predict all of the geological and geometrical conditions of man-made openings. In order to overcome these limitations, some numerical models have been proposed. For example, Hommand-Etienne et al. [11] proposed a model for numerically analyzing the damaged zone around an underground opening in brittle rock, and found that the highly damaged zones were formed in association with the zones of high compressive stress. Golshani et al. [12] also built a numerical model to analyze the damaged zone around an opening in brittle rock and suggested that moisture had a significant effect on the state of the damaged zone. They both concluded that the development of the EDZ was a function of time and shotcrete support was necessary to guarantee the stability of roadway and prevent further expansion and development of the damaged zone. Li [13] used a two-part liner elastic Hooke's numerical model in the TOUGH-FLAC3D code to study the mechanical response of the EDZ induced by excavation in clay/shale rocks and revealed that the results obtained by the numerical model were more consistent with observations in the field. Perras [14] provided numerical methodology to predict the dimensions of the EDZ using a continuum based modeling approach.

As stated by Dong et al. [15], the assessment of EDZ was mainly used to design a support system which could maintain the stability of man-made openings. The key factors to be considered for roadway support were the extent of EDZ and the bulking force caused by the EDZ. Therefore, the support design should be adjusted to utilize the self-bearing capacity of the surrounding rock masses. Song [16] designed an expert system which played an important role in stability classification of coal mine roadway surrounding rock masses and determination of roadway shape. In addition, the support parameters, output of the support design map, and assessment of the bolt-shotcrete support effect were also induced in the major returned values of this expert system.

As discussed above, a large amount of experimental studies and numerical investigations have been undertaken for characterizing and evaluating the EDZ. However, there is limited information available in the open literature about the selection of a large amount of test sites for obtaining a representative characteristic of the EDZ around roadway under dynamic pressure in coal mines, and comparative study of the EDZ under both dynamic and static pressure condition. In addition, the characteristic of EDZ influenced by unfavorable geological conditions and the relationship between the extent of the EDZ and roadway support system are also seldom reported on the literature. Therefore, in order to further investigate the characteristic of EDZ around the surrounding rock masses, the following works were conducted and reported in this paper. Firstly, the definitions of EDZ, EIZ, dynamic pressure and static pressure were presented and summarized in Section 2 of this paper. Secondly, a total of fourteen typical roadways (seven roadways under dynamic pressure, seven roadways under static pressure) in Daxing Coal Mine, Liaoning Province, China were selected to investigate the characteristics of the EDZ under both dynamic pressure and static pressure with Borehole Camera Detection and Nonmetallic Ultrasonic Detection techniques. Finally, based on the results of this investigation, an appropriate support system was designed for Daxing Coal Mine and implemented to maintain roadway stability.

2. Terminology definitions

2.1. Definitions of EDZ and EIZ

The terminologies for the different damaged zones around a roadway have been discussed by many researchers in the past decades. In early studies, the “disturbed zone” and “damaged zone” were both used for different projects [6,17]. Fairhurst and Damjanac [18] noted that “excavation damaged zone (EDZ) and disturbed rock zone (DRZ) are used synonymously to describe the region of rock adjacent to an underground opening that have been significantly damaged or disturbed due to the redistribution of in-situ stresses”. In a project carried out by Emsley et al. in 1997 [19], the terminologies of excavation damaged zone (EDZ) and excavation disturbed zone (EdZ) were pointed out to evaluate the damage and disturbance of surrounding rock masses under the construction method of blasting and tunnel boring. In this project, they proposed that a clear distinction between disturbance and damage should be made. Similarly, Marschall et al. in 1999 [20] pointed out that the excavation damaged zone (EDZ) and excavation disturbed zone (EdZ) had been ambiguously used in the past decades and suggested the different definitions and names for the damaged and disturbed zone should be established within different problems. In 2013, Hadj Abdi and Erman Evgin [21] stated that the damaged zone around a roadway can be subdivided into three different zones, i.e. highly damaged zone (HDZ), excavation damaged zone (EDZ), and excavation disturbed zone (EdZ). In their studies, the HDZ is defined as a zone where macro-scale fractures or spalling can occur and permeability may increase significantly by a factor of up to 10^3 or more. In contrast, the permeability in the EDZ may increase by a factor up to 10. Perras [14] also noted that the transition between these zones is gradual, and distinguishing between them can be difficult without in situ measurements. For this study, the EDZ is defined as the zone where the macro-scale fractures may occur and the region other authors would sub-classify into HDZ/EDZ is simply referred to as the EDZ.

In terms of the EdZ, Perras [14] pointed out that the lowercase ‘*d*’ is too easily confused with the uppercase ‘*D*’. The terminology of excavation influenced zone (EIZ) was recommended by Perras to illustrate a zone where possible hydro-mechanical and geochemical modifications can develop without changes in flow and transport properties. Therefore, the EIZ is employed for this study. The definition of EDZ, EIZ and Intact Zone are summarized below. Fig. 1 shows a detailed diagram illustrating EDZ, EIZ and Intact Zone located in sequence around the roadway. Location of EDZ, EIZ and Intact Zone in the view of stress–strain curve modified from Renaud et al. [22] is shown in Fig. 2.

The EDZ is defined as a zone with irreversible deformation and major changes in flow and transport properties due to the re-