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Application of Brillouin optical time domain reflectometry to dynamic monitoring of overburden deformation and failure caused by underground mining

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ABSTRACT

Brillouin optical time domain reflectometry (BOTDR), a fully-distributed optical fiber sensing technology, was applied to monitoring the deformation behavior of overlying strata during underground mining. Three types of optical cables, Metal kieso sensing optical cable (MKS), Glass fiber reinforced sensing optical cable (GFRS) and 10 m interval fixed-point sensing optical cable (10 m IFS), were embedded vertically into two boreholes that are located 582 m and 1746 m from the open-off cut, respectively. The strain distribution characteristics of the cables and variations of the mechanical and hydraulic properties in the overburden were analyzed with consideration of the lithology and mining positions. The results show that MKS cable has better performance in strength and accuracy than the GFRS and 10 m IFS cables. The strata in front of the panel provided front bearing loads and were compressed in the vertical direction. As the panel passed the cables to approximately 90 m, the tensile stress increased, and the peak value moved up gradually. With the occurrence and development of the caved zone, the strains of the lower optical drill were negative and in the compression state. Throughout the monitoring process, the upper cable showed a process from compression to tension, while the lower cable showed a process from compression through tension to compression. In addition, the strain distribution of the cables corresponded well with the strata. The vertical compression of the strata appears to be inversely proportional to their Young's modulus. Tensile failure dominates in the overlying strata during the mining process. With the advancing of the panel, the tensile failure zone moved upward episodically, and the height of the fractured zone reached the maximum where the distance between the face and cable was approximately 90 or 100 m. Compared with the traditional monitoring methods, BOTDR monitoring provided more accurate data on the dynamic height of the fractured zone. The research results are of practical significance for monitoring overburden deformation under mining, and they are helpful to prevent or mitigate water inrush and surface ecological geological disasters.

1. Introduction

Underground mining causes redistribution of stress in overlying strata, resulting in deformation, movement, separation, fracture and collapse of the overlying rock.[1,2] The overburden deformation and failure would affect the roadway safety and induce underground water inrush accidents, whereas the decline of phreatic water table induces destruction of the surface ecological geological environment.[3–6] Therefore, it is necessary to accurately, comprehensively and quantitatively investigate the deformation distribution and damage extent of the overburden and their dynamics.

Methods that have been utilized to study the deformation and failure of overlying strata include theoretical and empirical formula,[7] computer numerical simulation,[8] analogues simulation,[9] geophysical exploration,[10] and drilling investigation.[11] The utilization of these methods has effectively improved the understanding of macroscopic characteristics and laws of deformation and failure of overlying strata and provided some guidance for underground mining. However, the above methods suffer from several substantial defects in practical applications, such as low level of quantification, heavy reliance on personal judgment, and difficulty in reflecting the actual in-situ mining-induced deformation and failure of the overlying rock mass. In particular, these methods do not accurately and dynamically reflect the entire process of strain changes, deformation and failure of overlying

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strata over the course of mining.

In recent years, rapid development of distributed optical fiber sensing has provided new methods and technologies for stability monitoring in geotechnical fields,[12,13] geology,[14,15] water conservancy,[16] aerospace[17] and national defense.[18] Sensitive optical fibers have the advantages of being small in diameter, high precision, and anti-interference. They can be connected in parallel, or in series to install structural deformation monitoring networks. Distributed testing of structural deformation can be realized in the form of surface adhesion or internal implant.[19,20] One particular distributed sensing technique, Brillouin optical time domain reflectometry (BOTDR), has attracted much attention in engineering fields because of its unique characteristics of being single ended and long distance and high precision measurements.[13,21–23] BOTDR has been applied to study movements of the overlying strata in the interior tests.[24–26] In addition to BOTDR, Brillouin optical time domain analysis[27] (BOTDA) and Fiber bragg grating[28] (FBG) are also considered to be distributed sensing techniques. However, FBG does not meet the requirements of full distribution,[29] and BOTDA requires double ended testing and no intermediate break is allowed.[30] As a result, these two techniques were rarely used to the distributed monitoring of movements in the overlying formations.

In this paper, the in-situ monitoring was carried out to investigate the influence of mining on overburden. The distributed sensing fiber cables were embedded vertically in the overlying formation via boreholes prior to mining. BOTDR was used to monitor the strain distribution and its variation of the sensing cables as the mining progressed. The deformation and failure of overlying strata were then analyzed from the strain data with consideration of the lithology and panel positions. In addition, the dynamic height of the fractured zone was obtained with a better accuracy than that from the traditional methods.

2. Study area

The research was conducted at Jinjitan Coal Mine located in the northern part of the Shaanxi Province and to the south of the Mu Us desert, as show in Fig. 1. The study area belongs to arid and semi-arid climate region. The Pleistocene sand aquifer provides precious water resources to maintain the development of community, industry and agriculture and ecological environment balance.

No.108 stope was selected to install the BOTDR cables. The stope has a designed advance length of 5500 m and a face length of 300 m. The target mining coal seam is 2^{-2} coal seam of the Jurassic Yan'an Formation. The coal seam is near - horizontal at a depth of approximately 240 m with thicknesses ranging from 5.8 to 8.03 m. The roof is mainly composed of argillaceous sandstone, siltstone, fine-grained sandstone, and coarse-grained sandstone. The average thickness of each overlying stratum is approximately 10 m. Testing of core samples indicate that the compressive strength of the most overlying rocks is less than 40 MPa, which is considered mechanically weak.[31] The relatively younger age and poor bonding degree of the formations may have contributed to such mechanical characteristics. Water inrushes and ecological devastation associated subcutaneous water loss in the overlying aquifer are the greatest challenges for a full-scale production in the mine.

3. General movement of overburden strata and height of fractured zone

After a coal seam is extracted, the roof strata lose support of the lower coal seam and bend downward or fall into the mined-out void unless roof management is implemented. Shear stress accumulates at edges, which are supported by coal walls. When the stress exceeds the rock strength limit, the strata will be fractured, broken and even caved. With advance of the panel, the overlying strata undergo deformation and failure. According to the deformation and failure characteristics of the overlying strata and their hydraulic conductivity,[32] the overlying strata can be divided vertically from bottom to top into three distinct zones: caved zone, fractured zone, and continuous zone.[33,34] The water-conducting zone, consisting of the caved zone and fractured zone, constitutes the pathway for overlying water to rush into the mined-out area.[35]

After extraction of coal, the immediate roof stratum caves episodically and falls into the goaf. As a result, the caved zone is formed,

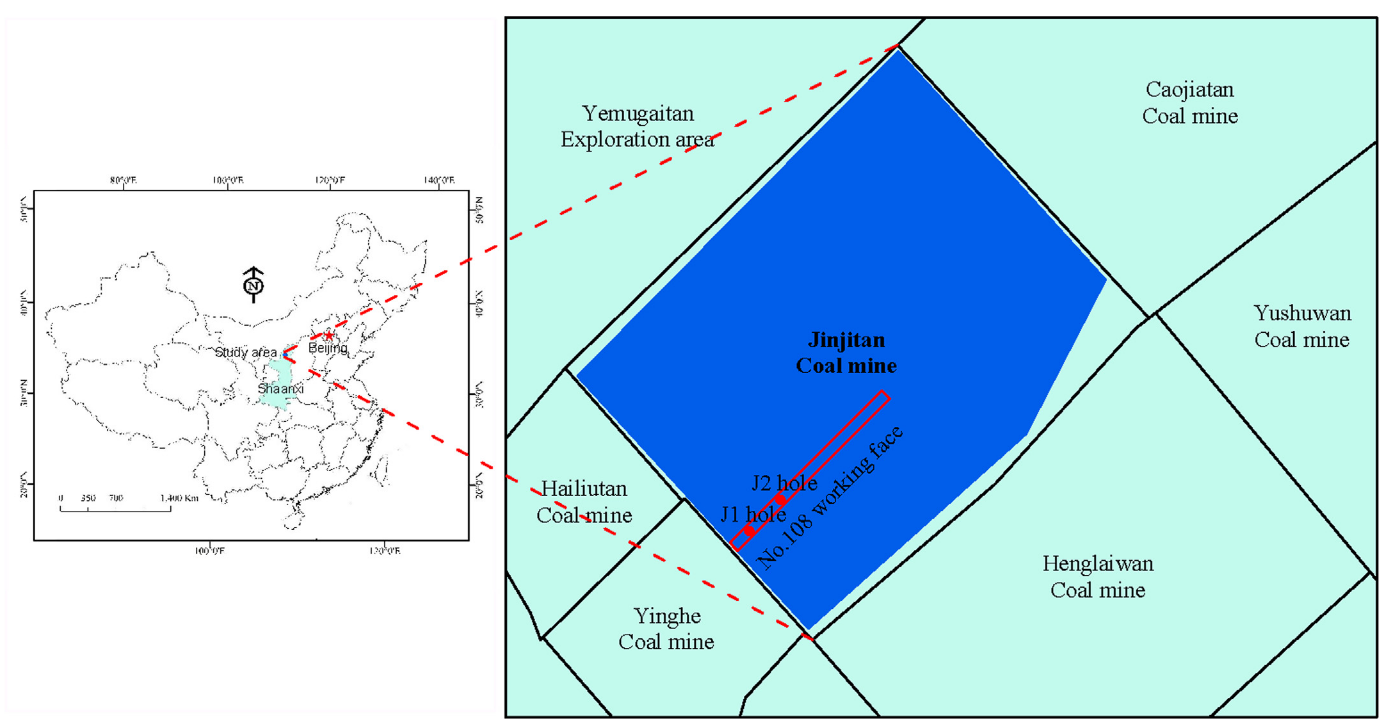

Fig. 1. Location of Jinjitan Coal Mine 1 and No.108 stope and holes.