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Research
Efficient Exploitation of Deep Mineral Resources—Review

Opportunities and Challenges in Deep Mining: A Brief Review

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ABSTRACT

Mineral consumption is increasing rapidly as more consumers enter the market for minerals and as the global standard of living increases. As a result, underground mining continues to progress to deeper levels in order to tackle the mineral supply crisis in the 21st century. However, deep mining occurs in a very technical and challenging environment, in which significant innovative solutions and best practice are required and additional safety standards must be implemented in order to overcome the challenges and reap huge economic gains. These challenges include the catastrophic events that are often met in deep mining engineering: rockbursts, gas outbursts, high *in situ* and redistributed stresses, large deformation, squeezing and creeping rocks, and high temperature. This review paper presents the current global status of deep mining and highlights some of the newest technological achievements and opportunities associated with rock mechanics and geotechnical engineering in deep mining. Of the various technical achievements, unmanned working-faces and unmanned mines based on fully automated mining and mineral extraction processes have become important fields in the 21st century.

1. Introduction

Since the exploitation of the earth's resources has a long history, coal and mineral resources at shallow depths have gradually become exhausted, and the exploitation of coal and mineral resources continues ever deeper into the earth. At present, deep mining at 1000 m is normal; the depth of coal mines has reached 1500 m, the depth of geothermal exploitation has reached more than 5000 m, the depth of non-ferrous metal mines has reached around 4500 m, and the depth of oil and gas exploitation has reached around 7500 m. Deep mining will become common in the future. Coal mining in Poland, Germany, Britain, Japan, and France had reached deeper than 1000 m as early as the 1980s, and China currently has 47 coal mines more than 1000 m deep [1,2]. In the case of metal mines, according to incomplete statistics, there were at least 80 mines more than 1000 m deep prior to 1996, mostly located in South Africa, Canada, the United States, India, Australia, Russia, and Poland. The average depth of metal mines in South Africa has reached 2000 m, and the Western Deep Level gold mine has reached 4800 m [3].

Deep rock mass is characterized by high *in situ* stress, high temperature, and high water pressure. Compared with shallow resource extraction, deep mining may be associated with disasters such as rockbursts, large-scale caving, and large inrush of mixed coal, gas, and water. These events are often complex in nature and difficult to forecast and control. The characteristics of the rock mass and the boundary conditions in deep mines are the primary causes of disasters in deep mining [2]. For example, when the mining depth reaches about 1000 m, the *in situ* stress caused by the overburden, tectonic features, and mining activities can cause stress concentration, resulting in damage to and failure of the surrounding rock masses [4]. Under high stress, as the accumulated deformation energy is more prominent, accidents may occur more frequently.

Under conditions of high stress, high temperature, and high water pressure, the disturbance generated by mining activities can

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lead to the sudden and unpredictable destruction of the rock mass, which is manifested by a large range of instability and collapse [5]. In addition, the deformation and failure characteristics of rock masses at great depths often exhibit strong time-dependent characteristics [6]. The disturbed stress- and time-dependence of deep mining engineering can result in the occurrence of disasters that are very difficult to forecast.

Emerging problems of rock mechanics and mining engineering have been studied for deep mining. Most of the current studies focus on the zonal disintegration of deep surrounding rock [7–10], large squeezing failure [11], transformation of brittleness to ductility [12], energy characteristics of dynamic failure in deep mining [13], visualization of stress fields [14,15], and rock strata deformation and movement induced by deep mining [1,16]. Although the results of these studies have revealed some mechanical characteristics of deep mining, some of the deep-mining-related theories, techniques, and methods are still at the primary stage. Xie [2] considered the reason for this to be the limitations of current theories of rock mechanics, because such theories are based on the mechanics of materials and are relatively unrelated to the depth in question and to field engineering activities. Moreover, new theories and techniques for deep mining are necessary, taking *in situ* and mining-induced characteristics into account.

2. Rock support for deep mines

In situ stress is the dominant factor influencing underground deformation and failure in mining and other underground engineering. As the mining depth increases, the influence of *in situ* stress on the stability and failure of the surrounding rock mass becomes more obvious, and the selection of rock support techniques becomes more vital.

He et al. [4] developed asymmetric coupling support technology for roadways in soft rocks, including controlling technologies for floor heave, double controls on the crossing points for large roadway sections with anchors, and intensive design technology for pumping station chambers. These technologies have been successfully applied to site support works [17]. According to the site test results, Niu et al. [18] suggested the adoption of a rigidity- and flexibility-coupled dynamic reinforcement technique by applying initial flexible support to stabilize the broken surrounding rocks in the early stage, using reserved deformation for the unloading of high stresses in the middle stage, and adopting a high-strength and high-stiffness support for the whole section in the late stage, in order to resist creep deformation. He et al. [17] further developed a designated experimental system for rockburst in deep mining. In order to resolve the failure of conventional support materials in large-deformational surrounding rock, an energy-absorbing bolt with large elongation and constant resistance was developed, as shown in Fig. 1(a) and Fig. 1(b) [17]. The bolt can resist the large squeeze of rock by counteracting the shock-produced deformation energy through the large deformation of the bolt. The pull-out force constantly ranges from 120 kN to 200 kN, and the deformation capacity is 0.5–1 m. Li et al. [19] developed an energy-absorbing rock-support device, the D-bolt (Fig. 1(c)), for burst-prone and squeezed surrounding rocks. The average impact load is 200–300 kN for a 200 mm D-bolt, and the cumulative dynamic energy absorption of the bolt is 47 $kJ\cdot m^{-1}$.

3. Intelligent mining

Digital mining originated with the mine/mining geographic information system as the inevitable outcome of the information age and knowledge economy [20]. The goal of digital mining is to promote the transformation of mine information; support automated mining and intelligent mining; ensure safe, efficient, green, and sustainable mining; and achieve scientific mining. Digital mine construction is a gradual process and requires complex system engineering [20].

The development of automated mining technology began in the mid-1980s. In Canada, Noranda Inc. has developed a variety of automated equipment, including load-haul-dump (LHD) machines, an optical navigation system, and an LHD remote control system, to meet the needs of underground hard rock mining automation [21]. In 1994, the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) launched the Mining Robot Research Project. CSIRO researchers developed an open-pit bucket cruise system, an accurate unloading model, and an underground metal mine LHD automatic control system. Norway Dyno Industrier ASA, Canada INCO Limited, and Finland Tamrock Corporation then launched an investment of $22.7 million in a mining automation program to improve labor productivity and reduce operating costs. Later, Sweden developed the Grountecknik 2000 strategic plan for mine automation. Today, unmanned working-faces and unmanned mines based on fully automated mining/unmanned mining processes have become important fields of study [20].

According to Wu et al. [20], the new task of a digital coal mine is to establish coal mines and real-time access to digital mine integration platforms in order to construct a multidimensional and dynamic coal mine virtual reality system. Four main directions were determined for digital mining in the new situation of deep mining: ① a digital mine integration platform; ② a mining simulation system; ③ underground positioning and navigation technology; and ④ mining environmental intelligence perception.

4. Enhanced continuous mining and tunnel-boring machine mining

Gu and Li [22] suggested that deep metal mining should adopt the technologies of enhanced continuous mining and high *in situ* stress-induced fragmentation. However, four critical issues remain for deep mining in hard rocks: ① characterization of and methods to understand high-stress fields and geological structures in deep mining; ② knowledge of full-block fracturing for hard rock under high *in situ* stresses; ③ support measures to control rockburst at high temperatures; and ④ knowledge of the flow and coupling of the integrated solid-gas-liquid medium in infiltration mining for low-grade mineral deposits.

The use of tunnel-boring machines (TBMs) in mining applications is difficult, due to the complex heterogeneity of the target rock mass. Over 70% of TBM failure in mines is due to geology-related problems [23]. In recent years, there has been an increase in the use of TBMs and in the average drill length for tunneling in hard rock mines. However, several limitations still restrict the use of TBMs in mining applications. Spalling or rockburst due to stress redistribution in highly stressed rock is a major drawback during TBM cutting in hard rock mines, and can affect safety and tunnel support installation. This issue has been alleviated in the recent Jinping II hydropower plant project by monitoring microseismic activity and tunnel deformation in order to effectively predict and avoid rockburst in tunneling. Highly fractured and blocky rock masses are another factor inhibiting the use of TBM cutters in a mining application. Loose chunks of rock are known to jam and damage front transfer chutes and cutter mounting buckets. Therefore, to extend the application of TBMs in deep mining, TBMs need modifications such as impact bars to avoid damage to cutters, mucking buckets, and belt conveyors.

In addition to the problems encountered in hard rock mines, other complications associated with water inrush and methane explosions affect the use of TBM cutters in coal mines. A novel integrated drilling-slotting technique has been implemented in the Pingdingshan coalfield in China for coal-methane co-exploitation; this technique enhances both coal and methane recovery, while reducing the