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Determination of the minimum thickness of crown pillar for safe exploitation of a subsea gold mine based on numerical modelling

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ABSTRACT

Sanshandao gold mine, located at the east coastline of Bohai Sea in the Shandong Province, is the first subsea metal mine in China. Since the mining activities are carried out under sea, it is of vital importance to maintain the stability of the crown pillar and to keep the sea water out from the excavations. In this paper, the minimum required thickness of crown pillar is determined based on 3D numerical modelling and analysis. A realistic geometric subsea gold mine is modelled by integrating the usage of SURPAC and FLAC^{3D}. The numerical analysis is carried out by FLAC^{3D}, in which the influences of sea water pressure as well as mining sequences have been considered. The distributions of the principal stresses, displacements, plastic zones and pore pressures in the crown pillar are obtained by simulating the cut-and-fill stoping method at different excavation levels (above level -115 m). The field displacement observation shows that the vertical deformation rate of crown pillar is smaller than 0.023%. It reveals that the reserved safety factor is about 1.43 when using cut-and-fill stoping method from level -165 m to -115 m in the subsea gold mine. The mining activities may extend to level -95 m according to the numerical analysis results. A four-year-field practice shows that the numerical analysis is helpful to determine the minimum crown pillar thickness in the challenging subsea gold mine.

1. Introduction

With the depletion of mineral resources in near surface ground, mining exploitation in challenging environments such as at great depth and under sea water has become an inevitable trend all over the world. There are plenty of mineral resources along and around the coastlines in China, where the total length of coastline is over 32,000 km. Therefore, it is imperative to carry out studies on rock mechanics-related problems with regard to the safe exploitation of subsea minerals. A key question for subsea mining is to determine the minimum required thickness of crown pillar and to keep the sea water out from mining excavations. The research in this field is relatively scarce except the Norwegian experience on subsea tunnels in the Nordic countries and recently in China [1–7]. Nilsen [8], Dahlo and Nilsen [9], Li et al. [4,5] have discussed the stability problem and the minimum thickness of the rock cover in subsea tunnels. However, the Norwegian experience in subsea tunnels cannot be directly applied to subsea mines because subsea mining is technically more complicated than subsea tunnel construction. The size of mining stope is usually larger than that of tunnels and the blasting induced disturbance in subsea mine is more severe than that in subsea tunnel. Nevertheless, the researches on the stability assessment of crown pillars for underground mines have been extensively reported and discussed [10–16]. Hutchinson et al. [13] pointed out that three types of methods were used to assess the stability of the crown pillar, which included empirical analysis methods, mechanistic analysis methods and numerical analysis methods. For example, the scaled span method, one of the empirical analysis methods suggested by Carter [10], has been used to determine the stability of surface crown pillars in both active and abandoned mines for more than a decade. However, for stress distribution and rigorous failure mode analysis of crown pillars, numerical analysis method is a better choice. In addition, the authors have conducted case studies on the determination of safe crown pillar thickness between underground stope and open-pit mine by using different analysis methods [17]. The experience can guide us to handle the relevant technical problem. However, the influence of sea water constitutes a new challenge.

Numerical modelling is an efficient technique to enhance the understanding of the mechanical response of crown pillars associated with subsea mining. The Itasca software FLAC^{3D} is widely used in geotechnical and mining engineering. The model construction part in FLAC^{3D} is however not easy for complex mining conditions [18]. Therefore, we resort to other commercial

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software for constructing numerical models, which are then input into $FLAC^{3D}$ for further analysis. The mining software SURPAC can realize a 3D vision of mines conveniently [19]. However, SURPAC cannot handle complex stability analysis. One approach to tackle that problem is to integrate SURPAC and $FLAC^{3D}$. Some successful underground mining model construction examples in China were introduced by Lin et al. [20], Liu et al. [21], and Luo et al. [22] through integrating SURPAC and $FLAC^{3D}$. More recently, Grenon and Hadjigeorgiou integrated a probabilistic limit equilibrium approach into Gemcom SURPAC for an open pit design and slope stability analysis [23]. Grenon and Laflamme carried out slope orientation assessment for open-pit mines based on the digital elevation model and GIS algorithms [24]. In this study, a 3D block model for a subsea gold mine is built in SURPAC, which is exported to $FLAC^{3D}$ by a MATLAB program. The crown pillar stability is then numerically assessed by $FLAC^{3D}$, in which the mining sequences and sea water pressure are taken into consideration. The in situ rock deformation observation and a four-year-field practice [25] prove that the numerical modelling based on integrating SURPAC and $FLAC^{3D}$ is helpful to determine the minimum thickness of the crown pillar for the subsea gold mine.

2. Engineering background

Sanshandao gold mine is located at the Sanshandao special industrial zone in Laizhou city, Shandong Province, China. It is on the east coastline of the Bohai Sea. The mining area is about 29 km north of Laizhou city and 45 km west of Zhaoyuan city. Via the Provincial Road S304, the mine is connected with the G206 National Road at about 16 km to the east, and it is also connected to the G18 Expressway at a distance of about 26 km to the east. The railway from Huangye to Yantai is under construction and it will pass through the mining area only at a distance of about 8 km to the east.

The Sanshandao gold mine is a medium size underground mine (the production capacity of Sanshandao gold mine is 8000 t/day) facing challenging mining environments. Take the Xinli Zone of Sanshandao gold mine as an example, the geological profile along the 31# exploration line is shown in Fig. 1. The main rock types surrounding the gold mine include metagabbro, monzogranite, and cataclastic rocks. The gold orebody extends from about level -40 m to below level -700 m under sea level. The orebody has a strike of NE 60–70°, and a dip angle of 40° to 50° towards southeast.

Different mining methods are commonly used in underground mines, including the room-and-pillar method, the cut-and-fill stoping method and sublevel caving, etc. [26]. In the Xinli Zone of the Sanshandao gold mine, a cut-and-fill stoping method has been adopted. A typical cut-and-fill stoping method is shown in Fig. 2, which is used from level -400 m to -165 m. The height of one mining stope is 40 m. The distance between two barrier pillars is 100 m. The square panel pillar is of a 5 m × 5 m cross section. The spacing between adjacent panel pillars is 15 m in each direction.

Sanshandao gold mine is the first subsea metal mine along the coastline of China. Besides this gold mine, Longkou Coal Mine is another subsea mine in China [27]. About 10m depth of sea water and a 35m thick of sea mud (silty clay) and Quaternary weathering layer exist above the orebody of the Xinli Zone at the Sanshandao gold mine.

How to handle the sea water above the mine is a critical issue for subsea mining. It would be disastrous if the sea water cannot be properly kept out from the mine excavation when mining under the sea. For example, a sea water inrush in a subsea coal

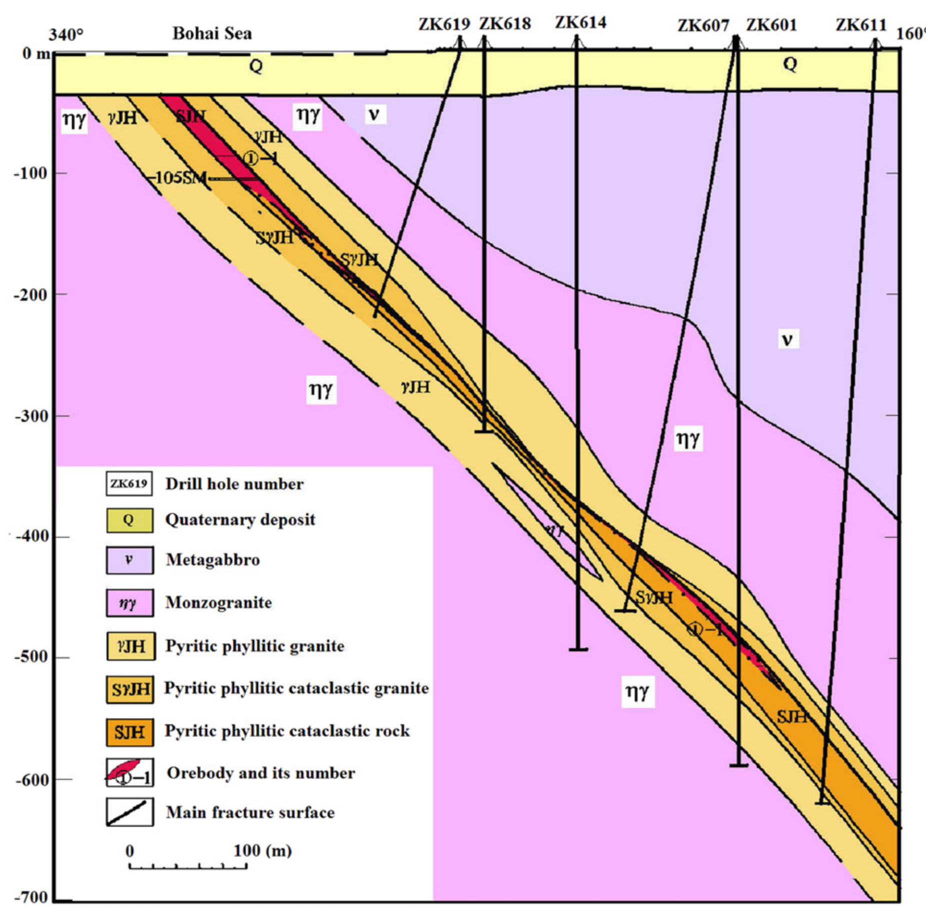

Fig. 1. The geological profile of Xinli Zone at Sanshandao gold mine along the 31# exploration line.