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Mathematical Model for Determining the Economic Well Depth in Mine Lots

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ABSTRACT

In order to better determine the economic depth of deep wells and improve the safety of exploitation in a mine lot, this paper introduces the integration of the fuzzy mathematical model with the cost analysis into the mining process. The economic exploitation depth in the mine lot is determined by substituting the model test, providing the clues to the study. The findings show that the production situation of the coal mine S at a mining depth of 780 meters has reached a reasonable critical limit in the economy, and the economic exploitation depth can hit upon 900~1000 m. It is thus clear that the increase of mining depth will improve the probability of occurrence of production accidents; the economic exploitation depth of the mine can reach 900~1000 meters, if the mining continues to extend downward, a heavy loss will be suffered.

INTRODUCTION

In response to the booming demand for energy resources, many countries have been depleted of shallow resources, and successively, they turn to deprive of deep resources. The deep resources of China's coal reserves exceed 50% of the total. It is likely attributed to the strong and stable IT industry, in that more and more mine lots in the country have accessed to deep reserves. Some scholars stated that the domestic mining depth has not reached the limits, and in order to improve the utilization of mine resources, there is a need to study the economic exploitation depth of deep wells in mine lots.

In this paper, we take the deep well of the mine S in Xinhan mine lot as a study case. First, the mining technology and the basic modelling are analysed. The integration between the fuzzy mathematical and the cost analysis models is used to analyse the calamity cost and reasonable mining depth, as well as the applications of the model.

PAST STUDIES

Mine dynamic disasters are the result of the combined action of crustal movement driven by power in the earth and mining disturbance. They are the dynamic failure process of mechanical deformation system composed of coal and rock mass under external disturbance. All kinds of mine dynamic disasters have a unified power source-elastic energy accumulated in the process of crustal movement. There is a unified mechanical mechanism and characteristics. In the mid-1960s, Hodot of the former Soviet Union and Cook of South Africa put forward the theory of rock burst and prominent energy, respectively. Petuhov of the former Soviet Union pointed out that coal seams with both rock burst and outburst danger are very common, so it is necessary to study the unified theory of rock burst and outburst. On the basis of comprehensive research, the force-energy theory of rock burst and outburst was put forward. A research forwards the theory of instability of rock burst and outburst. It considered that rock burst and outburst were both dynamic instability process of coal (rock) deformation system under unstable equilibrium state disturbed by various factors. The energy criterion of instability was used as the unified criterion of rock burst and outburst (Agusto 2017, Abdel-Maksou & Abdel-Maksoud 2017). A recent study pointed out that there was a close correlation between mine tremor and gas outburst by analysing the co-seismic phenomena of coal and gas outburst and mine tremor, and verified the triggering effect of gas fluid on mine tremor, especially the important role of the special properties of supercritical fluid in the occurrence of mine tremor (Apostol 2017, Aldaihani & Alenezi 2017, Bata et al. 2017, Chidumayo 2018). From the characteristics and laws of mine dynamic disasters, they are all local failure of coal and rock mass; the failure process is very rapid; they are brittle failure; and they are all in high stress areas. From the view of prevention measures of mine dynamic disasters, drilling cuttings method and sound pulse and micro seismic method of testing coal and rock damage are used to forecast in production; mining methods to avoid high stress concentration are adopted in the case of rock burst and outburst; and mining protective layer is taken as regional prevention measures. Local preventive measures such as water injection, borehole grooving and pressure relief blasting are adopted, and vibration blasting is used to induce slight rock burst or outburst to prevent the occurrence of high-intensity rock burst and outburst. Therefore, it is of great significance to establish a unified prediction theory for mine dynamic disasters.

Theoretical research and production practice show that mine dynamic disasters should be the result of interaction of two aspects, i.e. natural geological dynamic state of coal (rock) body and mining engineering activities. The uneven distribution of mine dynamic disasters in time and space and the difference of their apparent intensity depend on the natural geological dynamic state of mine. The geological dynamic state affects the dynamic disasters of mines by acting on a variety of factors. A research on some outburst mining areas in China showed that coal (rock) and gas outbursts mostly occurred in mining areas with the characteristics of geodynamic stress field. Higher horizontal stress often existed in the surrounding rock of outburst coal seam. The greater the horizontal stress was, the more serious the outburst was (Boulanger & Hill 2017, Hejazi et al. 2017, Hussin et al. 2017, Ilyas et al. 2018). In addition, many scholars and engineering technicians analysed the influencing factors of mine dynamic disasters under the action of geological dynamic state. A study described in detail the conditions of coal and gas outbursts, including geological structures, folds, igneous rock walls, changes in coal structure, coal permeability, and high-pressure gas, based on coal and gas outbursts seen in Northumberland and Durham, England (Gatapova & Kabov 2016, Khan et al. 2017, Khattak et al. 2018). Also mentioned the gas pressure, coal body structure, geological structure, coal porosity and other factors in the study of coal and gas outburst (Hockmann 2017, Nazihah et al. 2018, Nordin et al. 2018). Based on a study, summarized the factors as follows: rock stress, gas, physical and chemical properties of coal, macro-structure and self-weight of coal (Keshavarz et al. 2016, Nwankwoala et al. 2018). By 1974, the former Soviet Union had established the main geological factors determining the impact risk and the corresponding criteria: geological structural characteristics, mechanical properties of coal, rock composition of roof, strength and thickness, and coal seam burial depth.

Others argued that the comprehensive characteristics of rock and gas outburst meant that rock and gas outburst were not only regarded as physical phenomena of crops, but also as a complex multi-factor system. The multi-factors and their changes in time and space made it difficult to predict them (Montemor et al. 2017, Razzak et al. 2018). Besides, thought that the natural factors of outburst cause included gas desorption capacity, mechanical properties of coal seam and surrounding rock, geological structure, overburden pressure and so on (Ng et al. 2017, Tao 2018). A recent study summarized the relationship between outburst and mining depth, coal thickness, dip angle of coal seam and structure through a large number of outburst examples, and put forward the natural factors affecting rock burst, including fold and fault, tectonic stress zone, mechanical properties of coal and rock mass, mining depth, structural characteristics of roof and floor strata, coal seam thickness and coal seam inclination change band (Polymenakos & Tweeton 2015, Yun et al. 2017).

There are three stages in the development of technology for preventing and controlling outburst and rock burst in the world. After the two stages of taking safety measures as the main and adopting prevention and control measures universally, the technology has entered the stage of comprehensive prevention and control in the past 20 years. The prevention and control technology of coal mine can be categorized into four aspects: hazard area prediction, prevention and control measures, effect inspection and safety protection. Hazard area prediction is the premise of implementing comprehensive measures. Mining practice at home and abroad shows that the occurrence of mine dynamic disasters is regionally distributed. Therefore, regional prediction plays an important role in the prevention and control of mine dynamic disasters. Over the past decades, the commonly used methods of outburst risk prediction at home and abroad are single index method, geological statistics method and comprehensive index method. The prediction of rock burst at home and abroad is based on strength theory, energy theory, impact tendency theory, stiffness theory and instability theory. In recent years, geophysical methods and gas geology methods have been studied in China.

There are many factors affecting the occurrence of mine dynamic disasters, so it is difficult to meet the needs of prevention and control projects by using single factor index. A research used the geodynamic zoning method to evaluate the natural geodynamic condition of the mining area and predict the possibility of mine dynamic disasters (Wang et al. 2014, Pazand & Hezarkhani 2018). Liaoning University of Engineering and Technology cooperated well with Russia in Beipiao Mining Area. Geodynamic zoning method was introduced into China, and multi-factor pattern recognition probability prediction method for regional prediction was put forward.

In summary, the above research work mainly carries on the detailed analysis to each aspect influence factor of the mining area deep well in the actual development process, then uses the corresponding theory basis to carry on the related factor research. According to the prevention measures of mine dynamic disasters, drilling cuttings method, sound impulse and micro seismic method are used to predict coal and rock damage in production, and mining methods to avoid high stress concentration are adopted in the case of rock burst and outburst. Therefore, based on the above research status, the application of mathematical model in determining the economic mining depth of deep mines is mainly studied, and a suitable data model which can be well developed in this process is found, so that it can be more efficient in the practical application process.

PRINCIPLE AND METHODS

In the exploitation process of coal reserves, along with the deepening of coal mining, the existing conditions for the coal face itself will tend to be more complex, coupled with constantly versatile conditions such as transportation, water and electricity, instead, the underlying cost in production process stays on the upswing. With the reform of the national economic system, the country has raised the thresholds for the exploitation and utilization of mineral resources. In order to indulge the demand for energy resources, and adapt to the development of coal mines, we must fundamentally work around the effective utilization of resources, how to reasonably mine the reserves, and improve the economic efficiency. In the study of economically recoverable reserves in coal mines, it should be noted that: First, for aging and special mines, for example, it is required to grant public subsidies to treat them differently; second, if we intend not only to ensure economic benefits but also to effectively protect coal reserves in the mining, the economic evaluation must be based to clarify whether the mining of reserves have economic benefit. Third, individual coal mines with outdated technology and poor stewardship should not follow the current specifications or exploitation technology only.

The minimum thickness minable of coal seams (the minable thickness) presupposes the current exploitation technology conditions of coal mines. The economic exploitability of coal seams closely matters the raw coal production cost, market price, profit and tax, etc. According to the studies of experts in relevant fields in China, the mathematical model (1) is available:

$$a > P - c - t \qquad \ldots(1)$$

Where: a - profit of coal per ton (also called the coefficient of economic exploitability in coal seams);

P - unit price for commercial coal;

C - total cost for coal production;

t - taxes paid for coal per ton.

When a < 0, the coal seam is not economically minable; when a = o, the coal seam thickness is the minimum minable for coal seam. When a > 0, the coal seam is economically minable.

The economically exploitable depth of coal mines is the keystone of the study. The factors affecting the minable depth of coal mine include: geological condition, mining conditions, social and economic development, quality of workers and organization management, as shown in Fig. 1.

The reasonable mining depth of the mine means that the operating profit of coal mines is greater than or equal to zero, that is, they will not suffer a loss. Then, the economically reasonable maximum mining depth can be determined by a mathematical model such as (2):

$$op = p_r \times (1-t) - c(a,h) - s_c - m_c \geq 0 \qquad \ldots(2)$$

Where: op - operating profit per unit raw coal;

p_r - coal price per ton commercial coal;

t - tax rate of commercial coal;

s_c - sales cost per unit commercial coal, yuan / ton;

m_c - financial management cost per unit commercial coal, yuan / ton;

c(a,h) - cost of sales per unit commercial coal, yuan/ton;

Assume the operating profit of raw coal equals to zero, the economically reasonable maximum mine exploitation depth, Hmax(A), subjected to the total mine production capacity A can be obtained. When the operating profit is greater than zero, the reasonable mining depth is lower than Hmax(A); if certain social benefits are considered, for example, when the ton coal is given a certain economic subsidy, the reasonable mining depth can be greater than Hmax(A).

The economic model for reasonable mining depth of coal mines is built by six steps: establishment of the model objectives, qualitative analysis, data preparation, building model, model solution and model evaluation, as shown in Fig. 2.

As the mining depth increases, the probability that underground disasters occur also multiples. In this case, the losses of personal injuries and property caused by the calamity doubles. We call it uncertain calamity cost. With reference to historical data (see Table 1), according to the study direction and conditional limitations of the subject, this paper focuses on describing the economic losses caused by gas, water and rock burst and establishes a mathematical model (3):

$$C12 = F_{gas} + F_{water} + F_{impact} \qquad \ldots(3)$$

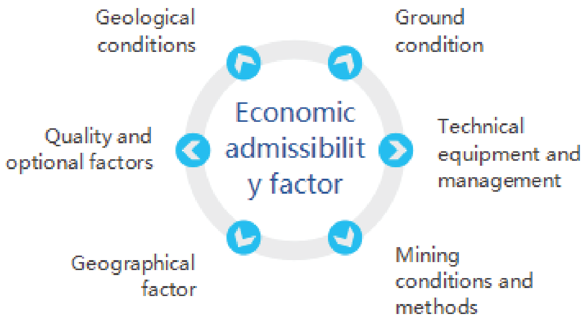

Fig. 1: Economic admissibility factors.

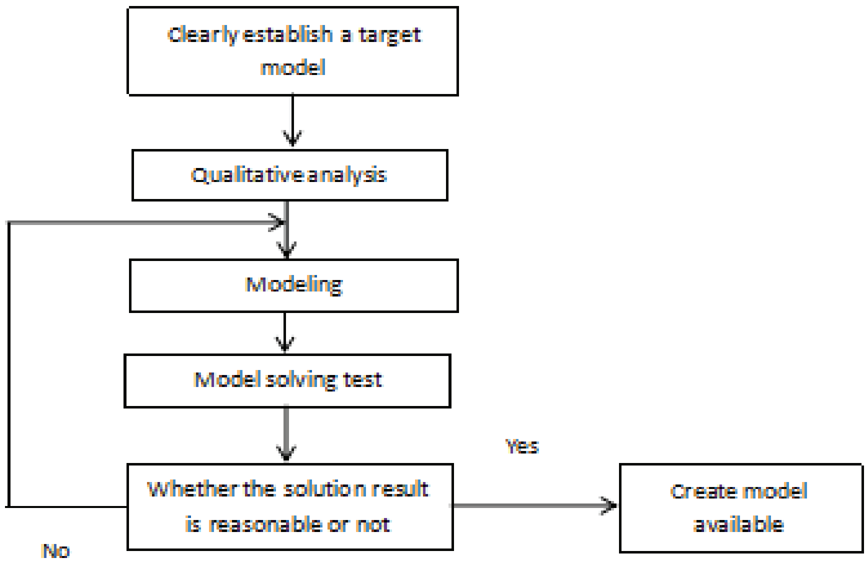

Fig. 2: Modelling step.

Where: C12 - total cost of underground uncertainty calamity;

F_{gas} - watt - gas disaster costs;

F_{water} - cost of underground water disasters;

F_{impact} - cost of roof disasters.

As shown in Table 1, the natural disasters occurred in actual large and medium coal mines in China are listed. Based on various natural disasters occurred in recent years as percentage of the total cases, we can see that it has attributed the calamities in mines to the gas, water and rock burst as the dominant factors.

The losses of working days due to minor, serious casualties caused by coal mine accidents are estimated, days/persons. Refer to Table 2.

Table 1: Coalmine of China accident disaster personnel casualty statistics.

	Impact pressure and top plate	Gas	Coal dust	Water damage	Fire
2015	2359	2935	142	521	106
2016	1441	2593	72	367	56
2017	1447	3502	67	367	46

Table 2: Coal casualties loss workday.

Casualty situation	Lost working day	Economic losses
Minor injury	100	0.333
Serious injury	3000	10
Death	6000	20

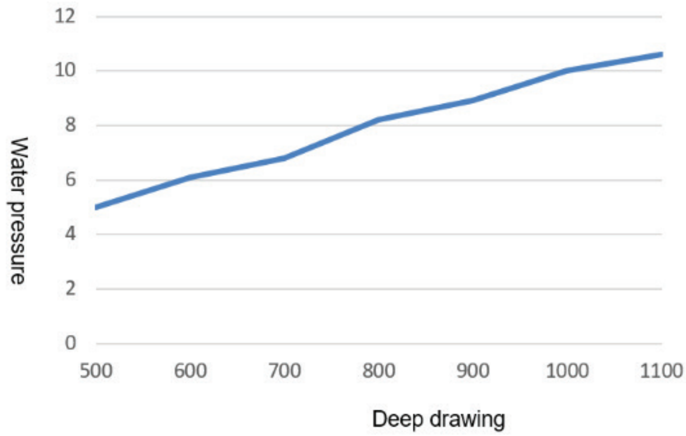

Fig. 3: Water values at different depths.

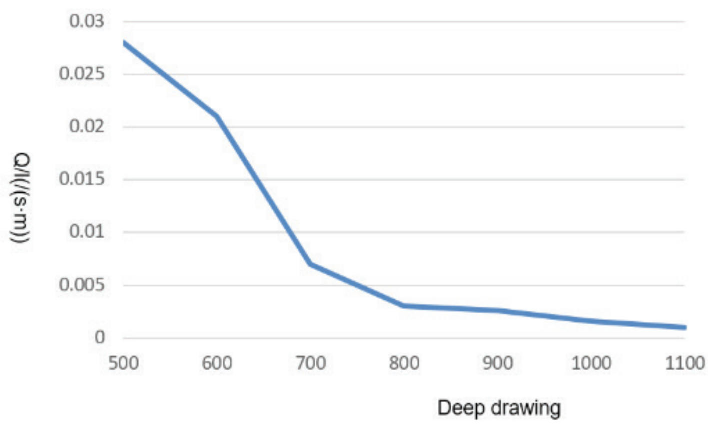

Fig. 4: unit water inflow and depth curve.

RESULTS AND ANALYSIS

It is discovered from the underground exploration data in Dongtan Coal Mine that the water inflow and pressure per unit of the Ordovician limestone aquifers at different depths change. As the mining deepens, the water pressure at the same fractured karst aquifer shows an upward trend. The relationship between the depth and water pressure is shown in Fig. 3. When deepening, the Geostress increases, the karst hydrodynamic environment gets worse, the karst development weakens, the fissures tend to be closed, the water permeability of the fractured karst aquifer decreases, and the water yield property of the fractured karst aquifer has a significant weakening tendency (See Fig. 4).

After the establishment of the economic mathematical model, we can obtain the most reasonable economic exploitation depth for the coal mine S in Xinhan mine lot, provided that the operating profit of the mine is assumed to be zero. The operating profit per ton coal is equal to the unit operating income minus the unit cost, that is, it equals to the unit operating income minus the unit tax, unit production

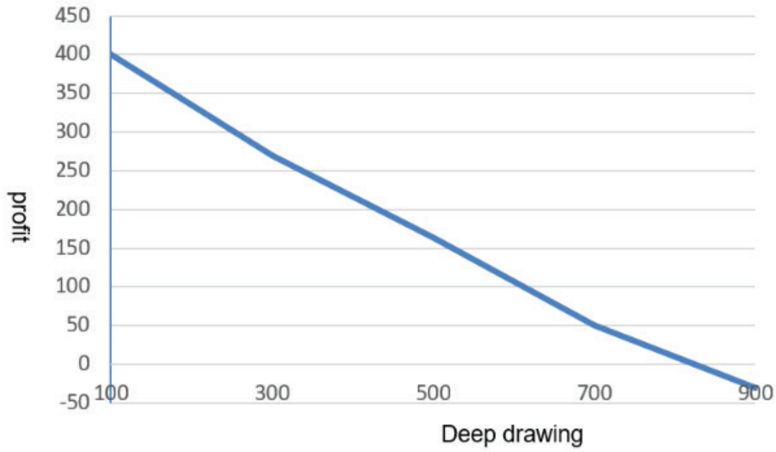

Fig. 5: Curve of the exploitation depth as a function of the profit per ton coal.

cost, unit sales expense and unit financial management expenses. Disaster costs are incurred when the probability of occurrence of calamities caused by mine gas, water, and rock burst is non-zero. The probabilities of occurrence of the three kinds of disasters matter the specific disaster level occurred underground in practices. Therefore, when calculating the probability cost, the actual coal yield, practical detection data and geological conditions of the mine should be considered to obtain it. In Fig. 5 below, the dotted line is the curve of the exploitation depth as a function of the profit per ton coal.

Based on the above analysis and as applicable to the current situation of the mines, under the annual production capacity of 1 million tons coal, the production situation of coal mine S at the mining depth of 780 m has reached a reasonable critical limit in the economy; if effective measures such as reducing costs and improving production efficiency are taken to improve the mine yield and increase the annual output of the mine by more than 10%. In theory, the economic exploitation depth of the mine can reach 900~1000m; in view of the current production system and mining conditions of the mine, if the mining further deepens, we will suffer a heavy loss in the economy. Given the above, considering the probability of uncertain disaster costs, the economically minable depth for coal mine S roughly falls within 900~1000m.

CONCLUSION

In theory, this paper aims to settle the real problems with mathematical modelling. The focus is on the reasonable exploitation depth of coal mines. It is concluded that: (1) the major factors affecting the mining depth include basic production cost and uncertain calamity cost; (2) with the increase of mining depth, the probability of occurrence of Schlagwetter calamity multiplies accordingly, so do the probabilities of occurrence of mine water and rock burst disasters. (3) based on the above analysis and the physical situation of the mine, it is assumed that the annual yield is 1 million tons. The production situation of the coal mine S at the mining depth of 780m has reached a reasonable critical limit in the economy; if some measures are taken, for example, reduce the costs, improve the production efficiency, increase the mine yield per unit, and make its annual yield improve by 10% or above, in theory, the economic exploitation depth of the mine can fall within 900~1000 meters; in view of the current production system and exploitation conditions of the mine, if the mining continues to decline, a heavy loss may be caused.

For writing paper, there are still some gaps in theory and practice. In addition, there are limitations in the collection and selection of materials. Therefore, although the fuzzy mathematical model is built, its accuracy and practicality still need to be studied in practice.

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