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EDITORIAL

New development in theory and practice in mine water control in China

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Introduction

Mine water inrush events often occur during coal mine construction and production in China and account for a large proportion of the nation's coal mine disasters and accidents. Figure 1 shows the number of water-related hazards and casualties in coal mines of China between 2000 and 2011. Over the 12 years, 1,089 water incidents have occurred with a total loss of 4,329 lives.

As the mining depths and mining intensity continue to increase, the encountered hydrogeological conditions will become more complicated. The Chinese mining engineers and hydrogeologists have been working hard to liberate approximately 27 % of their proved coal reserves that are currently threatened with water inrushes. In battling against the water hazards, they have overcome four major challenges and developed their solutions.

Water inrushes from aquifers underlying coal seams

One challenge is to prevent or predict water inrushes from the aquifers that underlie many of the coal seams. Because water inrush from the underlying aquifers is a non-linear dynamic process, its occurrence is controlled by multiple factors and involves complex mechanisms. Dynamic non-linear processes are not readily amenable to mathematical equations. The water inrush coefficient, introduced in the 1960s, has been widely used by most Chinese coal mine hydrogeologists because it had the advantages of being a simple physical concept, convenient to calculate, and easy to use. It has been modified several times to better reflect actual water inrush conditions and has played a positive role in resolving the dangerous problem of water inrush from underlying aquifers in China.

However, the water inrush coefficient method only considers two factors: the potentiometric pressure of the underlying confined aquifer and the thickness of the aquitard that functions as a water barrier between the coal seam and the underlying aquifer. Other factors also govern water inrush from underlying aquifers. In addition, the water inrush coefficient threshold is empirical and typically determined using reported water inrush incident statistics. Because geological and hydrogeological conditions can vary significantly in different areas, considerable deviations can exist between results of water inrush assessments and reality.

In recent years, an innovative approach has been proposed by Professor Qiang Wu and his group of China University of Mining and Technology Beijing, China, to evaluate water inrush vulnerability from underlying aquifers. The new approach has been implemented in many coal mines. Instead of evaluating only two factors, Professor Wu couples the geographic information system (GIS) with information integration so that many factors can be non-linearly integrated and a vulnerability index can be established at each mining location. The information integration consists of the artificial neural network (ANN), the weight of evidence, the logistic regression, the analytic hierarchy process (AHP), etc. The vulnerability index

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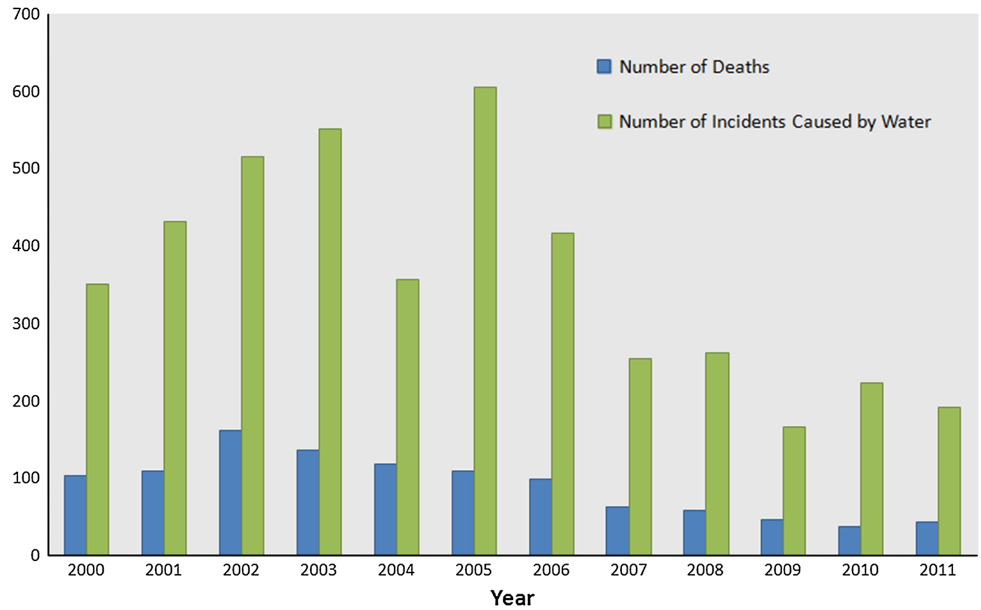

Fig. 1 Number of water-related incidents and casualties in the coal mines of China between 2000 and 2011

method has significantly improved the accuracy in evaluating the risk of water inrush.

The vulnerability index method developed by Professor Qiang Wu and his team represents one of the highest levels of academic accomplishment in predicting water inrushes from underlying aquifers in coal mines over the world. It lays a solid foundation for conducting further research on this topic so that the threatened coal reserves can be mined safely, efficiently and environmentally friendly. Selected publications on this topic are listed below:

Wu Q, Liu Y, Yang L (2011) Using the vulnerable index method to assess the likelihood of a water inrush through the floor of a multi-seam coal mine in China. Mine Water Environ 30(1):54–60

Wu Q, Liu Y, Liu D, Zhou W (2011) Prediction of floor water inrush: the application of GIS-based AHP vulnerable index method to Donghuantuo Coal Mine, China. Rock Mech Rock Eng 44(5):591–600

Wu Q, Zhou W, Zhang L (2011) China's environment: challenges and solutions. Environ Earth Sci 64(6):1503–1504

Wu Q, Xie S (2009) Prediction of groundwater inrush into coal mines from aquifers underlying the coal seams in China: application of vulnerability index method to Zhangcun Coal Mine, China. Environ Geol 57(5):1187–1195

Wu Q, Wanfang Z (2008) Prediction of groundwater inrush into coal mines from aquifers underlying the coal seams in China: vulnerability index method and its construction. Environ Geol 55(4):245–254

Wu Q, Xu H, Pang W (2008) GIS and ANN coupling model: an innovative approach to evaluate vulnerability of karst water inrush in coalmines of North China. Environ Geol 54(5):937–943

Wu Q, Dong S, Zhang Z (2007) Mine flood prevention and control. Press of China University of Mining and Technology

Water inrushes from aquifers overlying coal seams

Another challenge in mine water control is to prevent or predict water inrushes from the aquifers that overlie the coal seams. Groundwater intrusion from aquifers overlying coal seams can be a serious geo-hazard and hinder development of the coal industry. The traditional practice is to leave enough safety coal seams as a geologic barrier. With the increase in mining depth, however, more groundwater-related disasters occurred as a result of collapses of the rocks overlying the coal seams. The roof collapses increased the densities and openings of fractures in the rock above the openings and could connect to the upper aquifers. Nearly half of the mines in Kailuan have suffered from groundwater intrusions from the overlying formations. At Jinggezhuang Mine, the three main groundwater disasters that occurred in 1979 were caused by intrusions of water from the overlying sandstone aquifers. The maximum groundwater intrusion flux was 44 m^3/min, which flooded the entire working area. In working faces adjacent to faults or fractured zones, the overlying aquifers can jeopardize the mine operation. Therefore, coal mining in China, especially North China, is challenged with not only the groundwater intrusion from the underlying aquifers, but also the groundwater intrusion from the overlying aquifers. To address the overlying aquifer water inrushes, Professor Wu proposed a quantitative assessment method for prediction of groundwater intrusion from overlying aquifers. The method consists of three maps and two interrelated predictions.

The three maps are:

1. Distribution of water yield in the overlying aquifer;
2. Probability map describing connectivity of roof collapses with overlying aquifers;
3. Risk map of water intrusion from the overlying aquifers.

The two predictions are:

1. Groundwater flux rate prediction for the working face prior to mining;
2. Groundwater flow rate prediction for the working face during mining.

Literature research suggests that Professor Qiang Wu is the inventor of this quantitative approach. This unique approach has addressed three key elements in overlying aquifer water inrushes: water source, water pathway, and water inrush intensity. Utilization of this approach to coal mines in northwest, northeast, and north China has made it possible that no significant water inrushes have occurred for many years and many water-threatened coal reserves have been liberated. The research results have been published in Environmental Geology [Wu Q, Zhou W (2008) Prediction of inflow from overlying aquifers into coalmines: a case study in Jinggezhuang Coalmine, Kailuan, China, 55(4):775–780].

Water hazards caused by size-limited structures

The third challenge is to control water hazards caused by size-limited structures in the mining industry. Size-limited structures refer to faults with less than 5 m displacement, relative small-scale fissures and karst fractures. These structures not only form the main flow path for groundwater, but also threaten the stability of roof and floor during coal seam recovery. To avoid encountering these structures, some laneways have to change their paths, hence increasing the workload. Some coal seams cannot be mined for safety reasons, consequently reducing the efficiency of coal production. Many disasters, such as water inrushes, happen when the laneway or the roof/floor encounters these structures during mining practice. Rapid water intrusion not only increases the cost of pumping water but also seriously threatens human lives. Awareness of these structures on safety of the underground work environment and threat to human lives from increased disasters have initiated much wider studies on exploring and predicting the location of these structures.

A great deal of time, effort, and money has been expended to develop measures to predict these size-limited structures in mining areas. Predicting them has proved to be difficult due to limited size and lack of expression in subsurface. However, knowledge about such structures has been accumulated during long-term mining practice. The previous studies on small structure prediction mainly focused on two methods: geophysical prospecting and regional tectonic system analysis. Although the methods have exerted huge effects in the prediction of structures, they have individual deficiencies. They are costly and may incorrectly predict the position of these structures.

To overcome this challenge, Professor Qiang Wu and his group developed the size-limited structure prediction model as an alternative for forecasting. This prediction model, which involves quantitatively analyzing factors related to the site-limited structures, is based on artificial neural networks. Artificial neural networks are employed to replicate the way the human brain might process the data by learning relationships between influent factors and the risk to structures. The trained neural networks model is established from the actual data in coal mines. Its successful application to many coal mines indicates that size-limited structure prediction model provides an efficient tool that supports superior size-limited structure prediction, while accuracy is improved by minimizing the influence of subjective judgments. The technique provides the decision-makers with the necessary information to predict the size-limited structures in coal mines. The algorithm of this prediction model consists of:

1. Input training data through the network;
2. Adjust network weights to reduce error;
3. Validate network with output-of-sample data;
4. Use neural network to predict real data.

Its successful application to many coal mines indicates that size-limited structure prediction model provides an efficient tool that supports superior size-limited structure prediction, while accuracy is improved by minimizing the influence of subjective judgments. The technique provides the decision-makers with the necessary information to predict the size-limited structures in coal mines. The advantages of this model are relatively cheap in data collection and more objective in results. Detailed descriptions of this model can be found in the International Journal of Rock Mechanics and Mining Sciences. A sample of publications on this topic is listed below:

Wu Q, Ye S (2008) The prediction of size-limited structures in a coal mine using artificial neural networks. Int J Rock Mech Min Sci 45(6):999–1006

Wu Q, Wang M, Wu X (2004) Investigations of groundwater bursting into coal mine seam floors from fault zones. Int J Rock Mech Min Sci 41(4):557–571

Conflicts between mine drainage, water supply, and eco-environmental protection

The fourth challenge is to resolve the conflicts between mine drainage, water supply, and eco-environmental protection for the coal basins in China. Coal mining in the Permo-Carboniferous system is the major economic activity in the coal basins of China. The multiple thin-bedded limestone aquifers are inter-bedded within the coal layers. Their thickness is approximately 9–20 m. The coal layers are often connected hydraulically with a deep limestone aquifer located beneath the coal layers in a Middle-Ordovician system and/or with porous aquifers located above the coal layers in a Quaternary system. The geological formations create a hydraulically interconnected, multi-aquifer system with a varying degree of vertical connection. The depth of the limestone aquifer is approximately 200–600 m below the land surface. To mine the coal safely, high groundwater heads in the thin-bedded aquifers (which are nearest to the coal layers) must be lowered using powerful draining or pumping equipment. Draining operations will result in great decreases in groundwater heads both above and below the neighboring aquifers. Unfortunately, the groundwater level decrease can cause numerous problems for water supply plants, which often rely on both the deep limestone and shallow porous aquifers as major groundwater resources.

Owing to the unstable drainage flows and risk of contamination from chemicals entering the flow system during drainage processes under the coal mines, the water supply plant managers, who demand stable and high-quality water resources, are reluctant to use the drainage water as a viable source of water. Therefore, large quantities of the drainage water pumped to the surface from the mine pits, at great cost, are wasted. As a result, the water supply demand requires further groundwater extraction elsewhere, which, in turn, causes other serious eco-environmental problems. These problems include karstic collapses of the ground surface, groundwater contamination in deep aquifers, and land subsidence. Clearly, comprehensive management is necessary for the groundwater withdrawal for the mining drainage requirement and the water supply need from the aquifer system. The management challenge is to find an optimal approach to effectively control mine drainage, provide an adequate supply of water, and protect the environmental quality of the coal mining areas.

During the 1970s and 1980s, many studies were conducted in the USA to predict the effect of draining water from coal mines. Since then, however, study of this issue has decreased significantly, probably due to the shift in energy sources from coal to petroleum. Since the 1980s, on the other hand, predicting and remediating groundwater contamination has become an active research area, and many studies have been conducted to determine the optimal design of groundwater monitoring or remediation systems. Numerous management models have been proposed. However, most of these studies have focused on groundwater contamination caused by leakages from the ground surface or from surface water. Few studies have been conducted on the management of water in the coal mining industry. Currently, coal is the major source of energy in China and coal mining is still very active. Water management associated with coal mining activities needs to consider eco-environmental protection and development of the coal mining industry. Thus far, very limited studies have been conducted on this subject and these are primarily focused on analyzing conflicting approaches to managing and balancing mine drainage and water supply in China. One case study in China considers the use of powerful pumps to bring mine water to the ground surface for sales to various consumers. In the Rhineland mines of Germany, large volumes of mine water were pumped to the ground surface and then transported directly to thermal power plants through pipelines. In Hungary, the domestic water supply was mainly provided by water from coal mines. However, the models used in these studies are too simple to optimize usage of water resources where multiple issues need to be considered. Therefore, combining groundwater management modeling with coal mining activities is still a research gap that needs to be filled.

Through many years research, Professor Qiang Wu developed a comprehensive and practical management model applicable to solving coal mining-related water management problems. He is one of the first to propose that mine construction shall consider water and coal as a dual-resource system. The comprehensive management tool developed by Professor Qiang Wu can optimally manage an aquifer system with three factors: draining water from coal mines, providing an adequate supply of water, and protecting the eco-environment. The economic-hydraulic management model has been applied to coal mining basins in North China and become a powerful tool in solving the multi-factor problems of mine drainage, water supply, and environmental protection for coal mines located in the China coal basins. The model helps improve the groundwater management method used in China where drainage water, water supply, and environment projection are considered separately, rather than as an integrated system. This new management method avoids numerous overlapping field investigations conducted by separate entities and uses one model to simultaneously predict the influences and feedback among various groundwater seepage fields formed by the various engineering installations in the system. Therefore, this new method leads to improved water resource management practice in the coal mining areas in China and elsewhere. The research results can be found in Hydrological Sciences Journal, Environmental Geology, and Ground Water. A sample of publications on this topic is listed below:

Wu Q, Hu BX, Li W, Zheng C (2010) Coal mine water management: optimization models and field application in North China. Hydrol Sci J 55(4):609–623

Xing L, Wu Q, Ye C, Ye N (2010) Groundwater environmental capacity and its evaluation index. Environ Monit Assess 169(1–4):217–227

Wu Q, Pan G, Ye S (2009) Application of a discrete-continuum model to karst aquifers in North China. Ground Water 47(3):453–461

Wu Q (2006) Characterization of water bursting and discharge into underground mines with multi-layered groundwater flow systems in the North China Coal Basin. Hydrogeol J 14(6):882–893

Wu Q, Zhou W, Li D (2006) Management of karst water resources in mining area: dewatering in mines and demand for water supply in the Dongshan Mine of Taiyuan, Shanxi Province, North China. Environ Geol 50(8):1107–1117