An Optimal Management Model for Stereo Prediction of Groundwater Inflows into an Operating Coal Mine in Jiu Lishan, China

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ABSTRACT

Jiu Lishan coal mine, Jiao Zuo coalfield, is one of the most typical accident-prone karst groundwater-impregnated coal deposits in North China.

The hydrogeological conditions in the coal mine are extremely complex. A quasi-three-dimensional finite element model is used to simulate the stereo hydrogeological structure, in order to describe realistically the characteristics of the hydrogeological model in the Jiu Lishan coal mine. On the basis of the numerical simulation, the stereo prediction of groundwater inflow rates into the operating coal mine and the determination of the vertical recharge flows of a lineal fault belt inner boundary are achieved by optimal management models. Then, the final selected scheme for preventing and curing mine water in Jiu Lishan coal mine is presented, according to the optimal calculation results of the management models.

HYDROGEOLOGICAL SETTING

Jiu Lishan coal mine, Jiao Zuo coalfield, North China, was put into production in 1983. The planned production capacities in the coal mine are about 900,000 tons annually, but the actual capacity is only about 50% - 60% of this. The reason being the extremely complex hydrogeological conditions in the mine. The groundwater level elevations in the west part of the coal mine is still about 50 - 60 metres, although the total inflow rates of the pit-water have reached 70 - 80 cubic metres per minute in recent years. A long-term high hydraulic head distribution in the west part of the mine has resulted in frequent water-bursting accidents in production face No. 12, so that the mining activities in the face have finally been forced to stop. Therefore, the mining tasks have been mainly concentrated to the east part of the mine, and the mining production pressures in production faces No. 11 and No. 13 in the east part of the mine have been terribly increased. All of these factors bring about high tension conditions and shifting production in the coal mine. Thus, how to drain and to drop the high hydraulic head districts and to predict accurately the various inflow rates into mining environments are the first problems required to be solved, in order to turn round the present difficult situation in the coal mine.

The surface relief in Jiu Lishan coal mine is flat, its area is about 10 square kilometres. The annual average precipitation at the coal mine is about 675 millimetres. The main geological structure consists of normal faults with a high angle. There are two directional sets of faults; the faults in the northeast direction formed before the ones in the northwest direction.

The major aquifers, which threaten the safe mining activities in the coal mine, are as follows. The porous aquifers in the Quaternary system, namely Q, are in the top position. They can be divided into two aquifers;. up aquifer is a free one, its thickness is about 15 - 20 metres; down aquifer is a confined one, whose thickness is about 12 - 20 metres.

There are 8 - 9 thin-bedded karst aquifers in Carboniferous system, but the influential aquifers on mining activities in the coal mine are only two layers, namely L8 and L2. A thin-bedded karst aquifer, L8, is located 24 metres from the up coal layer, which is the major mining coal in the mine now. Average thickness for the aquifer L8 is about 8.46 metres, and its conductivity is about 3 - 25 metres per day. There is an asymmetric cone of depression, now, in aquifer L8 due to long-term drainage. The groundwater level elevation in the east part of it is about -50 to -60 metres, but in the west part the level elevation is about +50 to +60 metres.

The thin-bedded karst aquifer L2 is about 74.5 metres from the up coal layer, and is about 10 metres from the down thick karst aquifer 02. The average thickness for aquifer L2 is about 13.5 metres, and its conductivity is about 2 - 20 metres per day.

The extremely thick karst aquifer in the Middle-Ordovician system, namely 02, is at the bottom position. The thickness for aquifer 02 is about 200 - 400 metres, the karst phenomena in it are well developed and the specific yield in aquifer 02 is very rich, its groundwater level elevation is about 75 - 85 metres. It is a well confined aquifer, and seriously threatens safe mining of the up coal layers by groundwater-bursting at the bottom of coal layers.

The boundary hydraulic conditions for aquifer Q in the north, east, south and southeast are all recharged. The boundary hydraulic condition for aquifer L8 and L2 in north, east and southeast are all impermeable, but it is a recharged boundary in the south. The boundary hydraulic conditions for aquifer 02 in the north, east and south are all recharged, but the southeast boundary is impermeable. The west boundary conditions for aquifer Q, L8, L2 and 02 are all impermeable.

Two kinds of inner hydraulic boundaries have been determined on the basis of analysing comprehensively the characteristics of tectonic field, groundwater potential field, hydrogeochemistry field, and groundwater temperature field. The first one is a lineal fault belt inner boundary. The dislocation of the fault belt shortens the distances between the thin-bedded karst aquifers and the thick karst aquifer and causes hydraulic connections between both, and increases the groundwater recharge flow rates to the thin-bedded aquifers from the thick base aquifer 02. The high hydraulic head districts in the coal mine are all located in the west part of this inner boundary. The second one is a narrow band buried outcrop inner boundary, which is in the shallow part of the coal mine, the porous aquifer deposits lie directly on the thin-bedded karst aquifer L8 in the buried outcrop locations of L8. This kind of contact between aquifer Q and aquifer L8 leads to groundwater exchange for them.

To sum up, the stereo hydrogeological structure of four aquifers, which are hydraulically linked by a lineal fault belt and a narrow band buried outcrop inner boundaries, is a major characteristic of the mine hydrogeological conceptual model in Jiu Lishan coal mine.

NUMERICAL SIMULATION MODEL

By analysing every development stage of the mathematical models for predicting groundwater inflow rates into the coal mines, either by use of the stable theory of groundwater movement to the unstable theory, or from analytical to numerical methods, a common characteristic for the used models, is that the calculative scope of all the models limits only to a direct influential aquifer on the mining coal layer.

Previously used mathematical models, obviously, distorted the stereo mine-hydrogeological conceptual model in the coalfield in North China, and could not describe the major mine-hydrogeological characteristics of reality in detail.

In order to solve the past disjointed problems between mathematical models and reality this paper presents a quasi-three-dimensional finite element numerical simulation model. This model depicts completely the mine-hydrogeological structure in stereo dimension. It may not only consider the multilayer aquifers which are hydraulically connected, but also simulates the hydrogeological characteristics of the inner boundaries with various natures. Thus, it is pretty hopeful for this model to reduce greatly the model errors which are caused by the big differences between the hypothetical conditions of mathematical models and the objective conditions of the hydrogeological model.

A quasi-three-dimensional model in a confined state can be written in the form of:

$$\begin{cases} \frac{\partial}{\partial x}(T_{rx}\frac{\partial H_r}{\partial x}) + \frac{\partial}{\partial y}(T_{ry}\frac{\partial H_r}{\partial y}) + \sum_{z=1} \beta(r-z)\frac{K'_{zr}}{m'_{zr}}(H_z - H_r) - \sum_{k=1} Q_{rk}\delta(x-x_k,y-y_k) \\ \qquad = S_r\frac{\partial H_r}{\partial t} \qquad (x,y)\in\Omega r; \quad t>0; \\ H_r(x,y,t)|_{t=0} = H_{r0}(x,y) \qquad (x,y)\in\Omega r; \\ H_r(x,y,t)|_{\Gamma_{r1}} = H_{r1}(x,y,t) \qquad t \geqslant 0; \\ (T_{rx}\frac{\partial H_r}{\partial x}\cos<n,x> + T_{ry}\frac{\partial H_r}{\partial y}\cos<n,y>)|_{\Gamma_{r2}} = q_r(x,y,t) \qquad t \geqslant 0; \end{cases}$$

where

r-- the number of aquifers;

k-- the number of source wells and sink wells;

$$\beta(r-z) \text{— function} \begin{cases} 1 & |r-z| = 1 \\ 0 & |r-z| \neq 1 \end{cases}$$

$$\delta(x-x_k,y-y_k) \text{— function} \begin{cases} 1 & x = x_k, y = y_k \\ 0 & x \neq x_k, y \neq y_k \end{cases}$$

A four layer quasi-three-dimensional finite element numerical model is used based on a field hydraulic test concerning stepping up groundwater pressure in Jiu Lishan coal mine on July 25th, 1989. 94 nodes and 157 triangular units are cut open in one aquifer, there are altogether 376 nodes and 628 triangular units in four aquifers. Six homogeneous parameter sub-districts are divided in the light of the data from extensive pumping-out tests in single hole and of buried geological conditions for aquifer L8, L2 and 02. The equi-potential line maps in the model identification for four aquifers are presented respectively in Figure 1, Figure 2, Figure 3 and Figure 4, which are extremely similar to the real distributions of the piezometric surface.

The comparison between predicted and actual values in a single hole for four aquifers are given in Figure 5, Figure 6, Figure 7 and Figure 8, the comparisons are obviously quite good.

OPTIMAL MANAGEMENT MODEL FOR STEREO PREDICTION OF WATER INFLOW

On the basis of the model identification, a quasi-three-dimensional optimal management model for stereo prediction of groundwater inflow into coal mining environments was established. The management period selected was in 1977, when the guaranteed rate for precipitation in Jiu Lishan coal mine was 19%. Management time segments were divided into three. The minimum drainage rate was used as the objective function in the optimal model. One of the main constraint conditions, in the optimal model, was to control the groundwater level elevation in the west part of aquifer L8 to meet the safe elevation demands of the 13 strait nodes for mining the coal layers successfully. There are 69 policy-making variables in four aquifers. The discrete optimal management model can be written in the following:

$$
\begin{cases}
Obj\text{:}\ \ MinZ = \sum_{i=1}^{N}\sum_{j=1}^{3} C(i,j)Q(i,j) \\
St\text{:}\ \ \sum_{i=1}^{N}\beta(k,i,1)Q(i,1) = S(k,1) \\
\qquad \sum_{i=1}^{N}\beta(k,i,2)Q(i,1) + \sum_{i=1}^{N}\beta(k,i,1)Q(i,2) = S(k,2) \\
\qquad \sum_{i=1}^{N}\beta(k,i,3)Q(i,1) + \sum_{i=1}^{N}\beta(k,i,2)Q(i,2) + \sum_{i=1}^{N}\beta(k,i,1)Q(i,3) = S(k,3) \\
\qquad Q(i,j) \leqslant q_0(i) \\
\qquad Q(i,j) \geqslant 0
\end{cases}
$$

The optimal model was solved by linear programming. The final optimal management scheme, which well solves the problems for reasonable drainage in the four aquifer structure, is presented. The total inflow rate of groundwater in the first management time segment is 341,340 cubic metres per day, it is 310,310 cubic metres per day in the second time segment and 282,099 cubic metres per day in the third time segment.

In order to predict the vertical groundwater recharge flow rates of the lineal fault belt inner boundary in Jiu Lishan coal mine, a hypothetical ideal optimal management model is set up, which is completely equivalent to the real optimal management model except without the permeable lineal fault belt inner boundary. The hypothetical ideal model is solved with the same methods and managing conditions as the real ones, and the discrete optimal management scheme for the ideal model is obtained. The total inflow rate of groundwater in the first management time segment is 79,243 cubic metres per day, it is 72,039 cubic metres per day in the second time segment, and is 65,490 cubic metres per day in the third time segment.

It is obvious that the differences for the inflow rate of groundwater between the real model and the hypothetical ideal one in every management time segment should be the vertical groundwater recharge flow rate of the lineal fault belt inner boundary, that is to say, the vertical recharge flow rate is 262,097 cubic metres per day (341,340 - 79,243) in the first time segment, is 238,271 cubic metres per day (310,310 - 72,039) in the second time segment, and is 216,609 cubic metres per day (282,099 - 65,490) in the third time segment.

SCHEME FOR PREVENTING AND CURING MINE WATER

According to the above-mentioned data, the vertical groundwater recharge flow rate of the lineal fault belt inner boundary in every management time segment is as high as 76% of the total inflow rate of groundwater in the Jiu Lishan coal mine. Therefore, the scientific scheme for preventing and curing mine water should, first, block up the lineal fault belt inner boundary, and reduce the vertical groundwater recharge flow rate from the base thick karst aquifer to up thin-bedded karst aquifers along the inner boundary, after that, consideration to drain and to drop the groundwater in the west part of the coal mine should be made.

This scheme has been adopted by Jiu Lishan coal mine and has resulted in significant economic benefits.

CONCLUSIONS

A quasi-three-dimensional mathematical model with four aquifers which are hydraulically linked by two kinds of inner boundaries effectively depicts the objective stereo hydrogeological model in the Jiu Lishan coal mine. It looks very hopeful that the present disjointed problems between mathematical models and reality in the coalfield in North China can be solved satisfactorily. According to the successful case study in Jiu Lishan coal mine, a scientific scheme for preventing and curing mine water in the whole coalfield in North China may be laid down by making use of the techniques of the quasi-three-dimensional numerical simulation and optimal management.

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2. Li Jinkai. Preventing and curing karst water in coal mines. Publishing House of Coal Mining Industry, People's Republic of China, 1990.

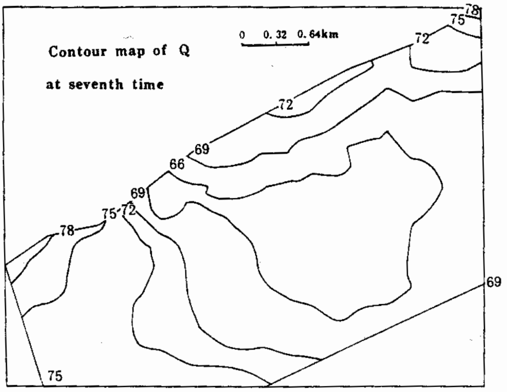

Figure 1. Simulant equi-potential map in Q at seventh.

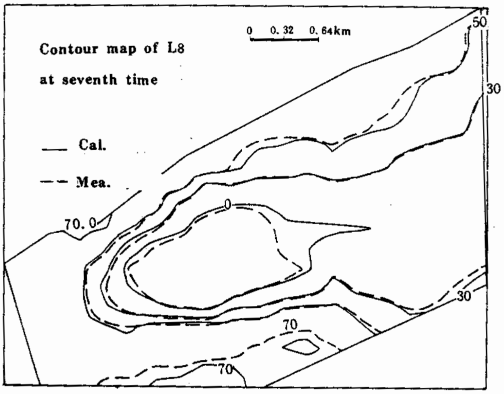

Figure 2. Simulant equi-potential map in L8 at seventh.

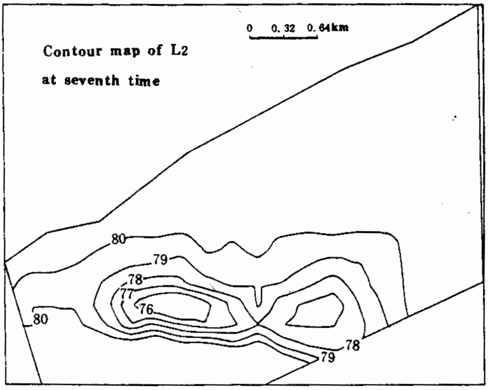

Figure 3. Simulant equi-potential map in L2 at seventh.

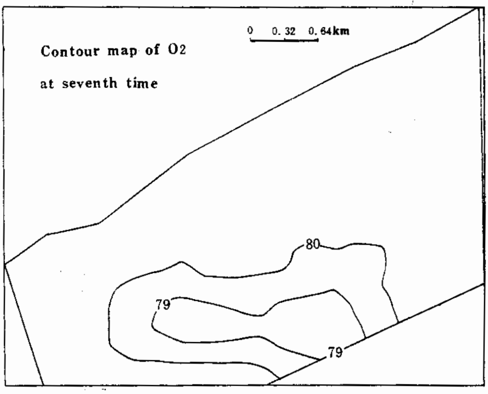

Figure 4. Simulant equi-potential map in 02 at seventh.

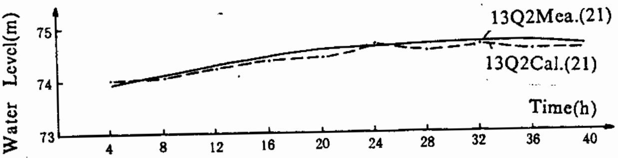

Figure 5. Predicted and actual curves at hole 13Q2 in Q.

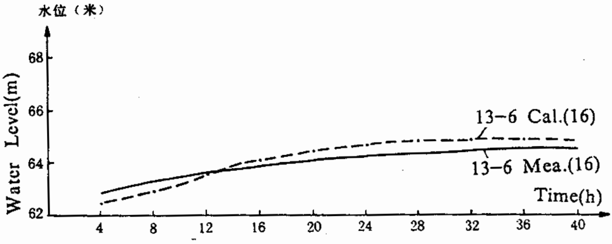

Figure 6. Predicted and actual curves at hole 13-6 in L8.

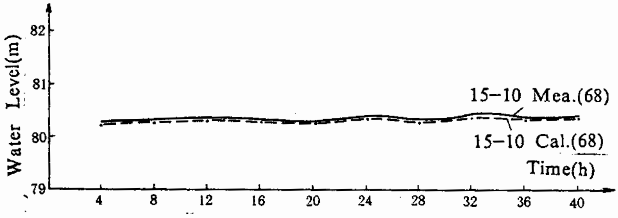

Figure 7. Predicted and actual curves at hole 15-10 in L2.

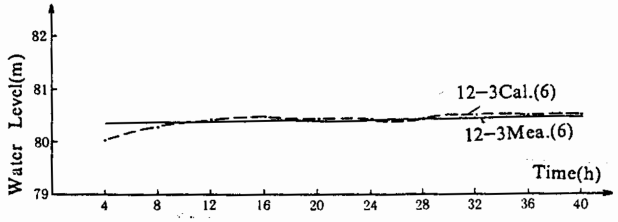

Figure 8. Predicted and actual curves at hole 12-3 in 02.