Forecasting of water yield of deep-buried iron mine in Yanzhou, Shandong

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Abstract: This paper compares analytical and numerical methods by taking the forecasting of water yield of deep-buried iron mine in Yanzhou, Shandong as an example. Regarding the analytical method, the equation of infinite and bilateral water inflow boundary is used to forecast the water yield, and in the case of numerical simulation, we employed the GMS software to establish a model and further to forecast the water yield. On the one hand, through applying the analytical method, the maximum water yield of mine 1 500 m deep below the surface was calculated to be 13 645.17 m^3/d; on the other hand, through adopting the numerical method, we obtained the predicted result of 3 816.16 m^3/d. Meanwhile, by using the boundary generalization in the above-mentioned two methods, and through a comparative analysis of the actual hydro-geological conditions in this deep-buried mine, which also concerns the advantages and disadvantages of the two methods respectively, this paper draws the conclusion that the analytical method is only applicable in ideal conditions, but numerical method is eligible to be used in complex hydro-geological conditions. Therefore, it is more applicable to employ the numerical method to forecast water yield of deep-buried iron mine in Yanzhou, Shandong.

Keywords: Analytical method; Numerical simulation; Forecasting of water yield; Yanzhou deep-buried iron mine

Introduction

It is undoubtedly necessary to forecast water yield at all stages to provide geological basis for the exploration and development of mining areas. At present, hydrogeological analogy method, water balance method, analytical method and numerical method are usually used in combination in forecasting water yield of mine (LIAN Hui-qing *et al.* 2014).

ZHOU Yi-yin, ZHANG Shi-tao *et al.* employed big well method to forecast water yield of mine in the copper mine field of Namphun, Laos (ZHOU Yi-yin *et al.* 2014). They believed that the accuracy of calculations could be influenced when big well method is used in heterogeneous fracture aquifers to obtain the permeability coefficient. However, HUA Jie-ming pointed out that big well method is not applicable to the forecasting of the water yield of mine according to its theoretical analysis and its results (HUA Jie-ming, 2009). Analytical method is not only inappropriate in harsh applicable conditions, but also not applicable in heterogeneous aquifers. Numerical method well applies to the forecasting of the water yield of mine in the mining area of Daoxian, Hunan with relatively high reliability, and this was conducted by XIAO Pan *et al.* (2011). Also, media generalization of dewatering

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conditions in complex karst mining areas was studied by LI Gui-ren, ZHAO zhen, CHEN Zhi-hua *et al.* (LI Gui-ren *et al.* 2012). They achieved fairly promising results based on the media generalization study through establishing a numerical simulation model of groundwater to forecast the water yield of mine.

It is obvious that the numerical method is applicable to various hydrogeological conditions and it could be used in forecasting water yield of mine in a relatively accurate manner. By comparing the numerical method with the analytical method, the same conclusion can still be drawn. ZHOU Hong-wei and his colleagues compared the numerical simulation method with others during studying the water yield of mine in Wanghao iron mine (ZHOU Hong-wei *et al.* 2013). They came to relatively satisfying conclusions because of the relatively simple hydro-geological conditions in this mine. PENG Hong-tao, WANG Hao and their colleagues employed the analytical method and the numerical method respectively to forecast water yield of mine (PENG Hong-tao *et al.* 2014). They compared the forecasting results of the two methods respectively with the actual water yield of mine in the late deposit mining. They found that the results obtained through applying the numerical method are closer to the actual water yield of mine.

In conclusion, the analytical method and the numerical method are both appropriate to be used to get accurate water yield results for mining areas with relatively simple hydrogeological conditions. However, for those mines with relatively complex hydrogeological conditions, the numerical method is preferable to acquire more accurate results compared with the analytical method.

The iron mine in this study area is hosted in metamorphic rocks of the Jining Group, Shandong, China, with the buried depth being 1 000 m, it can be seen as a deep-buried iron mine. This paper aims to discuss the method to forecast the water yield of mine by taking the water yield prediction in this mining area as an example. Nevertheless, there are some difficulties in forecasting the water yield in deep-buried mines, such as the lack of previous experiences and relevant information, as well as the fuzzy hydrogeological conditions.

1 Forecasting methods

1.1 Analytical method

Analytical method is an approach to forecasting water yield of mine by solving the equations based on groundwater movement with corresponding boundary conditions and initial conditions. The analytical method could be employed not only to forecast the water yield of all kind of conditions including roadway systems and dewatering facilities, but also to predict the level, range and time of dewatering. The following equations (FANG Pei-xian *et al.* 1996) can be employed:

$$\mathrm{Q} = \mathrm{BK}\frac{(2\mathrm{S}-\mathrm{m})\mathrm{m}}{R} \tag{1}$$

$$Q_{max} = 1.5Q \tag{2}$$

In these equations, Q stands for the water yield of mine (m^3/d), Q_{max} refers to the maximum water yield of mine (m^3/d), B means length of the horizontal projection of tunnel (m), K represents permeability coefficient of tunnel (m), S is drawdown of tunnel (m), M stands for aquifer thickness (m) and R means the influencing width of horizontal tunnel (m).

Analytical method is widely used, not only because it is relatively easy in calculating, but also thanks to its practicality and economical efficiency. However, it is only applicable to ideal conditions where aquifers have regular geometries, uniform properties, fixed thickness and single boundary conditions, and unfortunately these ideal conditions are very difficult to find or to create.

1.2 Numerical method

In this study, GMS software is employed to make a simulative forecasting of the water yield of mine. The governing equation (Michael *et al.* 2005) is as below:

$$S\frac{\partial \mathrm{h}}{\partial t}=\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\left(K_y\frac{\partial h}{\partial y}\right)+\left(K_z\frac{\partial h}{\partial z}\right)+\varepsilon \quad (3)$$

In this equation, H represents the elevation of groundwater level (m), K_x, K_y and K_z are the permeability coefficient of water-bearing media in x, y and z direction relatively (m/d), and ε refers to source and sink of the aquifer (L/d).

With more hydrogeological data, numerical method could simulate and forecast the variation of groundwater flow field and water level incomplex hydrogeological conditions and boundary conditions.

2 Forecasting the water yield of mine

2.1 Geological characteristics of water level in study mining area.

The study mining area is located in Yanzhou, Shandong, in the middle of the alluvial plain of Wensi River. It belongs to the zone of the sub-humid monsoon climate, with four distinct seasons. The buried depth of ore-bearing horizon in the mining area is very deep, which belongs to Jining Group, Archaeozoic erathem. F1 fracture cuts deep in the ore body that breaks the continuity of the ore. Therefore, F1 fracture could affect the water-filling ability of deposits to a relatively large extent (as shown in Fig. 1 and Fig. 2).

There are some differences in information, lithology and water abundance caused by drilling as well as the influence of groundwater on deposits, the groundwater is divided into four parts in vertical from top to bottom, as seen below:

a. Loose rock pore-water

Water in loose rock mass is distributed everywhere in the whole mining area. It is mainly recharged by lateral runoff. In terms of its major discharge forms, there are artificial water-pumping, lateral runoff and recharging karst water through vertical leakage.

b. Fracture-karst aquifers of Carbonate rock of Jiulong Group, Cambrian System and Majiagou Formation, Ordovician System

They are the main aquifers of the mining area. The karst groundwater is recharged by lateral runoff and the pore-water leakage from medium-deep layers in the upper parts. Also, its major discharge forms include lateral runoff and artificial groundwater exploitation. The underlying shale is very thick, its water abundance level is low, and they belong to Mantou Formation, Changqing Group, Cambrian System. They obstruct the hydraulic connection of fracture-karst water between the upper layer and the deeper layer because of their quite high thickness and relatively poor water abundance. So Mantou Formation shale could be seen as the relative impermeable layer.

c. Fracture-karst aquifers of Carbonate rock and basal conglomerate of Zhushadong Formation, Changing Group, Cambrian System.

They are distributed under the Mantou Formation, Changqing Group. The formation's fracture-karst cannot be developed. The groundwater is hosted in the fracture. They have little hydraulic connection with the upper Cambrian-Ordovician limestone fracture water. The groundwater is recharged by slow lateral runoff, and its discharge forms mainly include runoff.

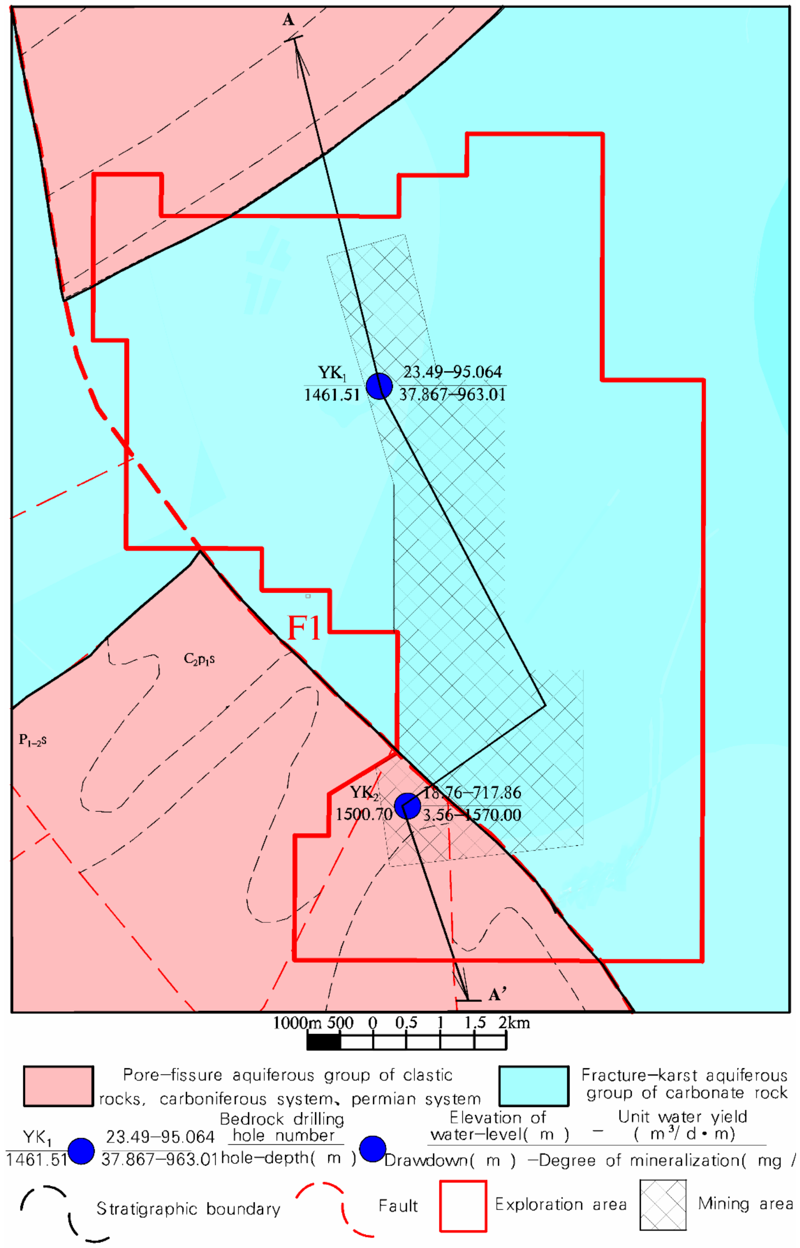

Fig. 1 Comprehensive hydrological figure in the mining area

d. Fracture aquifers of metamorphic rock of Jining Group

Metamorphic rock of Jining Group is ore-bearing strata, with relatively poor recharge, runoff and discharge of its fracture water. From the drilling situation, it is known that the groundwater is hosted in the phyllite fractured zone where the structure is compact and pore-fracture structure cannot be developed.

The main impermeable layers in the upper part of the deposits are the Mantou Formation, Cambrian System. In terms of lithology, there is shale which is colored from dark purple to green-gray, gray sandstones, sandy limestones, *etc*. The layers are distributed in a continuous form with relatively high thickness. Almost all of their fractures cannot be developed, and their water conductivity and permeability are rather poor. So the layers could obstruct the permeation of upper fracture-karst water to form complete relative impermeable layers on the top of the deposits.

Several pumping tests and water-lever recovery tests are carried out for two bedrock drilling-holes, named YK1 and YK2 respectively, in this research area to make clear the hydrogeological structure and to obtain the parameters of the mining area. On the one hand, the hole-depth of YK1 is 1 461.51 m, and here six stratifying pumping tests and water-lever recovery tests are conducted on the ore-bearing horizon. The aquifers of the second pumping test do not appear in the simulation range. On the other hand, concerning YK2, the hole-depth is 1 500.7 m, where four stratifying pumping tests are carried out. The third and the fourth pumping tests and water-level tests are conducted on the mining area horizon.

2.2 Forecasting of water yield

(1) Analytical method

The results obtained based on the application of Equation (1) and Equation (2) are listed in Table 1: Table 1 calculated water yield of mine based on the analytical method.

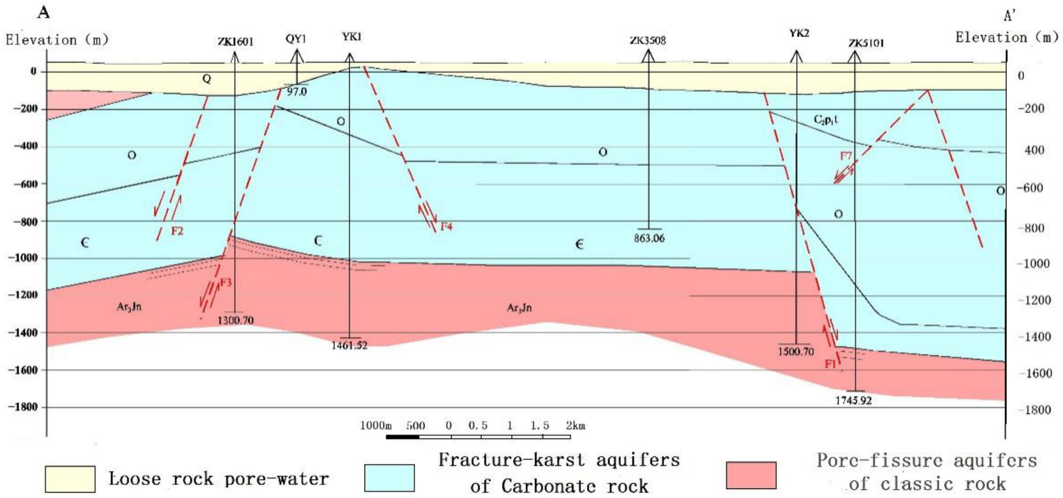

Fig. 2 A-A' Profile of the study area

Table 1 Calculated water yield of mine based on the analytical method

Forecasting position	Elevation of forecasted water-level	Length of tunnel	Permeability coefficient	Thickness of aquifer	Drawdown	Influencing width of tunnel
		B	K	m	S	R
	(m)	(m)	(m/d)	（m）	（m）	(m)
	-1 200	2 270	0.0013	200	1 220.64	440.11
	-1 300	2 270	0.0013	300	1 320.64	476.16
	-1 400	2 270	0.0023	400	1 420.64	681.32
	-1 500	2 270	0.0023	500	1 520.64	729.27

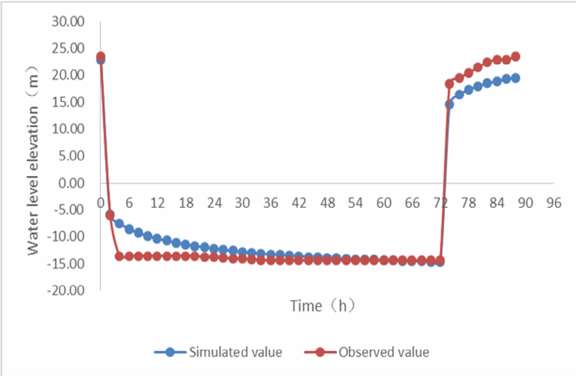

Fig. 3 Fitting curve of the first pumping test in YK1(April 8, 2009-April 10, 2009)

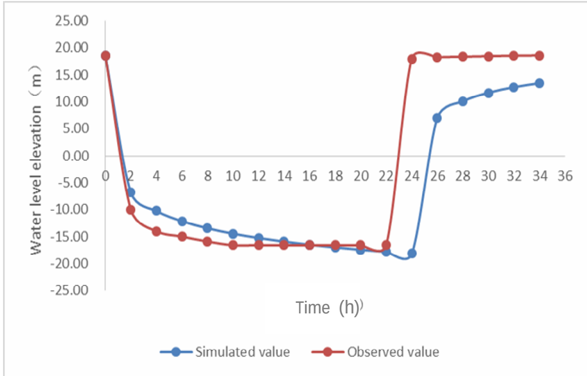

Fig. 4 Fitting curve of the third pumping test in YK1 (May 28, 2009-May 29, 2009)

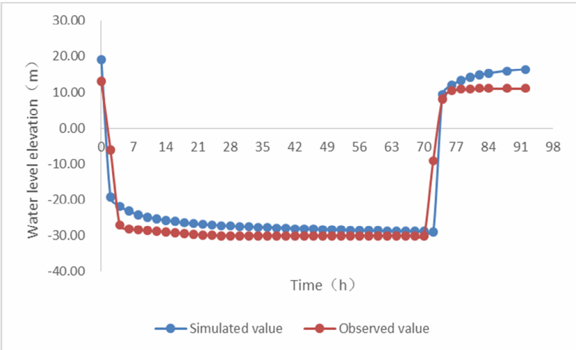

Fig. 5 Fitting curve of the fourth pumping test in YK1 (June 23, 2009-June 25, 2009)

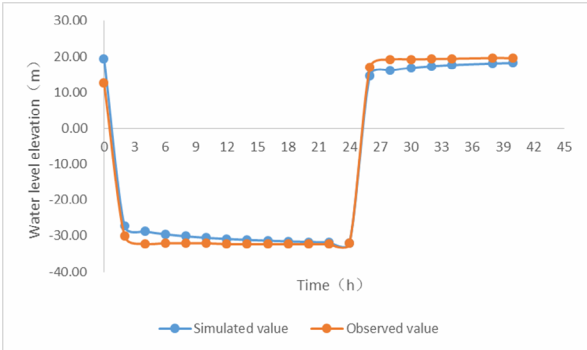

Fig. 6 Fitting curve of the fifth pumping test in YK1 (July 24, 2009-July 25, 2009)

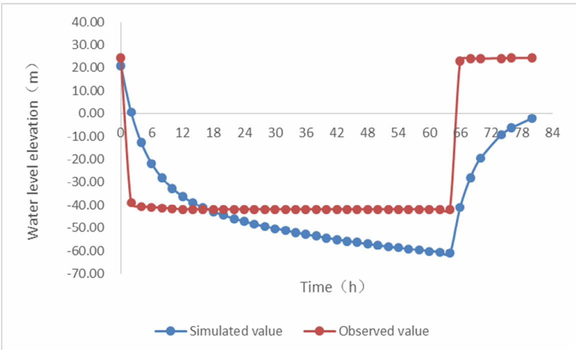

Fig. 7 Fitting curve of the sixth pumping test in YK1 (August 19, 2009-August 21, 2009)

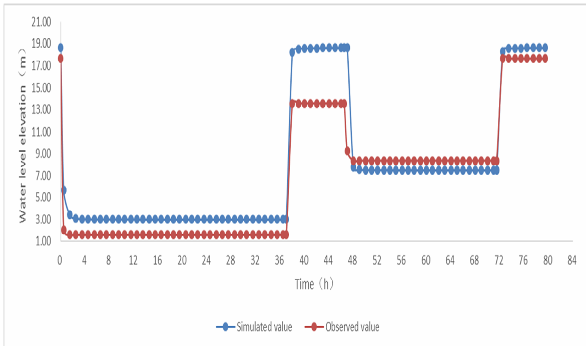

Fig. 8 Fitting curve of the third and the fourth pumping tests in YK2 (January 4, 2011-January 7, 2011)

(2) Numerical method

The simulation area of the model is 64.17 km^2, and the mesh dissection is 100 m×100 m. The model is vertically divided into four layers, with the first layer from -1 113 m to -1 338 m, the second from -1 338 m to -1 400 m, the third from -1 400 m to -1 417 m and the fourth from -1 417 m to -1 613 m. As the ore-bearing horizon is a deep-buried iron mine under the impermeable layer of Mantou Formation shale, the roof and floor could be regarded as the impermeable boundary, and the four side boundary of the model is general head boundary. 233 stress periods are summed up based on the results of the pumping tests and water-lever recovery tests. Local refinement is applied from 10 m to 100 m under the drilling position of YK1 and YK2 with a ratio of 1.8. One of the main influence factors of water yield forecasting in this mining area is that F1 fault cuts deeply in the ore body. According to the data, F1 fault could be determined as watercourse which is described by using permeability parts in the numerical model.

The model is calibrated according to the observation data of the water-level from the pumping tests in YK1 and YK2. The fitting results are shown as Fig. 3 to Fig. 8.

In general, from the fitting curves, it can be seen that the results of the pumping tests in YK1 are fairly good.

The aim of fitting the data of the third and the fourth pumping tests in YK2 is to identify the permeability parts of F1 fault. The area between YK2 drilling-hole and fault zone is combined and generalized as a divisional parameter because the hydrogeological structure of secondary faults is not identified. Fortunately, the fitting result is fairly good, as shown in Fig. 9.

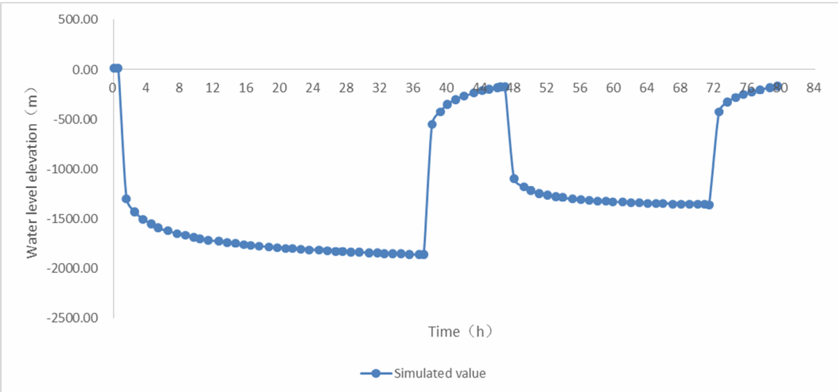

Fig. 9 The simulation result of the third and the fourth pumping tests in YK2 without the fault

The third and the fourth pumping tests in YK2 are simulated again after the divisional parameter of fault transition zone is rejected, of which the result is shown in Fig. 9 below, from which it can be seen that the pumping drawdown is quite large. It reflects the conductivity of the fault transition zone, and corroborates that F1 fault serves as the watercourse that connects the fracture aquifers of the metamorphic rock of Jining Group.

After identifying and fitting the model, the pumping well is set up to be the drainage tunnel according to the iron-mining technology. Also, the optimum plan is selected as the forecasting plan according to the flow-time curve and the drawdown-time curve.

Table 2 Forecasting results generated by the application of the analytical method and the numerical method respectively in tunnels

Working levels (m)	Normal water yield through the analytical method (m^3/d)	Maximum water yield through the analytical method (m^3/d)	Normal water yield through the numerical method (m^3/d)	Maximum water yield through the numerical method (m^3/d)
-1 200	3 005.62	4 508.43	2 047.62	3 071.44
-1 300	4 353.02	6 529.53	2 213.12	3 319.68
-1 400	7 483.08	11 224.62	2 378.61	3 567.92
-1 500	9 096.78	13 645.17	2 544.11	3 816.16

3 Discussions

It is known from Table 2 that the results obtained through using the two different methods vary significantly from each other. A comparison of the results tells us that the water yield of mine forecasted by using the numerical method is far smaller than that forecasted by using the analytical method. Based on the comprehensive analysis of information about the actual situation, the forecasting results obtained by using the numerical method agree better with the reality.

Firstly, the analytical method requires boundary generalization to be highly ideal, so that the subsequent equation calculation could be limited. According to the division from Exploring Specification of Hydrogeology and Engineering Geology in Mining Areas (GB12719-1991), the ore-bearing horizon in this research area is located in the fracture aquifer of metamorphic rock of Jining Group, of which the thickness is 10 m. The unit water yield of the 91 mm diameter drilling-hole is 0.0012 L/s·m-0.027 L/s·m. The water abundance level of aquifer is poor; moreover, it gets poorer as the depth of aquifer increases. High buried depth, undeveloped fractures and small water-storage space together lead to the result that the fracture water hosted in metamorphic fracture zone alternate relatively slowly. The water is considered to be under stable circumstances basically because the salinity is up to 5 930 mg/L-6 430 mg/L. In other words, the source of the water yield of mine can be basically seen as the static reserve of aquifer. However, the analytical method requires the aquifer to have infinite boundary. Analytical method is merely used to solve problems concerning two special boundaries, namely, constant water head boundary and impervious boundary. This paper uses analytical method to generalize this research area to infinite boundary of bilateral water inflow. It is considered that a large amount of water comes through the boundary when the pumping test is conducted, which is a totally different situation from the actual one, and the calculation result of the water yield of mine easily gets larger than the actual situation if the analytical method is applied. The numerical method can be employed in conditions other than the ideal one, solving differential equations. It could reflect true characteristics of the hydro-geological conditions. The boundary simulated from iron mine model is generalized to general water head boundary. This not only ensures that most water yield comes from the static reserve of the aquifer, but also make it possible that the water out of the boundary comes in when drainage is conducted. This situation of the numerical method conforms to the actual situation.

To calculate the width influence through using the analytical method, the empirical equation is chosen. In the empirical equation, R is very small, which makes the calculation result of the water yield larger. This is one of the disadvantages of equations using the analytical method. However, this problem will not appear if using the numerical method.

As for the limitations in terms of the application condition of the analytical method, aquifers are always considered to be homogeneous and isotropic in the calculation area. For the fracture aquifer of metamorphic rock in this research area, this is not in accordance with the actual situation and also to some extent can affect the calculation accuracy.

For this study area, F1 fault has an important impact on the mine water filling. It is the watercourse of the water yield of mine. However, this is not suitable for the analytical method. The numerical method uses different divisional parameters to make sure that water yield of mine influenced by F1 fault is taken into account in the calculation. This can be seen as fitting with the results of the third and the fourth pumping tests in YK2 with and without the fault in model identification as Fig. 9 mentioned. Therefore, through discussing the source of water yield, the generalization of hydrogeological conditions as well as the advantages and disadvantages of the analytical method and the numerical method themselves, we can see that the numerical method agrees fairly well with the actual situation of the mining area, and the result calculated through using the numerical method is more reliable than that through using the analytical method.

4 Conclusions

(1) Analytical method is a way to construct ideal analytical equations following reasonable generalization. Even though this method is simple and quick, it is only applicable to ideal conditions, *e.g.* aquifers with regular geometries, uniform properties, fixed thickness, as well as single boundary conditions.

(2) Numerical method could solve complex problems rapidly and reflect the actual situation veritably. The simulation results obtained by using the numerical method not only turn out to be fairly accurate and reasonable, but also perfectly match the actual situation.

(3) The ore-bearing horizon of Yanzhou iron mining area in Shandong is fracture aquifer. F1 fault cuts through the aquifer, exerting an important influence on water yield of mine. The maximum water yield of mine calculated through using the analytical method is 13 645.17 m^3/d at the depth of -1 500 m. However, the result obtained by using the numerical method is 3 816.16 m^3/d at the same location. Taking both sources of water yield is come from the aquifer itself and boundary conditions are not a constant water head boundary or an impervious boundary into consideration, we come to the conclusion that the numerical method agrees better with the actual situation. Besides, as the analytical method cannot consider the anisotropy of aquifers and the influence of F1 fault, the numerical method is more suitable than the analytical method in calculation of the water yield of mine of the iron mine in Yanzhou, Shandong.

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