A NEW METHOD OF MINE DRAINAGE PREDICTION USING UNIT STATIC RESOURCE METHOD

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ABSTRACT

The paper considers mine drainage prediction in a partially closed mine with a fractured karst aquifer which is highly permeable and quite thick. The aquifer is bordered along the edge of the mine by impermeable boundaries and zones, of low transmissibility. Inside the mine there are significant quantities of static resource ground water. However, the extent of ground water outside the mine is relatively less. In such a mine, a series of characteristics can be observed to accompany the pumpage when the pumped discharge exceeds the ground water recharge.

It is rather difficult to predict the drainage of such a mine, owing to the unsteady drawdown of the ground water level, and the complicated boundary conditions. In addition there is difficulty in measuring the hydrogeological parameters such as the permeability coefficient of the aquifer, etc.

Quoting the concept of "unit static resource" that has been well defined previously, this paper offers a new type of "unit static resource method". It was developed in 1972 and has been effectively applied to drainage prediction problems at several mines in the northern part of China.

The method is applicable not only to partially closed mines but also to completely closed ones, and furthermore, includes the earlier "unit static resource method". It can be used to appreciate water supply besides predicting mine drainage.

INTRODUCTION

During hydrogeological exploration of mineral deposits and mine drainage planning, a type of mine with an incompletely closed or semi-closed fractured karst aquifer is occasionally encountered, the outside of which is bordered by impermeable boundaries and low transmissibility zones. Inside the mine, the fractured karst aquifer is quite extensive, thick and highly permeable, and so contains significant quantities of static resource ground water. The ground water inside and outside the mine is connected by low transmissibility zones. Under natural conditions they are in dynamic equilibrium.

In general, the characteristics of the drawdown of ground water level resulting from intense pumping in the mine are as follows :

1. Because of the intense rate of pumping and the relatively low rate of replenishment from outside the mine, the static resource of ground water within the mine has to be consumed, and the ground water level falls, being difficult to stabilise.

2. As the level of ground water in the mine falls, the difference between the ground water levels inside and outside the mine increases. Consequently, the rate of recharge increases slowly. Thus, under the condition of steady pumping discharge, the rate of drawdown of water level could decrease gradually with time.

3. Because of the high permeability of the aquifer and its lack of replenishment the drawdown funnel is quite flat and often appears plate-shaped. Under the condition of steady pumping discharge, the situation of parallel falling down of the funnel appears very soon.

Due to ;

(i) the unsteady nature of the pumping process,

(ii) the complicated boundary conditions,

(iii) the difficulty of accurately determining hydrogeological parameters such as the coefficient of permeability and, in particular,

(iv) a lack of study of the low transmissibility zones which control the rate of replenishment of the mine,

it is difficult to predict the mine inflow or to determine the mine drainage by using the analytical methods of steady or unsteady flow theory or even by applying numerical methods.

A "unit static resource method" was developed previously in order to evaluate the dynamic, static and exploitable resources of fractured karst water with a closed basin of finite ground water extent. This method is only suitable when the rate of replenishment is constant, i.e. it does not increase as the drawdown of ground water level increases.

Considering the hydrogeological characteristics of partially closed mines with the fractured karst water and quoting the concept of a "unit static resource" that has been well defined previously, the author of this paper suggested a new type of "unit static resource method" based on the increase of the rate of replenishment with drawdown in the mine. This method was developed in 1972. It has been used to predict the mine inflows and to calculate the mine drainages at several mines containing fractured karst water in the northern part of China. It was tested initially in production wells and satisfactory results were obtained.

FORMULAE

Parameter Calculation Formulae

In the course of unsteady pumping, the pumping discharge Q is the sum of the lateral recharge quantity, Q_r, and the consumed static resource, Q_s, in unit time in the mine district :

$$Q = Q_r + Q_s \qquad (1)$$

When Q_s is expressed by the product of the unit static resource, q, (the consumed static resource in the mine when the water level drops one meter) and the falling rate of the ground water level, v, (falling amplitude of the depression funnel in unit time), then

$$Q_s = qv \qquad (2)$$

The relationship between Q_r and the drawdown of the water level of the district, s, should be considered as a power function.

For pumping discharges taken at three discrete times we have

$$Q_1 = Q_{r1} + Q_{s1} = Q_{r1} + qv_1 \ ; \qquad (3)$$

$$Q_2 = Q_{r2} + Q_{s2} = Q_{r1} \cdot m\sqrt{\frac{s_2}{s_1}} + qv_2 \ ; \qquad (4)$$

$$Q_3 = Q_{r3} + Q_{s3} = Q_{r1} \cdot m\sqrt{\frac{s_3}{s_1}} + qv_3 \ . \qquad (5)$$

From formula (3), (4) and (5) we can get

$$m = \frac{\overset{*}{\lg} s_3 - \lg s_1}{\lg(Q_3 - qv_3) - \lg(Q_1 - qv_1)} \ ; \qquad (6)$$

$$m = \frac{\lg s_3 - \lg s_2}{\lg(Q_3 - qv_3) - \lg(Q_2 - qv_2)} \ . \qquad (7)$$

The parameters q and m can be obtained by using formulae (6) and (7) and similarly the values of Q_{r1}, Q_{r2}, Q_{r3} and Q_{s1}, Q_{s2}, Q_{s3} may be calculated also.

In the formulae from (3) to (7)

Q_1, Q_2, Q_3 – the pumpages (cubic meter/day) of the three given pumping discharges;

v_1, v_2, v_3 – the falling rates (meter/day) of the water level of each pumping discharge at the given moment;

s_1, s_2, s_3 – accumulated falling values (meter) of the water level at each moment;

Q_{r1}, Q_{r2}, Q_{r3} – recharge quantities (cubic meter/day) related to s_1, s_2, s_3;

Q_{s1}, Q_{s2}, Q_{s3} – consumed quantities (cubic meter/day) of static resources related to v_1, v_2, v_3;

Note :- * $\lg = \log_e$

q - the unit static resource (cubic metre/metre);

m - the number of the power ($1 \leqslant m \leqslant 2$).

Recharge Quantity Calculation Formula

Let Q_{r0} express the obtained Q_{r1} (or Q_{r2}, Q_{r3}), S_0 similarly express s_1 (or s_2, s_3), s be any drawdown of ground water level, Q_r be the recharge quantity related to s, s_b be the initial drawdown of the water level in a certain drainage process which has been formed by previous drainage or water supply, Q_{rb} be the recharge quantity related to s_b, s_c be the expected drawdown of the water level at the end of the drainage process, Q_{rc} be the recharge quantity related to s_c. Based on the relationship of the power function we can get

$$Q_r = Q_{r0} \cdot \sqrt[m]{\frac{s}{s_0}} , \tag{8}$$

$$Q_{rb} = Q_{r0} \cdot \sqrt[m]{\frac{s_h}{s_0}} , \tag{9}$$

$$Q_{rc} = Q_{r0} \cdot \sqrt[m]{\frac{s_c}{s_0}} . \tag{10}$$

Calculation Formula for Dewatering Discharge and Dewatering Time

The dewatering discharge, Q_d (cubic metre/day) means a certain discharge intensity which is needed during the time, T, (day) in order to dewater the aquifer of a mine to a certain planned level, i.e. to get the expected value of drawdown. Obviously we have

$$Q_d = Q_r + Q_s . \tag{11}$$

Taking (2) and (8) substituting into (11) and using $\frac{ds}{dt}$ instead of v, then we get

$$q \frac{ds}{dt} = Q - \frac{Q_{r0}}{\sqrt[m]{s_0}} \cdot s^{\frac{1}{m}} .$$

Where t is the time variable. Separating the variables and letting the upper and lower limits of s be s_c and s_b and the upper and lower limits of t be T and 0, after integration we get

$$T = \frac{q}{Q_d} \int_{s_b}^{s_c} \frac{1}{1 - \frac{1}{Q_d} \cdot \frac{Q_{r0}}{\sqrt[m]{s_0}} \cdot s^{\frac{1}{m}}} \tag{12}$$

$Q_d > Q_{rc}$, i.e. $Q_d > \frac{Q_{r0}}{\sqrt[m]{s_0}} \cdot s_c^{\frac{1}{m}}$ is always kept for the dewatering of a mine, therefore, the integrated function can be expanded in an unlimited decreasing series with the equiratio within the integral range. Let $A = \frac{1}{Q_d} \cdot \frac{Q_{r0}}{m\sqrt{s_0}}$ and expand the integrated function, then we have

$$T = \frac{q}{Q_d} \left| \sum_{k=1}^{n} \frac{A^{k-1} s^{1+\frac{k-1}{m}}}{1+\frac{k-1}{m}} + \sum_{i=0}^{\infty} \frac{A^{n+i} s^{1+\frac{n+i}{m}}}{1+\frac{n+i}{m}} \right|_{s_b}^{s_c}$$

Let $\alpha = A\, s_c^{\frac{1}{m}} = \frac{Q_{rc}}{Q_d}$, $\beta = A\, s_b^{\frac{1}{m}} = \frac{Q_{rb}}{Q_d}$, then

$$T = \frac{q\, s_c}{Q_d} \left(\sum_{k=1}^{n} \frac{\alpha^{k-1}}{1+\frac{k-1}{m}} + \sum_{i=0}^{\infty} \frac{\alpha^{n+i}}{1+\frac{n+i}{m}} \right)$$

$$- \frac{q\, s_b}{Q_d} \left(\sum_{k=1}^{n} \frac{\beta^{k-1}}{1+\frac{k-1}{m}} + \sum_{i=0}^{\infty} \frac{\beta^{n+i}}{1+\frac{n+i}{m}} \right) \tag{13}$$

(13) is the relationship form between dewatering time and discharge. In practical calculations, only n terms in two brackets are needed, and the remaining brackets may be disregarded. Thus the resulting error in calculating the dewatering time will be

$$\delta = \frac{q\, s_c}{Q_d} \sum_{i=0}^{\infty} \frac{\alpha^{n+i}}{1+\frac{n+i}{m}} - \frac{q\, s_b}{Q_d} \sum_{i=0}^{\infty} \frac{\beta^{n+i}}{1+\frac{n+i}{m}}$$

$$< \frac{q\, s_c}{Q_d} \sum_{i=0}^{\infty} \frac{\alpha^{n+i}}{1+\frac{n+i}{m}} \leqslant \frac{q\, s_e}{(1+\frac{n}{m})\, Q_d} \sum_{i=0}^{\infty} \alpha^{n+i}$$

$$= \frac{q\, s_e}{(1+\frac{n}{m})\, Q_d} \cdot \frac{\alpha^n}{1-\alpha}$$

i.e. $$\delta < \frac{q\, s_c\, \alpha^n}{(1+\frac{n}{m})(1-\alpha)\, Q_d}, \tag{14}$$

DISCUSSION

The parameters q and m may also be determined by the formulae (6) and (7) based on the data at three different places during a given pumping discharge. The value q can still be expressed by the product of the average specific yield or volume fracture-karst ratio of the aquifer and the horizontally projected area of the dewatering region. If there are significant changes in the horizontally projected area of the dewatering region and/or the specific yield of the aquifer in a vertical direction, the dewatering region can be vertically divided into several sections according to practical data and each value of q can be determined separately. So, the dewatering time can be calculated section by section from top to bottom. The sum of dewatering times of all the divided sections is the dewatering time of the entire dewatering region.

Also, the values m and Q_{rc} can be determined by two or three steady pumping tests with smaller pumpages.

If the start point of dewatering is at the natural water level, i.e. $s_c = 0$, then the formula for calculating dewatering time and discharge is as follows :

$$T = \frac{q\ s_c}{Q_d}\left\{\sum_{k=1}^{n} \frac{\alpha^{k-1}}{1 + \frac{k-1}{m}} + \sum_{i=0}^{\infty} \frac{\alpha^{n+i}}{1 + \frac{n+i}{m}}\right\} . \qquad (15)$$

From the derivation process of the formula we can see that the dewatering discharge must be greater than the recharge quantity of the level to be dewatered, i.e. $Q_d > Q_{rc}$ in order for the expected result to be obtained, otherwise it could not be dewatered (when $Q_d < Q_{rc}$) or it is impossible to be dewatered in a finite time (when $Q_d = Q_{rc}$).

If the recharge quantity of the mine (Q_r) is a constant, in order to make (13) established, the hydrogeological meaning of the power number (m) may be disregarded and the number considered as an infinite number mathematically ($m \to \infty$). Thus, the (15) may be expressed as follows :

$$T = \frac{q\ s_c}{Q_d}\left\{\sum_{k=1}^{n} \alpha^{k-1} + \sum_{i=0}^{\infty} \alpha^{n+i}\right\} .$$

After slight substitution we can get

$$T = \frac{q\ s_c}{Q_d - Q_r} . \qquad (16)$$

In fact, (16) is merely the calculational form of the "unit static resource method" which was developed before. So, the previous formula is the practical form of the new "unit static resource method" for a mine district in which the recharge quantity should be a constant.

Apparently, (13) and (15) are suitable for completely closed mines. In this case $Q_r = 0$, therefore, (13) can be altered to

$$T = \frac{q(s_c - s_b)}{Q_d} , \qquad (17)$$

and (15) altered to

$$T = \frac{q\ s_c}{Q_d} . \qquad (18)$$

Besides the external recharge quantity, if there is local recharge (Q_L) inside the mine district by infiltration of surface water and/or rain, then Q_d must be greater than the sum of Q_{rc} and Q_L, and (Q_d-Q_L) should be used instead of Q_1 in calculating the predictions of dewatering time and discharge.

The new "unit static resource method" may be used not only in dewatering calculations, but also in evaluating the ground water resource for water supply. However, it is not universal and only suitable for the above mentioned specific hydrogeological conditions. It has most practical significance when for the mines to be dewatered or the regions of water supply, it is rather difficult to use the analytical or numerical methods. Where the analytical or numerical methods may be used the data for comparison and analysis can be obtained by using the new type of "unit static resource method".

EXAMPLE OF CALCULATION

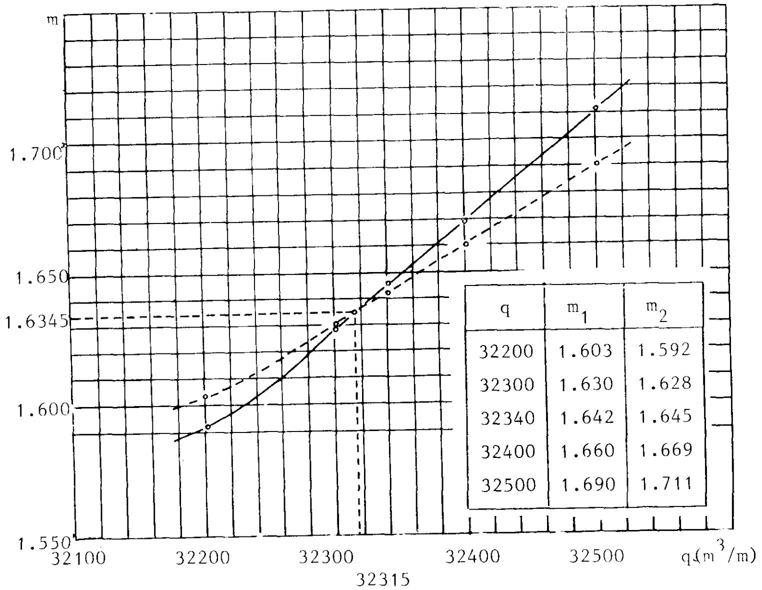
The chosen mine district in northern China is a partially closed fractured karst water reservoir. The hanging wall of the ore body at the mine is an Ordovician limestone aquifer with high permeability which slightly dips towards the west. Its eastern side is confined and western side unconfined. When the ground water is pumped in large quantities, as the water level continually falls, the unconfined area moves towards the east. In order to satisfy the needs of dewatering planning at the mine a pumping test made up of two step combining given discharge with the water supply in the district was performed. Before that, because of the exploitation of ground water over a long period of time the water level had dropped to 32 metres and the plate-shaped depression funnel had formed. As a result of the pumping test the drawdown of the ground water level increased to 39 metres.

In order to ensure that the selected data was correct many sets of data were taken from the tests to calculate the values q and m. The calculated results are almost the same. One set of the data is listed below in Table 1.

Table 1

Number	Q cubic metre/day	V metre/day	s metre
1	21168	0.270	32.614
2	19984	0.229	33.219
3	31347	0.544	38.479

The data from Table 1 substituted into (6) and (7) gives, q = 32320 cubic metre/metre and m = 1.635 by using the cut-and-try process and the diagrammatic decomposition method (see Figure). Further, the values Q and Q_r can be obtained from (3), (4) and (5) (Table 2).



q	m_1	m_2
32200	1.603	1.592
32300	1.630	1.628
32340	1.642	1.645
32400	1.660	1.669
32500	1.690	1.711

$m = f(q)$ curve

Fig.1.

Table 2

Number	$Q_s = qv$ m^3/d	$Q_r = Q - Q_s$ m^3/d
1	8280	12440
2	7400	12580
3	17580	13770

Take $Q_{r0} = 12440\ m^3/d$ and $s_0 = 32.61$ m, for the dewatering of the mine we consider $s_b = 40$ m and $s = 90$ m, then using (9) and (10) we can get

$$Q_{rb} = 14095\ m^3/d$$
$$Q_{rc} = 23146\ m^3/d$$

Further, take a series of given dewatering discharges, based on (13) a series of dewatering times can be obtained, and the calculating error may be evaluated by using (14), then the curve $Q_d = f(T)$ may be plotted in order to determine the optimum programme of dewatering discharge. The main calculated data is listed in Table 3.

Table 3

Q_{rb}	Q_{rc}	Q_d	α	β	n	δ	T
m^3/d						day	
14095	23146	35000	0.6613	0.4027	10	< 1	102
		40000	0.5787	0.3524	8	< 1	77
		45000	0.5144	0.3132	6	< 1	62
		50000	0.4629	0.2819	5	< 1	52
		55000	0.4208	0.2563	4	< 1	44
		60000	0.3858	0.2349	4	< 1	39

Computer programs have been developed for the above calculation. All the computation can be finished rapidly by using medium or small electronic computers.

CONCLUSIONS

An analytical technique for predicting the mine water inflow from disused mine workings or an abandoned mine is developed. The paper considers complex boundary conditions, unsteady drawdown, delay and variable recharge conditions. The method was originally developed in 1972 to predict the behaviour of a pumping well. It has since been used to predict the drainage requirements of fractured Karst water in several mines in northern part of China.