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TECHNOLOGY OF MINE WATER CONTROL IN CHINA

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ABSTRACT

The mines of the Permo-Carboniferous coalfield in North China and the Late Permian coalfield in the South are seriously threatened with Karst water from limestone, which results in frequent water inrush and mine inundation. The mines in the areas of the Yellow Huai and Shongliao plains are generally endangered by the water from Quaternary alluvium. Therefore, groundwater disaster is one of the main problems of coal mine safety in China.

After liberation, a great deal of research work on protecting against mine water has been done under the direction of the Ministry of Coal Industry. Successful results have been obtained in respects of studies of mine water inrush mechanisms, dewatering and depression of aquifer, sealing water inrush spots by grouting and cutting-off water flow by cement grout curtains, protecting against water at ground and underground as well as investigating the hydrogeological conditions in a mine area and calculating the mine inflow. Many practical problems in coal production have been solved, and the theory and technology of mine water control with China's typical features, have gradually been formed. However, further study and solution of some problems will be required because the hydrogeological conditions of the coalfields in China are extremely complicated.

INTRODUCTION

China is rich in coal resources. There are more than 10 coal-forming periods, from the early deposition of stone coal in the Cambrian period to the latest deposition of peat in the Quaternary period. The coal-bearing strata controls the distribution of coalfields, coal-forming period, sedimentary types and structural features, and also determines the hydrogeological characteristics of different types of coalfields. Therefore, coalfields in China can be divided into six hydrogeological type regions [6] (See Figure 1). Therein, Permo-Carboniferous coalfields in North China and Late Permian coalfields in the south of China belong to the Karst type region; coalfields in

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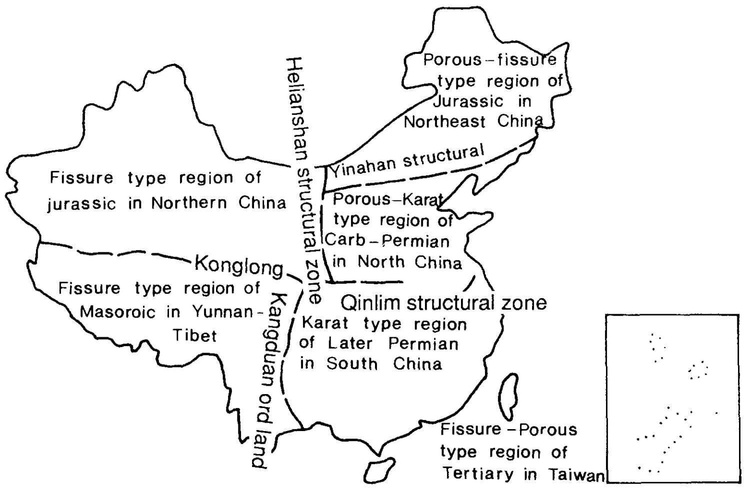

Figure 1 Sketch of hydrogeological type regions in China

the areas of Yellow-Huai and Shongliao plains are endangered by water from Quarternary alluvium. Hence, hydrogeological conditions in these coalfields are complicated, and coal mines are seriously endangered by groundwater. According to the statistical studies of the Ministry of Coal Industry, there are 222 pairs of state-owned shafts threatened with water, that have a productive capacity of 110 million tons, which is 30 percent of the whole productive capacity of state-owned coal mines. From 1955 to 1985, hundreds of mine flood accidents caused by groundwater inrush happened, which resulted in the great loss of 3 billion Yuan in the economy and 100 million tons in coal yield. From what has been mentioned above, it can be seen that groundwater disaster is the main problem of coal mine safety in China.

CALCULATION OF GROUDWATER INFLOW

The calculation of groundwater inflow is one of the key problems in the study of protecting against coal mine water. It not only has a direct relation to the disposition of mine water protection and discharge facilities, but provides an important basis for drawing up the overall plan for a mine water control project. The following four problems in research work of mine water control can be solved by calculation:

1. prognostication of normal mine inflow, the maximum inflow and inrush inflow;
2. design of an optimal scheme of dewatering and depression;

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3. evaluation of the effect of the cement curtain for cutting off groundwater flow;

4. quantitative demonstration of hydrogeological conditions in the mine area.

Although the four mentioned above are different in statement and focus of attention, the calculation methods are much the same. The methods adopted are mainly the hydrogeological analogy method, the hydrologic balance method, the correlation analysis, the analytical method, the systems engineering method, the modelling-analogue and the numerical methods, etc. At present, the numerical methods in common use include finite difference method, finite element method, subdomain balance method, boundary integral equation method (the boundary element method for short) and the combination of finite element and boundary element methods, etc. Whatever kinds of numerical methods are to be adopted they are based on clearly known hydrogeological conditions in the mine areas. The mathematical models must be set up first, which could be two-dimensional (including double-layers and multi-layers), or three-dimensional models. For instance, for the unsteady flow in a two dimensional, inhomogeneous, isotropic and confined aquifer, the mathematical model is

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + {}_{y}\left(T\frac{\partial h}{\partial y}\right) = S\frac{h}{t} + w$$

$$h(x,y,o) = g_1(x,y) \qquad (x,y)\ \varepsilon\ \Omega$$

$$h(x,y,t) = g_2(x,y,t) \qquad (x,y)\ \varepsilon\ \Omega_1 \qquad \ldots (1)$$

$$T\frac{h}{n} = g_o(x,y,t) \qquad (x,y)\ \varepsilon\partial\Omega_2$$

where

h = head

T = transmissivity

w = source function

S = storage coefficient

x,y = space variables

t = time

Ω = flow region

$\partial/\partial n$ = normal derivative ($\partial\Omega_1 \cup \partial\Omega_2 = \partial\Omega$)

g_1, g_2, g_o = known functions

If the Galerkin finite element scheme is used and the flow region is divided into a number of triangular elements, the discretization form of Equation (1) is

$$[B]h + [C]\frac{dh}{dt} + [F] = 0 \qquad \ldots (2)$$

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where the elements of the matrices [B] [C] and [F] are

$$B_{p,q} = \iint_{(\Omega)} T \frac{\partial\phi p}{\partial x}\frac{\partial\phi q}{\partial x} + \frac{\partial\phi p}{\partial y}\frac{\partial\phi q}{\partial y}) \, dx \, dy;$$

$$C_{p,q} = \iint_{(\Omega)} S\phi_p\phi_q \, dx \, dy;$$

$$F_i = \iint_{(\Omega)} w\phi_i \, dx \, dy - \int_{(\partial\Omega)} g\phi_i \, d(\partial\Omega)$$

where is the basis function. By solving Equation (2) the mine water inflow and piezometric heads in the vicinity of the mine can be obtained, which is called simulation of the solution or the direction problem. Usually, the hydrogeological parameters T and S in Equation (1) are unknown. These parameters can be determined by means of an optimization technique and hydrogeological test data, which is called the solution of the inverse problem or parameter identification. Many methods can be used to solve the inverse problem. However, it has been shown from practice that the parameter correction method and the Gauss-Newton method [3] are more powerful. The design of an optimal dewatering scheme for mines includes the determination of optimal arrangement, numbers, discharge and head of the dewatering wells. The main methods used in the calculation are linear quadratic and integer programming [3]. The algebraical equations formed by the numerical method, such as Equation (2), compose constraints. According to the different practical demands, the object function can be written in various ways. In general, in the course of dewatering in mines, the minimum discharge is expected to form the cone of depression as large as possible, so as to ensure the safe mining at the galleries and the working faces. From this purpose, the calculation of the optimal dewatering scheme can be formulated as the solution of the following linear programming problem:

$$\begin{aligned} &\text{Min } Z = \Sigma W_i \\ &[B]h + [C]\frac{dh}{dt} + [F] = 0 \\ &0 \leqq h_j \leqq H_o \\ &h_i \geqq 0 \\ &W_k = 0 \\ &W_1 \geqq 0 \end{aligned} \qquad \text{... (3)}$$

where Z represents the object function; W represents the discharges of dewatering wells; H_o represents the safe head. Of course, the cost of dewatering wells and drainage facilities and so on could be taken into consideration in the object function.

The calculation of mine water inrush inflow is one of the knotty problems in the calculation of mine water inflow. That is because the factors resulting in the mine water inrush are quite complex. Many of these factors

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are difficult to express quantitatively. From the analyses and studies of the water inrush practical cases than happened in some mine areas, it has been proved that the water inrush is random and obscure. Therefore, the factors associated with the mine water inrush have been sieved in terms of information theory, mathematical logic, obscure mathematics, systems engineering, probability and statistics. The forcast model has been set up and better results are obtained [11]. It could be expected that the research work on prediction of mine water inrush will get into a higher level with the development and application of new sciences such as cybernetics, systematology and abruption theory, etc.

In the past 30 years, the calculation of mine water inflow in our country has made great progress. In order to solve the problems about mine water inflow put forward by many mines, such as Zhibo, Feichen [5], Fengfeng, Jiaozhuo, Enkou, Meitanva, Huainan and Heshan in Kuangxi Province, plenty of research work and calculations were carried out and good results which solved many practical problems in coal production have been obtained.

WATER INRUSH MECHANISM

Water inrush in mines is the most widespread phenomena of ground water disaster in coal mines. It is referred to as a phenomenon that the water from the aquifers of the roof or floor of a seam overcomes the intensity of the relatively impervious rock body between aquifers and the resistance of the structural planes of faults and joints, and enters the mine galleries under the action of the water pressure and the mining pressure. Water inrush mechanisms study the factors causing water inrushes, the internal relations of these factors and the occurrence of water inrushes as well as the processes of its development.

As early as in the 1950s, it was realized that water inrush had been associated with the pressure of water in aquifers, the destruction of roof and floors caused by coal mining, the relative thickness of water-resisting layers and the existence of faults and joints. For example, when studying the dewatering plan for Xu Jiazhuang limestone in Zhibo Mine area in 1961, we considered the factors mentioned above as a comprehensive phenomenon. On the basis of the statistic data, we developed a concept of water inrush coefficient, which is defined as the critical value of water pressure borne by the unit thickness of a water-resisting layer. In 1966, a site test in which water was pressed into faults and water-resisting layers through wells was carried out to study the processes of water inrush. From the test, it is revealed that piezometric water with high pressure overcomes the resistance of structural planes in water-resisting layers and seeps in mine galleries. Meanwhile a great amount of potential energy converts into kinetic energy, the structural planes are washed and expanded, and inrush inflow becomes larger and larger. The limit intensities of different rock beds in thickness per metre obtained from the test are 10 kg/cm^2 for sandstone, 7 kg/cm^2 for sandy shale, 5 kg/cm^2 for bauxitic shale and 3.5 kg/cm^2 for fault zones. These values, however, are far greater than ones of actual water inrush. This was because destruction of the floor by mining pressure and the time effect of the rock intensity were not taken into consideration. For the sake of the application of these values to production, a concept of equivalent thickness of the water resisting layer was presented in 1977. Taking the intensity of a sandstone body as a standard unit, we gained certain ratios, for example, 0.7 for sandy shale, 0.5 for bauxitic shale and 0.35 for fault zones. Thus

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equivalent thickness of a water-resisting layer is its ratio times the actual thickness of water-resisting layer [7].

In 1979, the site observation to the destructive depth of the floors caused by coal mining was made in the Handan Mine area. By means of the observation wells with different depth, the destructive depth of the floors under mining pressure was determined to be from 8 to 12 metres. In 1982, the rupture and deformation of the floor beds arising from coal mining were tested and observed by using comprehensive methods with different observation instruments, such as water injection through boreholes, ultra-sonic detection and borehole radio-frequency detection, steel-string instrument and pressure pillow, etc. (See Figure 2). The results illustrate that the destructive depth of the floor usually is about 12 metres, the maximum less than 14 metres.

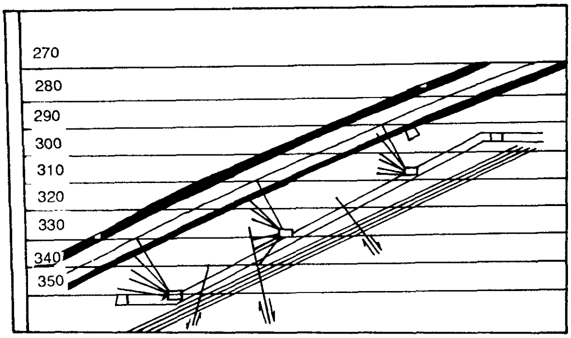

Figure 2 Sketch of a comprehensive test for the destruction of the floor by mining in Huai Nan Mine

The research work in water inrush mechanisms and regularity, especially Karst water inrush from the floor of seams under the high pressure, have guided mine water prediction and protection, so that great amounts of coal has been safely exploited in China.

DEWATERING AND DEPRESSION

Dewatering and depression refer to dewatering of aquifers in the roof of the seam and depression of aquifers in the floor of the seam in mining areas. In the 1950s, dewatering was carried out for Shanqing and Fuqing limestone in the Fengfeng mining area, for Taiyuan limestone in the Xushou mining area, and depression carried out for Xu Jiazhuang limestone in the Zhibo mining area. In the 1960s, the investigation of the procedure and the exploration method of dewatering was made in the Handan mining area. In the 1970s, the control of mine water inflow was studied to regulate the cone of depression in the Lianzao mining area [8], and a numerical method was developed for the calculation of water inflow at the same time. In the early 1980s, the overall study was carried out on dewatering and depression for Taiyuan limestone at 9 mines in the Huainan mining area.

The process of dewatering in mine exploitation can be divided into three stages - the dewatering exploration, the test dewatering and the dewatering

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for mining, each of which has its corresponding work contents and requirements. The dewatering exploration on the basis of the real situation in China, is a supplementary hydrogeological exploration for dewatering.

Its purpose is to further investigate hydrogeological conditions in mine areas, to obtain the information required by dewatering, to determine the necessity, feasibility and reasonableness of dewatering and to put forward a scheme of dewatering. In China, the dewatering exploration is accomplished by tests of pumping, discharging, hydrochemistry, hydrogeophysics, and laboratory modelling, etc. In the old mining area, the discharging test is commonly adopted, for it has the advantage of similarity to the real situation of dewatering and its engineering can be maintained and used as a part of dewatering engineering [9]. The traditional method of work of dewatering and depression can be seen from the example of dewatering of the the Xuazhuang-Lijin mine in the Zhibo mining area. There is a Xu Jiazhuang limestone bed of a thickness of 5 metres, which is 25 metres beneath the floor of No 10 coal seam at the Xiazhuang-Lijin mine and 25 metres over the Ordovician limestone of a thickness of 600 metres. On the 28th of October 1968, an accident of water inrush at the -6 metre level took place at the stope of No 10 seam and the gallery flooded. From analyses, the water was from the Xu Jiazhuang limestone. In order to avoid a similar accident when mining the No 10 seam, we used the vertical boreholes for depressing the water pressure of the Xu Jiazhuang limestone. The discharging boreholes were placed in the roadway of the -80 metre level of No 9 coal seam. There were six discharging boreholes with an interval of 100 metres. The discharge test was performed in the order of single borehole, double-boreholes and multi-boreholes, so as to determine the quantities of the recharge and the interference, the cone of depression, the residual heads and the hydraulic connection with other aquifers. The situation of the discharge test is shown in Figure 3.

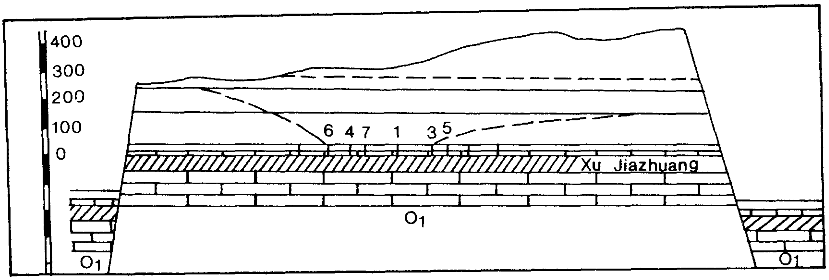

Figure 3 Sketch of depression in Xu Jiazhuang limestone at Zhiba Mine

After 200-days of water discharge, the target of depression was hit and the coal operation in No 10 seam above the -80 metre level was under a safe head. Then the stage of mine dewatering began.

In recent years, with the use of submersible pumps with high-lift and large discharge in mines of our country, the swift development of advanced dewatering and depression will occur.

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Grouting for Sealing Water Inrush Spots and Forming Cement Curtains for Cutting - off Groundwater Flow

Sealing the water inrush spots and cutting-off groundwater flow is one of the important measures of mine groundwater control in China's coal mines. From more than 30 years' practice, experience is obtained in respects of standing-water grouting and moving-water grouting to seal water inrush spots, grouting and forming cement curtains outside the mine area to cut-off ground water flow and so on. Standing-water grouting is used for sealing the water inrush spots when the mine water level is in a still state after the mine is completely flooded. In the early 1950s, to recover the Xia Jialing coal mine and the Shuangshan coal mine in the Zhibo mining area, sealing the water inrush spots by grouting was adopted and its effectiveness came to over 90%. Up to now, this method has still been used to restore the flooded mines in some coal mine areas. The technique of sealing the water inrush spots by grouting can be illustrated by the real example of the Bei Dajing mine in the Zhibo Coal Mine Bureau [12]. In the May of 1935, when No 10 coal seam was being mined in the Bei Dajing mine, the gallery cut into a normal fault with a throw of 30 metres, and this resulted in Karst water from Ordovician limestone rushing into the mine with an inflow of 443 m^3/min. The mine was completely flooded 78 hours later and 530 miners were killed in this accident. In the July of 1972, the location of water inrush spots was determined in the same area mentioned above. The locations of the spots and the paths of water flow into the mine were determined by means of the borehole radio-frequency detection technique developed by IGX. Borehole grouting from the surface was used to seal the spots and twenty boreholes were laid out in three rows with a total drilling distance of 5000 metres (See Figure 4). Until the May of 1975, the water inrush spots were completely sealed by using 9100 tons of cement, 115m^3s of water glass and 115 m^3s of pebble, and the effectiveness reached 100%.

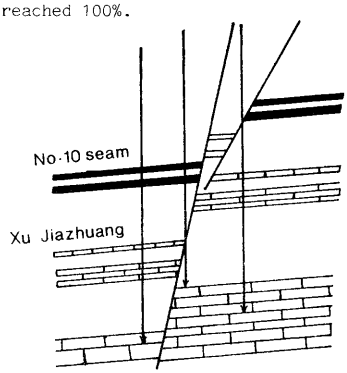

Figure 4 Sketch of grouting for inrush spots at Bei Dajing Mine

Moving-water grouting is used for sealing the water spots under the conditions of moving water when a mine is not completely flooded. In 1969, the grouting was carried out at the Dafen Mine of the Feichen Coal Mine Bureau to seal

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the water inrush spots where the inflow is 1500 m^2/h, and near which the actual flow velocity measured in limestone aquifers is 8640-31680 m^3/d. The effectiveness of the grouting was 99%.

In the June of 1984, groundwater from a Karst subsidence column in the Ordovician limestone suddenly rushed into the mines with a maximum inflow of 2053 m^3/min and a tragic disaster happened at the Fan Gezhuang mine of the Kai Luan Coal Mine Bureau. When the water level rose to the altitude of -156.7 metres, the water broke the boundary protecting pillar at the -232 metre level which bordered on the Lu Jiatuo mine and bursted into it with an inflow of 300 m^3/min. In this case, a series of new techniques were adopted in grouting for sealing water inrush spots, such as the combinational grouting for blocking up galleries under the conditions of running water with a high velocity. This method usually has three steps: firstly, injecting a large quantity of sand in front of the grouting section to form a water-resistance section; secondly, injecting mainly aggregate in front of water-resistance section to form the block-water section; finally, after the state of flow changed from piping to seepage, grouting through multi-boreholes simultaneously to rapidly seal the galleries. In addition, several kinds of instruments were used, such as the horizontal well fluid-velocity meter, the borehole radio-frequency detector, Kawa drag-bar-back-grout plug and so on. In this grouting operation, 75 boreholes were used. The total drilling distance was 32700 metres and 47100 m^3 of stone, 63100 m of dregs, 79100 m^3 of sand and 9000 m^3 of water glass were used. The effectiveness of it reached more than 99% in this work, which is the biggest and the most complicated one in the history of coal mining in the world [2].

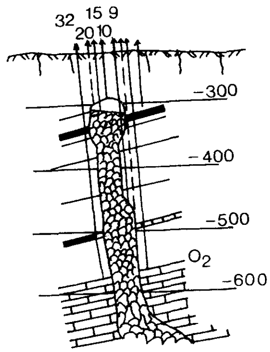

Figure 5 Sketch of grouting for blocking up water at Fan Gezhuang Mine

In the early 1960s, IGX under CCMRI has applied cement curtains to cutting-off water flows for coal mine water control. Cooperating with the coal mine bureaus of Xuzhou, Xinwen, Jiaozhuo, Zhaozhuang and so on, we studied the applied conditions of the curtains, the method of cutting off water flow and grouting technology. In thin Karst limestone, cement curtains suitable for four types of different hydrogeological conditions are built up; the type of recharging from the limestone to thin limestone, the type of recharging from alluvials to thin limestone, the type of recharging from Ordovician limestone to thin limestone and the type of recharging from rivers to thin limestone [10]. All of these have produced certain results

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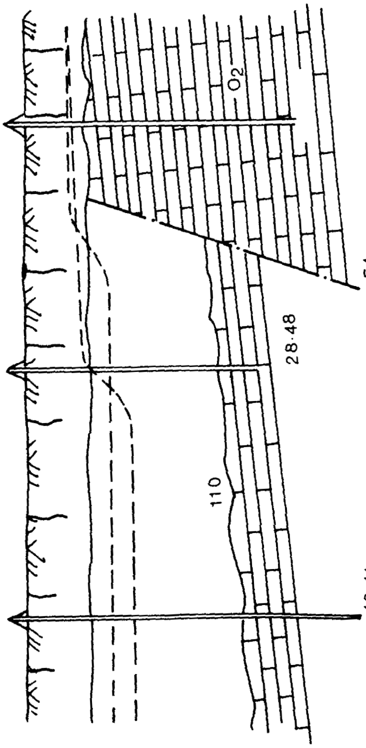

Fig 6 Sketch of grouting and forming cement curtains at Huang Beijing Mine

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in controlling mine water and keeping the ecological balance in mine areas. The cement curtain for cutting off water flow in the Juangbei Mine of the Zhaozhuang Coal Mine Bureau is shown in Figure 6. In this mine the Carboniferous coal seam is excavated and the water flow comes directly from the L_{10} limestone, having thicknesses from 5 to 8 metres. The L_{10} limestone is recharged by Karst water from the Ordovician limestone. After an investigation into No 4 fault, the main recharging section was determined to be 460 metres long with a recharge of 32 m^3/min. The cement curtain was built in the L_{10} limestone by using 77 boreholes with intervals of 10-20 metres. The total drilling distance was 1749 metres. The quantities of injection cement and waste were 1017 tons and 948 tons, respectively. After completing the curtain, the differences in piezometric levels between both sides of the No 4 fault was 12 metres and the inflow reduced to 20% of the original one. Although the cost of this engineering reached 330 thousand yuan in total, the cost saving for the water drainage was to be 150 thousand yuan each year. Furthermore, the problem of drinking water is solved in the mine area because the springs in the Ordovician limestone that dried up subsequently restarted.

UNDERGROUND FACILITIES FOR WATER PROTECTION

The principle of "Where there is a suspicion, there is detection" and "detection before excavation" is insisted on before coal mining takes place in an area where water disasters may happen. As the plan for coal mining is being drawn up, the plan for the detection of discharge water is also made and put into effect after the examination and ratification by the chief engineer of the mine. In the detection of discharge water from the abandoned mines, faults or Karst subsidence columns, the distance between discharge - detection lines is determined on the basis of the following factors: the reliability of water storage zone, the magnitude of water pressure, the physical and mechanical properties of the seam, adjoining rock and the geological structure.

The safety of personnel and mine safety are priorities in the detection of discharge water. Therefore, strict demands are set on the length of water discharge pipe and its sealing and fixing method, the water-controlling sluice gate of value of the pipe exit and safe measures for drilling etc.

The facilities for water protection in mines are mainly drainage systems. At present, underground horizontal pumps are used for discharging water in most of China's collieries. When mine water inflow surpasses the drainage capacity the mine is easily flooded. Therefore, it is indispensible to build the necessary sluice gates and walls for water protection.

Such sluice gates and walls must be constructed at proper places in those mines which are threatened with water, so that the water disaster may be controlled and division segregation of the mine may be made when water inrush happens. Steel sluice gates used in China's mines are designed in three shapes; plate, arch and membrane-flatshell. Among these, the membrane-flatshell gate has the advantages of lightness, anitpressure, and reasonable structure over the others. Most of the new sluice gates are this kind. The walls are designed by using two kinds of calculation methods.

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One is the cylindrical calculation method, which is based on the force borne by support surfaces of two sides of a wall. The other is based on the required shear thickness of the wall and embedded depth of the wall in the surrounding rock of a gallery. The formulae of the method are

$$E = P. F_1 [\delta] L$$

$$S = P. F_2/L [\tau]$$

E = embedded depth of the wall in the surrounding rock;

F_1 = whole area of one side of the wall bearing water pressure (cm^2);

F_2 = net area of other side of the wall (cm^2);

L = circumference of F_2 (cm^2);

$[\delta]$ = safe compressive strength of the concrete of the surrounding rock of the gallery (kg/cm^2);

$[\tau]$ = safe shear strength of the concrete (cm^2).

The leaving of coal pillars is vital for protection against water in coal mines. In China's mines, a large amount of this kind of work is being carried on. The coal pillars include those for protecting against water from fault zones, from surface water bodies, from the roofs of coal seams, from the floors of coal seams, from alluvions, from flooded areas and so forth. According to the "Mine Hydrogeology Regulations" established by the China Coal Ministry, special designs and plans for leaving pillars are presented by the professional departments engaging in the work of mine water control. These are put into effect after thay have been examined and ratified by the chief engineer in the Coal mine bureau. Thus, the coal mines, in accordance with their own conditions of geology, hydrogeology and coal seams, physical and mechanical nature of adjoining rock, the combination of rock formation, the coal mining method, the intensity of excavation and the form of support have a background of experience in leaning pillars.

On the basis of the designation of "the work rules of coal mine water control" presented by the Ministry of Coal Industry in the September of 1986, coal pillars must be kept for each of the following cases:

1. the weathering zone of a coal seam outcrop;
2. under open water bodies and water-bearing alluvions and near flooded areas;
3. faults having hydraulic connection with aquifers which have good transmissivity and coal seams of joining the faults with good transmissivity;
4. abandoned mines and mined-up areas full of water;
5. Karst subsidence column and caves of transmissivity and water inrush;
6. the boundaries of coal mining divisions.

For the purpose of study, various models of fault pillars for water protection have been built up on the basis of feature, throw, dip angle and transmissivity of faults, the feature of seams, the mechanical properties of seams, the relationships between seams and faults, the contact relation

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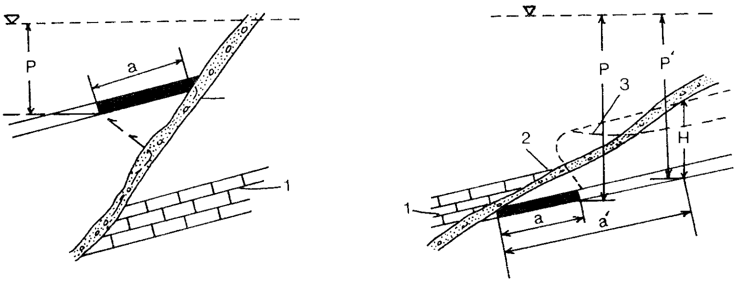
between two sides of a fault, the water pressure of aquifers as well as the repetitional destruction to faults caused by the pressure of adjoining rock in coal mining. The size of the pillars have been computed by means of experience equation, balance equation of mechanics and equations of water inrush coefficient.



1. Aquifer 2. Fault as a path of water 3. Ruptured zone after coal mining

a - Coal pillar for protecting against water a" - Expanded coal pillar

Figure 7 Sketch of keeping pillars for protecting water from faults

When a fault has a small dip angle, the pillars at the upper side and lower side of the fault should not only agree with the required width but also the minimum distance from the mining boundary to the fault zones or to aquifers which have good transmissivity must be more than the pillar value calculated by the formula (See Figure 7).

With regard to leaving the pillars under open water bodies, Quaternary alluvions and aquifers with good transmissivity, many coal mine bureaus, such as Kailuan, Fengfeng, Handan, Zaozhuang, Xingwen, Xuzhou, Huainan, Huaibei, Fuxing, Bwipiao, Xingtai, and Lianzhao, etc, have a lot of experience and have their own formulae.

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