Comparing control methods of water inrush disaster using mathematical programming: modelling, analysis and a case study

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ABSTRACT

Water inrush from coal floor is one of the main disasters in underground coal mining operations. When establishing or selecting control methods, various factors, such as cost, risk and operability, should be taken into consideration. However, due to the lack of effective mathematical models, the selecting process in practice relies solely on engineering experiences, which may not lead to an optimal and effective decision. This paper proposes a method that considers the parameters, variables, and constraints in water inrush control and it adopts economic factors as the objective function to construct a multi-objective optimization model. Using this method, one can not only rank different control measures but also obtain a preferred control effect level, which is a trade-off between efficiency and economy. A case study is used to demonstrate the robustness of the proposed approach.

1. Introduction

Coal has been the most important energy resource in China. Every year, some 3.8 billion tons of coal are produced and consumed, accounting for more than 70% of total energy. However, complexity of hydrogeological conditions of 60.51% of the coal mines in China range from medium to extreme. In these coal mines, mining operation is often threatened by floods, which are the second most serious disaster after gas disaster. Among various kinds of flood disasters, water inrush, a phenomenon in which water suddenly fills the mining space during ongoing mining operation, is the most dangerous one. It often leads to degradation of exploitation conditions, or inundation of tunnels and mines, causing loss of lives and property. According to the statistical data released by the State Administration of Coal Mine Safety, China, 496 major water inrush accidents occurred in the country from 2001 to 2015, resulting in 3255 deaths.

In order to mitigate water inrush disaster, many studies have been conducted in the past in terms of mechanism (Li et al. 2014; Wu et al. 2014; Yin et al. 2015; Li et al. 2016), classification (Gui and Lin 2016) and prevention (Yu et al. 2016). For example, Deb (2014) suggested that seepage problems will occur when working face is lower than ground water level. Jonek-Kowalska and Turek (2013) reported that mining in Karst areas would encounter groundwater gushing problems. Using Analytic Hierarchy Process (AHP), Wu et al. (2011) determined the vulnerability levels of different mine areas to address the potential possibility of water inrush disaster. Other similar mathematical
methods like empirical coefficients (Wu et al. 2015) and attribute synthetic evaluation (Li et al. 2014) were also proposed to evaluate the risks of water inrush. Likewise, Geographic Information System (GIS) techniques were introduced to construct dynamic three-dimensional model for water flow spreading process in order to develop emergency plans (Li et al. 2013). Dong et al. (2012) adopted a GIS-based Bayesian network to assess water inrush scenarios. Then, Shi et al. (2014) made a water inrush evaluation of coal seam floor by integrating the water inrush coefficient and the information of water abundance. Analyses by Shi (2009), Wu et al. (2013) and Sun et al. (2015) suggested that the disasters can be classified into water inrush from fault zone, water inrush from subsided column and water inrush from disturbed rock channels. Zhang et al. (1997), Zuo et al. (2010), Huang et al. (2010) and Zhang et al. (2014) concluded that the mechanisms of water inrush events are closely related to crustal stress, geological structure, water pressure, mining disturbance and other factors. Accordingly, a series of engineering methods, including drainage, grouting, and construction of water retaining wall, were proposed to control water inrush disasters (Jin et al. 2013; Li et al. 2016).

Generally speaking, water inrush disaster is a combined result of both nature processes and human activities, which involves many factors (Meng et al. 2012; Wu et al. 2016). The complexity of the problem demands decision-making based on a comprehensive evaluation, including considering cost, effectiveness, operability, environment impacts, and long-term benefits. However, due to the lack of efficient tools to evaluate the overall performances of different control methods under a given situation, methods selected may not yield the optimal solution and therefore result in inefficient water inrush treatment operation, long construction period, high cost, and low benefits.

To our knowledge, most of the existing researches focused on the improvements of theories of inrush water occurrence or techniques to control it. For this reason, we see a need to bring forward a general approach to compare different water inrush control methods under diverse conditions with the consideration of effectiveness, cost, benefits, and feasibility. Therefore, this paper proposes a multi-objective optimization model, which considers major parameters in water inrush disasters as well as control methods and economic factors. We then demonstrate the application of our model in a case study.

This paper is organized as follows. Section 2 presents the multi-objective optimization model and its application method. A case study of a coal mine in Shanxi, China adopting our model is demonstrated in Section 3. Section 4 summarizes the entire work and discusses the work needed in the future.

2. The mathematical programming-based selecting process

In general, there are four common water inrush control methods in practice: drainage, surface grouting, underground grouting, and construction of water-retaining wall. Drainage is the simplest method which drains water from tunnels to surface with pumps. It is often applied in conjunction with other methods. For instance, if water-retaining wall is selected to control a water inrush disaster, drainage would be conducted during the construction of water-retaining wall to maintain an acceptable working condition. Surface grouting and underground grouting are similar in nature – they both aim to plug the leaks or sometimes the entire water inrush tunnels. The difference is that surface grouting drills grouting holes from the land surface while underground grouting is executed in tunnels. The water-retaining wall is a sluice which is constructed at a chosen position in tunnel to stop water from exiting. The blocked water can then be used in the future.

Each of the four methods has their own advantages and has been proven to be sufficient in specific conditions. However, making right decision on which method to be applied is not just a matter of experiences. Various factors concerned with the disaster itself as well as costs should be taken into consideration. Currently, most coal mines use engineering cost as benchmark to evaluate each method separately, which, as we discussed above, is not sufficient. Therefore, we propose a series of economic indicators including (1) material cost, (2) human resource cost, (3) additional cost, (4) risk cost and (5) comprehensive additional income. Our goal is to select a control method based on
the economic indicators, which are closely tied to the conditions of the tunnel, water inrush characteristics, and the effectiveness of control methods. As a result, we will first define some parameters that can be utilized to describe these factors. Afterward, each of the five economic indicators will be expressed as mathematical equations with these parameters. Using these equations and the constraints in engineering practice, we construct a multi-objective optimization model. By solving the model, the optimal method as well as ranking sequence of all the methods is achieved. Also, we will try to obtain the most economic control effect level which would support the planning process of control methods.

In order to simplify the model without loss of generality, we make some assumptions: (1) The construction is reliable, i.e. the cost of construction failure is not considered. Note that the risks or difficulties of each project are reflected in risk cost. (2) Each method can control the disaster independently as long as the resources are enough. (3) After the executions of surface grouting, underground grouting and water-retaining wall, drainage can be used as a supplement method in order to drain the remaining water out of the tunnel. No combinations of these three methods are applied in our model.

2.1. Parameters and variables

In this section, we define a series of parameters and variables as preliminary for the main model. Here, parameters refer to the data that can be obtained before making any control plans, while variables stand for the decisions need to be made, which in this case is the optimal control method and its effect level.

2.1.1. Parameters

2.1.1.1 Disaster-related parameters. Many factors could induce the risk or process of water inrush (Wang et al. 2012), but our first priority is to choose parameters that represent the characteristics of water inrush disasters in order to model the selection process of control methods, which we call disaster-related parameters. One of these parameters is the inrush water flow of a disaster, \( w \), which represents the severity of the disaster. Note it is the steady flow in the lasting period, the unit of which is \( m^3/h \). The parameter, \( h \), represents the depth of the leakage (namely, floor water inrush point) from the land surface. We use \( r \) to represent the average RQD (Rock Quality Designation: a rough measure of the degree of jointing or fracture in a rock mass) level of the rock mass around the leakage. The larger the value of \( r \) is, the higher the rock quality is. In most cases, these three parameters (\( w, h \) and \( r \)) have a major impact on the construction difficulties of projects.

Besides these physical factors, other important factors that affect the choice of control methods are the duration of the water inrush disaster and the remaining service life span of the tunnel. For example, if the disaster is temporary (short term), there is no need to conduct a costly project. Likewise, a tunnel that has only a limited life span for service is not worth too much investment. We denote \( t \) as the minimum of these two time duration factors and name it time-scale factor.

These four parameters describe the fundamental characteristics of a water inrush disaster, which will eventually determine what kind of control method is suitable.

2.1.1.2 Control-related parameters. Another type of parameters is related to engineering practice, which are based on safety requirements or cost limit. In this paper, we use \( w_s \) to represent the allowable inrush water flow after control, which is a lower bound of the control target. The cost limit is presented as \( m_s \). Note that \( m_s \) only limits the one-time investment, i.e. other types of cost like the additional cost or risk cost is not included because they are not actual costs.

2.1.2. Decision variables

By solving the optimization model in this paper, we intend to obtain the optimal method as well as the preferred effects of the control measure. Thus, we define \( i \in I \) as the set of control methods.
In this research, as we take the four common control methods into consideration, we number drainage, surface grouting, underground grouting, and construction of water-retaining wall form 1 to 4, respectively. Let $x_i$ stand for the evaluation of the $i$th method. When the $i$th method is the optimal solution, $x_i = 1$, otherwise $x_i = 0$. Also, we denote $w_p$ as the actual inrush water flow after the control method is conducted, which represents the effectiveness of the control method.

Besides, as we mentioned above, five economic indicators are introduced to evaluate each method. Here, we denote $j \in J$ as a set of indicators and $m_j$ as the value of indicator $j$. The detailed structure of each indicator will be discussed in the next subsection. All the parameters and variables are listed in Table 1.

### 2.2. The economic indicators

In this section, the five economic indicators will be explained in detail.

#### 2.2.1. Material cost

Here, material cost includes not only raw materials such as cement, steel and sand, but resources like electricity, equipment and its wastage as well. According to engineering practice, material cost is closely related to the severity of the disaster, the depth of coal mining working face, geological conditions, and quality requirement of the control project. Obviously, material cost of every method is positively related to the inrush water flow $w$ and depth of leakage $h$. The RQD level of the rock mass around the leakage $r$ also affects the material cost of some methods. For grouting methods, a higher $r$ represents the better integrity of rock mass, which can reduce the construction difficulty and therefore reduces the material cost. Likewise, a stable rock mass has a beneficial effect on the construction and protection of water-retaining wall. As for drainage, the value of $r$ has no obvious influence. On the other hand, the inrush water flow after the control ($w_p$) reflects the effect of the control method. The smaller the $w_p$ is, the better the quality of control measure is, and at the same time, the higher the initial investment is. However, according to the theory of diminishing marginal utility, every control methods will face the reality of faster increasing cost and slower increasing construction quality. Theories and practices show that the material cost and the inrush water flow after the control are approximately in inverse proportion. Let $m_1$ be the value of material cost, we then obtain the expression as

$$m_1 = c_{i11}w + c_{i12}h + \frac{c_{i13}}{r} + \frac{c_{i14}}{w_p}.$$  \hspace{1cm} (1)

In the equation, $c_{ijk}$ is the coefficient of the $k$th parameter or variable in the expression of the $j$th cost when adopting the $i$th method. The value of each coefficient will be given based on experiences and

| Table 1. Parameters and variables. |
|------------------------------------|
| **Parameters**                     |
| $I$                                | Set of methods, $i \in I = \{1, 2, 3, 4\}$ |
| $J$                                | Set of indicators, $j \in J = \{1, 2, 3, 4, 5\}$ |
| $w$                                | Inrush water flow |
| $h$                                | Depth of leakage |
| $w_s$                              | Safety inrush water flow after control |
| $r$                                | RQD level of rock mass |
| $t$                                | Time-scale factor |
| $m_s$                              | Cost limitation |
| **Variables**                      |
| $w_p$                              | Inrush water flow after the control |
| $m_j$                              | Value of indicator $j$ |
| $x_i$                              | $= 1$, if method $i$ is optimal; $= 0$, otherwise |
historical data. The general expression guarantees that when calculating the costs of different methods, one only needs to change the coefficients.

2.2.2. Human resource cost
Despite that the number of workers and managers is different when adopting different methods, research shows that human resource cost and material cost have a positive correlation. The higher the raw material investment is, the greater the human resource cost is. Hence, the expression of human resource cost can also be written as a function of \( w, h, r \) and \( w_p \). If we say that \( m_2 \) represents human resource cost, we have

\[
m_2 = c_{i21}w + c_{i22}h + \frac{c_{i23}}{r} + \frac{c_{i24}}{w_p}.
\]

(2)

In order to simplify the model, the division of work as well as the constraint of construction period is not taken into account.

2.2.3. Additional cost
Even if a water inrush control project is well constructed, it can hardly eliminate the inrush water completely, i.e. \( w_p \approx 0 \). Although the inrush water is under control, drainage and maintenance are still needed, which result in additional cost. When the inrush water is substantial, the operational cost could continue throughout the remaining service life span. Otherwise, the cost only occurs in the period when water inrush lasts. Such cost is represented as \( m_3 \). Obviously, besides \( w, h \) and \( w_p \), \( m_3 \) is also positively related to the time-scale factor \( t \). Therefore, we shall obtain the following relationship:

\[
m_3 = (c_{i31}w + c_{i32}h + c_{i33}w_p) \cdot t.
\]

(3)

For drainage method, since the inrush water flow has not decreased, the calculation of additional cost is similar to initial cost. As for the rest methods, their additional cost is only related to \( w_p \). Therefore, we have \( c_{133} = 0 \) and \( c_{231} = c_{331} = c_{431} = 0 \).

2.2.4. Risk cost
There are risks in the implementation process of every method. Once failure occurs, remedies are needed to fix the operation, which increases the total cost. Therefore, we introduce the risk cost \( m_4 \) to describe the possible cost resulted from ineffective projects or failures. As mentioned above, the main index to evaluate the result of each method is the water-sealing effect, namely the residual inrush water flow after control \( w_p \). If \( w_p \) is smaller, the effect of control method is better, which leads to a lower risk. On the contrary, a larger \( w_p \) means higher risk. Hence, we add a constant term \( d_i \) into the expression to represent the initial risk of all methods, which can be reduced depending on the control effect. Meanwhile, the risk cost is also related to the characteristics of the method itself and disaster-related parameters. For instance, in a 500-m-deep tunnel, the main risk of surface grouting comes from the uneven terrain, which might cause the drilled borehole to miss the designated position. In addition, the grouting channel might encounter geological features like caves, fracture and holes that result in additional grout. Furthermore, the underground grouting method starts with the construction of temporary water-retaining wall, and then fills in cement and sand. However, if the inrush water flow is too strong, the grout might be washed away. Although the construction of water-retaining wall guarantees the water-sealing effect, large amount of high-pressure underground water is sealed in the channel, causing potential water inrush risk for other pending mining work face. Thus, risk cost has positive correlation with the water inrush flow \( w \) as well as the depth of leakage \( h \). Based on the analyses above, we formulate \( m_4 \) as follows:
$$m_4 = d_i + c_{i41} w + c_{i42} h - \frac{c_{i43}}{w_p}.$$  

(4)

### 2.2.5. Comprehensive additional income

In general, water inrush disaster control programme focuses on the control effect and pays less attention to possible benefits. In recent years, however, with the trend of green mining as well as the development of engineering technologies, academia and industry began to discuss the comprehensive additional income in the management of disaster control programme. The comprehensive revenues mainly come from the impacts of disaster control programme on geological and water resources conditions. If the control method is able to improve the geological condition (e.g. strengthening the rock mass and stabilizing rock slope or tunnels), it will enhance the future mining operation. Besides, some control methods take not only the control of inrush water but also the utilization and protection of water resource into consideration (e.g. stored water for dust or fire control). Therefore, these additional revenues can be expressed as the water resource-related income:

$$m_5 = c_{i51} (w - w_p).$$  

(5)

### 2.3. Mathematical model

After determining the evaluation indicators, we formulate our optimization problem as follows:

$$\begin{align*}
\min z &= \sum j \lambda_j m_j \\
\text{s.t.} \quad m_1 &= \sum_i x_i \left( c_{i11} w + c_{i12} h + \frac{c_{i13}}{r} + \frac{c_{i14}}{w_p} \right) \\
m_2 &= \sum_i x_i \left( c_{i21} w + c_{i22} h + \frac{c_{i23}}{r} + \frac{c_{i24}}{w_p} \right) \\
m_3 &= \sum_i x_i \left[ (c_{i31} w + c_{i32} h + c_{i33} w_p) \cdot t \right] \\
m_4 &= \sum_i x_i \left( d_i + c_{i41} w + c_{i42} h - \frac{c_{i43}}{w_p} \right) \\
m_5 &= \sum_i x_i \left[ c_{i51} (w - w_p) \right] \\
m_1 + m_2 &\leq m_s \\
w_p &\leq w_s \\
\sum_i x_i &= 1 \\
m_j, w_p &\geq 0 \\
x_i &\in (0, 1).
\end{align*}$$

(7)–(16)

The objective function (6) is the weighted sum of five economic indicators we proposed above. The coefficient $\lambda_j$ represents the importance of each indicator in different situations, by adopting which we combine multi-objectives into one expression. Note that since it is a minimization problem, the coefficient of comprehensive additional income $\lambda_5$ is negative, which means a larger comprehensive additional income is better. Constraints (7)–(11) are the definitions of indicators in our model, which are the product of their original expressions and logical variable $x_i$. When $x_i = 1$, the cost of the $i$th method is calculated, otherwise it equals 0.

Constraint (12) is the initial investment constraint. Theoretically, if the effect of water inrush control project is nearly perfect, it will definitely provide a better working environment for future
production. However, better effect means higher cost, which might be beyond the financial capability of the coal mine. In practice, the management always has a budget, and tries to control the total investment without sacrificing the quality. Among the five economic indicators, material cost \( m_1 \) and human resource cost \( m_2 \) are the initial investment, and should be raised in a short term, which have the most significant influence on the operation of the coal mine. Therefore, we use initial investment constraint as our cost constraint.

Constraint (13) ensures that the effect of the control method must meet the engineering requirement. We use the inrush water flow after treatment as an indicator to measure the control effect. If the result cannot reach the standard of the engineering manual or technical target, there would be risks in follow-up production.

Constraint (14) ensures the mutual exclusivity of all the methods. As we mentioned in the assumptions, only one of the four options is adopted as the main method. This constraint guarantees the optimal method can be determined. Then, we filter out the optimal method and keep looking for the suboptimal method. In the same manner, one can obtain the ranking sequence of all methods. Constraints (15) and (16) define the domain of variables.

Because of the nonlinearity of the constraints, the model is a nonlinear programming model. It comprehensively summarizes the considerations in the process of choosing water inrush control methods. Not only is the characteristics of each method considered but also the parameters of water inrush disaster are included. By solving the model, the optimal methods as well as the optimal control effect are obtained, which can effectively support the decision-making process.

### 2.4. Framework of model application process

In this section, we propose a framework of the application process, which indicates the appropriate use of the model and defines the input as well as output.

Figure 1 is the flow chart of the model application process. Once a water inrush disaster occurs, the management of a coal mine first measures and collects the disaster-related data, including the inrush water flow \( w \), the depth of leakage \( h \), the condition of rock mass around the leakage \( r \) and the time-scale factor \( t \). Then, the coefficients in the expressions of each cost function, i.e. \( c_{ijk} \) and \( d_i \), are determined by regression of corresponding historical data. Meanwhile, parameters like the weight factors of the objective function \( \lambda_j \) need to be determined using engineering experience and management preferences. Also, the constant term \( d_i \) might need to be adjusted due to the differences of working conditions. After that, the cost constraint is given according to the financial capability of the coal mine, and the effect constraint is given by the engineering manual. Finally, by solving the optimization problem, we obtain the optimal method \( x_{opt} = 1 \) and its best control effect \( w_p \).

However, the management may not rely solely on the optimal solution because other factors besides economic benefits also affect the decision. For example, if the coal mine has success in conducting surface-grouting projects, managers may incline to the previous experiences. Such preference has been studied in prospect theory (Kahneman and Tversky 1979). Since our model can be solved in a relatively short time, it provides an easy access to the ranking sequence of all the methods, which may further support the decision-making process. Adding constraint \( x_{opt} = 0 \) to the current model, we can obtain the suboptimal method by solving the new problem. Using the iterative approach, after traversing all the methods, we achieve the ranking sequence of each method and its corresponding optimal control effect.

It should be pointed out that the determination of coefficients should not be waited until the occurrence of water inrush disaster. After the treatment of a disaster, the related data need to be put into database, by which the accuracy of current parameters will be improved through regression and other statistical methods in order to provide a more reliable basis for future production. In the next section, we will illustrate the detailed application of the model by a case study.
3. Case study: water inrush disaster control in a coal mine in Shanxi Province

3.1. Background

The Ganhe mine studied in this paper is located in the north of Houdong County, Shanxi Province, China, with an area of 35.6 km² and an annual output of 3 million tons of coal. At present, Carboniferous coal seams 1 and 2 are being mined. The main aquifer includes Carboniferous K2 limestone, Ordovician upper Fengfeng Formation and upper Majiagou Formation. The average thickness of K2 limestone is 9.11 m and the water level is about 505 m, while the average thickness of upper Fengfeng Formation is 29.92 m and upper Majiagou Formation is 58.97 m. The water level of the Ordovician aquifers is about 520 m. The sequences of coal measure strata and Ordovician strata in Ganhe mine are separately shown in Figures 2 and 3. The faults and Karst collapse columns are well developed in the mine, and the hydrogeological conditions are complex.

On 4 December 2012, a floor water inrush from fault zone occurred on the 1081 reverse working face with the maximum flow of 730 m³/h. The working face arrangement surrounding the leakage is shown in Figure 4 (Qi 2016). Inrush water immediately inundated 1081 reverse roadway and 108 connection roadway. After emergency drainage, the water level was under control at the point 100 m away from the entrance of 2-1081 reverse roadway, and the water flow was stable at 300 m³/h or so.

This water inrush accident had several characteristics. (1) The water came from K2 and Ordovician limestone. (2) The recharge and displacement of inrush water had achieved dynamic stability.
at 300 m³/h or so, which meant the water supply was sufficient. (3) The leakage was buried at the depth of 500 m (87 m elevation) withstanding the water pressure of about 4.3 MPa. Based on the measurements in the exploration period, the surrounding rock mass was relatively stable and the \( r \) (RQD) value was 80%. Meanwhile, the current mining tunnel still had a service life span of 10 years left, indicating that the control project should consider the effect in long term.

**Figure 2.** The coal measure strata in Ganhe mine.
Based on the characteristics of this water inrush accident, we set up the method comparison and selection model according to formulas (6)–(16) established in Section 2.3. We first achieved the value of disaster-related parameters as shown in Table 2. According to Zhang et al. (2003), the allowable inrush water flow after control equals 60 m$^3$/h in current situation.

**3.2. Establishment of the model**

![Figure 3. The Ordovician measure strata in Ganhe mine.](image)

| Stratum units | Thickness | Lithology          | Aquifers          |
|---------------|-----------|--------------------|-------------------|
| $O_{2f}^2$    | 29.92     | Mainly limestone   | Strong Karst aquifer |
| $O_{2f}^1$    | 199.30    | Limestone, dolomite, muddy limestone | Weak Karst aquifer |
| $O_{2m}^2$    | 58.97     | Mainly limestone   | Strong Karst aquifer |
| $O_{2m}^1$    |           | Limestone, dolomite | Weak Karst aquifer |
Based on the local economic and technical conditions, resource cost and engineering construction survey, we obtained the following values of model coefficients:

\[
c_{11k} = \begin{bmatrix}
1771.2 & 864 & 0 & 0 \\
4500 & 5000 & 430,000 & 150,000 \\
4000 & 9000 & 450,000 & 210,000 \\
2000 & 1800 & 3,200,000 & 180,000
\end{bmatrix} \quad (17)
\]

\[
c_{12k} = \begin{bmatrix}
400 & 180 & 0 & 0 \\
3000 & 4500 & 14,000 & 162,000 \\
1800 & 5400 & 13,500 & 216,000 \\
1350 & 450 & 320,000 & 54,000
\end{bmatrix} \quad (18)
\]

\[
c_{13k} = \begin{bmatrix}
0.82 & 0.4 & 0 \\
0 & 0.4 & 0.82 \\
0 & 0.4 & 0.82
\end{bmatrix} \quad (19)
\]

**Figure 4.** Underground working face arrangement surrounding the water inrush point.

**Table 2.** Disaster-related parameters.

| Parameter | Value |
|-----------|-------|
| \( w \)  | 300 m\(^3\)/h |
| \( r \)  | 80% |
| \( t \)  | 87600 h |
| \( w_s \) | 60 m\(^3\)/h |
| \( h \)  | 500 m |
| \( m_s \) | CNY 12 million |
The first rows of the coefficient matrices represent the corresponding coefficients of drainage. Following the same pattern, all the coefficients $c_{ijk}$ are shown.

As for $d_i$, we assumed that the residual inrush water would no longer produce the risk cost when the water flow was less or equal to 5% of the safety value stipulated in the engineering standard. That is,

$$d_i - \frac{c_{i43}}{0.05w_s} = 0. \tag{22}$$

Therefore, we obtained

$$d_i = [0, 5000, 6000, 8000]^T. \tag{23}$$

Finally, we gathered information from the management and engineers to evaluate the importance of each type of cost and obtained:

$$\lambda_i = [1, 1, 0.4, 0.8, -0.3]^T. \tag{24}$$

Such values of $\lambda_i$ reflected that the managers paid more attention to immediate investment, and cared less about the additional cost as well as income.

### 3.3. The solution

We solved the established nonlinear programming model by calling the CPLEX solver through YALMIP in MATLAB 2012. The platform was a personal computer with CPU of Intel Core i7-3520M and memory of 8GB. The solution in Table 3 was obtained in 1.258 s using the branch-and-bound method.

From the solution, we could see that the variable $x_4$ that represented the method of construction of water-retaining wall equalled 1, which indicated that such method was the best. Meanwhile, when the water-retaining wall could control the inrush water flow at the level of 2.7366 m$^3$/h, the total cost was the lowest. Adding the constraint $x_4 = 0$ into the model, we obtained the suboptimal method. In the same way, after four iterations of calculations, we got the ranking sequence of all the methods as listed in Table 4.

After achieving the optimal solution in current iteration of the algorithm, we eliminated it from the list of remaining methods by simply adding an extra constraint which set the corresponding $x_i$
to be 0. Such method is convenient to conduct, but it increases the calculation for CPLEX solver because the feasible region becomes more complex. This property explains the increasing CPU time. However, since the CPU time in this case is still quite low, it is reasonable not to optimize the algorithm in order to save computation time. The calculation results were consistent with previous engineering experiences. Under the value of current parameters and constraints, not only was the immediate investment of the construction of water-retaining wall low, but the comprehensive income was decent as well. Note that according to the calculation, the control effect needed to be improved to a quite high level ($w_p = 2.7366$ m$^3$/h). Although this would raise the material and human resource cost, it significantly reduced the risk cost as well as additional cost and made good use of water resources, resulting in long-term benefits. The costs of grouting methods were higher because the grouting operation itself was more difficult and the follow-up risk, that the position of the fault zone was difficult to be accurately grasped, could not be ignored. Comparing with underground grouting, the construction site of surface grouting was larger and the technique was simpler, leading to lower human resource cost. Despite that the one-time investment of drainage was lower under current condition, the total cost was high because of the high risk cost and additional cost in the remaining service time of the tunnel.

### 3.4. Project implementation and effect

After controlling the water level at the point 100 m away from the entrance of the roadway by high-power drainage pump, the suitable construction location was selected in the roadway where the surrounding rock was stable. Then, in the 50-m-long roadway, the construction workers stripped the loose rock and sprayed C30 concrete slurry to the construction roadway until the thickness of concrete reached 150 mm. After the cement slurry was solidified, an additional grouting measure was taken to reinforce the surrounding rock. Following the Mining Engineering Design Manual, the water-retaining section of arch (8 m), the body wall and the back section of water-retaining arch (8 m) were built in sequence, to form the water-retaining chamber. Calculations based on the optimal control effect obtained from the model showed that the body wall should be 6.5 m long, filled with cement and sodium silicate. Two ø325 × 12 mm seamless steel drainpipes were designed to meet the drainage capacity requirements of 350 m$^3$/h at stable condition and 700 m$^3$/h at maximum condition. Figure 5 is the real scene picture taken in April 2013 when the project was nearly completed. After the project was finished, the pressure test showed that a slight seepage (about 1.5 m$^3$/h) would occur on the roadway floor. By further grouting into the floor, the seepage was almost 0.

The project took three months to complete, with a total cost of 7.45 million yuan, of which 5.02 million yuan was the material and its transportation cost, 1.08 million was the drainage cost and 1.35 million was the construction and underground handling cost. The actual investment was consistent with the calculation of the model. From May 2013, the coal mine started to use the water-retaining wall to conserve the water resource. The comprehensive income was then realized since the water inside was used in underground road construction, sprinkling dusting, cooling mining machine, etc.

### 3.5. Discussion under different $w$ and $h$

To further understand the model, after obtaining the optimal solution, we try to extend our result and discuss the performance of each method under different conditions. In this case, the RQD level

| Iteration | $x_1$ | $x_2$ | $x_3$ | $x_4$ | Method               | $Obj$ (unit: CNY) | $w_p$ (unit: m$^3$/h) | CPUtime (unit: s) |
|-----------|------|------|------|------|---------------------|------------------|--------------------|------------------|
| 1         | 0    | 0    | 0    | 1    | Water-retaining wall| $1.5438 \times 10^7$ | 2.7366             | 1.258             |
| 2         | 0    | 1    | 0    | –    | Surface grouting    | $1.5592 \times 10^7$ | 3.2308             | 1.822             |
| 3         | 1    | –    | 0    | –    | Drainage            | $1.6970 \times 10^7$ | 0                  | 1.073             |
| 4         | –    | –    | 1    | –    | Underground grouting| $1.7944 \times 10^7$ | 9.0424             | 1.423             |
of rock mass, the time-scale factor $t$, and all the coefficients remain unchanged. Therefore, the parameters that influence the decision are the inrush water flow $w$ and the depth of leakage $h$. We then conduct a series of computational experiments, in which $h$ took the value of 50, 100, 150, 200, 250, 300, 350 and 400, respectively, and $w$ took the value of 100, 200, 300 and 400, respectively. The computational result is shown in Table 5.

In Table 5, every method is represented by its initial, i.e. D, S, U, W stands for drainage, surface grouting, underground grouting and water-retaining wall, respectively. Obviously, drainage is only applicable to the case where inrush water flow is small, only in which the electricity cost, drainage pump cost and human resource cost are lower. When the water flow becomes larger, due to the need for long-term continuous drainage, the additional cost will grow dramatically, resulting in high total cost. Besides, the cost of drainage involves water resources tax and sewage treatment cost as well, which also contributes to the total cost.

Under the experiment environment, surface grouting is the optimal solution in many situations. This is because the environment is mild, i.e. under most of the conditions, the inrush water flow is not too large and the leakage is not too deep. As the drilling and grouting process are conducted on the surface, the project is easier to control since the transportation of materials and construction are

![Figure 5.](image)

**Figure 5.** Real scene picture in April 2013.

| Optimal solution | $w$ (unit: m$^3$/h) | 50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 |
|------------------|--------------------|----|----|----|----|----|----|----|----|
| Drainage (D)     | S                  | S  | S  | S  | D  | D  | D  | D  | D  |
| Surface grouting (S) | S            | S  | S  | S  | U  | S  | S  | S  | S  |
| Underground grouting (U) | U            | S  | S  | S  | S  | S  | S  | W  | W  |
| Water-retaining wall (W) | W               | S  | S  | S  | S  | S  | W  | W  | W  |

*Table 5. The optimal method under different parameter levels.*
more convenient in an open site. However, with the growth of inrush water flow, the cost and risk of surface grouting grows quickly. The reason is that the material needed as well as the workload of surface grouting will increase significantly as the disaster becomes severer. In this case, as a more direct and accurate method, underground grouting appears to be better. But such a method only suits for the situations where the leakage is shallow since deeper working condition means higher transportation cost as well as greater difficulty. On the other hand, when the leakage is deep under the ground, the construction of water-retaining wall is the optimal solution because the additional cost is low and the water resource can be further utilized, resulting in higher comprehensive income.

4. Conclusion

The hydrogeological conditions of many coal mines in China are complex, which often have led to rather serious groundwater disasters. Wise selection of control methods is critical to swiftly resume normal coal production and to effectively protect the ecological environment.

In this paper, we develop an algorithm for the optimal selection of coal mine water inrush control methods. We first consider five economic indexes frequently used in water inrush control engineering, establish a mathematical relationship between these indexes and treatment parameters, and then combine it with the operational constraints of controlling the water inrush accident, and finally construct a nonlinear comparing optimization model for selecting optimal water inrush disaster control methods.

In order to illustrate the applications of this algorithm, we apply it to a real water inrush scenario in which the steady inrush water flow is 300 m³/h and the depth of water inrush point was 500 m. In this case, algorithm determines the construction of water-retaining wall in underground tunnel is the most cost-effective control method. In addition, we also investigate cases where the inrush water flow and depth are different. The optimal control measures selected by the algorithm all seem logical, in accordance with engineering principles, cost-effectiveness, and protecting environments. The application and demonstrations of the model show that the algorithm can reduce economic costs, increase comprehensive benefit, improve the scientific decision-making level of coal mine accident treatment, and provide scientific basis for similar water inrush accidents.

In the future, we are to analyze the uncertainty of the model results due to uncertainty in parameters. This uncertainty analysis could enhance the adaptability of the model to more realistic conditions, where accurate information about the water inrush events is not fully available.

Geolocation information

The Ganhe mine studied in the case is located approximately 23 km north to Hondong County, Shanxi Province, China. The latitude and longitude coordinates of the mine field are as follows: 36°26′18″N to 36°30′09″N, 111°37′11″E to 111°41′51″E.

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