Optimization of underground mine water supply network

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Abstract. A qualified and effective mine water supply system is of great significance for mine dust prevention, mine cooling, fire fighting and other related mining activities that contributing to mine safety. The study in this paper was to improve the efficiency of an underground mine water supply network while taking the water demands, hydraulic conditions, resilience capability and economic cost into consideration. By means of model predictive control technology, an optimal control sequence was computed to minimize a multi-objective cost function that was subject to both physical and operation constrains in the actual network. Comparison of the performance between the original and optimized network was undertaken at a hydraulic condition with typically severe breakdown. Results showed the optimized mine water supply network achieved 95.5% increase for resilience performance with only 17.6% additional investment budget.

1. Introduction

Awareness of mine safety has increased in recent decades. More attention has also been drawn to the design, maintain and optimization of a more effective mine water supply network in underground mines. As an important role to guarantee the proper and safe mining production, mine water supply network supplies adequate qualified water for dust prevention, fire fighting, mine cooling, construction of supporting system and other related activities [1, 2]. Typically, for the mine water supply network, water is carried from surface to underground areas close to workplaces, with flexible hoses used for the final connections. It is difficult to keep the mine water supply network always running with initially designed performance, because of its physically limited service life and ongoing mining activities. The variability of hydraulic conditions may lead to insufficient water supply, and finally threaten health and safety of mine workers, as well as lead to economic loss. This presents a research necessity to improve the operation status and reliability of mine water supply network.

Traditional methods to design and modify mine water supply networks are commonly based on practical experience by trial and error. The progress in computational methods and tools in recent years has enabled improvement of analyzing and understanding the complex interactions between the water supply network components, and helped make predictions, evaluations and decisions [3-5]. In this study, to overcome the calculation difficulty that the hydraulic condition was dynamic and subject to multiple limits, model predictive control (MPC) technology was used to achieve an optimization of a present mine water supply network based on a minimum multi-objective cost function subject to physical and operation constraints.
2. Methods and settings

The study in this paper was conducted for the underground water supply network of a coal mine in Kailuan Group, Hebei Province. The mining depth of this mine at present is between -700m and -1100m, and it will be extended deeper in the future. The underground water supply network is driven by gravitational energy with multi-source from three tanks. Figure 1 showed the structure of the present mine water supply system, along with the information of key node elevations, pipe lengths, pipe diameters and demand nodes’ locations. All original pipes were designed to be equal diameters, which is 108mm. In the real operation conditions, there occurred hydraulic failures such as pipe failures or demand failures with this original network. To deal with this problem, MPC technology was employed to compute an optimal control sequence that minimized a multi-objective cost function subject to physical and hydraulic constraints. MPC technology is to use a dynamic model to forecast system behavior, and optimize the forecast to produce the best decision[6]. It takes the diameter as the independent variable to establish a mathematic model of the mine water supply network. This work was carried out using MATLAB R2012b. A series of selected commercial diameters instead of continuous diameter pipes were used, while the original operation data used were collected through continuous monitoring over a month period. EPANET 2.0 software was used as a hydraulic solver and called by MATLAB.

2.1. Objective functions

Reliability is defined as the probability of a system to perform its mission, under specified conditions or during a specified time period. Two objective functions, residual pressure head (\( I_p \)) and resilience index (\( I_r \)) were used to make reliability computations.

\[
I_p = \frac{\sum_{i=1}^{n} Q_i (H_i - H_{req,i})}{\sum_{i=1}^{n} Q_i} 
\]

\[
I_r = \frac{\sum_{i=1}^{n} Q_i (H - H_{req,i})}{\left[ \sum_{j=1}^{n} \left( \frac{Q_{T_j}}{n} \sum_{i=1}^{n} \Delta H_{T_j} \right) - \sum_{i=1}^{n} Q_i H_{req,i} \right]}
\]

where \( H_{req,i} \) and \( Q_i \) represent the minimum required pressure head and the available flow of demand node \( i \); \( Q_{T_j} \) is the available flow provided by water source tank \( j \); \( \Delta H_{T_j} \) is the pressure
head difference between the tank $j$ and the demand node $i$; $m$ and $n$ are the number of tanks and demand nodes respectively.

The construction cost $(I_c)$ depends on the length and diameter of pipes. The desirable minimum construction cost is to be achieved along with the satisfaction of all the demand nodes needs under normal or abnormal conditions.

$$I_c = \sum_k (a + bD_k^\alpha)l_k$$

where $a$, $b$ and $\alpha$ are the price function parameters for the network, $D_k$ and $l_k$ are the diameter and length of pipe $k$ respectively.

### 2.2. Settings of Constraints

The overall optimization for water supply network can be stated mathematically in terms of the nodal pressure head and flow, etc., which are subject to physical and operational constraints. Except for the conservation of mass, conservation of energy and head loss equations, there are still other limitations:

**Tank volume constraint:**

$$\sum_{j=1}^{m} TV_{\text{backup}} \leq \sum_{j=1}^{m} TV_j \leq \sum_{j=1}^{m} TV_{\text{max}}$$

Where $TV_{\text{backup}}$ is the minimum storage requirement of tank $j$ for emergency conditions such as fire fighting; $TV_j$ and $TV_{\text{max}}$ are the available volume and maximum volume of tank $j$ respectively.

**Pipe diameter constraint:**

$$D_k \in [D_{\text{min,k}}, D_{\text{max,k}}]$$

By using a long but very small-diameter pipe, the cost based on pipe may be lower but not reasonable. An additional constraint has to be added to the limitation of the pipe diameter. It should be optimized among selected commercial diameters instead of treated as continuous variables.

**Outflow constraint:**

$$0 \leq Q_j^{\text{req}} \leq Q_j^{\text{avl}}$$

Where $Q_j^{\text{req}}$ is the required flow at demand node $i$; $Q_j^{\text{avl}}$ is the available outflow at node $i$, which is calculated by:

$$Q_j^{\text{avl}} = \sum_{k \in \text{in}(i)} q_k - \sum_{k \in \text{out}(i)} q_k$$

Where $\text{in}(i)$ and $\text{out}(i)$ are the sets of pipe flows entering and emanating from node $i$, respectively; $q_k$ is the flow in pipe $k$.

**Pressure constraint:**

$$H_{\text{req,i}} \leq H_i \leq H_{\text{max,i}}$$

Where $H_{\text{req,i}}$ and $H_{\text{max,i}}$ are the minimum required pressure head and the maximum allowed pressure head of demand node $i$ respectively.

### 3. Results and discussion

#### 3.1. Water demands analysis

According to the required water quantity during 24 hours for different types of workface, as shown in Figure 2, it could be concluded that the water demands were time-varying nonlinear parameters which depended on the production arrangement. The blasting mining faces consumed more water than the blasting driving faces and the developing workfaces. To illustrate the location of different workfaces in the water supply network topology, they were represented as a set of nodes (Node 4, 5, 9, 11, 12, 14, 15,
16, 19, 20, 21) in Figure 1. It could be seen that there were some nodes (Node 5, 9, 19, 20, 21) representing two workfaces. This was because those workfaces were very close to each other, so they were drawn together to simplify the topology for calculation. What’s more, the water demands of these nodes were higher than other nodes by calculation based on the data in Figure 2. Thus, if there was a breakdown in the mine water supply network, these key nodes would suffer from high risk of water shortage. This situation would probably do harm to the working environment underground, interrupt the mining activity, and even finally bringing in big economic loss. With the optimization research based on MPC, this problem was identified, and the optimized water supply network presented better anti-risk capability, which would be addressed in the later part.

Figure 2. Water demand of different workfaces in a day

3.2. Optimization of hydraulic performance

With a dynamic optimization using MPC based on time-dependent water demands and multiple constraints, diameters of pipes were redesigned to improve the reliability of the underground mine water supply system. The comparison of pipe diameter and flow between the original and optimized water supply network were presented in Table 1. The flow was calculated as an example to show the advantage of the optimized network, as illustrated in the following.

When there was sufficient water storage in all of the three tanks, fluctuation of the water level in each tank would not have a big impact on the total flow energy, while a hydraulic condition when all demands of pressure head and flow for various production activities could still be achieved. The reason is that there were relatively larger elevation differences between the tanks and demand nodes, in comparison to the water level variation values. If breakdown happened in Tank 1 or in pipes connecting Tank 1 and downstream nodes, water in Tank 1 would not be available for supporting the pipe network. Thus, water sources would be only Tank 2 and Tank 3. In this case, with the original water supply network, hydraulic calculation based on conservation of mass and energy showed an error that negative pressure head occurred in some nodes such as Node 18, 19 and 20 if all the water demand objectives were set to be rigidly satisfied. This indicated that the total loss of head in the network exceeded the minimum total available head required to satisfy all the water demands, so the actual pressure head in Node 18, 19 and 20 were lower than the minimum pressure head they required. If the water demands at Node 19 and 20 were not included, then other demand nodes could be well satisfied by water provided by Tank 2 and Tank 3, as shown in Figure 3. Therefore, the original mine water supply network did not have adequate capability to bear the risk of breakdown in Tank 1 or pipes connected to Tank 1.

However, the optimized network, by contrast, showed a distinct better hydraulic performance. When the Tank 1 failed to supply water, the whole network could still operate effectively, fulfilling all the water demands, as shown in Figure 4. Since Tank 1 has the highest elevation among all tanks, the
assumed condition that Tank 1 was unavailable represents one of worst operating conditions of the mine water supply network. This presents a strong support for the better anti-risk effect achieved by the optimization of the pipe network.

Figure 3. Hydraulic conditions of the original mine water supply network when Tank 1 was unavailable

Figure 4. Hydraulic conditions of the optimized mine water supply network when Tank 1 was unavailable
### Table 1. Comparison of the pipe diameter and flow between the original and optimized water supply network when Tank 1 was unavailable

| Pipe | Flow direction From Node i to Node j | Original Diameter (mm) | Flow (m³/h) | Original Diameter (mm) | Flow (m³/h) |
|------|---------------------------------------|------------------------|-------------|------------------------|-------------|
| 1    | 3-4                                   | 108                    | 53.11       | 159                    | 63.54       |
| 2    | 4-5                                   | 108                    | 45.51       | 127                    | 55.94       |
| 3    | 5-6                                   | 108                    | 27.91       | 127                    | 38.34       |
| 4    | 2-7                                   | 108                    | 32.79       | 159                    | 57.56       |
| 5    | 7-6                                   | 108                    | 32.79       | 159                    | 57.56       |
| 6    | 6-8                                   | 108                    | 60.70       | 127                    | 95.90       |
| 7    | 8-9                                   | 108                    | 31.67       | 127                    | 64.93       |
| 8    | 9-10                                  | 108                    | 14.07       | 127                    | 47.33       |
| 9    | 8-11                                  | 108                    | 29.03       | 108                    | 30.97       |
| 10   | 11-14                                 | 108                    | 5.10        | 60                     | 5.10        |
| 11   | 11-12                                 | 108                    | 18.83       | 89                     | 20.77       |
| 12   | 12-13                                 | 108                    | 13.73       | 89                     | 15.67       |
| 13   | 1-18                                  | 108                    | 0.00        | 159                    | 0.00        |
| 14   | 19-20                                 | 108                    | 0.00        | 89                     | 17.60       |
| 15   | 18-19                                 | 108                    | 0.00        | 159                    | 35.20       |
| 16   | 10-18                                 | 108                    | 0.00        | 127                    | 35.20       |
| 17   | 10-21                                 | 108                    | 17.60       | 89                     | 17.60       |
| 18   | 13-10                                 | 108                    | 3.53        | 108                    | 5.47        |
| 19   | 13-15                                 | 108                    | 10.20       | 108                    | 10.20       |
| 20   | 15-16                                 | 108                    | 5.10        | 60                     | 5.10        |

#### 3.3. Resilience and economy analysis

There is no doubt that the resilience can be increased with a higher budget. Results in this study showed the minimum construction cost (RMB1,440,000.00) for the optimal network design was 17.6% more than the original investment (RMB 1,224,221.00). The resilience value of the optimized network was calculated to be 0.43, while that of the original one was 0.22. It could be concluded that with an additional 17.6% investment, the resilience performance would be increased by 95.5%. Even if a severe breakdown happened when one of the tanks should be disconnected from the system for 24 hours, the optimized network could guarantee the demand fulfillments. Overall, the optimized mine water supply network would be more effective with better resilience performance.

#### 4. Conclusion

(1) Water demands of the underground mine water supply network were time-varying nonlinear parameters and depended on the production arrangement. Demand nodes that required higher flow might suffer from high risk of water shortage.

(2) With the optimization using MPC technology based on time-dependent water demands and multiple constraints, diameters of pipes were redesigned. The resilience performance of the water supply network could be increased by 95.5% with only an additional 17.6% investment budget.

(3) Better operation performance and anti-risk capability were achieved than the original network. Even if Tank 1 failed to provide water supply, the optimized network could recover from the breakdown and continue to operate effectively.

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