INTRODUCTION

A mine ventilation system is an integral part of a coal mine system.1-6 Its mission includes supplying fresh air to underground personnel, diluting and discharging harmful gases and floating dust, and regulating mine climate conditions to create a good production environment.7-9 In addition, when a mine disaster occurs, such as a fire or an explosion, the ventilation network can be adjusted to control the air volume or change the direction of the wind flow to control the disaster situation and reduce the accident loss.10,11

The mine ventilation system is large and complex. When studying the mine ventilation system, conducting field experiments can be cumbersome and uneconomical. Numerical simulations do not have such shortcomings, so a large number of mathematical models have been established for the simulation of mine ventilation systems. The accuracy of a numerical simulation depends on the rationality of the model and the accuracy of the parameters. Due to the complexity of the ventilation system structure, large amounts of storage space and calculation time are required for numerical simulation on a computer, so the ventilation system is often simplified during modeling. For example, a one-dimensional model is commonly used to simulate a mine ventilation system.12,13

Abstract

A mine ventilation system is a large and complex system. Its stability is affected by many factors, and wind resistance change is one of the common influencing factors. In order to study the influence of branch wind resistance changes on the branch air volume and the stability of the ventilation system, this paper introduced the concept of sensitivity, constructing a mathematical model of the influence of branch wind resistance changes on air volume. Based on the model, the sensitivity of each branch can be calculated, the sensitivity matrix can be constructed, and the influence of the branch wind resistance change on the air volume change can be quantitatively expressed. The sensitivity matrix can be used to analyze the stability of the mine ventilation system and can be used as an indicator of the optimization and comparison of the ventilation system. The branch with the most influence and the most affected degree in the ventilation system can be obtained, so the sensitivity matrix can accurately determine the best branches to raise resistance (or reduce resistance). This study can guide the design and optimization of mine ventilation systems.
Stability is an important evaluation criterion for a mine ventilation system, since it directly affects the production conditions in the underground and the breathing environment of workers. However, the stability of the mine ventilation system can be affected by many factors, including continuous tunneling and roof falling.\textsuperscript{14-17} The essence of these factors is the fluctuation of wind flow caused by the change of roadway wind resistance, which in turn affects the stability of the entire mine ventilation system. In addition, theory and practice have proved that if there is a diagonal branch in the mine ventilation system, it will become more complicated.\textsuperscript{16,18} Some researchers have done a lot of research on the stability of mine ventilation systems. In the paper of Semin,\textsuperscript{6} an algorithm was proposed to calculate and evaluate the stability of mine ventilation systems. Jia et al\textsuperscript{19} used multiple regression analysis to analyze the stability of mine ventilation systems with diagonal branches. El-Nagdy\textsuperscript{20} combined the Hardy Cross algorithm with switching parameters to study the interaction between fans and their effects on the stability of the ventilation network. According to the real situation of the mine ventilation system, the stability of the mine ventilation system was analyzed based on the determination of system resistance.\textsuperscript{18}

The above research works on mine ventilation systems have enabled us to have a deeper understanding of the stability of such systems. However, the stability of the mine ventilation system reflects the overall, macroscopic state of the system, which is formed by the relationships between each branch and other branches. If the wind resistance of any branch changes, this may cause changes in the air volume of this branch and other related branches. This kind of research based on the variation of branch wind resistance and its effects on the stability of other branches and even all branches. This kind of research based on the variation of branch wind resistance changes to air volume effects to construct a sensitivity matrix, which can be used to quantitatively analyze the impact of branch wind resistance changes on the stability of the mine ventilation system, and thus provide guidance for the design, optimization, and adjustment of the ventilation system.

As shown in Figure 1, it is a simple ventilation network and the parameters of the branches are shown in Table 1. It is assumed that the volumetric airflow rate of the $e_2$ branch needs to be increased to 6 m$^3$/s, then an air window (the air window is a ventilation structure used to increase the resistance of the roadway and adjust the air volume of the roadway) can be added in the $e_3$ branch to decrease the volumetric airflow rate, and increase the volumetric airflow rate of the $e_2$ branch. Then, the ventilation resistance of the $e_3$ branch will increase because of the air window, and the ventilation resistance of the $e_2$ branch will increase as the addition of the airflow, and the total ventilation resistance of the ventilation system will increase from H to H'. However, during the actual adjustment process, it was found that the reduced volumetric airflow rate of the $e_3$ branch is not numerically equal to the increased volumetric airflow rate of the $e_2$ branch. As shown in Figure 2, the wind resistance of the whole network will increase from $R$ to $R'$. Assuming that the characteristics of the fan are constant, the operating point will change from $M$ to $M'$, and the total volumetric airflow rate of the ventilation system will decrease from $Q$ to $Q'$.

The ventilation system is an organic unity, which means a change in the wind resistance of a branch will cause the air volume of this and other branches, or even all branches

\textbf{TABLE 1} Ventilation system branch parameters

| Branch | $e_1$ | $e_2$ | $e_3$ | $e_4$ |
|--------|-------|-------|-------|-------|
| Air resistance (N s$^2$/m$^8$) | 0.2 | 0.3 | 0.3 | 0.2 |
| Volumetric airflow rate (m$^3$/s) | 10 | 5 | 5 | 10 |

\textbf{FIGURE 1} Ventilation network diagram

\textbf{FIGURE 2} Wind resistance change diagram
to change. At this time, the air volume of some branches may no longer meet requirements and need to be adjusted. Therefore, when a branch’s wind resistance changes, it is particularly important to analyze the air volume stability of each branch in the ventilation network and determine which branch(es), if any, require adjustment. This paper introduces sensitivity and the sensitivity matrix to analyze such issues.

### 2.1 Sensitivity

As the ventilation network is an organic unity, the change of the wind resistance $r_j$ of any branch in the network may cause changes in the air volume of itself and all branches and even the entire network. When the wind resistance $r_j$ of the $j$-th branch changes by $\Delta r_j$, the air volume $q_i$ of any $i$-th branch in the network also changes by $\Delta q_i$, accordingly. When $|\Delta r_j| \to 0$, there is

$$
\frac{\Delta q_i}{\Delta r_j} = \frac{\partial q_i}{\partial r_j} = \lim_{|\Delta r_j| \to 0} \frac{\Delta q_i}{\Delta r_j} = d_{ij}
$$

where $d_{ij}$ is defined as the sensitivity of the air volume $q_i$ of the $i$-th branch relative to the change of the $j$-th branch wind resistance $r_j$.

### 2.2 Sensitivity matrix

All circuits in the ventilation network satisfy the law of pressure balance; that is, in any circuit, the wind flow in different directions has the same total resistance value, and the equation is as follows:

$$
\sum_{i=1}^{n} b_{ij} r_j q_i |q_i| - b_{ij} h_{ij} = 0
$$

where $r_i$ is the wind resistance of the $i$-th branch; $h_{ij}$ is the additional resistance on the $i$-th branch; and $b_{ij}$ is the flow coefficient of the $i$-th branch in the independent $l$-th circuit, based on the direction of the remaining branch. The value of $b_{ij}$ is as follows:

$$
b_{ij} = \begin{cases} 
1 & \text{When the flow direction of the } i \text{-th branch in the independent } l \text{-th circuit is positive} \\
0 & \text{When the independent } l \text{-th circuit does not contain the } i \text{-th branch} \\
-1 & \text{When the flow direction of the } i \text{-th branch in the independent } l \text{-th circuit is negative}
\end{cases}
$$

In order to obtain sensitivity $d_{ij} = \lim_{|\Delta r_j| \to 0} \frac{\Delta q_i}{\Delta r_j}$, Equations (2) and (3) are used to obtain the partial derivative of $r_j$.

$$
\sum_{i=1}^{n} a_{ki} \frac{\partial q_i}{\partial r_j} = 0
$$

Equation (4) is the mathematical model of sensitivity.

For a ventilation network with $n$ branches, the sensitivity of each branch can be obtained. The sensitivity of the whole network is $n \times n$, which can form an $n \times n$-dimensional matrix and it is called the sensitivity matrix, which is recorded as:

$$
D = \begin{bmatrix}
d_{11} & d_{12} & \cdots & d_{1n} \\
d_{21} & d_{22} & \cdots & d_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
d_{n1} & d_{n2} & \cdots & d_{nn}
\end{bmatrix}
$$
2.3 | Sensitivity matrix characteristics

The sensitivity matrix is unique under certain conditions of the system. The sensitivity value is independent of the choice of the independent circuit; that is, the sensitivity has a fixed solution. Only when the system state changes, will its solution change.

The i-th row element in the sensitivity matrix D represents the sensitivity of the i-th branch air volume in the network to all branch wind resistance changes; the j-th column element represents the sensitivity of the j-th branch wind resistance's influence on other branch air volume. In addition, the sensitivity matrix has the following properties.

1. Under some state, the elements in the sensitivity matrix are positive and negative. The sign of sensitivity reflects the structure of the ventilation network. \(d_{ij} > 0\), indicating that the corresponding i-th branch and j-th branch are in parallel relationship, not on the same flow path; \(d_{ij} < 0\), indicating that the i-th branch and the j-th branch are in series relationship and exist on the same flow path.

2. From the sensitivity matrix \(D\), we can compute:

\[
U_j = \sum_{i=1}^{n} |d_{ij}|, (j = 1, 2, ..., n)
\]

where \(U_j\) is the sum of the influences of the wind resistance changes of the j-th branch on the air volume of each branch of the network and is called the influence degree of the j-th branch. The size of the influence degree indicates how dominant the branch is in the network.

3. We can also compute:

\[
V_i = \sum_{j=1}^{n} |d_{ij}|, (i = 1, 2, ..., n)
\]

where \(V_i\) is the sum of the influences of wind resistance changes of each branch in the network, on the air volume of the i-th branch and is called the influence degree of the i-th branch. The influence degree indicates the sensitivity of i-th branch in the network.

Therefore, the Cross method is used for iteration in practical applications.21

The basic idea of the Cross iterative method is to construct the iterative sequence, \(k = 0, 1, 2, \ldots\) (\(k\) is the number of iterations), based on the definition of sensitivity and the Cross method of network solution. The k-th iteration gives \(r_j\) a small perturbation \(dr_j^{(k)}\); assuming that it causes the air volume of the i-th branch to change to \(q_i^{(k)}\) from \(q_i^{(k-1)}\), \(q_i^{(k)}\) can be obtained by network solution. According to Equation (1), the k-th iteration of the sensitivity \(d_{ij}^{(k)}\) is as follows:

\[
d_{ij}^{(k)} = \frac{q_i^{(k)} - q_i^{(k-1)}}{r_j^{(k)} - r_j^{(k-1)}} = \frac{q_i^{(k)} - q_i^{(k-1)}}{dr_j^{(k)}}
\]

In the calculation of \(d_{ij}^{(k)}\), the disturbance value \(d_{ij}^{(k)}\) is successively reduced, in order to accelerate convergence: set \(dr_j^{(k)} = dr_j^{(k-1)}/\omega\) (\(\omega\) is the acceleration factor, \(1 < \omega < +\infty\) and it usually takes the value \(1 < \omega < 10\), when \(|dr_j^{(k)} - dr_j^{(k-1)}| \leq \varepsilon\), then the calculation is terminated (\(\varepsilon\) is the calculation accuracy).

The sensitivity iteration calculation steps are as follows:

a. It is known that \(r_j, j = 1, 2, \ldots, n\), is a branch number.

b. Set \(d_{ij}^{(k)} = 0, i = 1, 2, \ldots, n; j = 1; k = 1; dr_j^{(1)} = r_j/x;\)

c. Using the Cross method for network solution, the air volume \(q_i\) of i-th branch can be obtained when the air resistance changes from \(r_j\) to \(r_j + dr_j^{(k)}\), \(i = 1, 2, \ldots, n;\)

d. Calculate the sensitivity of the k-th step, \(d_{ij}^{(k)} = \frac{q_i^{(k)} - q_i^{(k-1)}}{dr_j^{(k)}}\) \(i = 1, 2, \ldots, n;\)

e. If \(\max\{|d_{ij}^{(k)} - d_{ij}^{(k-1)}|\} < \varepsilon\), the result of the calculation meets the criteria, \(d_{ij}^{(k)} = d_{ij}^{(k)}\), and the calculation result is recorded in the j-th column of the sensitivity matrix and turn to (f); otherwise, turn to (c);

f. Set \(j = j + 1\), if \(j + 1 > n\), turn to (g); otherwise, go to (b);

g. End.

The specific sensitivity calculation process is shown in Figure 3.

The author has written sensitivity calculation software according to the above calculation steps that can quickly and accurately calculate the sensitivity of each branch to construct a sensitivity matrix.
1. Stability analysis of ventilation network

Sensitivity is a quantitative indicator of the stability of a ventilation system. The greater the branch sensitivity values of the ventilation system, the greater the change rate of the air volume with the wind resistance. That is, the more sensitive the branch air volume is to the wind resistance, the worse the stability of the ventilation network. In order to ensure the stability of the ventilation system air volume, the sensitivity value should be as small as possible, that is, the sensitivity of the entire ventilation system $\beta = \sum_{i=1}^{n} \sum_{j=1}^{n} |d_{ij}| \rightarrow \min$ or branch sensitivity $a_j = \sum_{i=1}^{n} |d_{ij}| \rightarrow \min$.

2. Comparison of ventilation network stability

If the ventilation system needs to be optimized, the ventilation system or branch with lower sensitivity will have better air volume stability under the same conditions. If $\sum_{i=1}^{n} \sum_{j=1}^{n} |d_{ij}^{(A)}| < \sum_{i=1}^{n} \sum_{j=1}^{n} |d_{ij}^{(B)}|$, the stability of ventilation network A is better than that of ventilation network B; and if $\sum_{j=1}^{n} |d_{ij}| < \sum_{j=1}^{n} |d_{ij}|$, the stability of the $a$-th branch is better than that of the $b$-th branch.

3. Ventilation network air volume adjustment

Ventilation network air volume adjustment is done by changing the wind resistance of some branches in order to change the air volume at a given branch to meet the requirements of that location. However, the choice of which branches to adjust is difficult. According to the previous analysis, the sensitivity reflects the influence degree of a branch wind resistance change on the variation of the wind volume of the branch. The greater the sensitivity value, the greater the influence of the wind resistance of a branch on the air volume of the branch. Therefore, before adjusting the air volume, the adjustment branch can be compared by calculating the sensitivity of each branch.

If the air volume allocated of a certain working place ($i$-th branch) is less than the required air volume, a resistance increase should be performed on a $j$-th branch that satisfies the following formula:

$$\frac{\partial q_i}{\partial r_j > 0}$$

(8)

Conversely, if the air volume allocated of a certain workplace ($i$-th branch) is greater than the required air volume, a resistance increase should be performed on a $j$-th branch that satisfies the following formula:

$$\frac{\partial q_i}{\partial r_j} < 0$$

(9)

5. Sensitivity application example

5.1 Sensitivity matrix calculation

As shown in Figure 4, the ventilation network case is taken from Jinhui Rongtai Coal Industry (which is located in

FIGURE 3 Sensitivity calculation flow chart

FIGURE 4 Ventilation network case diagram
Luliang Lishi District, Shanxi Province, China) with a production scale of 1.2 million tons per year. The mine currently has 4 shafts, the main vertical shaft, the auxiliary vertical shaft, and 2 return air shafts. The air enters the mine from the main vertical shaft and the auxiliary vertical shaft, passes all places where the air is used and enters the return air shafts eventually. As the ventilation system of the whole coal mine is too complicated, a simplified ventilation network is taken from one of the working faces, and the wind resistance parameters are shown in Table 2.

Sensitivity is related to the specific state of the ventilation system. For a particular system, the sensitivity matrix will be different depending on whether there is a fan. For ease of calculation, the ventilation system in this example does not take into account the effects of a fan. The total air volume in the ventilation system is 20 m$^3$/s. During the calculation process, the network solution uses the Cross method with fixed total air volume. Taking $\omega=100$, $\xi=100$, and $\epsilon=0.005$ , the calculated sensitivity matrix is as follows:

$$
\begin{bmatrix}
0 & -1.6116 & 0.7997 & -0.3363 & -0.0654 & 0.5918 & 0 \\
0 & 1.6116 & -0.7997 & 0.3362 & 0.0654 & -0.5918 & 0 \\
0 & -0.6292 & 0.3150 & -0.4968 & 0.0201 & 0.8756 & 0 \\
0 & -0.9824 & 0.4847 & 0.1606 & -0.0855 & -0.2838 & 0 \\
0 & 0.6292 & -0.3150 & 0.4968 & -0.0201 & -0.8756 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

### 5.2 Sensitivity model verification

In the above case, if the $e_2$ branch needs to increase the air volume, the most effective method is to increase the resistance in the $e_3$ branch. In order to verify the accuracy of the sensitivity matrix, it is assumed that the wind resistance of each branch increases by 10%, and the influence of wind resistance changes of each branch on the air volume of the $e_2$ branch is analyzed.

According to the network settlement result, the amount of change in wind resistance of each branch and the amount of change in air volume corresponding $e_2$ branch are shown in Table 3.

The wind resistance effect of each branch on the wind volume of the $e_2$ branch is compared with the data in the sensitivity matrix, as shown in Figure 5.

It can be seen in Figure 5 that the variation of the wind resistance of each branch has a high consistency with the calculated value of $\Delta q_2/\Delta r_j$ and the value of the sensitivity matrix. It can be seen that the sensitivity matrix can describe the influence of the wind resistance change on the air volume change with high accuracy.

### 5.3 Results analysis

According to the above sensitivity matrix data, it can be shown that:

1. In the whole sensitivity matrix, $d_{32}$ is the largest; that is, the wind resistance change of the $e_2$ branch has the greatest influence on the air volume of the $e_3$ branch, and the air volume of the $e_3$ branch is most sensitive to the wind resistance change of the $e_2$ branch, and if the $e_3$ branch needs to increase the wind volume, the most effective adjustment is the $e_2$ branch, followed by the $e_3$ branch, which is consistent with the real situation of the mine ventilation system.$^{16,18}$

2. In the first row, the seventh row, the first column, and the seventh column, the sensitivity values are all 0. This is because in the $e_1$ branch and the $e_7$ branch, the total air volume changes little when the wind resistance changes and can be regarded as a fixed value. Therefore, no matter how the wind resistance of other branches changes, the air volume of this branch is almost unchanged, so the sensitivity value is 0.

3. In the second row, $|d_{22}|$ is the maximum; that is, the wind resistance change of the $e_2$-th branch has the greatest influence on the air volume of the $e_2$ branch; $|d_{22}|$ is the minimum; that is, the wind resistance change of the $e_5$ branch has the least influence on the air volume of the $e_2$ branch. $d_{23}>0$, indicating the $e_2$ and $e_3$ branches are in a parallel relationship, not in the same flow path; and $d_{24}<0$, indicating that the $e_2$ and $e_4$ branches are in series, in the same flow path.

4. The degree of influence in the sensitivity matrix is as follows:

$$
U_1 = \sum_{i=1}^{7} |d_{i1}| = |d_{11}| + |d_{21}| + \cdots + |d_{71}| = 0
$$

Using the same method, we can get:

$$
U_2 = 5.4639; U_3 = 2.7130; U_4 = 1.8268; U_5 = 1.8268; U_6 = 0.2566; U_7 = 3.2186; U_7 = 0.
$$

| Branch | $e_1$ | $e_2$ | $e_3$ | $e_4$ | $e_5$ | $e_6$ | $e_7$ |
|--------|-------|-------|-------|-------|-------|-------|-------|
| Air resistance (N s$^2$/m$^3$) | 0.3750 | 0.1500 | 2.0000 | 4.6875 | 12.5000 | 1.7361 | 0.5000 |

**Table 2** Ventilation system branch wind resistance value
It can be seen that $U_2$ is the maximum; that is, the $e_2$ branch is dominant in the network, and the sum of its wind resistance changes on the branch air volume in the entire ventilation network is the largest, so it is necessary to pay attention to the change state of the $e_2$ branch when the ventilation system is running. Except for $U_1$ and $U_7$, $U_5$ is the smallest; that is, the change of the wind resistance of the $e_5$ branch is the least influential on the change of the air volume of other branches; and this situation can also be verified in the actual mine ventilation system.

5. The degree of influence in the sensitivity matrix is as follows

$$V_j = \sum_{j=1}^{7} |d_{ij}| = |d_{1j}| + |d_{12}| + \cdots + |d_{17}| = 0$$

(11)

Using the same method, we can get:

$$V_2 = 3.4047; V_3 = 3.4047; V_4 = 2.3367; V_5 = 1.9971; V_6 = 2.3367; V_7 = 0.$$  

The comparison shows that the maximum $V_2 = V_3$, that is, the $e_2$ and $e_3$ branches are the most affected, and the wind resistance changes of the branches in the ventilation network have the greatest influence on the air volumes of $e_2$ and $e_3$ branches. Therefore, when the wind resistance of each branch changes, attention should be paid to whether the air volume of $e_2$ and $e_3$ branches can still meet requirements.

6. When the air volume of a branch in the system needs to be increased, the branch corresponding to the maximum value of the row in the sensitivity matrix can be adjusted for resistance increase; if the air volume needs to be reduced, the branch corresponding to the minimum value of the row in the sensitivity matrix can be adjusted for resistance increase.

Through the above analysis, the sensitivity and influence degree of each branch in the case ventilation system and the branch with the greatest influence degree can be known, and the stability of the ventilation system under the specified ventilation state can be quantitatively analyzed, which can be used to guide the adjustment and optimization of the system.

6  | CONCLUSIONS

1. This paper introduced the concept of sensitivity and established a mathematical model for quantitative analysis of the change of branch wind resistance on the air volume in the ventilation system. Under the same conditions, the greater the sensitivity of the ventilation network, the greater the change rate of the air volume with the change of wind resistance, and the lesser the stability of the ventilation network air volume.

2. Using sensitivity as an evaluation index, the stability of ventilation systems can be analyzed and compared. The lower the sensitivity values of the ventilation system, the better its stability. Therefore, when optimizing the ventilation network, the sensitivity of the ventilation network or branch should be as small as possible.

3. According to the sensitivity matrix of the ventilation network, and the sensitivity of each branch, the branch with the greatest influence and the branch with the most affected degree in the whole ventilation network can be known, which has guiding significance for the adjustment of the network.
ACKNOWLEDGMENTS
This research was supported by the National Natural Science Foundation of China (Grant No. 51374121) and the Liaoning Distinguished Professor Funding Project (Grant No. 551710007007).

CONFLICT OF INTEREST
Authors declare that there is no conflict of interest.

ORCID
Peng Jia https://orcid.org/0000-0001-7251-1457

REFERENCES
1. Zhou A, Wang K. A transient model for airflow stabilization induced by gas accumulations in a mine ventilation network. J Loss Prev Process Ind. 2017;47:104-109.
2. Zhou A, Wang K, Wang J, Feng T. The role of methane buoyancy on the stability of airflow airflow in underground coal mine ventilation. J Loss Prev Process Ind. 2018;54:346-351.
3. Xu G, Jong EC, Luxbacher KD, McNair HM. Effective utilization of tracer gas in characterization of underground mine ventilation networks. Process Saf Environ Prot. 2016;99:1-10.
4. Nyaaba W, Frimpong S, El-Nagdy KA. Optimisation of mine ventilation networks using the Lagrangian algorithm for equality constraints. Int J Min Reclam Environ. 2014;29(3):201-212.
5. Xu G, Huang J, Nie B, Chalmers D, Yang Z. Calibration of mine ventilation network models using the non-linear optimization algorithm. Energies. 2017;11(1):31.
6. Semin MA, Levin LY. Stability of air flows in mine ventilation networks. Process Saf Environ Prot. 2019;124:167-171.
7. Kursunoglu N, Onder M. Selection of an appropriate fan for an underground coal mine using the Analytic Hierarchy Process. Tunn Undergr Space Technol. 2015;48:101-109.
8. Wallace K, Prosser B, Stinnette JD. The practice of mine ventilation engineering. Int J Min Sci Technol. 2015;25(2):165-169.
9. Cheng J, Yang S. Data mining applications in evaluating mine ventilation system. Saf Sci. 2012;50(4):918-922.
10. Xiao Y, Chen L, Zhang X, Ren S, Li D. Controlling fire of belt conveyor and ventilation network calculation in underground coal mines. IOP Con Ser: Earth Environ Sci. 2018;189:042028.
11. Liang Y, Zhang J, Ren T, Wang Z, Song S. Application of ventilation simulation to spontaneous combustion control in underground coal mine: a case study from Bulianta colliery. Int J Min Sci Technol. 2018;28(2):231-242.
12. Kruglov YV, Levin LY, Zaitsev AV. Calculation method for the unstable air supply in mine ventilation networks. J Min Sci. 2011;47(5):651-659.
13. Wu Z, Li S, Wang K, Shen S, Wang L. Critical air velocity of methane draft pressure-caused airflow reversion in upward ventilated parallel tilted airways. J Loss Prev Process Ind. 2018;56:498-504.
14. Rusiński E, Moczkó P, Odyjas P, Pietrusiaik D. Investigation of vibrations of a main centrifugal fan used in mine ventilation. Arch Civ Mech Eng. 2014;14(4):569-579.
15. Xu G, Luxbacher KD, Ragab S, Schafrik S. Development of a remote analysis method for underground ventilation systems using tracer gas and CFD in a simplified laboratory apparatus. Tunn Undergr Space Technol. 2013;33:1-11.
16. Kazakov BP, Shalimov AV, Semin MA. Stability of natural ventilation mode after main fan stoppage. Int J Heat Mass Transf. 2015;86:288-293.
17. Brune JF. Mine ventilation networks optimized for safety and productivity. Advances in Productive, Safe, and Responsible Coal Mining. 2019:83-99.
18. Cheng G, Qi M, Zhang J, Wang W, Cheng Y. Analysis of the stability of the ventilation system in Baishan Coalmine. Proc Eng. 2012;45:311-316.
19. El-Nagdy KA. Stability of multiple fans in mine ventilation networks. Int J Min Sci Technol. 2013;23(4):569-571.
20. Sun C, Ti Z, Zhao T. Mine complex wind network visualization solution system based on improved Cross algorithm. J Liaoning Tech Univ (Nat Sci Ed). 2008;S1:25-27 (in Chinese).

How to cite this article: Jia J, Jia P, Li Z. Theoretical study on stability of mine ventilation network based on sensitivity analysis. Energy Sci Eng. 2020;8:2823–2830. https://doi.org/10.1002/ese3.699