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Research Article

A GIS Based Unsteady Network Model and System Applications for Intelligent Mine Ventilation

Hui. Liu, Shanjun Mao, Mei. Li, and Pingyang Lyu

Institute of Remote Sensing and Geographic Information System, Peking University, Beijing 100871, China

Correspondence should be addressed to Shanjun Mao; sjmao_@pku.edu.cn

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With the development of state-of-the-art technology, such as the artificial intelligence and the Internet of Things, the construction of "intelligent mine" is being vigorously promoted, where the intelligent mine ventilation is one of the primary concerns that provides the efficient guarantee for safety production in the underground coal mine system. This study aims to integrate the geographical information system (GIS) and the unsteady ventilation network model together, to provide location based information and online real-time support for the decision-making system. Firstly, a GIS based unsteady network model is proposed, and its algorithm steps are brought out. Secondly, a prototype web system, named 3D VentCloud, is designed and developed based on the front and end technique, which effectively integrates the proposed algorithms. Thirdly, the model is validated, and the system is applied to a real coal mine for ventilation solution, which demonstrates that the model is reasonable and practical. The online simulation system is efficient in providing real-time support. The study is potential and is expected to guide the real-time coal mine safety production.

1. Introduction

The "intelligent mine" is being constructed and developed vigorously in recent years, which is expected to provide reliable, fast, smart and accurate decision support for safety operation and production in underground coal mine. Mine ventilation system is one of the most important and basic systems to ensure safety production. An efficient ventilation system is potential to guarantee a health working environment for coal miners and ensure sustainable development of the underground coal mine system. The concept of the intelligent mine ventilation is being proposed, while there are still a lot of scientific issues to be solved [1, 2].

The current research on ventilation network model and ventilation software is mainly focused on the traditional steady calculation model. However, mine ventilation system essentially belongs to a dynamic complex system with geospatial and temporal characteristics. For example, although the ventilation state is steady during normal production of coal mine, various internal disturbances and ground air pressure would have certain influence on airflow and pressure inside the laneway; thus, it causes airflow pulsation [3]. Besides, due to gas outburst, mine fire, and other major accidents, the ventilation state will change instantaneously and cause transient disorder of airflow inside the laneway. Therefore, the ventilation states during normal production or disaster should all be regarded as unsteady flow; thus, it requires to establish a unified ventilation simulation model, and that is well adapted with the concept of the intelligent mine ventilation [4].

Besides, the current data acquisition and processing procedures for mine ventilation lack an online integrated system to better adapt to intelligent mine ventilation system. Nowadays, there are a lot of ventilation software systems that implemented informatization for mine ventilation, for example, Polish Academy of Sciences developed VENTGRAPH and Mine Fire Simulation software [5–7]. Chasm company in Australia developed Ventsim software, which is widely used around the world [8]. The US and UK also developed some ventilation software systems such as VentPC 2003, Ventilation Design, VR-MNE, and Datamine [9]. There are also some successful domestic ventilation systems such as MFire, MVSS, and VentAnaly developed by Chinese institutes and universities [10, 11]. With the deep understanding for mine ventilation system and the great demand for practical production, mine ventilation belongs to a typical geographical environment, which has spatial, temporal, and attribute data as well as the spatial topological relationship [12]. Fortunately, the geographic information system (GIS) is regarded as one of the most effective ways to manage the geospatial data [13]. Therefore, based on traditional GIS technology, a great number of ventilation software systems have been developed. For instance, LongruanGIS, LKGIS, and VRMine GIS platform and some secondary developed systems based on AutoCAD or ArcGIS are developed and have been widely used [14–17].

However, it is difficult to deal with the spatial, temporal, and attribute data as well as the topological relationship using AutoCAD. In addition, the ventilation software systems based on GIS are mostly focusing on the combination of traditional GIS or static GIS with steady ventilation simulation model. Thus, a unified unsteady ventilation model integrated with GIS technology is needed to provide online and fast decision support to better satisfy the requirement of intelligent mine ventilation.

Therefore, this study aims to provide a fast online ventilation simulation solution to promote the construction of intelligent mine ventilation by integrating the unsteady ventilation network model and GIS as well as the system development. Firstly, the basic ventilation theory is introduced and an algorithm of GIS based unsteady network model is proposed. Secondly, based on the data structure of the ventilation model as well as the laneway network, a prototype simulation web system, called 3D VentCloud, is designed and developed. Thirdly, two experiments are implemented to validate the ventilation model and apply the web system, respectively.

2. GIS-Based Unsteady Network Model

Mine ventilation is a daily work to ensure safety production of coal mine, which requires accurate simulation to learn about the onsite ventilation situation. Rather than the traditional steady ventilation simulation model, this section mainly introduces the unsteady network model based on GIS technology as well as the model integration with the online web system.

2.1. Mathematical Models. Firstly, an ideal geometric laneway model is established to build the basic equation for the unsteady ventilation network model. As can be seen in Figure 1, the laneway length is L and cross section area is A, without considering the compressible properties of airflow.

Without any external force, the airflow inside the laneway belongs to the steady state. If the wind pressure at the ends of the laneway suddenly changes, there will be an equivalent external force F to the ends of the air column. According to the Newton's second law, suppose that the external force gives the acceleration a, and the air column has the corresponding equations [18]:

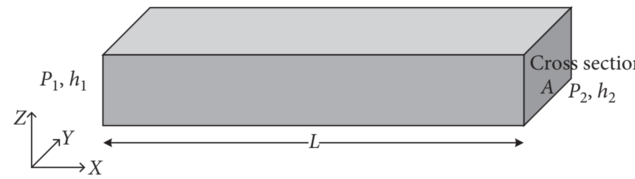


Figure 1: An ideal geometric laneway model.

$$a = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{1}{A}\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{F}{m} = \frac{\Delta PA}{AL\rho} = \frac{\Delta P}{L\rho},$$
$$\Delta P = (p1 - p2) + \left(\frac{1}{2}\rho v_1^2 - \frac{1}{2}\rho v_2^2\right) + \rho g\Delta h + h_r - RQ^2, \tag{1}$$

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{A}{L\rho}\left[(p1 - p2) + \left(\frac{1}{2}\rho v_1^2 - \frac{1}{2}\rho v_2^2\right) + \rho g\Delta h + h_r - RQ^2\right], \tag{2}$$

where R is the ventilating resistance, p_1 and p_2 are static pressures, v_1 and v_2 are the velocities at the laneway ends, and h_r is the external power. Assuming that a laneway is single and horizontal, both ends are connected with the atmosphere. When a fan placed at the end of the laneway suddenly starts, the pressure difference in equation (2) is 0, then we obtain

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{A}{L\rho}\left[h_r - RQ^2\right]. \tag{3}$$

As for the airflow inside the laneway network, the air is assumed to follow three basic laws of wind flow, which are the law of ventilation resistance, the law of pressure balance in loops, and the law of wind balance at nodes. These three laws represent the restriction and equilibrium relationships for three basic ventilation parameters, that is, air volume and ventilating resistance for laneway branch and node pressure in the ventilation network model [19]. A simple ventilation network graph is shown in Figure 2.

The three basic laws of wind flow can be described as

$$h_i = R_i \cdot |Q_i| \cdot Q_i, \quad (i = 1, 2, \ldots, N),$$
$$\sum_{i=1}^{N} \varepsilon_{ki} Q_i = 0, \quad k = 1, 2, 3, \ldots, (b-1), \tag{4}$$

$$\sum_{i=1}^{N} C_{ji}\beta_i \frac{\mathrm{d}Q}{\mathrm{d}\tau} = \sum_{i=1}^{N} C_{ji}\left(\Delta P_i - R_i Q_i |Q_i|\right), \quad j = 1, 2, 3, \ldots, M, \tag{5}$$

where N is the number of the laneway branches, and M is the number of network nodes. ε_{ki} and C_{ij} are the elements from basic correlation matrix and independent loop matrix of the network graph, and the value is 0, 1 or −1. $\Delta P_i = h_{Fj}(Q) \mp h_{Nj}(Q)$ stands for the ventilation power, including fan power $h_{Fj}(Q)$ and natural power $h_{Nj}(Q)$. Equation (5) can also be simplified to the matrix form of loop equations:

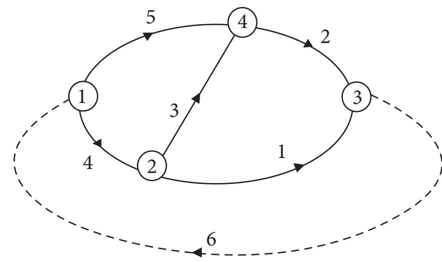


Figure 2: Ventilation network graph.

$$\frac{dQ(\tau)}{d\tau} = C^T\left(C\boldsymbol{\beta}C^T\right)^{-1}D, \quad (6)$$

where C is the loop matrix, and the elements in D are $D_j = \Delta P_j - \sum_i C_{ji}R_iQ_i(\tau)|Q_i(\tau)|$, $j = 1, 2, \ldots, b$. Based on this, the Runge-Kutta iterative algorithm can be applied to simulate the air volume changing with time for each laneway branch [20, 21]. The following is our specific solution based on the classical fourth-order Runge-Kutta method.

$$Q(\tau_{k+1}) = Q(\tau_k) + \frac{h}{6}(K_1 + 2K_2 + 2K_3 + K_4), \quad (7)$$

$$K_1 = f(Q(\tau_k)), \quad (8)$$

$$K_2 = f\frac{Q(\tau_k) + hK_1}{2}, \quad (9)$$

$$K_3 = f\frac{Q(\tau_k) + hK_2}{2}, \quad (10)$$

$$K_4 = f\frac{Q(\tau_k) + hK_3}{2}. \quad (11)$$

2.2. Data Models for Ventilation Network. Based on GIS theories and methods, the data model for unsteady ventilation network model is designed. Firstly, the ventilation network graph is described as $G = (V, E)$, where $V = \{v_1, v_2, \ldots, v_m\}$ is a set of nodes in network graph, and $E = \{e_1, e_2, \ldots, e_n\}$ is a set of laneway branches in network graph. Consider that airflow on every laneway branch has a wind direction; thus, the ventilation network graph is a directed graph. Then, we obtained the adjacency matrix, incidence matrix, cut set matrix, loop matrix, and path matrix of the network graph, which stores the topological information of the ventilation network graph. Besides, based on the perspective of GIS, the ventilation network graph and model belong to typical geospatial objects, including spatial data, attribute data, temporal data, and the spatial relationship, where the spatial relationship mainly includes the topological relation of the ventilation network graph, which connected the laneway branches and nodes, and is stored as point-line (node-branch) indexed structure based on GIS data organization, as can be seen in Table 1.

The specific data structure for laneway branch and nodes is established and presented in Table 2.

Table 1: Point-line indexed structure for topological relation.

Laneway branch ID (line)	Start node ID (point)	End node ID (point)

2.3. Algorithm Design. The whole algorithm is designed for the GIS based unsteady ventilation network model. Table 3 shows the specific procedure of the whole structure. This model and data organization structure provides more details of geospatial and attribute data for ventilation network by integrating geographical information.

3. System Design and Development

A prototype system, called 3D VentCloud, is designed in this study, which is developed by combing the front-end and the back-end technologies. The front-end is developed by using Html, JavaScript, and CSS. The back-end mainly includes the model and algorithm, which is developed by C++ and Python. Besides, Tornado is adopted as the server to transmit data between the front-end and back-end, and thus the two ends are connected. The system mainly includes three layers. As presented in Figure 3, they are, respectively, technology layer, service layer, and application layer.

Each layer and its functions are specifically described as follows:

(1) Technology layer. This layer contains the data source and the GIS based unsteady ventilation network model, which is the key technology for the system development. The data source includes the original obtained centerline data of the laneway network, which is processed and stored in GIS database as GeoJson format, including the geospatial, attribute, and temporal data of the laneway branch and nodes. The GIS based unsteady network model includes the generation of the topological relationship of the ventilation network graph, and the unsteady ventilation simulation model, where the topological relation and the dynamic simulation results are linked by the point-line indexed structure. These models jointly constructed the core model library and the key technology for the ventilation simulation system.

(2) Service layer. In this layer, the Tornado architecture is applied as the service, and WebSocket interface is utilized to link the front-end of JavaScript with the

Table 2: Data structure for laneway branch and node.

Data type	Laneway branch attribute (line)	Data type	Node attribute (point)
Int	ID	Int	ID
String	name	String	name
String	Kind	Double	Coordinate (x, y, z)
Double	Length	Double	Pressure
Double	Cross section area	Double	Humidity
Double	Perimeter	Double	Density
Double	Wind drag	Double	Temperature
Double	Ventilating resistance	vector<int>	Adjacent laneway ID
Vector <double>	Air volume (time series)		

Table 3: The algorithm for GIS Based Unsteady Network Model.

Algorithm 1. Algorithm steps for GIS based unsteady network model
Step 1: Establish the ventilation network graph, initialize the geospatial and attribute data for laneways and nodes.
Step 2: Generate the topological relation for the ventilation network graph and stored as point-line indexed structure and basic incidence matrix.
Step 3: Sort the laneway branches according to wind drag, and generate the minimum spanning tree based on Dijkstra shortest path algorithm.
Step 4: Search the cotree branches, generate the independent loop and loop matrix.
Step 5: Main iteration based on Runge-Kutta algorithm; see equations (7)–(11).
Step 6: Save the results as time series air volume for each laneway branch based on point-line indexed structure.

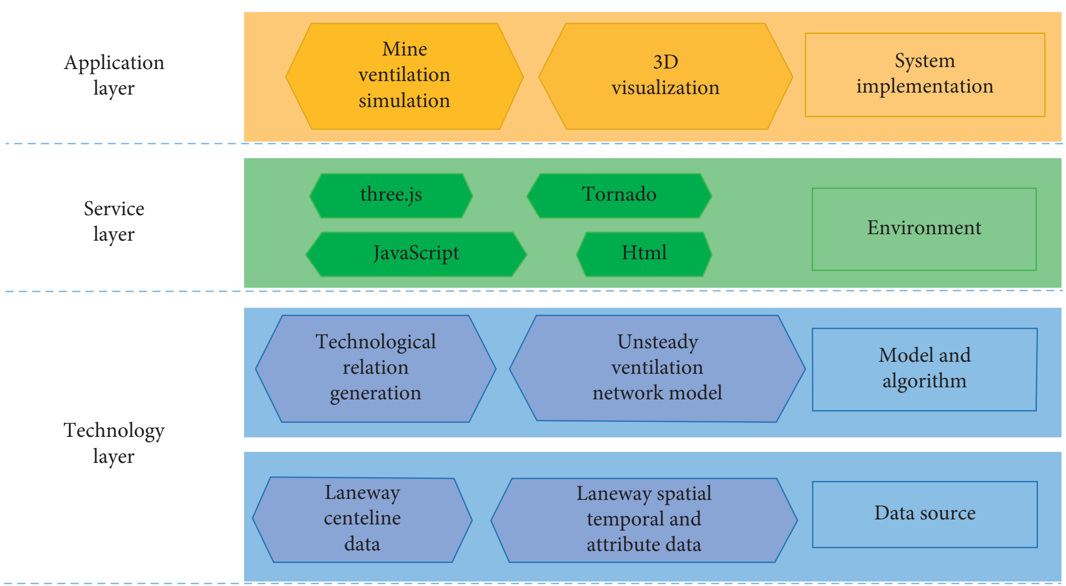


Figure 3: The architecture of 3D VentCloud system.

back-end of Python and C++ program to realize the data transmission. Three .js are adopted to implement the 3D visualization function.

(3) Application layer. This layer provides the unsteady ventilation simulation function, 3D visualization and spatiotemporal attribute query function of the laneway network, and simulation results. The system can read the original data of laneway centreline to store it and display the 3D laneway model and output the .stl file of the laneway geometric model. When the simulation function is implemented, each of the laneway branches can also be rendered with different colors based on different air volume, and the geospatial coordinates and attribute data of the laneway can be queried and displayed to show more geographical laneway details.

4. Results and Discussion

4.1. GIS-Based Unsteady Ventilation Network Model Validation. In order to verify the GIS based nonsteady network model before field application, we acquired the data from reference [3]. The simplified mine ventilation network diagram and its minimum spanning tree are shown in Figure 4. The network diagram has 11 laneway branches including one virtual branch, and 8 nodes. Table 4 presents

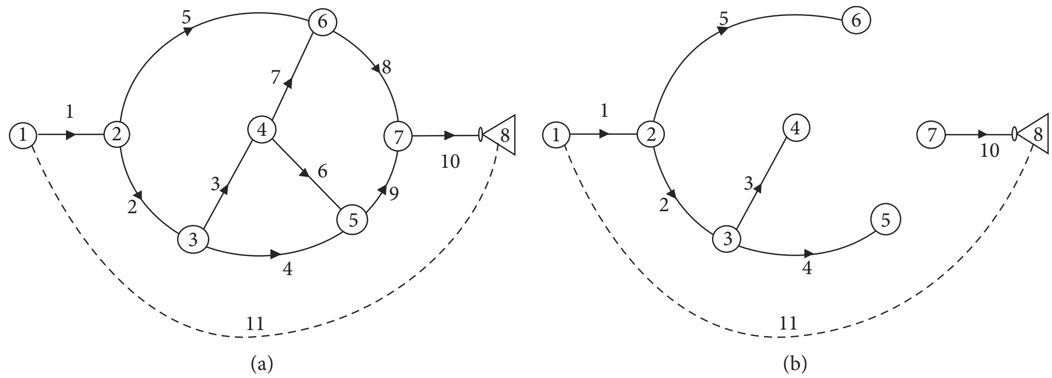


FIGURE 4: Mine ventilation network diagram (a) and its minimum spanning tree (b).

TABLE 4: Basic ventilation parameters for the network.

Laneway branch number	Start node number	End node number	Wind drag (kg·m^{-4})	Ventilating resistance (Pa)
1	1	2	0.020	105
2	2	3	0.001	0
3	3	4	0.010	0
4	3	5	0.050	0
5	2	6	0.069	0
6	4	5	0.010	0
7	4	6	0.020	40
8	6	7	0.0045	0
9	5	7	0.010	0
10	7	8	0.02	150
11	8	1	0	0

the basic ventilation parameters for the network. The case study investigated wind flow and pressure disturbance caused by the mine car movement in the transportation laneway, which belongs to the unsteady flow phenomenon.

In this case study, the mine car is moving windward inside the transportation laneway (with the branches numbers 2 and 3), which would lead to the increase of dynamic wind drag and the corresponding decrease of air volume in laneway branches 2 and 3. Based on the nonsteady network model, we simulated the variation regularity over time of air volume for each laneway, as can be seen in Figure 5. The positive value represents the reduced air, and the negative value stands for the increased value of air quantity. It is obvious that the transportation laneway with branches numbers 2 and 3 has the maximum air reduced quantity, while branch number 5 has the maximum air increased quantity, which is easy to understand because most of the airflow from the air intake laneway flows into the laneway (with branch number 5) that is connected with transportation laneway in node 2.

Besides, we also investigated the particular laneways and nodes to observe the changing regularity over time of air volume and pressure after mine car stops moving to windward. As presented in Figures 6 and 7, the laneway branches 2 and 5, nodes 3 and 5 are taken as examples to show the nonsteady characteristics of air volume and pressure change. It shows that, with the mine car moving to windward, air volume reduction in laneways 2 and 5 presents a significantly rising trend and falling trend, respectively, and then keeps a steady state. After the mine car stops moving to windward, air volume reduction in laneways 2 and 5 appears with an opposite tendency and finally reaches the initial steady state. The wind pressure variation has the similar regularity. The result is in accord with the published research in [3] and is consistent with the variation law of airflow and wind pressure in ventilation network model.

4.2. A Case Study Application for a Real Mine Ventilation Network. This study is also applied to Xinqiao coal mine (located in Henan province, China) to extend the practicality of the model and investigate the real mine ventilation to further promote the development of intelligent ventilation. Therefore, the real mine ventilation network data from Xinqiao coal mine is obtained, which contains 290 laneways and 222 nodes. The three-dimensional geometric model of Xinqiao laneway network is read and visualized by 3D VentCloud system, as presented in Figure 8.

The specific spatial data and attribute data include the ID and name of the laneway, the ID and coordinates of the start node and end node, the area and perimeter of laneway section, laneway length, laneway type, wind drag, ventilating resistance, and friction resistance. Here, some of the basic ventilation parameters are shown in Table 5.

The topological structure for ventilation network graph of Xinqiao coal mine is established based on GIS to simulate the ventilation state. At first, the shortest path algorithm is

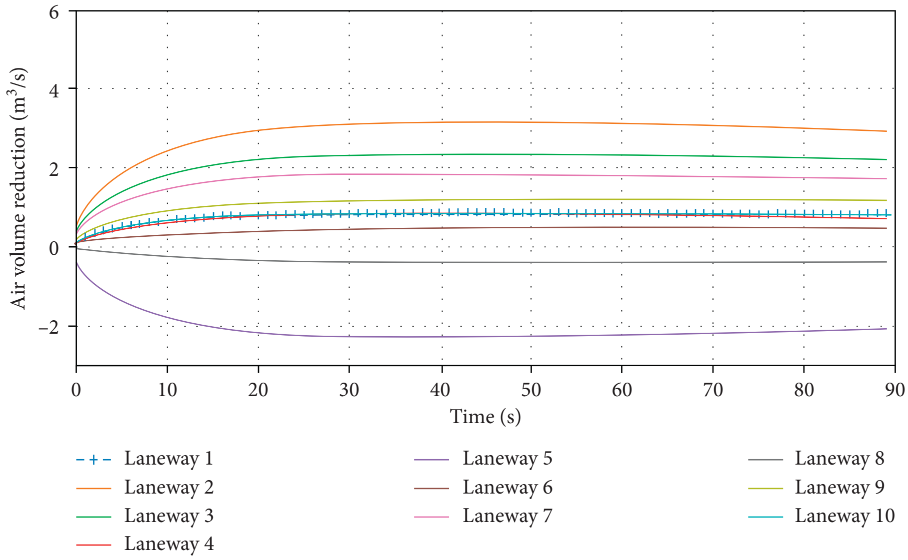
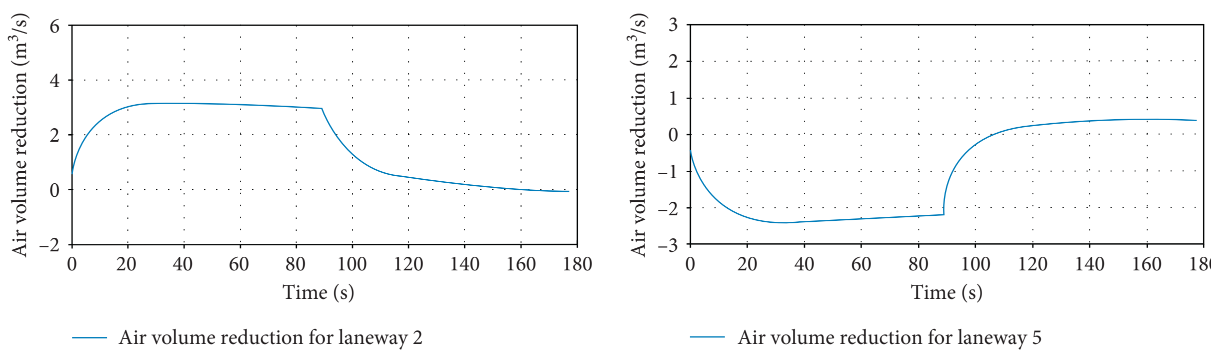
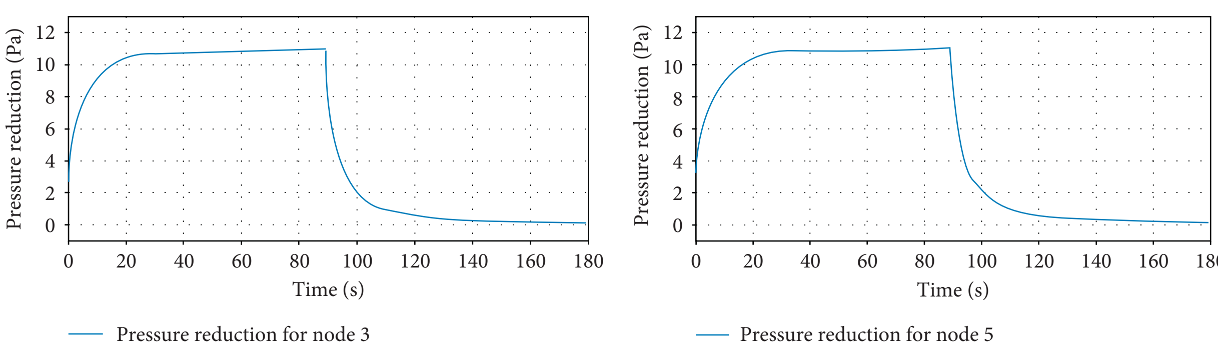


Figure 5: Air volume reduction for each laneway with mine car moving to windward.



(a) (b)

Figure 6: Air volume reduction for laneways 2 (a) and 5 (b) with mine car stops moving to windward.



(a) (b)

Figure 7: Wind pressure reduction for nodes 3 (a) and 5 (b) with mine car stops moving to windward.

applied to sort the laneway ventilating resistance, based on which 70 residual tree branches and the corresponding minimum spanning tree of the network graph are generated. By adding each of the residual tree branches to the minimum spanning tree, 70 independent circuits are created, respectively. Then, the GIS based nonsteady network model is applied to conduct the ventilation simulation. We obtained the air volume of each laneway branch changing with time. When the ventilation of Xinqiao coal mine reaches the steady state, the result is almost the same with the state based

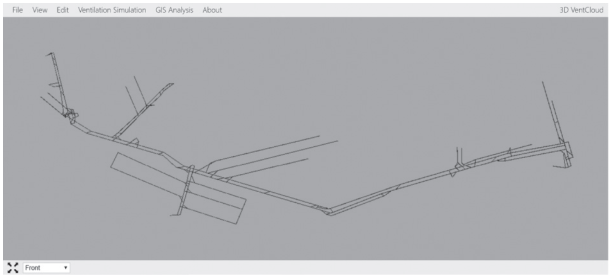


Figure 8: The 3D laneway network model of Xinqiao coal mine.

Table 5: Some of the ventilation attribute data for Xinqiao coal mine laneway.

Laneway ID	Start node ID	End node ID	Wind drag ($N\cdot s^2/m^8$)	Section area (m^2)	Section perimeter (m)	Laneway length (m)
1	1	2	122.336	18.14	15.78	32
2	3	4	114.535	18.67	15.46	40.10
3	5	6	145.384	18.28	15.23	3.30
4	7	8	0.00016	24.00	20.37	612
5	9	10	0.00043	14.06	15.89	584

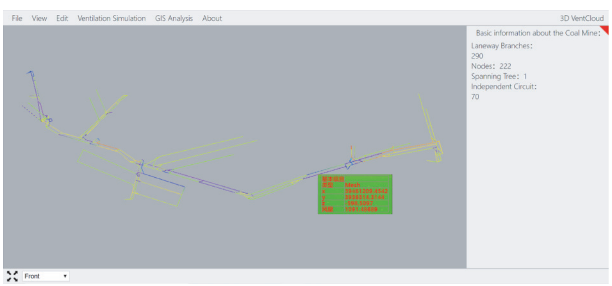


Figure 9: The 3D visualization of mine ventilation simulation result.

on the traditional steady ventilation network model. This study takes a few seconds at the web end to get the simulation result, it consumes 4.72 s in our latest experiment, which is expected to provide fast or real-time decision support for afterwards site applications.

The 3D geometric model of Xinqiao laneway network is rendered based on the simulation results and visualized on 3D VentCloud, as can be seen in Figure 9. The web system supports user interaction such as the geospatial query function. For example, the spatial and attribute features will be shown on web page by clicking on each laneway branch.

5. Conclusions

This paper investigated the unsteady mine ventilation simulation model based on GIS technology and developed a prototype web system to implement the online ventilation simulation, which can better adapt and promote the construction of intelligent mine ventilation.

Specifically, by integrating the GIS technology and unsteady ventilation simulation model, this study provides a unified GIS based ventilation network model, which can effectively simulate the dynamic changes of the unsteady ventilation state as well as the steady ventilation state. Besides, a prototype web system is developed based on the proposed algorithm, which can provide fast simulation result and location based information. The result is demonstrated to be effective in simulating the unified ventilation result, and the simulation system is expected to provide the online and real-time decision making support for coal mine safety production.

However, the ventilation system belongs to a complex and dynamic 3D system. Mine accidents are occasionally happened inside the laneway network. The future work should comprehensively consider the inner structure and 3D characteristics of the laneway network as well as the airflow, and the quantitative accuracy of the model is also worth study in the future.

Data Availability

The data used in this study are confidential. The readers can access the data by sending e-mail to the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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