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Mine Water Inrush Propagation and Escape Route Planning Based on DEM-VC and TDSP Combined Model

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Abstract: *Aiming at the problems of water inrush diffusion simulation and emergency escape decision-making of personnel in complex mine roadway networks, this paper proposes a combined framework of Discrete Event-Volume Conservation (DEM-VC) and Time-Dependent Shortest Path (TDSP). The DEM-VC model takes node volume conservation as the core constraint, uses the horizontal/downslope equal distribution rule to advance the water flow front, and realizes accurate and robust roadway filling judgment through net inflow integration. The TDSP model maps dry roads, shallow water and deep water into time-dependent edge weights, and introduces a reasonable waiting strategy to avoid deep water blockages and achieve the shortest safe escape time. The proposed method unifies water propagation simulation and escape path optimization into a single decision framework, which is the major innovation of this study. Compared with traditional path planning algorithms, it can dynamically adapt to the time-varying passability of roadways and greatly improve the safety and feasibility of escape routes. The global volume conservation mechanism effectively eliminates cumulative errors in long-term simulation and ensures the reliability of water distribution prediction. Experimental results on two sets of real mine network data show that the model can accurately identify main water channels and key blocking sections, support real-time release and dynamic adjustment of escape schemes, and has strong engineering practicability and robustness.*

Keywords: *Mine Water Inrush, Volume Conservation, Discrete Event Simulation, Time-dependent Shortest Path, Escape Route Planning*

1. Introduction

Mine water inrush is one of the most catastrophic disasters in underground coal mining, which frequently causes equipment damage, roadway blockage, and heavy casualties [1–3]. With the increase of mining depth and complexity of roadway networks, the water flow propagates rapidly along inclined tunnels and intersections, forming time-varying dangerous zones that significantly threaten the survival of miners [4–5]. Therefore, accurate simulation of water propagation and real-time generation of safe escape routes have become key technical issues for mine emergency management. However, traditional hydraulic models are computationally intensive and difficult to satisfy real-time requirements, while conventional path planning methods rarely consider the dynamic passability of roadways over time, leading to unreasonable or even unsafe evacuation routes.

In recent decades, extensive studies have been conducted on water inrush simulation and escape planning. Volume conservation and discrete event methods have been widely used to simulate flow propagation in mine networks [6–7]. Time-dependent shortest path (TDSP) algorithms have been gradually introduced into emergency evacuation to adapt to dynamic environments [8–9]. Meanwhile, many intelligent optimization methods, such as ant colony and particle swarm optimization, have been applied to improve path planning efficiency. Nevertheless, most existing studies separate water simulation and escape decision-making; few models achieve strict global volume conservation to reduce cumulative errors; and few frameworks support waiting strategies to avoid temporary deep-water blockages. These limitations restrict the accuracy, stability, and engineering practicability of current methods.

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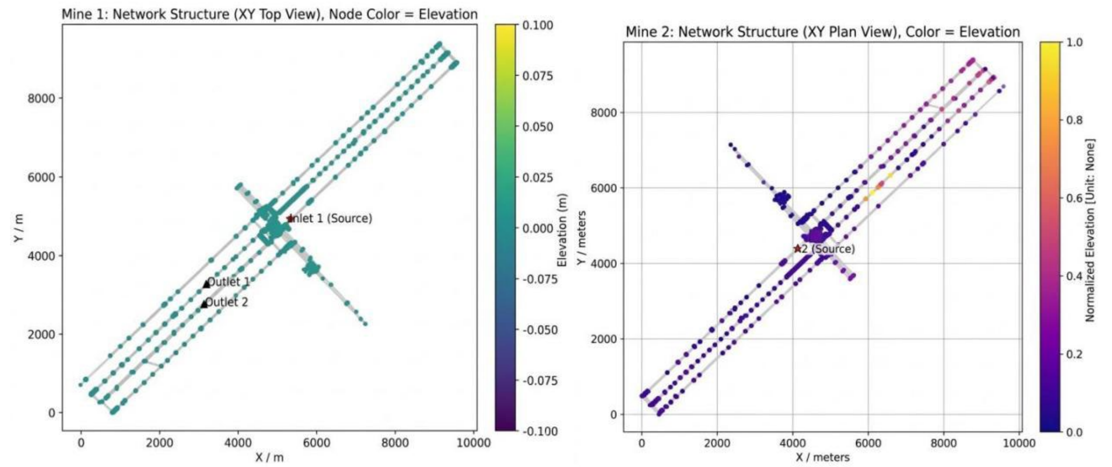
To overcome the above shortcomings, this paper proposes a unified framework combining Discrete Event-Volume Conservation (DEM-VC) and Time-Dependent Shortest Path (TDSP). The main contributions are threefold. First, a DEM-VC model is established with global volume conservation and horizontal/downslope equal distribution, which improves the accuracy and stability of water arrival and filling time prediction. Second, a time-dependent path-planning model is constructed with dry/shallow/deep water speed mapping and waiting strategies, which generates safer and more efficient escape routes. Third, the two modules are integrated into a real-time decision system that can identify main flow channels and key blocking sections, and dynamically adjust escape plans under single-source and dual-source water inrush scenarios. Experimental results on two real mine networks verify the effectiveness and engineering value of the proposed method.

2. Methodology

2.1. Data preprocessing

This study utilizes two sets of mine roadway networks[10]. Mine 1 comprises 663 endpoints and 977 roadways, with coordinates ranging approximately from 0-9589m and 0-9399m respectively, and a near-constant elevation (10m), serving for single-source validation and algorithm testing. Figure1 (a) illustrates the planar structure and elevation distribution of Mine 1, marked with water inrush point A1 and two exits (Exit 1/2). Mine 2 similarly contains 663 endpoints and 977 roadways, maintaining the same coordinate ranges as Mine 1 but exhibiting more pronounced elevation fluctuations between 0.00–71.53m, used for comparative validation. Figure1(b) presents the network topology and elevation distribution of Mine 2.



(a) Mine 1 *(b) Mine 2*

Figure 1. Mine roadway network and elevation

Data preprocessing: The water inrush points A1 and B1 are added as endpoints to the mine 1 roadway network. As more endpoints are added, the roadway codes are updated accordingly. Four additional roadway code sets are introduced as follows in Table 1:

Table 1. Four-group roadway coding

Roadway ID	Roadway Node 1	Roadway Node 2
H0978	S_A1	P0358
H0980	S_B1	P0520
H0977	P0351	S_A1
H0979	P0518	S_B1

The water inrush points A2 and B2 are added as endpoints to the roadway network of Mine 2. The endpoint and roadway codes in Attachment 2 are updated using the aforementioned method.

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2.2. Model 1: water inrush propagation

2.2.1. Model formulation

Mine roadway networks typically consist of numerous intersecting horizontal, inclined, and vertical segments. When a water inrush occurs, water spreads rapidly along low-potential directions, posing a severe threat to personnel safety. It is necessary to predict the arrival and evolution of water flow in roadways within the shortest time, i.e., to establish a flow propagation model for inrush water in roadways. Given the three-dimensional, complex, and bifurcated characteristics of roadway networks, an improved discrete event-volume conservation model is proposed based on the "front advance + node splitting + dead-end water storage" approach. Specifically:(i) The splitting rule is adjusted to allow equal distribution to all outgoing edges;(ii) After each event, the flow rates of all in-transit fronts are redistributed uniformly, and arrival times are recalculated to ensure volume conservation;(iii) The "full water" condition is extended to non-terminal roadways, using net inflow integration and slope wedge correction. With a rectangular roadway cross-section (4m × 3m) and a continuous inrush rate of 0.5 m^3/s, the front velocity is calculated using volume conservation, and arrival times and filling times are determined via piecewise constant integration.

(1) Velocity and Arrival Time

If the outflow rate of an edge is q_e, the front velocity is:

$$v_e = \frac{q_e}{A} \tag{1}$$

For an edge length L_e, the travel time is:

$$\Delta t_e = \frac{L_e}{v_e}, \quad t_{arr,e} = t_{start} + \Delta t_e. \tag{2}$$

(2) Volume Conservation

At any node v, the input flow Q_{in} satisfies:

$$Q_{in}(t) = \sum_{e \in Out(v)} q_e(t). \tag{3}$$

(3) Water Storage Judgment

In a roadway segment e, the accumulated water volume is:

$$V_e(t) = \int_{t_0}^{t} (Q_{in,e}(\tau) - Q_{out,e}(\tau)) d\tau. \tag{4}$$

2.2.2. Algorithm implementation

The algorithm steps are as follows:

Initial Inrush Injection: Construct the mine graph $G = (V, E)$. Set the origin s, fixed flow Q0, and effective front cross-sectional area A0=Bh. Write the event $(t_0 = 0, s, Q_0)$ into the priority queue PQ.

Pop Earliest Event: Extract the earliest event (t, u, Q_{in}) from PQ. If t>T(u), discard it (an earlier arrival already exists).

Flow Splitting (Horizontal/Downslope): Determine allowed outgoing edges $O(u) = \{e = (u \to w) | z(w) \leq z(u)\}$. If $|O(u)| = 0$, proceed to filling judgment; if $|O(u)| > 0$, equally distribute Q_{in} to each edge as initial flow.

Uniform Flow Redistribution and Arrival Time Recalculation: At the network level, take the current event time t as the division point. For all in-transit fronts and newly generated outgoing edges, solve the instantaneous flow $q_e(t)$ of each edge by combining node volume conservation and the "horizontal/downslope equal distribution" rule. Update the arrival time and the earliest arrival record of the target node via $v_e(t) = \frac{q_e(t)}{A_0}, \hat{t}_e = t + L(e)/v_e(t)$.

Filling Judgment (Net Inflow Integration): For dead-end/blocked segments e, perform piecewise

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constant integration on the net inflow Jk with event times as division points, accumulating the volume. When it first reaches $V_{fill}(e) = A_0L(e)$, record the full water time F(e), and make this state effective in the next round of "uniform redistribution".

Event Enqueue: Write the latest arrival events of all fronts $(\hat{t}_e, down(e), Q_{in})$ into the priority queue, return to step 2 until PQ is empty.

Termination and Output: Obtain the earliest arrival time $T(\cdot)$ of each node and the filling time $F(\cdot)$ of each roadway; mark unreachable nodes with "—". This process ensures global volume conservation after each event.

2.3. Model 2: Optimal Escape Path Based on Time-dependent Graph

2.3.1. Model Formulation

After a single-source water inrush, an effective escape plan must be formulated for each worker as soon as possible. Escape paths use time-dependent shortest paths and allow waiting strategies. The escape process follows the principle of proximity to exits: when only shallow water appears along the path after notification, the shortest-time path tends to converge to the nearest exit. It follows risk-avoiding detouring: if the main channel is about to exceed the 0.3 m threshold, the algorithm automatically switches to alternative roads to avoid deep water blockage. It follows strategic waiting: waiting for a very short time at individual nodes can significantly reduce the total time (avoiding imminent blockages). Three speeds (dry road, shallow water, deep water) are mapped to time-dependent edges, solved using a Dijkstra framework with time complexity $O(m + n \log_2 n)$.

(1) Edge Weight Construction

The speed on each edge in different time intervals is:

$$v_{edge}(t) = \begin{cases} 4, t < t_{arr} \\ 2, t_{arr} \le t < t_{0.3}, \text{flow with the current} \\ 1, t_{arr} \le t < t_{0.3}, \text{countercurrent flow} \\ \infty, t > t_{0.3} \end{cases} \tag{5}$$

where ∞ indicates impassable.

(2) Waiting Strategy

If at node v, an edge e is currently impassable but will become passable at a future time topen, waiting until topen is allowed to ensure reachability.

(3) Path Optimization: A time-dependent Dijkstra algorithm is used, with the update rule:

$$T(u) = \min_{e=(u,v)} \{T(u) + c_e(T(u))\}, \tag{6}$$

where $c_e(t)$ is the edge travel time when departing at time t.

(4) Escape Plan Under Single-source Inrush

Based on the mapping between time-dependent shortest paths and "passable time windows", the optimal paths of three miners all show the common characteristics of "proximity, avoiding deep water, and short stays when necessary":

Proximity to Exits Principle: When only shallow water appears along the path after notification, the shortest-time path tends to converge to the nearest exit.

Risk-avoiding Detouring: If the main channel is about to exceed the 0.3 m threshold, the algorithm automatically switches to alternative roads to avoid deep water blockage.

Strategic Waiting: Waiting for a very short time at individual nodes can significantly reduce the total time (avoiding imminent blockages).

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3. Results

3.1. Water inrush propagation

3.1.1. Node arrival time and roadway filling time

The single-source inrush results for Mine 1 and Mine 2 are summarized in Table 2 and Table 3, respectively, which present the top 10 node arrival times and roadway filling times.

Table 2. Single-source inrush results of mine 1

Panel a: Node Water Arrival Time		Panel b: Roadway Full Water Time	
Node ID	Arrival Time (min)	Roadway ID	Filling Time (min)
P0351	5.28	H0395	1028.93
P0358	5.28	H0396	1093.08
P0357	6.74	H0486	49793.02
P0349	6.91	H0603	374364.20
P0352	6.92	H0010	2619335.00
P0350	10.07	H0009	5048883.00
P0348	11.12	H0493	11478105.00
P0347	17.54	H0806	13246826.00
P0346	19.52	H0807	21889834.00
P0332	22.25	H0020	1.71e+8

Table 3. Single-source inrush results of mine 2

Panel a: Node Water Arrival Time		Panel b: Roadway Full Water Time	
Node ID	Arrival Time (min)	Roadway ID	Filling Time (min)
P0358	0.86	H0505	22952.52
P0357	1.59	H0495	23977.80
P0660	11.50	H0519	45197.41
P0659	12.22	H0000	—
P0661	15.19	H0001	—
P0662	15.34	H0002	—
P0427	21.26	H0003	—
P0425	22.76	H0004	—
P0422	196.30	H0005	—
P0423	200.53	H0006	—

From the results, the node arrival times of Mine 1 follow a long-tailed distribution: 5 nodes (0.8%) are reached within 1–10 minutes, 22 nodes (3.3%) within 10–100 minutes, and 275 nodes (41.5%) remain unreachable within the simulation time frame (≥10,000,000 minutes). In contrast, Mine 2 shows more localized water propagation due to its pronounced elevation fluctuations, with high-elevation roadways (e.g., H0000–H0006) remaining dry (marked as "—" in filling time). This indicates that the model can accurately capture the influence of topography on water spread.

3.1.2. Water propagation distribution

To visualize the temporal and spatial evolution of water flow, Figure 2 (Mine Water Flow Propagation Distribution Map (Log Scale)) is plotted based on the arrival time data of Mine 1.

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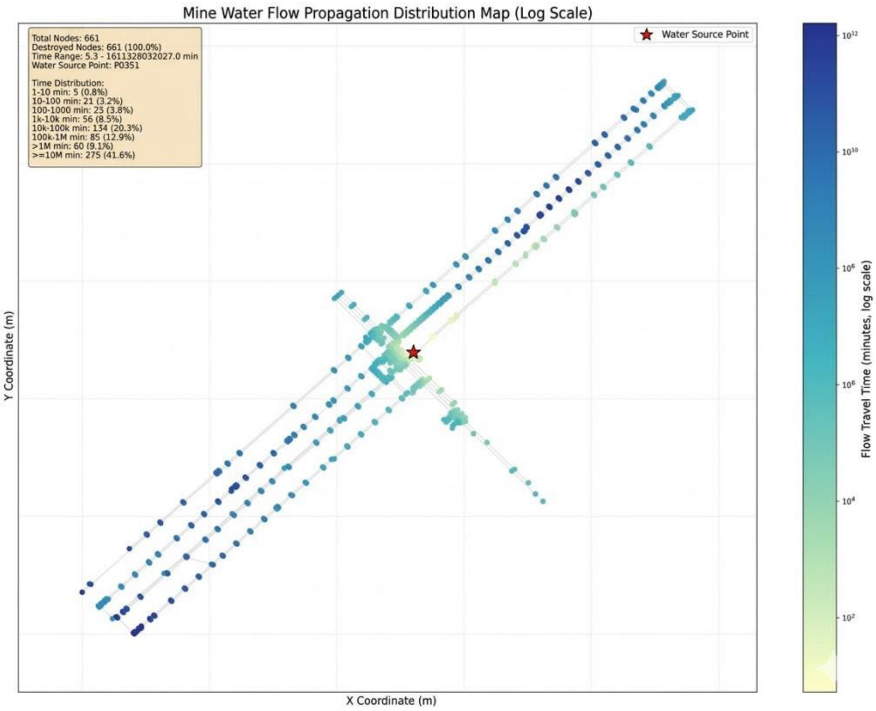

Figure 2. Mine Water Flow Propagation Distribution Map (Log Scale)

The figure uses a logarithmic color scale to represent the arrival time of water at each node, with light yellow indicating early arrival and dark blue indicating late arrival. It clearly shows that water spreads gradually from the inrush point along the roadway network, following the low-potential direction. The main propagation channels and key blocking sections are intuitively identified, which validates the accuracy of the discrete event-volume conservation model in simulating water inrush propagation.

3.2. Inrush escape path optimization

3.2.1. Escape path visualization

The optimal escape paths for three representative workers under single-source inrush are visualized in Figure 3 (Escape Paths of Workers Under Single-source Inrush) and Figure 4 (Comparison of Worker Escape Paths Under Single-source Inrush).

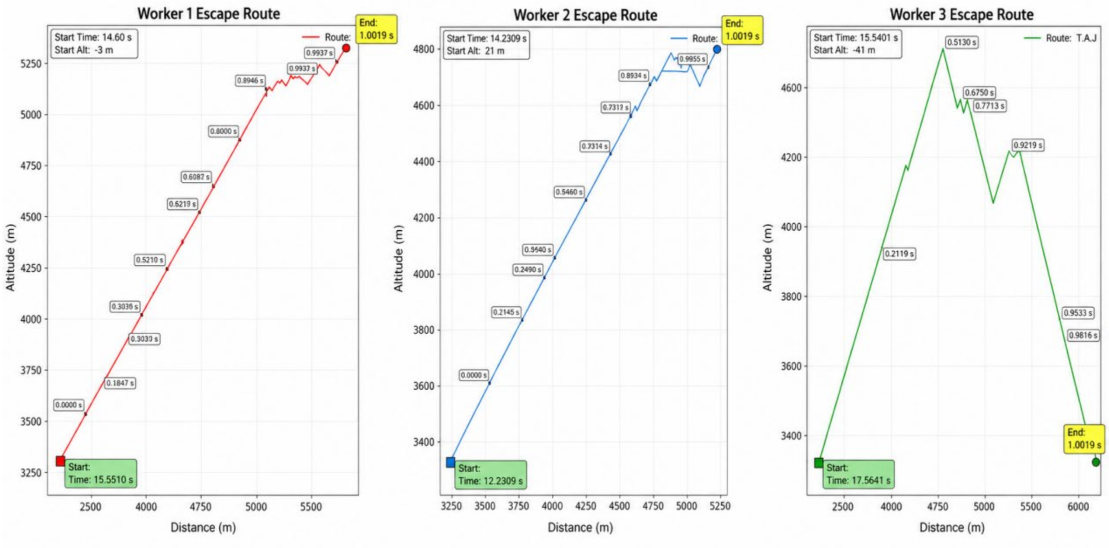

Figure 3. Escape Paths of Workers Under Single-source Inrush

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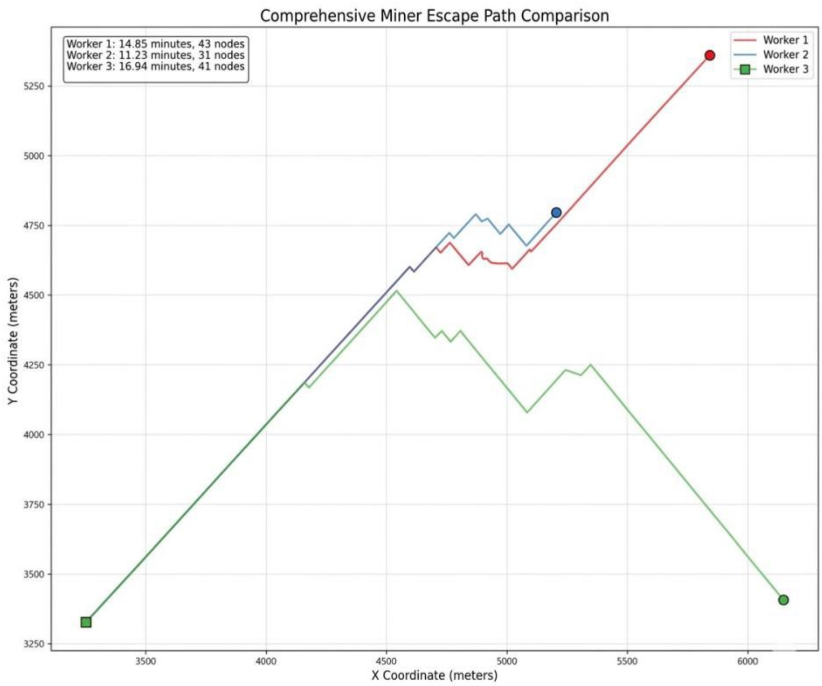

Figure 4. Comparison of Worker Escape Paths Under Single-source Inrush

Figure 3 presents the individual escape trajectories of each worker, with different colors representing different workers, and labels indicating the total escape time and number of nodes passed. Figure 4 overlays all three paths to facilitate direct comparison of their lengths and time costs.

3.2.2. Escape time and path characteristics

The statistical results of the escape paths are shown below in Table 4:

Table 4. Escape time statistics

Mine	Worker	Total Escape Time (min)	Number of Nodes Passed
1	1	14.85	43
1	2	11.23	31
1	3	16.94	41
2	1	12.26	30
2	2	17.97	40
2	3	15.58	33

All workers can escape within 20 minutes, which is far less than the minimum roadway filling time of 22952 minutes, ensuring that the escape process completely avoids submerged or be about to submerged roadways. The optimal paths exhibit three key characteristics:

Proximity to Exits: Paths tend to converge to the nearest exit when only shallow water is encountered.

Risk-avoiding Detouring: The algorithm automatically switches to alternative roads to avoid deep water blockages when the main channel is about to exceed the 0.3 m threshold.

Strategic Waiting: Short waiting times at individual nodes are used to avoid imminent blockages, significantly reducing the total escape time.

4. Conclusions

This study establishes a unified framework for mine water inrush propagation simulation and emergency escape path optimization, consisting of a discrete event-volume conservation model for inrush scenarios and a time-dependent shortest path model for escape planning. The volume conservation model accurately captures the spatio-temporal evolution of water flow in complex roadway networks, identifying main propagation channels and key blocking sections, while the time-dependent Dijkstra algorithm with waiting strategies generates safe and efficient escape routes that adhere to the principles of proximity, risk avoidance, and strategic waiting. Results from two real mine networks show that all workers can escape

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within 20 minutes, well before roadway filling, and the model effectively adapts to accelerated water propagation and path switching under dual-source inrush conditions, demonstrating high accuracy and robustness.

The proposed framework exhibits strong engineering practicability and real-time performance, compatible with existing mine roadway data and capable of supporting dynamic emergency decision-making. Future work will focus on integrating real-time monitoring data to enhance short-term prediction accuracy, extending the model to multi-objective group evacuation optimization, and developing 3D visualization platforms to improve situational awareness. Further validation through field tests and machine learning-based parameter optimization will also be conducted to advance its reliability in practical mine safety applications.

References

[1] Li Wei, Sun Liang, Wei Gang, et al. An intelligent HPSO-MLP model for predicting coal spontaneous combustion temperature and optimizing inhibitor to enhance mine safety[J]. Process Safety and Environmental Protection,2026,210:108679.
[2] Yu Shuai, Li Dong, Xie Xing, et al. Multi-Constraint and Shortest Path Optimization Method for Individual Urban Street Tree Segmentation from Point Clouds[J]. Forests,2025,17(1):27.
[3] Dong Xu, Li Song, Ma Rui, et al. Cloud-based slope risk monitoring and early warning system for open-pit coal mines: a case study of Zhonglian Runshi[J]. Scientific Reports,2025,15(1):44396.
[4] Aldhafferi N. Time and Memory Trade-Offs in Shortest-Path Algorithms Across Graph Topologies: A, Bellman–Ford, Dijkstra, AI-Augmented A* and a Neural Baseline[J]. Computers,2025,14(12):545.*
[5] Sekei S V, Wang Jun, Prosoer K K, et al. Human Factors in Mining Accidents: A Systematic Review of Behavioral Safety Interventions[J]. Open Journal of Social Sciences,2025,13(12):56-70.
[6] Liu Feng, Wang Peng, Bhattacharjya A, et al. A Novel Spherical Shortest Path Planning Method for UAVs[J]. Drones,2024,8(12):749.
[7] Zhang Yu, Hu Xiang, Li Hao, et al. A Fuzzy Variable H Strategy Based Ripple-Spreading Algorithm to Find the k Shortest Paths[J]. Mathematics,2024,12(23):3670.
[8] Elnaz A, Abbas S. Solution algorithms for shortest path network interdiction with symmetric and asymmetric information[J]. International Journal of Systems Science: Operations & Logistics, 2023, 10(1):1-12.
[9] Stefan K, Florian N. Efficient parameterized algorithms for computing all-pairs shortest paths[J]. Discrete Applied Mathematics,2023,341:102-119.
[10] John H. Monitoring edge-geodetic sets: Hardness and graph products[J]. Discrete Applied Mathematics, 2023,340:79-84.