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Safety Risk Immunization Strategies for Subway Shield Construction in Water-Rich Silty Fine Sand Layers: A Complex Network Approach

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Abstract: To mitigate safety risks in subway shield construction within water-rich silty fine sand layers, a risk immunization strategy based on complex network theory was proposed. Safety risk factors were systematically identified through literature review and expert consultation, and their relationships were modeled as a complex network. Unlike traditional single-index analyses, this study integrated degree centrality, betweenness centrality, eigenvector centrality, and clustering coefficient centrality to comprehensively evaluate the importance of risk factors. Results indicated that targeted immunization strategies significantly outperformed random immunization, with degree centrality (DC) and betweenness centrality (BC) immunization demonstrating the best performance. Key risk sources included stratum stability, allowable surface deformation, surface settlement monitoring, and shield tunneling control. Furthermore, the optimal two-factor coupling immunization strategy was found to be the combination of DC and BC strategies, which provided the most effective risk prevention. This study is the first to apply complex network immunization simulation to safety risk management in subway shield construction, enhancing the risk index system and validating the impact of different immunization strategies on overall safety. The findings offer scientific guidance for risk management in complex geological conditions and provide theoretical support and practical insights for improving construction safety.

Keywords: Water-rich silty fine sand layers; Subway shield construction; Safety risks; Complex network theory; Immunization strategies

1 Introduction

With its excellent adaptability and high efficiency, the shield method is widely used in the construction of metro tunnels, especially in the development of urban underground space. However, with the expansion of the urban metro network, the number of tunnel construction projects in special strata is increasing, and the possibility of tunnel construction under the special conditions of water-rich silty fine sand layers is also increasing. The geological characteristics of this kind of tunnel are complex, with fine particles and high water content, which increases the uncertainty and complexity of construction, and easily leads to high-risk events such as water gushing, stratum instability and collapse, which brings great challenges to shield construction. There have been many construction accidents in related projects. For example, in 2020, during the shield construction of Hangzhou Metro Line 7, due to the poor stability of water-rich fine sand strata, surface subsidence and collapse accidents occurred during the construction process. In February 2018, the right line construction site of a shield section of Foshan rail transit was flooded by water-rich silty sand and mud, which caused the collapse of the tunnel and road surface, killing 11 people and causing serious damage. At the same time, many scholars at home and abroad also pointed out that when the shield passes through the water-rich fine sand layer, it is prone to collapse, sand gushing water, etc, emphasizing that the shield construction of the water-rich fine sand layer is a universal high-risk and high-hazard situation. Therefore, it is of great significance to study deeply the safety risk of subway shield construction in water-rich fine sand layer.

2 Literature Review

2.1 Current Status of Research on Risk Identification of Shield Construction in Metro Tunnels

Risk identification is the basis of risk management. Scholars mainly identify the risk of subway tunnel shield construction through the combination of qualitative analysis and quantitative mode [1–4]. Common qualitative analysis methods include expert investigation method, case analysis method, fault tree analysis method, etc. Hyun et al. [5] investigated the potential risk of adverse events that may occur in shield tunnel boring machine (TBM) method in tunnel construction based on previous cases and expert investigations. The relevant risks are divided into four categories from adverse events: tool related failures, machine blockage or retention, slag problems hindering the transportation of excavated materials, and segment defects. During the construction of Guiyang rail transit line 3, Sun et al. [6] used expert survey method to conduct qualitative analysis on the risk of shield tunnel in Karst Area Based on WBS-RBS technology, and determined the weight of each risk factor. Liu et al. [7] used fuzzy mathematics and grey system theory to improve the uncertainty and fuzziness of risk factor identification in metro tunnel shield construction, considering the characteristics of large-scale construction, complex technology and special geological surrounding environment.

2.2 Current Status of Research on the Risk of Shield Construction in Metro Tunnels

In the research of subway tunnel shield construction risk, scholars mainly use a variety of models to quantitatively or qualitatively evaluate the construction risk level [8–10]. For example, Huang et al. [11] proposed a risk assessment method based on two-dimensional cloud model (TDCM), which quantifies the risk assessment criteria, improves the conversion relationship between risk level and quantitative domain, and accurately predicts the risk level of shield tunnel projects. Zhang et al. [12] expressed the evaluation information of experts with interval numbers, and calculated the risk level of each potential risk factor by using the operation rules and membership functions of interval numbers. Sousa et al. [13] predicted geological changes based on Bayesian network, combined with geological prediction model and construction management model of risk assessment, and then changed the construction strategy, systematically evaluated the decision-making theoretical support framework of shield construction risk and risk aversion. Lei et al. [14] studied the risk control technology of shield tunnel construction under the operation railway in sandy gravel stratum, and concluded that the main risk sources were sandy gravel layer, delayed grouting and wrong earth pressure setting in the cavity. Meng et al. [15] studied the control of cumulative risk in subsea tunnel shield construction, introduced the concepts of cumulative risk and vulnerability and system dynamics theory, established the risk transmission network, and analyzed the risk transmission mechanism based on vulnerability. Huang et al. [16] studied the risk of metro shield tunneling in coastal areas, and proposed a new safety evaluation method for metro shield tunneling by using entropy weight method and matter-element theory. Yao et al. [17] evaluated the construction risk of shield tunnel in large-size water rich pebble stratum, selected the compressive strength of pebble layer, the volume content of Boulder, and the permeability coefficient to establish the evaluation system, and established the risk assessment framework based on cloud model, analytic hierarchy process and entropy weight method. Although some scholars' research involves the risk of subway tunnel shield construction in special strata, there is a lack of systematic research on the risk factors of subway tunnel shield construction in specific strata, such as water rich silty fine sand layer [18–20].

2.3 Current Status of Numerical Simulation of Underground Shield Construction in Water-Rich Fine Sand Layer

In the field of subway shield construction in water rich silty fine sand layer, numerical simulation research mainly focuses on the ground deformation, freezing effect, construction safety control and other aspects during the construction process [21]. Li et al. [22] introduced the reinforcement effect of atomic force microscope in four aspects: subway connecting channel, shield inlet and outlet, interval tunnel and damage repair through engineering examples. The analysis found that the reinforcement effect of artificial freezing method in water rich weak stratum was very good. Jiang et al. [23] revealed the mechanism of sand blasting caused by the damage of tunnel working face in water rich sandy dolomite stratum, which is helpful for the safe construction of the tunnel, and proposed comprehensive control measures such as ultra detection risk identification, double-layer closed pipe shed, grouting plugging and dehydration technology. Wu et al. [24] analyzed the seismic response of shield tunnel in water rich sand layer under different compactness conditions through three-dimensional numerical simulation, and concluded that the compactness of the stratum has an important impact on the seismic performance of the tunnel, and the tunnel in sand layer with lower compactness is more prone to deformation. According to the actual engineering case, You et al. [25] analyzed the influence of the construction of the new double track tunnel on the seepage field and stress field of the shallow water rich sand layer, and proposed the foundation reinforcement measures to ensure the safety of shield construction through the numerical simulation results. Based on the case of a large-scale river crossing shield tunnel project in China, Liang et al. [26] analyzed the change of pore water pressure in water rich sand formation during shield tunneling. These studies provide scientific basis and technical support for shield construction under complex geological conditions by optimizing the construction scheme and technical control measures.

The complex network immunization theory can identify the safety risk factors that play a key role in the network. By simulating different immunization strategies (such as random immunization and targeted immunization), the safety risk factors that effectively reduce the overall risk can be determined [27]. This theory has been widely used in various fields of system research, and has become the frontier method of underground engineering safety risk research in recent years. The complex network theory is derived from graph theory, which can analyze network characteristics from multiple perspectives and facilitate the identification of safety risk factors in the construction process [28]. Therefore, based on the complex network immunization theory, this study obtains the optimal immunization strategy and key safety risk factors and two-factor combination through immunization strategy simulation, in order to provide reference for practical engineering.

3 Safety Risk Identification of Metro Tunnel Shield Construction in Water-Rich Silty Fine Sand Layers

3.1 Preliminary Identification of Safety Risk Factors

The search terms "shield construction in water-rich silty fine sand layers", "safety risk of shield construction in water-rich silty fine sand layers", "safety risk of shield construction in metro tunnel" were selected to search in CNKI, WOS, Wanfang and other databases. A total of 172 relevant literatures (including 129 journal papers and 43 dissertations) were obtained. Excluding those inconsistent with the theme, 44 articles with reference value were finally selected [29–31]. According to the standards of *Shield Tunnel Construction and Acceptance Specification*, *Metro Tunnel Shield Construction Technical Specification*, combined with the literature and 4MIE theory, the safety risk factors of metro shield construction in water-rich silty fine sand layers are divided into five categories: personnel, machinery, technology, stratum and management, and 29 second-level risk factors are preliminarily identified, as shown in Table 1.

Table 1. Safety risk indicator system

Safety Risk	Level 1 Security Risk Factors	Secondary Security Risk Factors
Safety Risks of Metro Shield Construction in Water-Rich Chalky Sand Layer	Personnel factors	Safety awareness, experience in similar projects, physical and mental health, personnel violations
	Mechanical equipment factors	Shield machine selection, cutter configuration, cutter wear, maximum cutter drive torque, main drive seal design pressure capacity
	Technical factor	Shield tunneling attitude control, slag improvement technology, shield tunneling control, synchronized grouting technology, grouting quality control, surface settlement monitoring
	Environmental factor	Allowable value of deformation of pipeline network along the line, hydrogeology along the line, distribution of pipeline network along the line, dynamic characteristics of groundwater, permeability of strata, water pressure of strata, deformation resistance of strata, stability of strata, allowable value of deformation of ground surface
	Management factors	Production safety system, special construction program evaluation system, construction quality inspection, safety training system, emergency plan system

3.2 Optimization of Safety Risk Index System

Through expert interviews, a total of 10 experts from geology, civil engineering, shield construction and risk management were invited to form a team. There are 3 professors, 2 associate professors, 3 senior engineers and 2 senior engineers in the field of subway tunnel construction, who have been engaged in the field of subway construction for at least 5 years. Based on professional knowledge and experience, the expert group divided the risk importance into five levels: very unimportant, unimportant, generally important, important and very important, and evaluated the risk factors. After discussion, the cutter head wear and rotation speed are considered in the cutter head configuration, and the cutter head wear is eliminated. The grouting quality control considers the grout ratio at the initial stage of synchronous grouting, and the synchronous grouting technology can more comprehensively reflect the grouting process. Hydrology along the line Geology is not enough to directly reflect the characteristics of water rich silty fine sand layer. Due to the poor stability of this layer, targeted indicators such as formation stability, formation permeability, formation water pressure, and formation deformation resistance should be selected. The situation of the pipeline network along the line should be changed to the allowable value of the deformation of the pipeline network along the line, so as to more accurately express the safety risk. According to experts' opinions, changing "environmental factor" to "formation factor" can more accurately reflect the characteristics of water rich silty fine sand layer. After eliminating 5 unsuitable factors, 24 safety risk factors for shield construction of metro tunnel in water rich silty fine sand layer were finally determined, as shown in Figure 1.

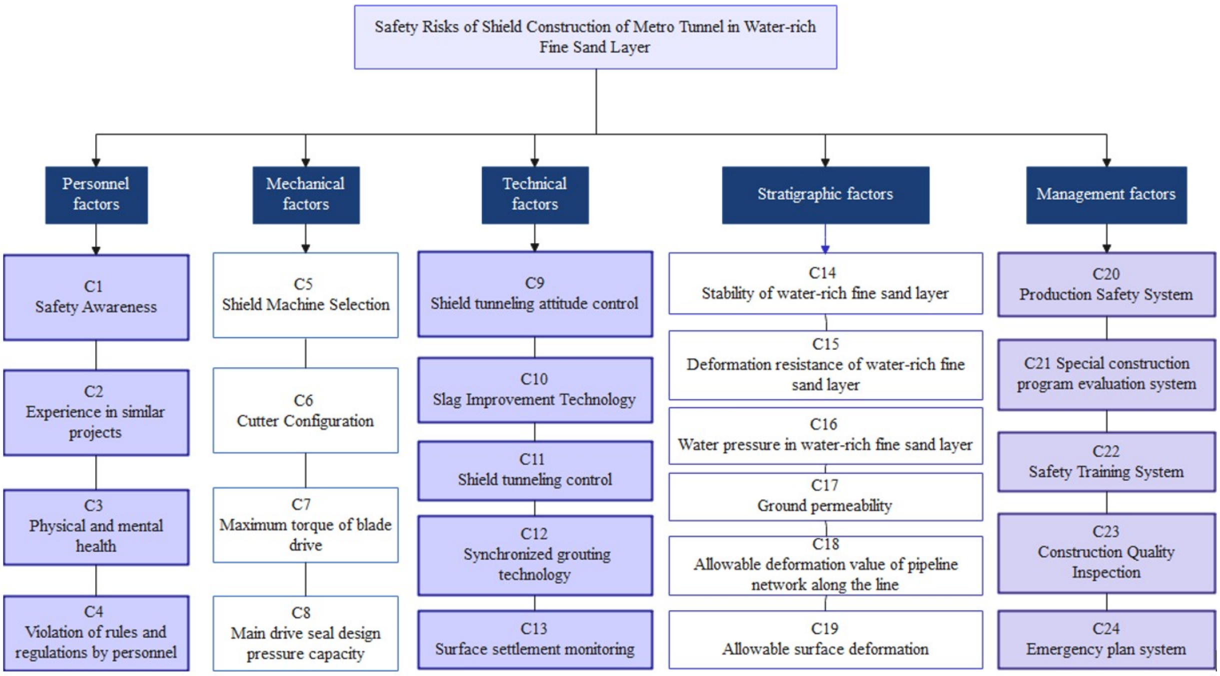

Figure 1. Risk factors of shield tunneling construction in subway tunnels with rich water and fine sand layers

4 Construction and Analysis of Complex Network of Metro Tunnel Shield Construction Safety Risk of in Water-Rich Silty Fine Sand Layers

4.1 Construction of Complex Network of Metro Tunnel Shield Construction Safety Risk in Water-Rich Silty Fine Sand Layers

A questionnaire survey was conducted among 10 experts to assess the degree of mutual influence between safety risk factors in shield tunneling construction in water-rich fine sand layers. The influence scores ranged from 0 to 5, where 0 indicates no influence, 1 indicates a mild influence, 2 indicates a moderate influence, 3 indicates a strong influence, 4 indicates a very strong influence, and 5 indicates an extremely strong influence. Experts scored anonymously based on their experience and project knowledge. The scores were averaged across all experts, and the results were statistically analyzed and fed back to the experts over multiple rounds of surveys. This iterative process allowed the experts to re-evaluate their opinions, gradually converging towards a unified prediction or recommendation. Ultimately, an expert scoring matrix was obtained.

The results indicated that the safety risk factors do not exist independently and that the relationships between them are complex, making them suitable for analysis using complex network theory. The expert scores were concentrated around 2.5 [32, 33]. Sensitivity analysis validated that this threshold effectively distinguished between high-risk and low-risk events, thus justifying the use of 2.5 as a reasonable threshold. Scores greater than 2.5 were recorded as 1, while those less than or equal to 2.5 were recorded as 0. Based on the frequency of 0 or 1, the expert consensus score was determined to be 0. In cases of ambiguity, the high-frequency score was recorded, resulting in a 0-1 matrix that formed the basis for constructing the safety risk network. Arrows from node C_i to node C_j indicate that the occurrence of C_i directly affects C_j. Ultimately, this process generated a safety risk network consisting of 24 nodes and 278 unweighted directed edges, as shown in Figure 2.

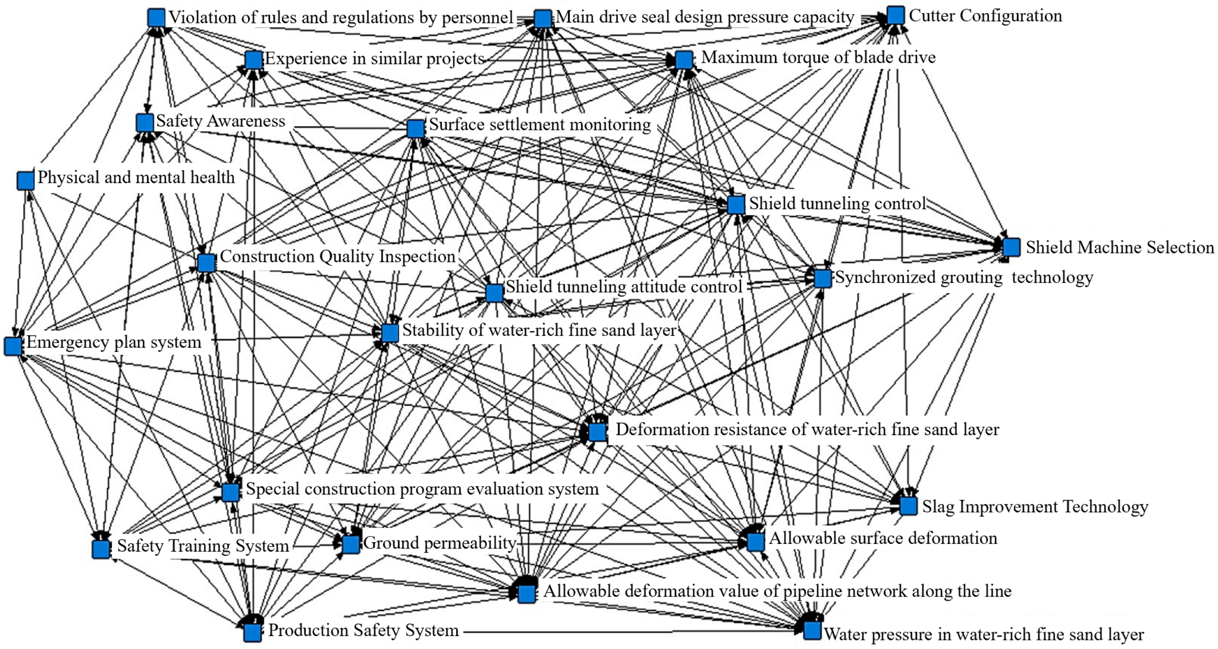

Figure 2. Safety risk network diagram of shield tunneling construction in subway tunnels with rich water and fine sand layers

4.2 Node Importance Analysis

Four indexes of degree centrality, betweenness centrality, clusterig coefficient and eigenvector centrality of nodes are used to quantify the importance of nodes in the construction safety risk influence network.

4.2.1 Degree centrality

The index to measure the node's own connectivity. The higher the value, the more important the node is, which is numerically equal to the sum of the number of edges directly connected to the node (including out-degree and in-degree). The formula is as follows Eq. (1), and the results are shown in Figure 3.

$$C_i = C_i^{\text{in}} + C_i^{\text{out}} \tag{1}$$

In the formula, C_i represents the degree centrality of node i, C_i^{in} and C_i^{out} represent in-degree and out-degree respectively.

From Figure 3, it can be seen that the out-degree of C_{14} the stability of water-rich silty fine sand layers, C_{13} surface subsidence monitoring, C_9 shield tunneling attitude control, C_{11} shield tunneling control, and C_6 cutter head configuration are large, indicating that these risk factors have a significant impact on other factors. The in-degree of C_{15} the anti-deformation ability of water-rich silty fine sand layers, C_{13} surface subsidence monitoring, C_{14} the stability of water-rich silty fine sand layers, C_{16} the water pressure of water-rich silty fine sand layers and C_1 the awareness of safety production are large, indicating that these factors are susceptible to other factors. The safety risk factors with large degree centrality are: C_{14}, C_{13}, C_{19} surface deformation allowable value, C_5 shield machine selection. These factors occupy the core position in the safety risk influence network and have strong influence.

4.2.2 Betweenness centrality

Betweenness centrality measures the importance of nodes in propagation risk or influence. The information transmission between nodes is mainly through the shortest path. There are differences in the shortest paths that each node passes through, resulting in different influences. This difference is represented by the betweenness. The calculation formula is shown in Eq. (2), and the calculation results are shown in Figure 4.

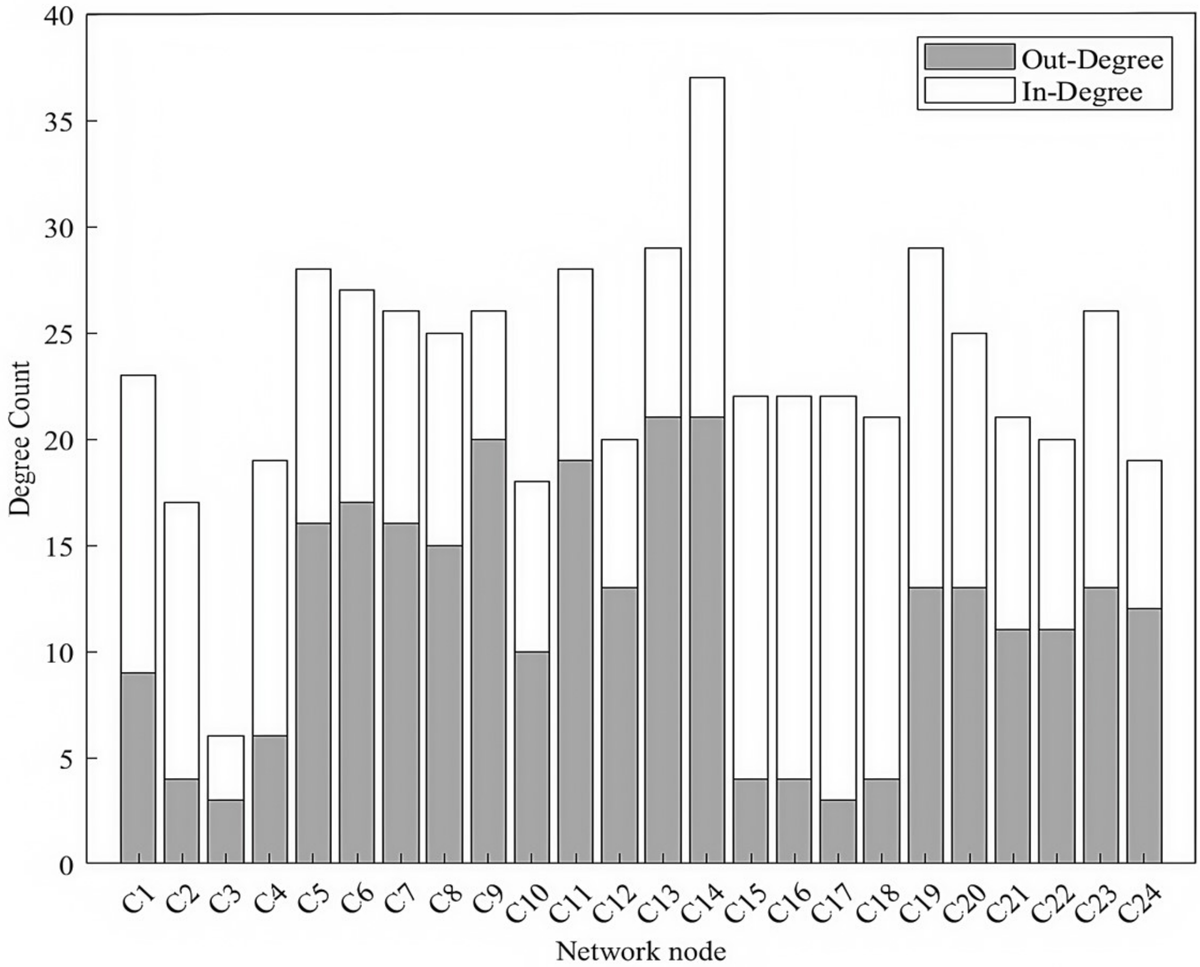

Figure 3. Node centrality

In the formula, B_i represents the betweenness centrality of node i, σ_{st} refers to the number of shortest paths between node s and node t, $\sigma_{st}(\mathrm{i})$ refers to the number of shortest paths between node s and node t passing through node i.

$$B_i = \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}} \tag{2}$$

It can be seen from Figure 4 that the betweenness centrality of C_{14} water-rich silty fine sand layers stability, C_{19} surface deformation allowable value, C_{20} safety production system, C_{13} surface subsidence monitoring and C_{11} shield tunneling control is the largest, which has a strong effect on risk diffusion control.

4.2.3 Clustering coefficient

The clustering coefficient measures the degree of local aggregation of network nodes. The larger the value, the more susceptible the nodes are to adjacent nodes, and the higher the correlation with adjacent nodes [34, 35]. Its value is equal to the ratio of the actual number of connected edges between adjacent nodes to the maximum number of connected edges. The formula is shown in Eq. (3), and the calculation result is shown in Figure 5.

$$C_{ci} = \frac{2e_i}{C_i\,(C_i - 1)} \tag{3}$$

In the formula, C_{ci} represents the clustering coefficient of node i. C_i is its degree centrality. e_i is the actual number of edges connected to each other between C_i adjacent nodes.

It can be seen from Figure 5 that the clustering coefficient values of C_3 physical and mental health status, C_{12} synchronous grouting technology, C_{10} muck improvement technology, C_2 similar engineering experience and C_{19} surface deformation allowable value are higher, indicating that these nodes are closely linked to adjacent nodes, with strong aggregation and easy to cause chain reaction.

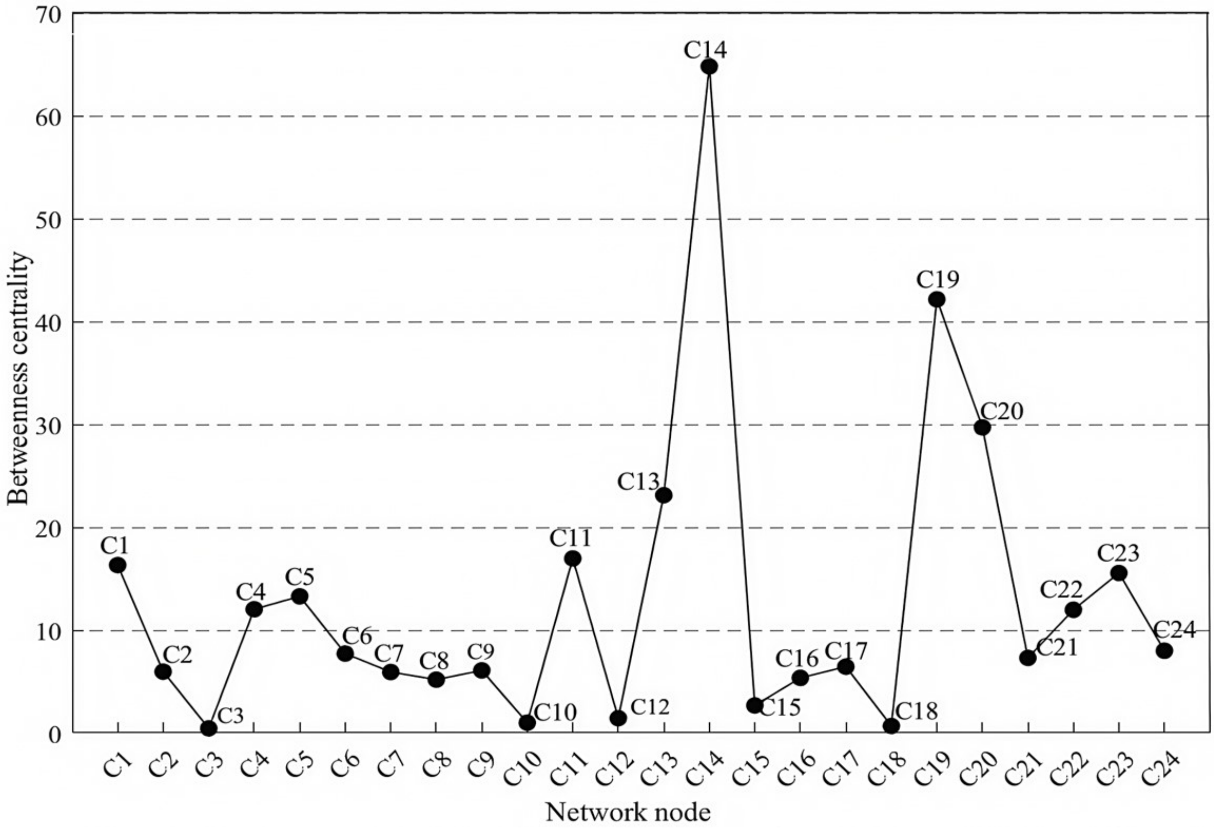

Figure 4. Node betweenness centrality

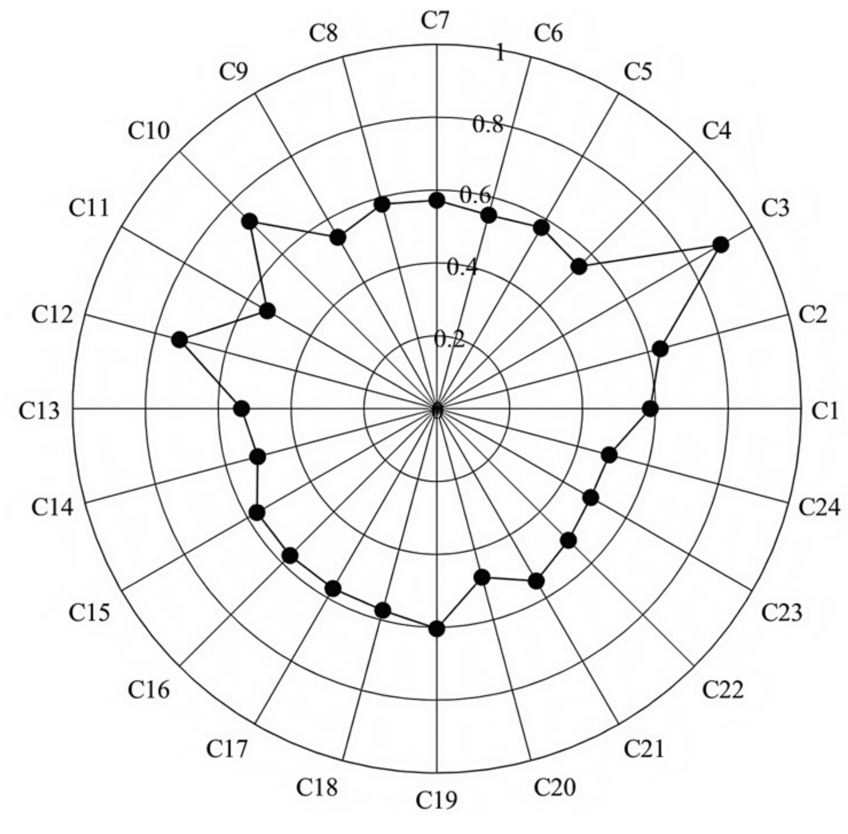

Figure 5. Node clustering coefficient

4.2.4 Eigenvector centrality

The eigenvector centrality measures the influence of the node. If the importance of the adjacent nodes of the node is high, the larger the eigenvector centrality of the node is, the higher the importance is [36, 37]. The calculation formula is shown in Eq. (4), and the results are shown in Figure 6.

$$E_{ci} = \lambda^{-1} \sum_{j=1}^{n} a_{ij} x_{ij} \tag{4}$$

In the formula, E_{ci} is used to represent the eigenvector centrality of the node. n is the total number of nodes in the network. Λ and x_{ij} are eigenvalues and eigenvectors respectively. A_{ij} is an element of the adjacency matrix.

It can be seen from Figure 6 that C_{14} the eigenvector centrality of water-rich silty fine sand layers stability, C_9 shield tunneling attitude control, C_{13} surface subsidence monitoring, C_{11} shield tunneling control and C_{15} waterrich silty fine sand layers anti-deformation ability is large. It shows that these factors are of high importance to adjacent nodes and need to be controlled.

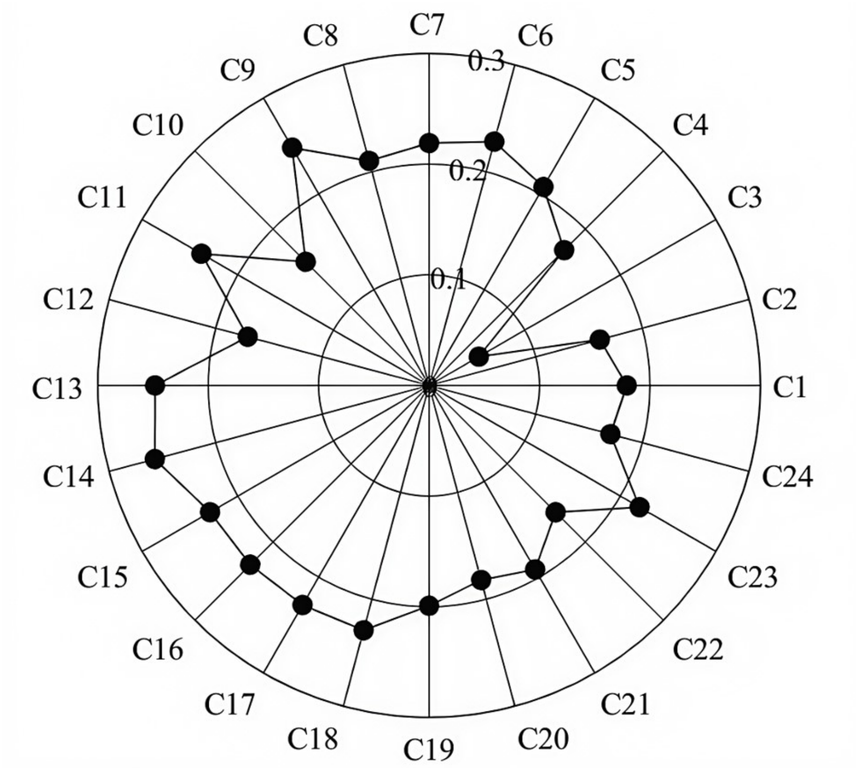

Figure 6. Node eigenvector centrality

5 Immunity Simulation of Safety Risks in Metro Shield Construction in Water-Rich Silty Fine Sand Layers

According to the theory of complex network, if the risk network of shield construction of subway tunnel in water-rich fine sand layer has a smaller average path length and a larger clustering coefficient, it has a small world effect. Matlab software is used to generate a random network with the same number of nodes and average degree value with the risk network of shield construction of subway tunnel in water-rich fine sand layer, and the comparison results are shown in Table 2, the average path length of the former is 1, and the average clustering coefficient is 0.6109, while the average path length of the random network is 1.637, and the clustering coefficient is 0.176. The small-world characteristics cause it to have strong diffusivity, and the risk can quickly spread and propagate in the subway construction system, which will bring great challenges to the safety management of shield con-struction in subway tunnels with water-rich fine sand layer if it is not well controlled.

The scale-free characteristic is judged by the cumulative degree distribution of the network nodes. Using MATLAB software to get the cumulative degree distribution of the network, the results approximately obey the power law distribution, a small number of nodes with large degree value, most smaller and preferentially connected to the nodes with large degree value, verifying the scale-free characteristics, indicating that there are a small number of risky nodes in the network whose degree value is much larger than that of the other nodes, and that these risks have a strong radiating ability, and once they appear, the impact and reach caused by them are much larger than that of other risk factors, and they need effective prevention and control strategies. Therefore, it is necessary to take effective preventive measures and control strategies for them.

Table 2. Comparison of risk network and random network parameters in shield tunneling of subway tunnels with rich water and fine sand layers

Network Type	Average Path Length	Average Clustering Coefficient
Risk network for shield construction of subway tunnels in water-rich fine sand layer	1.000	0.6109
Random network 1	1.637	0.176
Random network 2	4.285	0.083

5.1 Safety Risk Immunization Strategy

According to the complex network theory, if the safety risk network of metro tunnel shield construction in water-rich silty fine sand layers has a smaller average path length and a larger clustering coefficient, it has a small-world effect [38]. Using Matlab, a random network with the same number of nodes and average degree value as the safety risk network of metro tunnel shield construction in water-rich silty fine sand layers is generated. The average path length of the complex network is 1, and the average clustering coefficient is 0.6109. The average path length of the random network is 1.637, and the clustering coefficient is 0.176, which satisfies the small-world network. Through the cumulative degree distribution of network nodes to judge the scale-free characteristics, it is concluded that the cumulative degree distribution of the network approximately obeys the power-law distribution. A few nodes have larger degree values, most of them are smaller and have priority to connect the nodes with larger degree values, which verifies the scale-free characteristics [39]. Therefore, the complex network can be analyzed by immunization simulation.

In the actual metro tunnel shield construction in water-rich silty fine sand layers, risk immunization reduces or avoids these safety risks by controlling and optimizing the relevant construction process, which is reflected in the network that the risk node is removed from the network. Based on the risk immunization theory, the node immunization strategy is divided into targeted immunization and random immunization. The targeted immunization is to remove the nodes in turn according to the importance of the nodes in the safety risk network. According to the risk nodes of the central function ability, aggregation degree and hub ability , the degree centrality (DC), betweenness centrality (BC), clustering coefficient (CC) and eigenvector centrality (EC) are selected, and the nodes are removed in the order from large to small. The random immunization is carried out by using the RAND function in Excel, and the specific immunization order is shown in Table 3.

Table 3. Single-factor safety risk immunization strategy for shield construction in subway tunnels with water-rich fine sand layers

Immunization Strategy	Node Immunity Ordering
RI Randomized Immunization	$C_{15}, C_{11}, C_{20}, C_9, C_{21}, C_1, C_{22}, C_{18}, C_8, C_{13}, C_{14}, C_2, C_6, C_3, C_7, C_{16}, C_{10}, C_4, C_5, C_{24}, C_{17}, C_{12}, C_{23}, C_{19}$
TI Targeted Immunization	DC Immunization: $C_{14}, C_{13}, C_{19}, C_5, C_{11}, C_6, C_7, C_9, C_{23}, C_8, C_{20}, C_1, C_{15}, C_{16}, C_{17}, C_{18}, C_{21}, C_{12}, C_{22}, C_4, C_{24}, C_{10}, C_2, C_3$
	BC Immunization: $C_{14}, C_{19}, C_{20}, C_{13}, C_{11}, C_1, C_{23}, C_5, C_4, C_{22}, C_{24}, C_6, C_{21}, C_{17}, C_9, C_2, C_7, C_{16}, C_8, C_{15}, C_{12}, C_{10}, C_{18}, C_3$
	EC Immunization: $C_{14}, C_9, C_{13}, C_{11}, C_{15}, C_{16}, C_{17}, C_{18}, C_6, C_{23}, C_7, C_8, C_5, C_{19}, C_{21}, C_{20}, C_1, C_4, C_{12}, C_{24}, C_{22}, C_2, C_{10}, C_3$
	CC Immunization: $C_3, C_{12}, C_{10}, C_2, C_{19}, C_1, C_8, C_5, C_{18}, C_7, C_{15}, C_{16}, C_{17}, C_4, C_6, C_{21}, C_9, C_{11}, C_{13}, C_{22}, C_{14}, C_{24}, C_{23}, C_{20}$

5.2 Single-Factor Immunization Simulation Analysis

According to the degree centrality (DC), betweenness centrality (BC), clustering coefficient (CC) and eigenvector centrality (EC) ranking from high to low for immunization, the risk nodes are removed one by one, the network connectivity is changed, observing the changes of network efficiency. The lower the network efficiency after node failure, the weaker the risk correlation, the better the immunization effect. Effectively controlling the risk nodes in the immunization strategy can better manage the safety risks of metro tunnel shield construction in water-rich silty fine sand layers. With the help of Matlab software programming, the dynamic changes of network efficiency under different immunization strategies can be obtained, as shown in Figure 7.

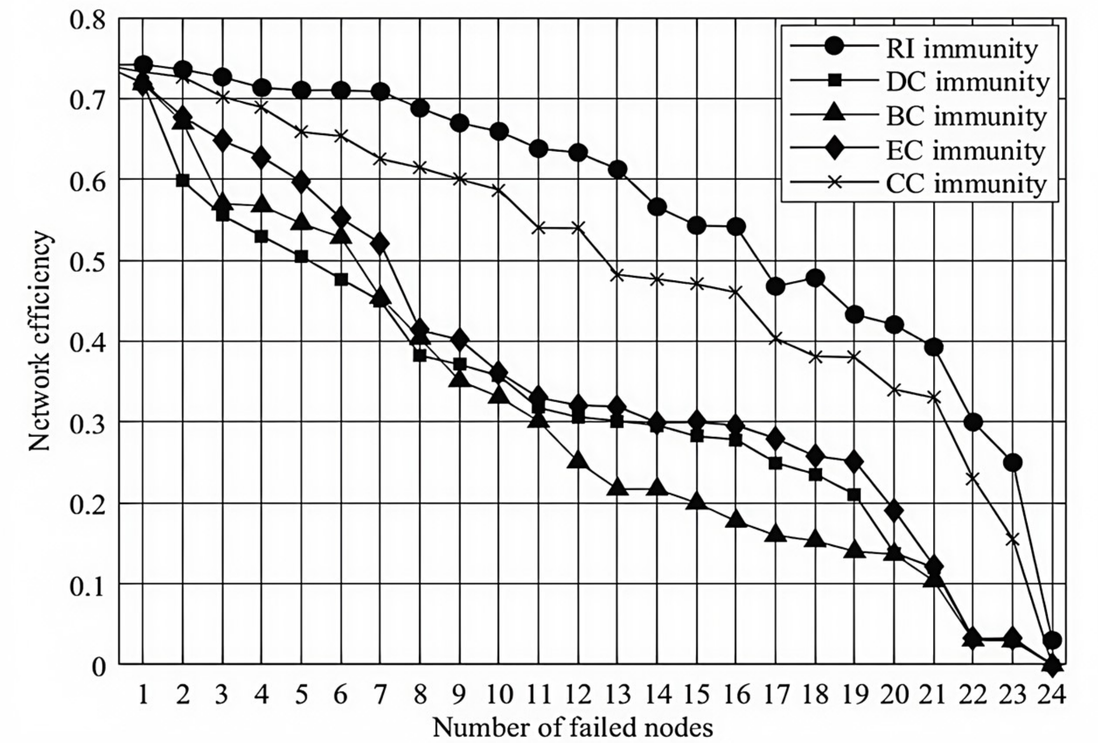

Figure 7. Dynamic changes in network efficiency under different immunization strategies

It can be seen from Figure 7 that the decline rate of network efficiency under random immunization is the slowest. The network efficiency value is generally high, the effect is obviously inferior to the target immunization. This is because the random immunization node is generated by the rand function in excel, and the immunization effect shows great randomness and fluctuation. Under the four targeted immunizations, the decline rate of network efficiency is higher than that random immunization. It indicates that the immunization effect is better than random immunization. Random immunization can not effectively control the safety risk of metro tunnel shield construction in water-rich silty fine sand layers. Targeted immunization can effectively reduce network efficiency and control the transmission and occurrence of safety risks.

The network efficiency under the four targeted immunization strategies shows a significant downward trend in Figure 7. In the early stage, the decline rate of DC immunization is the fastest, followed by BC immunization. DC immunization, BC immunization, and EC immunization have the same effect, and the efficiency of CC immunization decreased significantly slower. This is because the clustering coefficient mainly reflects the connection degree between the neighbors of nodes. It focuses on the existence of local triangles. Even if the node fails, the connection between its neighbors may remain unchanged. Especially in large-scale networks, local changes have little effect on the overall clustering coefficient. When multiple key nodes fail, the network may paralyze. After removing enough key nodes, the safety risk network of metro tunnel shield construction is no longer a connected network. Therefore, the network efficiency in the figure will infinitely approach zero with the removal of nodes until the network fails. Node failure actually means that the risk factor is eliminated. If the network efficiency is greatly reduced after removal, it means that the risk factor plays a key role in ensuring the safety of the whole construction system, and it is necessary to take priority to take measures to control these factors. In different stages, the immunization effects of DC, BC and CC are also different. For example, in the process of the first 9 nodes failure, the network efficiency of DC immunization decreases fastest and the value is the lowest, followed by BC immunization is better than EC immunization, the effect of CC immunization is worse. The effect of BC immunization in the middle and late stages is significantly better than that of DC and EC immunization. Therefore, DC immunization and BC immunization strategies should be preferred for safety risk control, focusing on controlling safety risk factors with large degree centrality and betweenness centrality, such as C_{14} the stability of water-rich silty fine sand layers, C_{13} surface subsidence monitoring, C_{19} surface deformation allowable value and C_{11} shield tunneling control.

In the shield construction of metro tunnel in water-rich silty fine sand layers, it is very important to strictly control the key risk factors to ensure the construction safety. During the construction process, the stability of the water-rich silty fine sand layers is strictly monitored, the surface settlement is monitored in real time, and a reasonable allowable value of surface deformation is set. At the same time, it is to ensure the formation stability to accurately control shield tunneling parameters, such as the advancing speed, the earth chamber pressure and the grouting amount, so as to effectively prevent the settlement and deformation, so as to fully guarantee the construction safety.

5.3 Two-Factor Immunization Simulation Analysis

Based on the above, it is concluded that DC immunization and BC immunization have the best effect. The occurrence of metro shield construction accidents in water-rich silty fine sand layers is usually not caused by a single factor, but often caused by multiple factors. Therefore, further exploring the combination of safety risk factors that are most prone to accidents can prevent the coupling of risk factors in construction. Three immunization strategies were adopted, and the two-factor combination was carried out on the basis of the single-factor immunization sequence. Pair wise combination according to the single factor sequence, 36 pairs of two-factor combinations were generated. DC immunization, BC immunization, and DC and BC double immunization strategies (here in after referred to as DB immunization) were performed to obtain a two-factor combination with high risk. The immune sequence is shown in Table 4.

Table 4. Two-factor safety risk immunization strategy for shield construction in subway tunnels with water-rich fine sand layers

Immunization Strategy	Node Immunity Ordering
DC Immunization	C_{14}-C_{13}, C_{19}-C_5, C_{11}-C_6, C_7-C_9, C_{23}-C_8, C_{20}-C_1, C_{15}-C_{16}, C_{17}-C_{18}, C_{21}-C_{12}, C_{22}-C_4, C_{24}-C_{10}, C_2-C_3
BC Immunization	C_{14}-C_{19}, C_{20}-C_{13}, C_{11}-C_1, C_{23}-C_5, C_4-C_{22}, C_{24}-C_6, C_{21}-C_{17}, C_9-C_2, C_7-C_{16}, C_8-C_{15}, C_{12}-C_{10}, C_{18}-C_3
DB Immunization	C_{14}-C_{19}, C_{13}-C_{20}, C_5-C_{11}, C_6-C_{23}, C_9-C_4, C_8-C_{24}, C_1-C_{21}, C_{15}-C_{17}, C_{22}-C_{15}, C_4-C_{12}, C_{24}-C_{10}, C_2-C_3

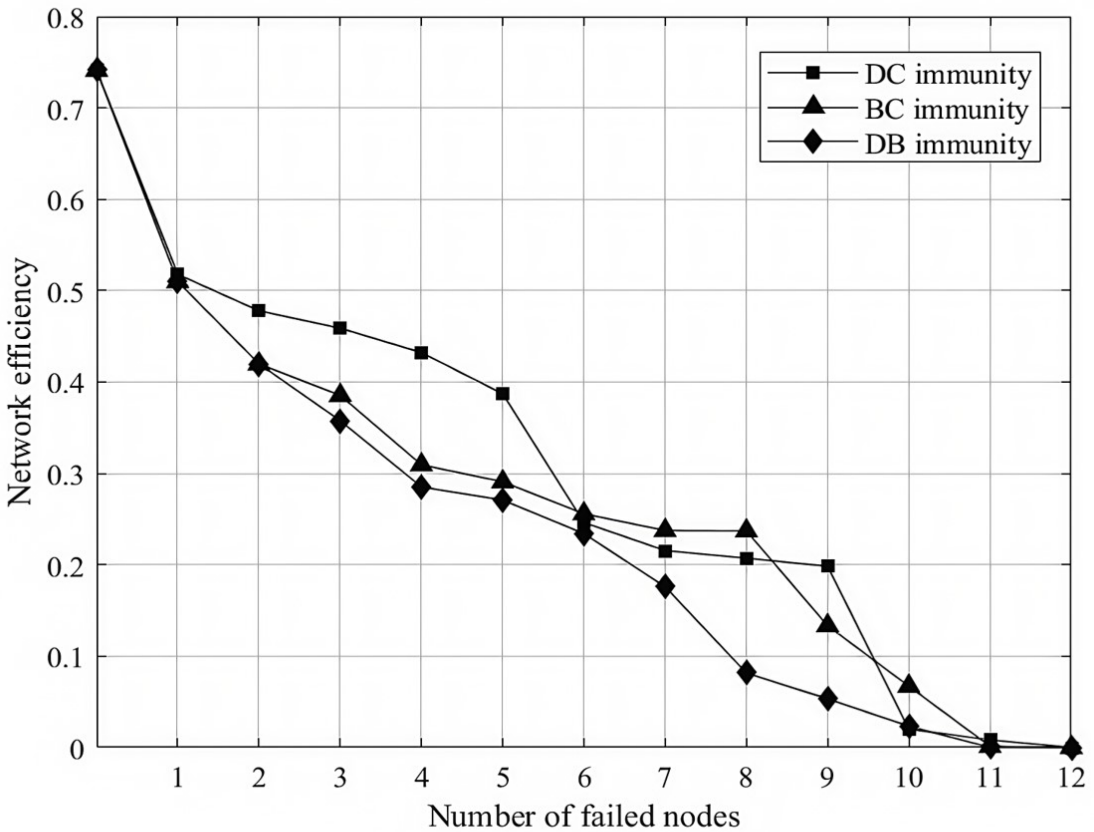

Figure 8. Dynamic changes in network efficiency under different immunization strategies

According to the above immunization sequence combination, the immunization simulation is carried out, and the network efficiency under the condition of double nodes failure is further calculated. It is obtained that the two-factor combination of the best immunization strategy and the highest risk. The trend chart is drawn, as shown in Figure 8.

It can be seen from Figure 8 that the initial decline rate of the three immunization strategies is the same. After the failure of the first group of key nodes, the network efficiency decreases the fastest, and then tends to decline. This is because the first group of nodes is the most critical node. After immunization, the key nodes of the entire network are removed resulting in a sharp decline in network efficiency. With the removal of the remaining safety risk combinations, the network efficiency gradually approaches zero. DB immunization has the fastest rate of network efficiency decline and the largest value , that is, the BC and DC combination immunization effect is the best. The network efficiency decreases significantly faster by comparing with the single-factor immunization, and the two-factor combined immunization effect is better than the single-factor immunization. High-risk two-factor combination C_{14} includes the stability of water-rich silty fine sand layers and C_{19} the allowable surface deformation value, C_{13} surface subsidence monitoring and C_{20} safety production system, C_5 shield machine selection and C_{11} shield tunneling control, C_6 cutter head configuration and C_{23} construction quality inspection. In the construction process, attention should be paid to cutting off the relationship between the key factors with high safety risks, which can more effectively ensure the construction safety.

According to the research results, spot managers can adopt the following strategies to carry out construction safety management and control to ensure the safety of shield construction of metro tunnel in water-rich silty fine sand layers.

(1) Before construction, geological characteristics are detected by geological radar, seismic wave and other technologies, and unstable areas are grouted to block pore water, set up a separation wall or reinforced by freezing method. Equipped with efficient residue improvement device to reduce the fluidity of fine sand; partition construction, dynamic adjustment of parameters (such as thrust and torque), real-time monitoring and early-warning and rapid response to surface deformation to ensure the stability of water-rich silty fine sand layers.

(2) Set up high-precision monitoring points, used to global navigation satellite system (GNSS), laser scanning and other technologies to monitor surface subsidence and deformation in real time. Different subsidence levels are divided and early warning values are set. When the monitoring value is close to or exceeds the allowable value, the emergency plan is immediately started, which adopt grouting reinforcement method or adjust driving speed reasonably. Building a data sharing platform to timely feedback real-time monitoring information to the safety production department. Developing a joint emergency plan and regularly organizing training and exercises to ensure that the surface subsidence monitoring results meet the requirements.

(3) According to the geological conditions, the buried depth of tunnel and the structure of the surrounding buildings, the allowable values of surface deformation (such as inclination, settlement and horizontal displacement) are formulated. According to the allowable value, the shield parameters (such as thrust, speed, grouting pressure) are adjusted to avoid over-excavation and under-excavation. Used to synchronous grouting and secondary grouting reduce formation loss and surface deformation. Before construction, pre-reinforcement measures are taken for important buildings to control the surface deformation within the allowable range.

(4) Scientifically selecting of shield machine and matching tunneling parameters according to the geological exploration and monitoring data strictly. The automatic control system is used to optimize the tunneling parameters and reduce the human operation error.To formulate rapid response measures (such as emergency grouting, suspension of excavation) for sudden situations such as permeable and sand gushing. Strengthen the coordination between operators and monitoring teams to ensure smooth information transmission, regularly train and drill operators to improve emergency response capabilities to reduce the risk of shield tunneling control.

6 Management Implications

(1) Optimization of construction schemes. Given the identified key risk factors, construction schemes should prioritize measures that enhance the stability of water-rich silty fine sand layers. Advanced ground treatment techniques such as grouting or freezing can be used to improve ground conditions before shield tunneling.

(2) Enhanced Monitoring and Early Warning Systems. Implement real-time monitoring of surface subsidence and deformation, with a focus on the identified critical values. Establish early warning thresholds to trigger immediate corrective actions if deviations exceed allowable limits. This proactive approach can prevent potential accidents and reduce construction risks.

(3) Targeted Risk Mitigation Strategies. Based on the immunization simulation results, prioritize risk mitigation efforts on the most critical factors and factor combinations. For instance, integrating DC and BC immunization strategies can effectively reduce the propagation of risks within the construction network.

(4) Dynamic risk assessment. Continuously update the risk assessment model during construction to reflect real-time changes in the construction environment. This dynamic approach ensures that emerging risks are promptly identified and managed.

(5) Collaborative Decision-Making. Form a technical expert group comprising design units, supervisory units, owners, and construction units to jointly review and approve critical construction plans. This collaborative effort can enhance the feasibility and safety of construction schemes.

7 Conclusion

Based on complex network theory and network immunization simulation, this paper deeply discusses the safety risk of metro tunnel shield construction in water-rich silty fine sand layers, identifies key risk factors and key two-factor risk combination. The main conclusions are as follows:

(1) Construction of safety risk factor index system: Using literature research and expert interviews, a safety risk factor index system for shield construction of metro tunnels in water-rich silty fine sand layers was constructed. This system includes five first-level indicators (personnel factors, mechanical factors, technical factors, stratum factors, and management factors) and 24 second-level safety risk factors.

(2) Immunization strategy evaluation: Through single-factor immunization simulation, the targeted immunization strategy showed significantly better results than the random immunization strategy among the five immunization strategies. Specifically, Degree Centrality (DC) and Betweenness Centrality (BC) immunization strategies were the most effective. The key safety risk factors identified include the stability of water-rich silty fine sand layers, surface subsidence monitoring, allowable surface deformation values, and shield tunneling control. Two-Factor immunization simulation: The combination of DC and BC immunization strategies demonstrated the best immunization effect. The two-factor combinations with the greatest risk include the stability of water-rich silty fine sand layers and allowable surface deformation values, surface subsidence monitoring, and the safety production system.

(3) Future research directions: This paper focused on single-factor and two-factor risk immunization simulations. Future research can explore three-factor and multi-factor immunization simulations to enhance the generalization ability of the method. Specifically, developing multi-factor coupled dynamic models and conducting empirical validation through real-world engineering cases are recommended. This can provide a more comprehensive understanding of risk interactions and improve the applicability of the method.

(4) Limitations and future validation plans: The current study primarily focuses on theoretical simulation, lacking empirical data from real-world engineering cases. Future work should address this limitation by conducting case studies to validate the proposed model. Additionally, the model's assumptions and simplifications should be critically discussed to highlight its applicability and potential areas of improvement. Further application and validation of the method will be explained in detail in the next article.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares no conflict of interest.

References

[1] E. Forcael, H. Morales, D. Agdas, C. Rodríguez, and C. León, "Risk identification in the Chilean tunneling industry," *Eng. Manag. J.*, vol. 30, no. 3, pp. 203–215, 2018. https://doi.org/10.1080/10429247.2018.1484266

[2] R. Kochen and J. C. O. Andrade, "Predicted behavior of a subway station in weathered rock," *Int. J. Rock Mech. Min.*, vol. 34, no. 3-4, pp. 160–e1, 1997. https://doi.org/10.1016/s1365-1609(97)00209-8

[3] D. Wu, Y. Zhang, R. Zhao, T. Deng, and Z. Zheng, "A coupled thermal-hydraulic-mechanical application for subway tunnel," *Comput. Geotech.*, vol. 84, pp. 174–182, 2017. https://doi.org/10.1016/j.compgeo.2016.12.006

[4] Z. Zhou, S. Liu, and H. Qi, "Mitigating subway construction collapse risk using Bayesian network modeling," *Automat. Constr.*, vol. 143, p. 104541, 2022. https://doi.org/10.1016/j.autcon.2022.104541

[5] K. C. Hyun, S. Min, H. Choi, J. Park, and I. M. Lee, "Risk analysis using fault-tree analysis (FTA) and analytic hierarchy process (AHP) applicable to shield TBM tunnels," *Tunn. Undergr. Sp. Tech.*, vol. 49, pp. 121–129, 2015. https://doi.org/10.1016/j.tust.2015.04.007

[6] H. Sun, Y. Rui, Y. Lu, Y. Dai, X. Wang, and X. Li, "Construction risk probability assessment of shield tunneling projects in karst areas based on improved two-dimensional cloud model," *Tunn. Undergr. Sp. Tech.*, vol. 154, p. 106086, 2024. https://doi.org/10.1016/j.tust.2024.106086

[7] H. M. Liu, L. Liu, and X. L. Ji, "Identification and analysis of Metro Foundation Construction Safety Risk based on fault tree analysis," *Chem. Eng. Trans.*, vol. 51, pp. 979–984, 2016. https://doi.org/10.3303/CET1651164

[8] A. Focaracci, G. Greco, and L. Martirano, "Smart tunnel and dynamic risk analysis," *Ieee T. Ind. Appl.*, vol. 56, no. 3, pp. 2338–2347, 2020. https://doi.org/10.1109/tia.2020.2974139

[9] R. Mikaeil, S. Shaffiee Haghshenas, and Z. Sedaghati, "Geotechnical risk evaluation of tunneling projects using optimization techniques (Case study: The second part of Emamzade Hashem tunnel)," *Nat. Hazards*, vol. 97, no. 3, pp. 1099–1113, 2019. https://doi.org/10.1007/s11069-019-03688-z
[10] P. Vidmar, "Risk evaluation in road tunnels based on CFD results," *Therm. Sci.*, vol. 26, no. 2B, pp. 1435–1450, 2022. https://doi.org/10.2298/tsci201108174v
[11] Z. Huang, W. Zhang, H. Sun, Q. Pan, J. Zhang, and Y. Li, "Risk uncertainty analysis in shield tunnel projects," *Tunn. Undergr. Sp. Tech.*, vol. 132, p. 104899, 2023. https://doi.org/10.1016/j.tust.2022.104899
[12] Y. Zhang, J. Zhang, H. Guo, Y. Zhou, G. Ma, and C. Wang, "A risk assessment method for metro shield tunnel construction based on interval number," *Geotech. Geol. Eng.*, vol. 38, pp. 4793–4809, 2020. https://doi.org/10.1007/s10706-020-01328-z
[13] R. L. Sousa and H. H. Einstein, "Risk analysis during tunnel construction using Bayesian Networks: Porto Metro case study," *Tunn. Undergr. Sp. Tech.*, vol. 27, no. 1, pp. 86–100, 2012. https://doi.org/10.1016/j.tust.2011.07.003
[14] M. Lei, D. Lin, Q. Huang, C. Shi, and L. Huang, "Research on the construction risk control technology of shield tunnel underneath an operational railway in sand pebble formation: A case study," *Eur. J. Environ. Civ. En.*, vol. 24, no. 10, pp. 1558–1572, 2020. https://doi.org/10.1080/19648189.2018.1475305
[15] K. Meng, M. Li, and J. Zhou, "Study on control of cumulative risk for submarine tunnel shield construction," *Adv. Civ. Eng.*, vol. 2023, no. 1, p. 8819066, 2023. https://doi.org/10.1155/2023/8819066
[16] W. Huang and B. Wu, "Risk assessment of shield tunnel construction in Coastal areas." *Pol. J. Environ. Stud.*, vol. 33, no. 3, 2024. https://doi.org/10.15244/pjoes/175264
[17] P. Yao, Z. Yu, Y. Lv, B. Shi, Y. He, H. Wang, D. Liu, and S. Wei, "Safety level assessment of shield tunneling in water rich sandy pebble strata with large particle size," *Sci. Rep. Uk*, vol. 13, no. 1, p. 3854, 2023. https://doi.org/10.1038/s41598-023-30718-5
[18] G. C. K. Balta, I. Dikmen, and M. T. Birgonul, "Bayesian network based decision support for predicting and mitigating delay risk in TBM tunnel projects," *Automat. Constr.*, vol. 129, p. 103819, 2021. https://doi.org/10.1016/j.autcon.2021.103819
[19] A. Sharafat, K. Latif, and J. Seo, "Risk analysis of TBM tunneling projects based on generic bow-tie risk analysis approach in difficult ground conditions," *Tunn. Undergr. Sp. Tech.*, vol. 111, p. 103860, 2021. https://doi.org/10.1016/j.tust.2021.103860
[20] N. Swannell, M. Palmer, G. Barla, and M. Barla, "Geotechnical risk management approach for TBM tunnelling in squeezing ground conditions," *Tunn. Undergr. Sp. Tech.*, vol. 57, pp. 201–210, 2016. https://doi.org/10.1016/j.tust.2016.01.013
[21] C. Li, W. Zhang, X. Wang, B. Pan, H. H. Zhu, and B. F. Spencer Jr, "Modeling dynamic responses of a cross-river road shield tunnel under stochastic vehicle loads," *Tunn. Undergr. Sp. Tech.*, vol. 102, p. 103432, 2020. https://doi.org/10.1016/j.tust.2020.103432
[22] J. Li, J. Li, Y. Cai, D. Wu, C. Guo, W. Zhao, K. Tang, and Y. Liu, "Application of artificial freezing method in deformation control of subway tunnel," *Adv. Mater. Sci. Eng.*, vol. 2022, no. 1, p. 3251318, 2022. https://doi.org/10.1155/2022/3251318
[23] Y. Jiang, P. Zhou, F. Zhou, J. Lin, J. Li, M. Lin, Q. Yongli, and Z. Wang, "Failure analysis and control measures for tunnel faces in water-rich sandy dolomite formations," *Eng. Fail. Anal.*, vol. 138, p. 106350, 2022. https://doi.org/10.1016/j.engfailanal.2022.106350
[24] H. Wu, Z. Ye, Y. Zhang, H. Liu, and H. Liu, "Seismic response of a shield tunnel crossing saturated sand deposits with different relative densities," *Soil Dyn. Earthq. Eng.*, vol. 166, p. 107790, 2023. https://doi.org/10.1016/j.soildyn.2023.107790
[25] Q. You, Z. Zhang, H. Wang, and M. Xu, "Risk identification of subway tunnel shield construction based on WBS-RBS method," *Int. J. Crit. Infrastruct.*, vol. 19, no. 3, pp. 261–273, 2023. https://doi.org/10.1504/IJCIS.2023.130915
[26] Y. Liang, Y. Xiao, and Y. Lin, "Pore water pressure responses in sand stratum during shield tunnelling: A case study," *Adv. Civ. Eng.*, vol. 2020, no. 1, p. 6139246, 2020. https://doi.org/10.1155/2020/6139246
[27] G. D. Smith and D. Spiegelhalter, "Shielding from covid-19 should be stratified by risk," *The BMJ*, vol. 369, 2020. https://doi.org/10.1136/bmj.m2063
[28] C. Li, Y. Wang, and Y. Zhang, "Study on safety risk evolution paths and prevention of drilling and blasting method in railway tunnel construction in mountainous areas," *J. Railw. Sci. Eng.*, vol. 21, no. 8, pp. 3358–3369, 2024. https://doi.org/10.19713/j.cnki.43-1423/u.T20231830
[29] H. Chung, J. Park, B. K. Kim, K. Kwon, I. M. Lee, and H. Choi, "A causal network-based risk matrix model applicable to shield TBMtunneling projects," *Sustainability*, vol. 13, no. 9, p. 4846, 2021. https://doi.org/10.3390/su13094846

[30] M. Guarascio, E. Alakbarli, C. Despabeladera, V. Cardinale, A. Ghasemichamazkoti, and N. Darabi, "Assessing risk acceptability and tolerability in Italian tunnels with the Quantum Gu@ larp Model," *Entropy*, vol. 26, no. 1, p. 40, 2023. https://doi.org/10.3390/e26010040

[31] M. Kang, K. Pham, K. Kwon, S. Yang, and H. Choi, "A hybrid numerical-ML model for predicting geological risks in tunneling with electrical methods," *KSCE J. Civ. Eng.*, vol. 28, no. 12, pp. 5972–5986, 2024. https://doi.org/10.1007/s12205-024-0066-z

[32] P. Bruttini, M. Gallo, P. Mariani, and T. Menini, "Management styles and innovation," *Manage. Decis.*, 2024. https://doi.org/10.1108/md-09-2023-1681

[33] K. Örsdemir, "Epistemological beliefs of NNEST's based on the NEST-NNEST dichotomy," *Eur. J. Educ.*, vol. 5, no. 2, pp. 100–117, 2022. https://doi.org/10.26417/ejed.v1i3.p73-83

[34] R. E. Kooij, N. H. Sørensen, and R. Bouffanais, "Tuning the clustering coefficient of generalized circulant networks," *Phys. A: Stat. Mech. Appl.*, vol. 578, p. 126088, 2021. https://doi.org/10.1016/j.physa.2021.126088

[35] N. Masuda, M. Sakaki, T. Ezaki, and T. Watanabe, "Clustering coefficients for correlation networks," *Front. Neuroinf.*, vol. 12, p. 7, 2018. https://doi.org/10.3389/fninf.2018.00007

[36] T. Agryzkov, L. Tortosa, J. Vicent, and R. Wilson, "A centrality measure for urban networks based on the eigenvector centrality concept," *Environ. Plan. B: Urban Anal. City Sci.*, vol. 46, no. 4, pp. 668–689, 2019. https://doi.org/10.1177/2399808317724444

[37] L. Baldesi, L. Maccari, and R. L. Cigno, "On the use of eigenvector centrality for cooperative streaming," *Commun. Lett.*, vol. 21, no. 9, pp. 1953–1956, 2017. https://doi.org/10.1109/lcomm.2017.2713361

[38] D. J. Watts and S. H. Strogatz, "Collective dynamics of 'small-world'networks," *Nature*, vol. 393, no. 6684, pp. 440–442, 1998. https://doi.org/10.1038/30918

[39] A. L. Barabási and R. Albert, "Emergence of scaling in random networks," *Science*, vol. 286, no. 5439, pp. 509–512, 1999. https://doi.org/10.1126/science.286.5439.509