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Embrittlement Mechanism Analysis of Shield Construction System for Parallel Gas Pipelines Based on Improved DEMATEL-ISM Method

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Abstract: To conduct a more accurate and effective embrittlement mechanism analysis of the shield construction system for parallel gas pipelines (SCSPGP), combined with previous accident investigation reports, system-level accidents and hazards were determined, unsafe control behaviors during shield preparation and shield tunneling were identified through building a control feedback model, and a list of embrittlement factors from the four dimensions of physics, psychology, human, and environment was constructed; Considering the uncertainty of human evaluation, the IPFS (Interval Pythagorean Fuzzy Set) was introduced to propose an improved DEMATEL-ISM (the Decision Making Trial and Evaluation Laboratory and the Interpretative Structural Model) method. The method was applied to Zhengzhou Rail Transit Line 12 to identify the key embrittlement factors of SCSPGP and to analyze their hierarchical correlations and influence pathways. The results indicate that the embrittlement factors exhibit a seven-layer and three-order structure, encompassing a total of 40 embrittlement paths, of which safety and technical communication, complex stratigraphy and groundwater emerge as the most fundamental embrittlement factors, while irregular operation and pipeline fatigue play critical roles in the embrittlement process.

Keywords: SCSPGP; Embrittlement factors identification; Embrittlement mechanism analysis; STPA; IPFS-DEMATEL-ISM.

1. Introduction

As tunnel construction progresses year by year, the shield tunneling construction network has become more and more advanced, and conflicts between newly constructed shield tunnels and existing structures have become increasingly apparent. Compared to general pipelines [1], gas pipelines have higher requirements for soil settlement control, greater burial depths, and smaller vertical distances between the pipeline and tunnel, making shield tunneling construction more likely to trigger safety incidents. For example, during the construction of Wuhan Metro Line 3 in 2015, a gas pipeline was cut by the cutterhead of the shield machine, leading to a gas leak and explosion, causing two fatalities. Due to wiring requirements, tunnel excavation is usually parallel to the direction of most pipelines [2]. The disturbance caused by shield construction on parallel gas pipelines is the result of the interaction between the pipeline, soil, and tunnel, with numerous influencing factors and a complex mechanism. Shield construction not only needs to ensure the safety of the tunnel structure itself but also maintain the normal operation of gas pipelines, making it a typical complex system involving human-machine-environment interaction and multi-type information fusion. The greater the system's vulnerability, the more severe the consequences of accidents [3]. Therefore, analyzing the embrittlement mechanism of the shield construction system for parallel gas pipelines (SCSPGP) is crucial for preventing field accidents and implementing safety management.

Vulnerability originated in natural disaster research and later extended to the field of safety science. Compared to risk research, vulnerability research focuses more on the flaws, weaknesses, and the ability of the supporting structure to handle risks, mainly focusing on the identification of embrittlement factors and vulnerability assessments. Scholars often explore embrittlement factor identification from perspectives like sensitivity-adaptability [4], exposure-sensitivity-adaptability [5], and pressure-state-response[6]. However, traditional safety analysis methods based on literature surveys [7], Delphi methods [8], and accident chains [9] have not adequately considered the nonlinear characteristics like coupling, inherent uncertainty, and volatility in complex systems. They also lack in-depth analysis of interactions between embrittlement factors. Moreover, embrittlement factor identification lacks theoretical support and scientific basis, failing to integrate various aspects like physics, psychology, and human factors. STPA (System theory process analysis) converts safety issues in complex systems into control problems by imposing constraints within the system to identify various causes leading to system vulnerability [10]. This method has gradually been applied in multiple fields. For instance, Jiang et al. [11] used STPA to identify risk factors in pipe bag cofferdam construction. Chen et al. [12] used STPA to analyze potential factors for ground subsidence induced by shield tunneling. In vulnerability assessment, scholars often use methods like AHP [13], catastrophe theory [4], cloud model [3], extension theory [14], and BP neural networks [15]. However, these methods mostly focus on quantifying the fragility of influencing factors, ignoring the correlations between embrittlement factors, and failing to effectively reveal the embrittlement mechanism. Currently, scholars generally use DEMATEL-ISM (the Decision Making Trial and Evaluation Laboratory and the Interpretative Structural Model) to address correlations between embrittlement factors. Pang et al. [16] used DEMATEL-ISM to analyze the internal hierarchical structure of vulnerability factors in forest fruit cold chain logistics. Zhang Y et al. [17] used DEMATEL-ISM to study the vulnerability index structure and logical relationships between indicators in offshore squid jigging fisheries. However, these studies rely on expert evaluations to determine factor relationships, leading to high uncertainty and unstable results.

In view of this, this study uses the STPA method to identify unsafe control behaviors in the parallel pipeline shield construction system. Based on causal analysis, the study adopts and extends system methodology (WSR) to determine embrittlement factors from four dimensions: physics, logic, human factors, and environment (WSRH). To overcome the subjectivity of human evaluation, the Interval Pythagorean Fuzzy Set (IPFS) is used to quantify expert semantic evaluations, and the DEMATEL method is applied to analyze the attributes, importance, and impact of the embrittlement factors. The ISM method is used to analyze the key embrittlement factors and their hierarchical logical relationships, further analyzing the embrittlement mechanism of SCSPGP. This provides a theoretical basis for scientific management and vulnerability prevention in relevant projects.

2. Embrittlement Factors Identification of SCSPGP

2.1. Determination of System-Level Accidents and Hazards

STPA is a risk analysis method based on the STAMP accident causation model. It starts from the system theory and control theory perspectives to identify and analyze potential safety issues in complex systems. This method takes into account the risks of interactions between components, component failures, and the failure of the system to adequately address external disturbances [18]. By using the STPA method, the identification of embrittlement factors in SCSPGP can be made more reasonable and scientifically valid. The specific steps are shown in Figure 1.

Figure 1. STPA Analysis Process

A system-level accident is an event that leads to unexpected loss in a system. Through the analysis of previous accident investigation reports, the system-level accidents were determined as follows: personnel injuries (A1), gas explosions (A2), and tunnel structure damage (A3). Personnel injuries refer to those caused by gas explosions or tunnel structure damage. Gas explosions are caused by gas leakage into the tunnel, which mixes with air and reaches the explosive limit, resulting in an explosion. Tunnel structure damage occurs due to operational errors, management defects, or factors such as gas explosions.

System-level hazards refer to the conditions or states that lead to system-level accidents. Based on the literature review, the primary system-level hazards include: surface subsidence (H1), pipeline deformation (H2), and design defects (H3), as shown in Table 1.

Table 1. System-Level Hazards

Numbering	System-Level Hazards	System-Level Accidents
H1	Surface subsidence [19]	A1、A2、A3
H2	Pipeline deformation [20]	A1、A2、A3
H3	Design defects [20]	A1、A2、A3

2.2. Control Feedback Model Construction

The control feedback model is a safety control structure composed of four components: the controller, actuator, control process, and sensor. These components interact through active control and feedback information. The shield construction manager acts as the controller, issuing instructions based on dashboard and monitoring data (sensors) to the shield machine operators and shield machine captain (actuators), aiming to control shield tunneling parameters and carry out equipment maintenance and care. The ground disturbance caused by shield construction is transmitted to the parallel high-pressure gas pipeline. If the pipeline leaks, the tunnel will generate a certain dynamic response. Based on the work process mentioned above, the control feedback model for SCSPGP is shown in Figure 2.

2.3. Unsafe Control Behavior Identification and Causality Analysis

STPA suggests that the occurrence of system-level hazards is due to the implementation of potentially dangerous control actions (UCA). The UCAs are categorized into four types: failure to provide control actions (UCA1), providing dangerous control actions (UCA2), providing control actions at incorrect timing (UCA3), and terminating control actions too early or extending their duration too long (UCA4). Based on the constructed control feedback model, unsafe control behaviors (UCAs) in both the shield preparation and tunneling processes were analyzed for their causes, as shown in Table 2.

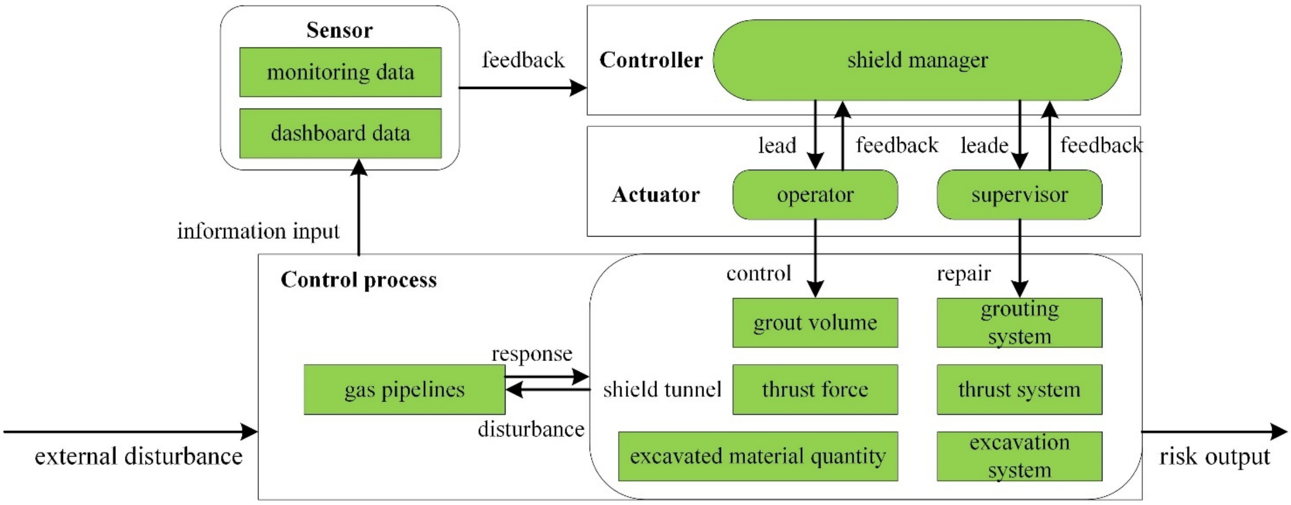

Figure 2. Control Feedback Model

Table 2. Unsafe control behaviors

Construction Process	UCA1	UCA2	UCA3	UCA4
Shield preparation	UCA1-1: The actual burial depth of the gas pipeline was not checked against the elevation shown in the drawings [H2, H3] UCA1-2: The service life of the gas pipeline was not investigated [H2]	UCA2-1: Failure to conduct safety education and safety technical disclosure seriously [H1,H2] UCA2-2: Unreasonable design of pipe-tunnel spacing [H2,H3]	–	–
Shield tunneling	UCA1-3: No maintenance has been performed on the gas pipeline [H1, H2]	UCA2-3: No regular emergency plan drills conducted [H1,H2] UCA2-4: Safety production responsibility system not implemented [H1,H2] UCA2-3: Excessive disturbance to the formation [H1,H2]	UCA3-1: Untimely synchronous grouting [H1, H2]	UCA4-1: Insufficient coverage period of monitoring equipment [H1, H2]

(1) Shield preparation stage

Frequent ground disturbance may cause changes in the pipeline's burial depth. If the design team fails to confirm the actual position of the gas pipeline with the pipeline company, the risk of the pipeline being cut by the cutterhead increases. Pipeline-tunnel spacing is a significant factor in parallel pipeline shield construction systems. Under single-line tunneling, smaller horizontal spacing increases the shield's impact on the gas pipeline, while in dual-line tunneling, different horizontal spacings show varying effects on pipeline settlement and displacement [21]. When the ground is disturbed, stress concentration may occur in the pipeline, leading to higher loads at specific locations, thus accelerating fatigue damage. If the construction team neglects risk identification and hazard elimination, it may increase the risk of pipeline deformation. Furthermore, if safety education and technical briefing personnel focus too much on formality, leading to insufficient safety awareness among workers, this may also heighten the risks of surface subsidence and pipeline deformation.

(2) Shield tunneling stage

To prevent pipeline leakage and reduce the load on equipment while ensuring construction progress, maintenance personnel must regularly inspect the gas pipeline and shield equipment. Failure to do so increases the risk of surface subsidence and pipeline deformation. Improper tunneling parameters may cause excessive ground displacement, increasing the risk of pipeline leakage. Ground displacement risks can be attributed to four key tunneling parameters. First, soil pressure in the chamber must be balanced to avoid potential cave-ins or excessive settlement due to excessive excavation face pressure. Second, increasing tunneling speed raises the excess pore pressure in the soil ahead, affecting tunnel face stability. Third, improper control of grouting volume, pressure, and duration may result in insufficient filling of the gap between the tunnel and surrounding soil or excessive soil pressure, causing ground settlement. Lastly, excessive or insufficient thrust force may cause soil movement around the cutterhead to move in opposite directions, destabilizing the tunnel face. Additionally, if construction personnel lack safety awareness or engage in violations, and if monitoring personnel fail to track changes in pipeline settlement, ground subsidence, pipeline-tunnel spacing, and burial depth, the likelihood of system-level accidents increases.

2.4. Establishment of Embrittlement Factor List

The WSR system methodology is an important tool for studying and solving complex problems with a thinking approach based on understanding physics, psychology, and human factors [22]. However, WSR lacks consideration of the external environment's threat to the system. Therefore, based on the causal analysis results in Section 2.3, this study extracts the embrittlement factors of SCSPGP from four dimensions: physics, psychology, human , and environment (WSRH). To ensure the rationality of the embrittlement factors, expert interviews and analysis of safety accident reports were conducted to verify and expand the factors. The final list of embrittlement factors is shown in Table 3.

Table 3. Embrittlement Factors List

Category		Embrittlement Factor
Physics	Shield equipment and gas pipelines	W1- Equipment load operating condition; W2- Pipeline fatigue condition; W3- Equipment and pipeline maintenance
Psychology	Safety Monitoring Status	S1- Pipeline settlement; S2- Strata settlement; S3- Pipeline-tunnel parallel spacing; S4- Pipeline burial depth
	Tunneling Parameter Control	S5- Soil chamber pressure; S6- Excavation speed; S7- Grouting synchronization; S8- Jacking force
	Daily Management Status	S9- Safety education and training; S10- Safety technical briefing
	Institutional Implementation Status	S11- Safety production responsibility system implementation; S12- emergency plan drills
Human	Design Personnel	R1- Communication and coordination ability
	Construction Personnel	R2- Safety awareness; R3- Skill level; R4- violation of operations
Environment		H1- Complex strata； H2- Groundwater

3. Basic Methods and Model Construction

3.1. Improved DEMATEL-ISM Method

DEMATEL is a system methodology based on graph theory and matrix tools, aimed at quantifying and analyzing the logical relationships between influencing factors and determining their relative superiority [23]. However, the DEMATEL method typically relies on expert scoring, which is heavily influenced by subjective factors. IPFS is an extension of intuitionistic fuzzy sets, overcoming the limitation that the sum of membership and non-membership degrees must equal 1. It also addresses the issue of representing fuzzy relationships between influencing factors and the uncertainty in expert evaluation [24]. ISM is a method that uses mathematical computational procedures to analyze the structure of complex systems, providing a more intuitive representation of the hierarchical relationships between influencing factors [25]. In this paper, IPFS, DEMATEL, and ISM are combined to study the key embrittlement factors and their mechanisms in SCSPGP.

3.2. Analytical Model Construction

The specific calculation steps of the IPFS-DEMATEL-ISM model are as follows:

(1) The degree of interaction between each embrittlement factor is classified as: no effect "0", low effect "1", medium effect "2", high effect "3", and very high effect "4". Experts are invited to evaluate the relationships between the embrittlement factors. The evaluation results are converted into IPFS values to establish a direct impact matrix A. The semantic conversion is shown in Table 4.

Table 4. Transformation [26]

Evaluation Criteria	Expert Scoring	IPFS Value
Extremely High Impact	4	([0.80,0.95]),([0.00,0.10])
High Impact	3	([0.60,0.80]),([0.10,0.30])
Moderate Impact	2	([0.40,0.60]),([0.30,0.50])
Low Impact	1	([0.20,0.40]),([0.50,0.70])
No Impact	0	([0.00,0.20]),([0.70,0.90])

$$p = ([a,b],[c,d]) \tag{1}$$

$$\pi_-^2 = 1-(b^2+d^2) \tag{2}$$

$$\pi_+^2 = 1-(a^2+c^2) \tag{3}$$

$$D(p) = (a^2+b^2+2-c^2-\pi_+^2-d^2-\pi_-^2+ab+\sqrt[4]{(1-c^2-\pi_+^2)\times(1-d^2-\pi_-^2)})/6 \tag{4}$$

In the formula: p represents the IPFS fuzzy number, a and b are the interval membership degrees, c and d are the interval non-membership degrees, π_- is the lower bound of hesitation degree, π_+ is the upper bound of hesitation degree, D(p) is the fuzzy value after the fuzzyization of the IPFS fuzzy number.

(2) Calculate the normalized impact matrix M.

$$M = \frac{1}{\max\limits_{1\le i\le n}\sum_{i=1}^{n} X_{ij}} \tag{5}$$

(3) Calculate the comprehensive influence matrix T.

$$T = \lim(M + M^1 + \cdots M^n) = M(I-M)^{-1} \tag{6}$$

(4) Calculate the impact degree D, the influenced degree C, the centrality M, and the causality degree R.

$$D_i = \sum_{j=1}^{n} t_{ij} \tag{7}$$

$$C_i = \sum_{j=1}^{n} t_{ji} \tag{8}$$

$$M_i = D_i + C_i \tag{9}$$

$$R_i = D_i + C_i \tag{10}$$

(5) Calculate the overall impact matrix H.

$$H = T + I \tag{11}$$

(6) Use the threshold λ to remove relationships with a smaller degree of influence between embrittlement factors, obtaining the reachability matrix K.

$$k_{ij} = \begin{cases} 0(h_{ij} < \lambda) \\ 1(h_{ij} \leq \lambda) \end{cases}. \tag{12}$$

(7) Based on the reachability matrix, calculate the reach set R, the predecessor set P and the intersection set Q, sequentially determining the factors at each level, and construct a multi-layer hierarchical structure model.

4. Case Analysis

4.1. Project Overview

The tunnel section from Xizhou Station to Huanghenan Road for the first phase of Zhengzhou Metro Line 12 is constructed using the shield tunneling method. The minimum curve radius of the tunnel in this section is 400 meters, the maximum longitudinal slope is 28%, and the minimum longitudinal slope is 2%. The tunnel's arch crown depth ranges from 17.7 to 27.3 meters. The main soil types in this section are silty clay and fine sand. The underground water layers consist mainly of phreatic water and confined water, with groundwater depths ranging from 12.6 to 17.4 meters, located in a water-rich sand layer region. Additionally, a DN500 high-pressure gas pipeline is located 10.4 meters above the tunnel, with a design pressure of 4 MPa and made of steel. The specific positional relationship between the shield tunnel and the gas pipeline is shown in Figure 3.

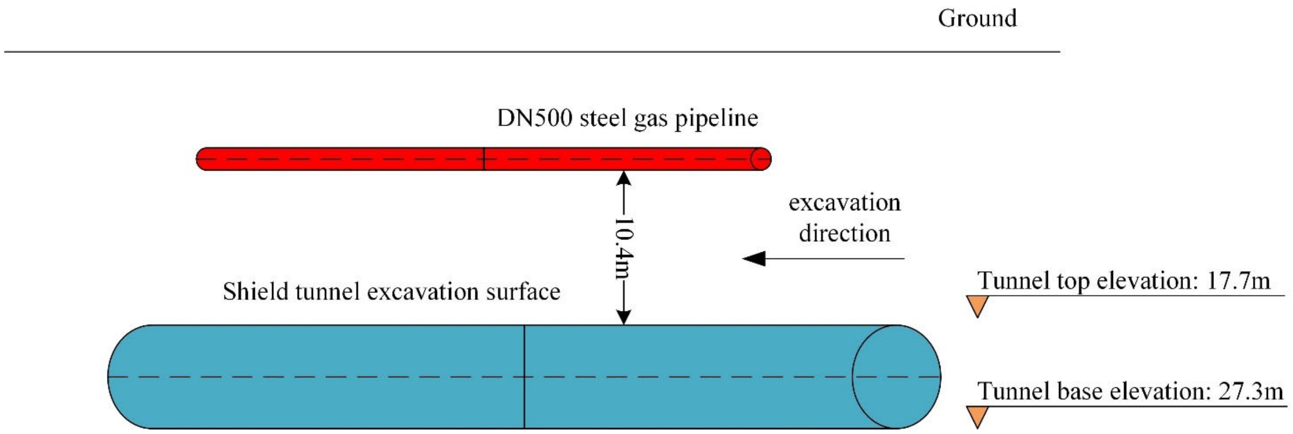

Figure 3. Position of shield tunnel and gas pipeline

4.2. Embrittlement Factor Analysis

Ten experts with over five years of experience in relevant fields were invited, including five professors and associate professors from universities, and five senior engineers. They conducted a bidirectional scoring on the degree of interaction between each embrittlement factor. The most frequent values in the scoring table were processed using the highest frequency value method, and the results were converted into the interval Pythagorean direct impact matrix A through Table 1 and Equations (1) to (4). After normalization and MATLAB computations, the normalized direct impact matrix M and comprehensive impact matrix T were obtained.

Based on the comprehensive impact matrix T, the influence degree, influenced degree, centrality, and causality degree of each embrittlement factor were calculated, as shown in Table 5. The influence degree represents the intensity of the overall impact of each embrittlement factor on other factors; the influenced degree indicates the extent to which each embrittlement factor is affected by other factors; centrality degree is the sum of the influence degree and influenced degree, reflecting the importance of each embrittlement factor in the system; causality degree is the difference between the influence degree and the influenced degree. If the causality degree is greater than 0, the embrittlement factor has a greater influence degree, and its impact is greater than the influence it receives, making it a causal factor. Conversely, if the causality degree is less than 0, the embrittlement factor is a result factor, being more influenced by others than causing its own impact.

Table 5. DEMATEL calculation result

Factor	Influence	Influenced	Centrality	Causality	Attribute
W1	1.759	2.218	3.977	-0.458	Result
W2	1.168	2.957	4.125	-1.790	Result
W3	1.301	2.179	3.480	-0.879	Result
S1	1.404	2.715	4.120	-1.311	Result
S2	1.790	2.540	4.330	-0.751	Result
S3	1.430	1.164	2.594	0.266	Causal
S4	1.219	1.390	2.609	-0.172	Result
S5	1.670	2.041	3.710	-0.371	Result
S6	1.432	2.153	3.586	-0.721	Result
S7	1.638	2.292	3.930	-0.653	Result
S8	1.653	2.218	3.870	-0.565	Result
S9	1.815	0.949	2.764	0.866	Causal
S10	2.288	1.296	3.584	0.992	Causal
S11	2.043	1.350	3.393	0.693	Causal
S12	1.692	1.340	3.032	0.351	Causal
R1	1.620	1.081	2.701	0.539	Causal
R2	2.043	1.943	3.986	0.099	Causal
R3	2.104	1.366	3.470	0.739	Causal
R4	1.860	2.321	4.181	-0.461	Causal
H1	2.695	0.892	3.587	1.803	Causal
H2	2.623	0.839	3.462	1.784	Causal

From Table 5, it can be observed that:

The top three embrittlement factors based on centrality degree ranking are: strata settlement (S2), violation of operations (R4), and pipeline fatigue condition (W2). These factors hold a higher position in the system and are considered important embrittlement factors.

(2) Causal factors include: pipeline-tunnel parallel spacing (S3), safety education and training (S9), safety technical briefing (S10), safety production responsibility system implementation (S11), emergency plan drills (S12), communication and coordination ability (R1), safety awareness (R2), skill level (R3), complex strata (H1), and groundwater (H2). These factors have strong controlling effects and mainly serve as triggering factors in the system. Among these, complex strata (H1), groundwater (H2), and safety technical briefing (S10) are the top three factors in terms of influence degree, with a strong overall impact on other embrittlement factors. They should be considered key elements in the vulnerability management system. Result factors include: equipment load operating condition (W1), pipeline fatigue condition (W2), equipment and pipeline maintenance (W3), pipeline settlement (S1), strata settlement (S2), pipeline burial depth (S4), soil chamber pressure (S5), excavation speed (S6), grouting synchronization (S7), jacking force (S8), and violation of operations (R4). These factors have high sensitivity and are easily influenced. Among these, pipeline fatigue condition (W2), pipeline settlement (S1), and strata settlement (S2) are the top three factors based on the influenced degree, meaning they are significantly impacted by other embrittlement factors and should be key points for daily supervision. Therefore, safety management personnel should focus on the relationship between causal factors and result factors. Management should be approached starting from the causal factors, with changes in result factors serving as the measure of the effectiveness of the vulnerability management actions taken.

(3) Centrality and causality degree are important indicators for identifying key embrittlement factors [27]. In this study, the key embrittlement factors were determined based on the sum of the absolute values of centrality and causality degree. The final key embrittlement factors identified for SCSPGP are pipeline fatigue condition (W2), pipeline settlement (S1), and complex strata (H1).

4.3. Analysis of embrittlement mechanism

The size of the threshold λ impacts the system's classification. If the threshold λ exceeds a certain range , it may lead to an overly simplistic or overly complex system hierarchy, making it difficult to clearly reveal the hierarchical topology of the embrittlement factors. To ensure an optimal system hierarchy, this study determines the threshold λ based on the sum of the mean μ and standard deviation $\cup$ of the comprehensive impact matrix T. The calculated mean (μ=0.0845) and standard deviation (υ=0.0392) for the IPFS comprehensive impact matrix T, so the threshold (λ) is set to 0.1237.

The reach set, predecessor set, and intersection set of the reachability matrix K were calculated. Based on the principle of dividing when the reach set and intersection set are equal, the multi-layer hierarchical structure model of the embrittlement factors in SCSPGP was finally obtained, as shown in Figure 4. This model divides the embrittlement factors into seven layers and three major factor sets, with the L1 layer representing surface factors, layers L2 to L6 representing transitional factors, and the L7 layer representing essential factors. Based on the structural model, the embrittlement mechanism of SCSPGP is analyzed from two main aspects: the impact hierarchy and the impact pathways.

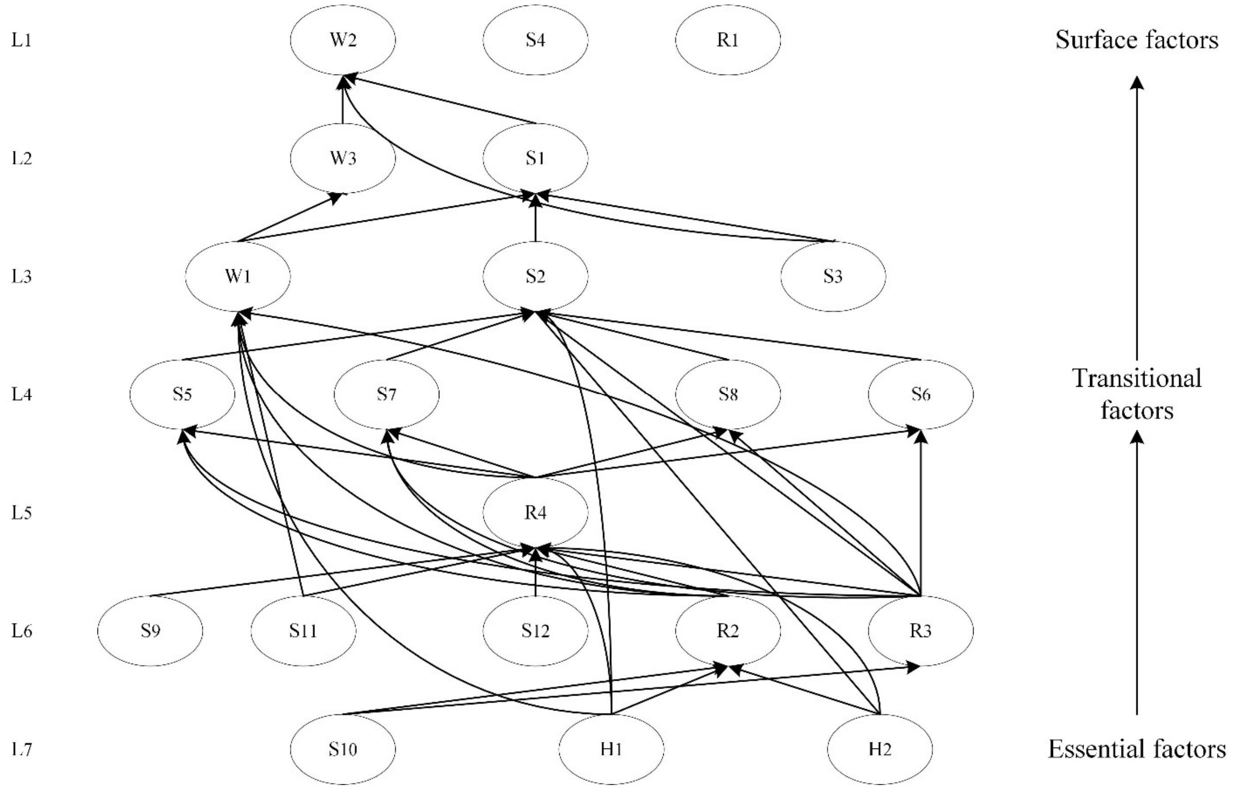

Figure 4. Multi-level hierarchical structural model

4.3.1. Impact Hierarchy Analysis

Surface factors are the direct influencing factors of the vulnerability of SCSPGP, while other factors affect the surface factors either directly or indirectly. Therefore, strengthening the control over lower-level factors is the main measure to reduce the impact of these factors on the vulnerability of SCSPGP. Among these, pipeline fatigue condition (W2) is largely influenced by the transitional embrittlement factors, while pipeline burial depth (S4) and communication and coordination ability (R1) are relatively independent.

Transitional factors are the indirect influencing factors of the SCSPGP's vulnerability, with complex relationships and transmission effects. Among these, Pipeline Settlement (S1), Strata Settlement (S2), Grouting Synchronization (S7), Violation of Operations (R4), and Safety Awareness (R2) are the embrittlement factors with the largest centrality in each layer. Managing these factors can effectively interrupt the transmission of embrittlement paths.

Essential factors are the fundamental influencing factors of the vulnerability of SCSPGP. Among these, complex strata (H1) has the largest centrality, and the centrality of safety technical briefing (S10) and groundwater (H2) are close to it. Therefore, when considering the impact of complex strata and groundwater on the vulnerability of SCSPGP, managers should also focus on building and improving the safety technical briefing system.

4.3.2. Impact Pathway Analysis

Based on the structural model and hierarchical classification, the impact pathways are divided into main pathways and secondary pathways. The main pathways are those formed by the transmission of embrittlement factors across different layers, while the secondary pathways are formed by the transmission of embrittlement factors across layers. There are 16 main pathways, such as: safety technical briefing (S10)→ safety awareness (R2)→ violation of operations (R4)→ soil chamber pressure (S5)→ strata settlement (S2)→ pipeline settlement (S1)→ pipeline fatigue condition (W2). Among these, violation of operations (R4), strata settlement (S2), pipeline settlement (S1), and pipeline fatigue condition (W2) are key components of each main pathway. A well-established safety technical briefing system can help employees develop safety awareness, clearly define their responsibilities and duties, and improve safety skills through the transfer of theoretical knowledge and practical training. Additionally, the presence of complex strata and groundwater increases the uncertainty and danger in SCSPGP, constantly testing employees' alertness to potential risks and their safety awareness for risk prevention. Improved safety awareness and skill levels help to prevent violations and reduce the risk of accidents, particularly in areas such as complying with laws and regulations, standardizing construction behaviors, and improving supervision efficiency. Violation of operations can impact the rationality of tunneling parameter settings, such as soil chamber pressure, excavation speed, grouting synchronization, and jacking force. Irregular parameters may lead to excessive strata settlement. Strata settlement causes stress changes in the surrounding soil layers, and due to the soil-pipe interaction, pipeline settlement is also affected. In parallel pipeline shield construction, the maximum settlement of the pipeline occurs directly above the tunnel axis, and the settlement decreases as the parallel horizontal spacing increases. When the settlement exceeds the safety allowable value of the pipeline, it can cause structural damage to the pipeline and accelerate pipeline fatigue.

The secondary pathways consist of 24 routes, such as safety production responsibility system implementation (S11)→ violation of operations (R4)→ equipment load operating condition (W1)→ pipeline settlement (S1)→ pipeline fatigue condition (W2). This type of impact pathway mainly influences pipeline fatigue condition by affecting violation of operations. If shield tunneling equipment, such as the grouting system, muck removal system, and jacking system, operates under high-load conditions, equipment failures may occur, subjecting the gas pipeline to additional stress and deformation. Therefore, regular maintenance of equipment and pipelines not only extends the service life of the equipment but also effectively reduces the pipeline fatigue rate.

In summary, both the main pathways and secondary pathways collectively impact the structural stability of pipelines. Violation of operations (R4) and pipeline fatigue condition (W2) are the key node factors in the stability impact pathways. By improving employees' safety awareness and skill levels, optimizing excavation parameters, regularly maintaining pipelines and equipment, and increasing the frequency of settlement monitoring, pipeline structural damage can be effectively prevented and mitigated, thereby reducing the vulnerability of SCSPGP.

5. Conclusion

This study proposes an improved DEMATEL-ISM embrittlement mechanism analysis model based on the characteristics of SCSPGP. The main conclusions are as follows:

(1) A control feedback model for SCSPGP was established, and unsafe control behaviors in parallel construction were identified and causal analysis was performed based on STPA. Using the WSRH influencing factor identification framework, a list of embrittlement factors for SCSPGP was developed, providing emergent input for the DEMATEL-ISM integrated model.

(2) The IPFS-DEMATEL-ISM method was proposed, and a multi-layer hierarchical structure model was constructed. The embrittlement mechanism of SCSPGP was analyzed from two aspects: impact hierarchy and impact pathway.

6. CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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