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Research on Resilience Evaluation and Enhancement of Deep Foundation Pit Construction Safety System

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Abstract: Deep foundation pit (DFP) projects have been a high incidence area of safety accidents because of their own high danger and complexity. Therefore, it is necessary to study the resilience of their construction safety system. This paper systematically identifies the key factors affecting the resilience of deep foundation pit construction based on the analysis of the composition of the deep foundation pit construction safety system (DFPCTSS), the synergistic relationship of its subsystems in the face of the interference and impact of internal and external disaster-causing factors, and the causal mechanism of typical accidents in DFP accidents and the emergent process of system resilience. A resilience evaluation indicator system based on four capacity dimensions of prevention absorption, resistance, recovery, and learning adaptation was constructed by using the fuzzy Delphi method, which is characterized by the resilience emergence process. Then the correlation and weight of evaluation indexes were analyzed based on the DEMATEL–ANP method, the boundary cloud parameters of the resilience evaluation grade were set according to the normal extension cloud model, and the membership degree of the resilience evaluation level was calculated to complete the evaluation of the resilience level. Finally, taking a DFP project of a metro station as an example, the above model was used to evaluate the resilience level of its construction safety system, and suggestions for resilience enhancement were put forward. The results show that the evaluation results are consistent with the actual situation of the project, and the evaluation model is conducive to providing a systematic analysis method and improvement countermeasures for deep foundation pit construction safety management from the perspective of resilience.

Keywords: deep foundation pit; resilience of construction safety system; resilience evaluation indicator system; DEMATEL–ANP-extension cloud model; resilience enhancement advice

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1. Introduction

The deep foundation pit project, as the foundation or main project of underground rail transit station facilities and urban commercial complex and high-rise buildings, has been a high-frequency field of safety accidents due to its complex construction conditions, large environmental impact, and strong technical comprehensiveness. Scholars have been studying safety management for a long time, but they mainly focus on engineering risk assessment and monitoring from the perspective of safety risk management based on reliability theory [1,2]. For example, Finno and Bryson [3] evaluated the risk of deep foundation works and support stages with reference to parameters such as load values of the deep foundation support structure system, building settlement, and lateral displacement distance of soil, as well as based on damage characteristics such as width and depth of cracks in surrounding structures. Castaldo and Jalayer [4] evaluated the risk of groundwater seepage by considering construction defects and uncertainties in geological structures and construction parameters during the deep foundation works phase. Based on the fault tree analysis, Heravi and Taherkhani [1] applied fuzzy integrated analysis and Monte Carlo simulation to study the sensitivity and root causes of risk responses in deep foundation pit construction and proposed some useful suggestions to reduce reliability failures in deep foundation pits based on Bayesian network analysis.

In recent years, given that the traditional safety management research paradigm emphasizing results and causes and advocating accident prevention and accident analysis can no longer meet the needs of engineering safety management, engineering safety resilience research with the concept of resilience as the core and emphasizing continuous resistance and active recovery has been greatly developed, and scholars have begun to pay attention to engineering safety resilience research. However, the existing research mainly focuses on the safety resilience of urban infrastructure systems and lacks relevant research on deep foundation pit construction safety systems from the perspective of resilience. Therefore, this paper introduces the resilience theory to identify, measure, and evaluate the key indicators that affect the resilience level of DFPCTSS from the perspective of dynamic process based on the capability characterization of each stage of resilience emergence. This study aims to construct a set of evaluation index system and evaluation model that can objectively and truly reflect the resilience characteristics to provide a basis for the government construction safety management department to evaluate the resilience level of DFPCTSS. The study results can also provide a basis for contractors to improve construction safety system resilience and accident prevention and response capabilities.

The rest of this paper is structured as follows. Section 2 reviews the relevant literature, and the overall research methodology is given in Section 3. In Section 4, the evaluation indicator system for DFPCSS is constructed. The resilience evaluation model is proposed in Section 5. Then a numerical case study based on Metro Line 1 of a certain place is conducted in Section 6. Finally, Section 7 concludes this paper.

2. Literature Review

Since few studies have directly addressed the resilience of DFPCSS, this study expands the scope of the review to include studies on the resilience of other infrastructure engineering safety systems in the analysis to provide a reference for the study of deep foundation pit safety systems.

2.1. Research on Resilience Assessment of Engineering Safety System

Resilience-based assessments are critical for identifying preventive measures to mitigate the consequences of various disruptive events [5]. The resilience assessment index system and method have been studied extensively. Zhu and Manandhar [6] constructed a system including vulnerability, expectations, redundancy, adaptability, rapidity, intelligence, cross-scale interaction, and learning culture to assess the resilience of the power and water infrastructure systems. Mottahedi and Sereshki [7] proposed a quantitative assessment scheme for critical infrastructure system resilience based on expert judgment and fuzzy set theory, considering the limitations of lack of historical data and information sources in traditional system resilience assessment and described the process of identifying and quantifying the factors affecting resilience, thus improving the effectiveness of modeling based on the influencing factors. Heravi and Taherkhani [1] combined the dynamic Bayesian network with the functional resonance analysis method to provide a better method for the rigorous quantitative analysis of the resilience of complex process systems based on the level of technology–human–organization interaction. Using a dynamic network flow model, Goldbeck and Angeloudis [8] constructed a dynamic integrated modeling and simulation framework that combines the network and performance representation of infrastructure systems, compensating for the defect that current resilience-assessment methods ignore the interdependence of critical infrastructure systems. Guo and Shan [9] screened resilience evaluation indicators based on bibliometric and Delphi methods and constructed an ANP–Extended Cloud comprehensive evaluation model to evaluate the resilience of subway construction site safety systems. Qiang and Jiaqi [10] established a tunnel construction safety resilience evaluation index system based on the properties of resilience, such as resistance, adaptability, and recovery and constructed a tunnel construction safety resilience evaluation model based on ideal fuzzy matter–element. Dan et al. (2021) identified 24 resilience assessment frameworks from 24 high-quality papers; extracted and summarized 16 dimensions; and concluded that technical, organizational, social, and economic dimensions might be the four most basic assessment dimensions. He and Wang [11] established an employee relationship network based on the social network analysis and studied the measurement of resilience of construction projects from the perspective of employee behavior in terms of four characteristics: robustness, redundancy, rapidity, and intelligence.

2.2. Research on Safety and Risk Assessment of Deep Excavations Construction System

The relevant studies were mainly conducted in terms of the construction of evaluation index system and the selection of evaluation methods. Zhang [12] determined the evaluation indexes through expert survey and combined ANP–fuzzy hierarchical fuzzy comprehensive evaluation method to evaluate the safety condition and engineering risk of deep foundation pit construction. Wang and Zhao [13] screened out the key hazard sources affecting the safety of DFP projects from three aspects, namely construction, management, and environment based on the temporal and functional attributes of system elasticity; constructed a risk evaluation index system; and realized the risk assessment of DFP construction based on the two-dimensional entropy power cloud model. Wu and Zhang [14] constructed an extension cloud risk assessment model based on the theory of extensibility and combined with the characteristics of DFP construction and realized the transformation from qualitative evaluation results to quantitative data presentation. Bo [15] constructed a construction safety evaluation index system from five aspects, namely management factors, equipment reasons, personnel factors, technical indicators, and environmental impact, combined with the actual construction of a subway deep-excavation project and expert advice, and used the BP neural network training model to train the output evaluation data to determine the safety evaluation level of the project site.

In conclusion, scholars have studied the construction of resilience evaluation index systems and evaluation methods for critical infrastructure systems and construction safety systems. However, there is no research on the construction of resilience evaluation index system and evaluation method for the DFPCSS. Therefore, this paper constructs the resilience evaluation index system of DFPCSS based on the systematic identification of key factors affecting the safety and resilience of DFP construction and according to the capacity characteristics of each stage of resilience emergence. Then the correlation and weights of evaluation indexes are analyzed based on the DEMATEL–ANP method. After that, the boundary cloud parameters of the resilience level are set according to the normal extended cloud model, the membership degree of the resilience evaluation level is calculated, and the evaluation of the resilience level is completed. This study realizes the process evaluation of DFPCSS resilience, which provides a basis for comprehensive improvement of DFP construction safety and accident response capability.

3. Methodology

3.1. Definition and Connotation of DFPCSS Resilience

The mainstream division of existing engineering systems is mainly based on the "4M1E" theory, that is, the five management elements of man, machine, material, method, and environments [16]. Based on the theory of engineering system safety resilience, this paper divides the DFPCSS into four major components, namely personnel organization, material, technology, and environmental system, according to the five safety management dimensions of "4M1E". The four components of DFPCSS are explained in detail as follows:

(1) Personnel organization system

The safety awareness of personnel, safety avoidance skills, and the organization's emergency management capability are important representations of the resilience level of construction safety system. The personnel organization management system includes personnel composition and organization management mode. The personnel can be divided into operation personnel, supervisory personnel, and construction management personnel. Organizational management mode includes organizational structure, organizational division of labor, organizational management methods and systems, etc. Good organizational control has a positive effect on the resilience of material management system and technical management system.

(2) Material system

In the theory of system safety and resilience, "material" often refers to the "hardware", which is different from technology. It includes mechanical equipment and monitoring equipment, materials, safety protection materials, emergency facilities, etc., required for deep foundation pit construction. The material management system provides the necessary material foundation and safety guarantee for deep foundation pit construction and plays a very important role in all stages of construction safety system resilience.

(3) Technology system

Technology is the "software" element, which is different from material. It includes all kinds of technologies in the construction process, such as support, drainage and precipitation, excavation and slope release, slope protection, and pit monitoring. The technical management system can eliminate the "unsafe state of objects" and "unsafe behavior of human" during DFP construction and provide the necessary safety technology guarantee. The role is especially significant in the early and middle stages of the system's safety resilience.

(4) Environmental system

The environmental system contains the construction environment, natural environment, and social environment. The environmental system is the place where energy, information and material are exchanged between the DFPCSS and the outside world, as well as the internal elements, and it is also the carrier guarantee for the smooth operation of each subsystem, which plays a fundamental role in the system safety resilience.

The disaster resistance of DFPCSS refers to the system's ability to prevent, absorb, and resist adverse effects through the joint operation and synergy of internal subsystems when facing the interference and influence of internal and external disaster-causing factors (Figure 1); to maintain the safe state and basic functional operation of the construction site; to reduce casualties and structural damage losses; and to quickly return to the initial or better safety state until normal construction operations.

3.2. The Construction Process of Resilience Evaluation Index System

Firstly, the key influencing factors of resilience are determined based on the mechanism of typical accidents, the causes of typical accidents, and the process of resilience in accidents. Then, based on industry norms and the research from the literature, the index system was initially constructed. Finally, based on the fuzzy Delphi method, the key evaluation indicators of resilience were screened, and then the resilience evaluation index system was constructed. The construction process is shown in Figure 2.

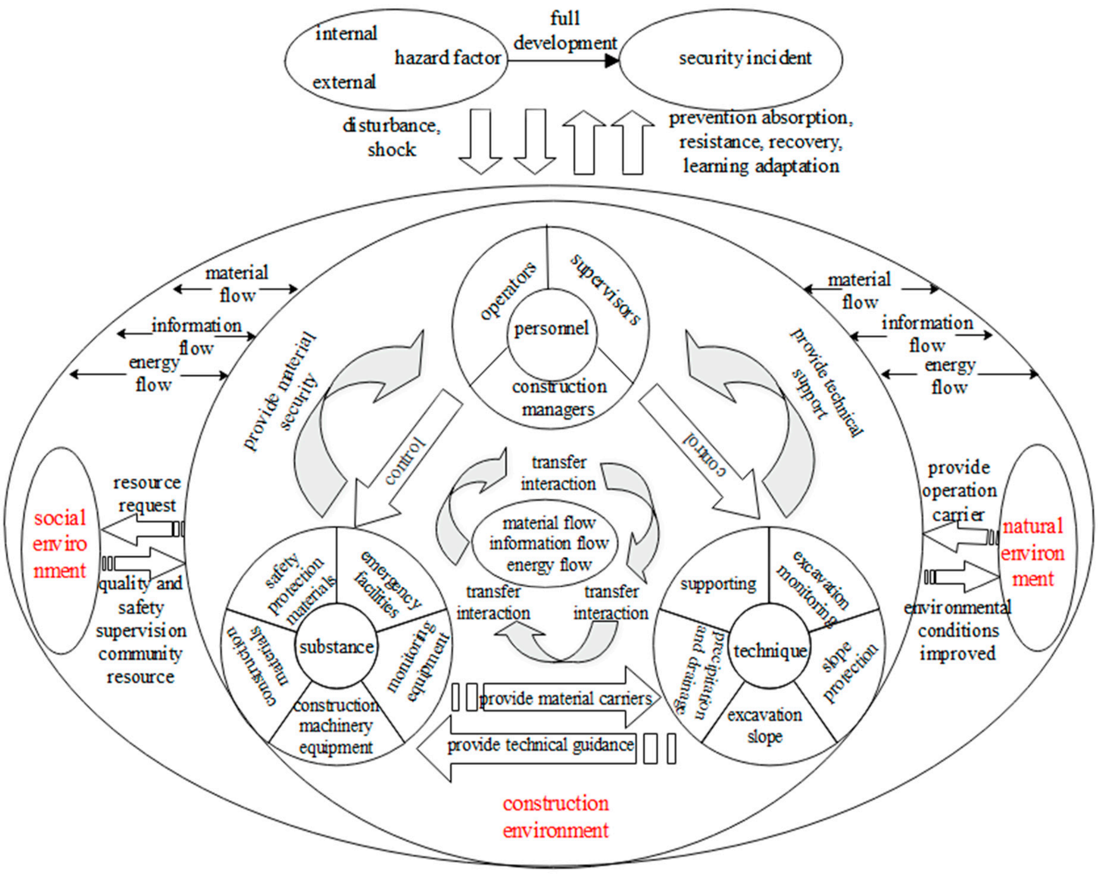

Figure 1. Composition and synergy diagram of deep excavations construction safety system.

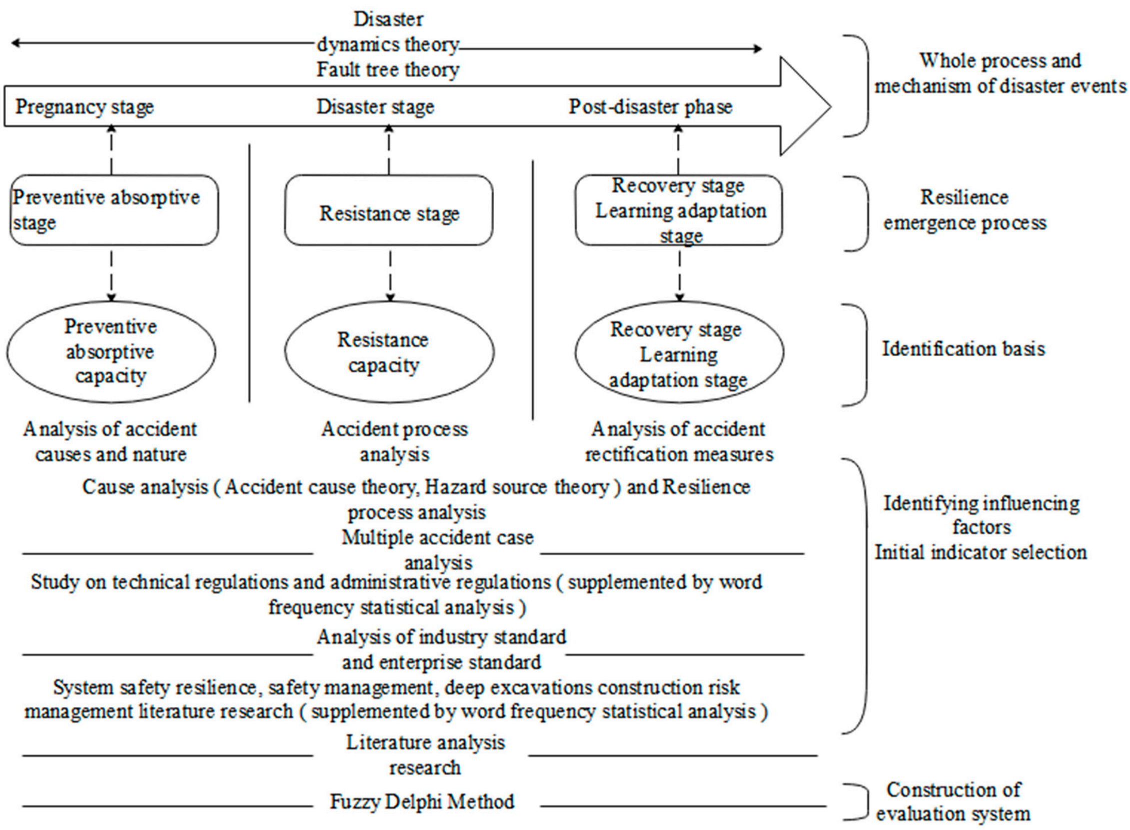

Figure 2. Construction process of resilience evaluation index system.

3.3. The Construction Process of Resilience Evaluation Model

First, the influence relationship between indicators is determined based on the DEMATEL method, and the ANP network structure diagram is constructed. Then, on the basis of expert questionnaire and group discussion, the assignment of the relative dominance of indicators is completed, and the judgment matrix of the dominance of indicators is constructed, and the weights of indicators are determined. Finally, the extended cloud resilience evaluation model is constructed to determine the matter elements of evaluation, evaluation level boundary, membership degree, and security resilience level evaluation to complete the resilience evaluation.

4. Identification of Resilience Influencing Factors and Establishment of Evaluation Index System

4.1. Identification of Resilience Influencing Factors

(1) Influencing factors identification based on disaster mechanism analysis

A Fault Tree Analysis (FTA) is a top-down deductive failure analysis method that uses Boolean logic to combine lower-order events to analyze undesired states in a system [17]. An FTA is primarily used in the fields of safety engineering and reliability engineering to understand the causes of system failure and to find the best way to reduce risk or to identify the incidence of a safety incident or a specific system failure. In this paper, based on the literature on typical deep foundation pit construction accidents and disasters, a fault tree analysis is conducted to study the disaster process for typical deep foundation pit projects such as slope collapse, water surge, pit bottom uplift, surface cracking, fall from height, and object strike. The key factors of the disaster are identified and sorted out (factor codes a1~a51). For example, the key factors causing slope collapse accidents are as follows: a1, improper excavation method; a2, inadequate slope protection measures; a3, improper slope rate setting; a4, improper drainage; a5, illegal piling on the slope; a6, external load disturbance; a7, inadequate soil investigation; a8, prolonged slope exposure; a9, poor soil bearing capacity; a47, poor personnel safety awareness; and a50, inadequate safety inspection.

(2) Influencing factors identification based on multi-accident case analysis

According to the statistics of 70 DFP accidents from 1994 to 2021 from the website of the State Administration of Work Safety of China and the official website of the Ministry of Emergency Management of China, 36 typical safety accidents (accident codes A1~A36) are selected according to the research purpose of this paper. The accident causes are summarized based on the accident causation theory, and the factors affecting the resilience level in the process of accidents were identified based on the system resilience theory (factor codes b1~b35).

(1) Analysis of the influencing factors based on the accident cause theory

The factors identified in the case study (b1~b35) are summarized into four dimensions, namely personnel organization management, material management, technology management, and environment, and the related accidents are listed accordingly (A1~A37). The results are shown in Table 1.

Table 1. Resilience influencing factors based on the causal summary of typical accident cases.

Identify Dimensions	Identify Factors	Associated Accident
Personnel organization management	b1 Security technology disclosure is missing	A7/A10/A12/A15/A17/A23/A25/A30/A33
	b2 Inadequate safety education and training	A3/A7/A10/A11/A12/A15/A19/A20/A23/A25/A30
	b3 Personnel not qualified	A8/A14/A15/A22/A23/A30
	b4 Personnel security awareness is weak	A1/A12/A18/A19/A20/A32
	b5 Personnel lack the ability to escape and avoid danger	A20
	b6 Poor subcontract management	A7/A8/A10/A11/A22
	b7 Inadequate project site safety management	A1/A2/A4/A5/A6/A7/A11/A13/A14/A17/A18/A19/A20/A31/A35
	b8 Unimplemented main security responsibility	A5/A10/A12/A17/A18/A19/A20/A22/A24/A35
	b9 Inadequate security supervision inspections	A2/A3/A4/A6/A7/A8/A10/A11/A12/A13/A17/A18/A20/A21/A22/A25/A26/A29/A30/A32/A33/A34
	b10 Inadequate security officers	A7/A10/A17/A19/A22
	b11 Lack of attention to potential hazards	A12/A14/A21/A27/A30/A32/A33/A34
	b12 Inadequate emergency organizational management measures	A10/A20/A23
	b13 Inadequate management of security managers	A8/A12/A33
	b14 Violating command	A6/A8/A15/A25/A32
Material resource management	b15 Insufficient equipment for fire facilities	A14/A19
	b16 No special ladder is provided	A15
	b17 Illegal material stacking	A2/A4/A7/A15/A28/A34
	b18 Construction machinery, vehicle disturbances	A2/A23
	b19 No cordon and safety signs	A19
Technical management	b20 Inadequate geological environment survey	A1/A15/A16
	b21 Irrational design scheme	A6/A15/A18/A28/A34/A36
	b22 No dynamic design methodology	A1
	b23 Information construction not implemented	A1
	b24 Construction did not follow the design and construction scheme	A2/A5/A6/A7/A18/A20/A21/A22/A26/A31/A33/A36
	b25 Unreasonable special construction plan	A6/A23/A30
	b26 Improper drainage	A5/A11/A34
	b27 Improper supporting measures for excavation	A5/A6/A9/A12/A15/A17/A20/A21/A23A24/A26/A27/A34
	b28 Illegal excavation	A2/A5/A6/A15/A10/A21/A23/A26/A28/A32
	b29 Improper slope protection measures	A2/A4/A6/A25
	b30 Improper setting of slope rate	A2/A4/A9/A15/A16/A29/A32
	b31 Inadequate monitoring and early warning measures	A23/A26
	b32 Inadequate handling of hazardous source technologies	A10/A25/A33/A34/A36
Environment	b33 Extreme rainfall weather	A3/A5/A11/A13/A22/A23/A29/A32
	b34 Inadequate supervision of construction administrative departments	A2/A7/A13/A15/A16/A22/A23/A32
	b35 Poor condition of foundation soil	A1/A11/A12/A21/A22/A27/A28/A29/A30/A18

(2) Influencing factors of resilience based on accident process analysis

Based on the theory of disaster dynamics [18], with reference to the complete description of the accident process in the investigation report of a typical accident case, the factors (c1–c28) affecting the resilience level in the resilience emergence process (prevention absorption, resistance, recovery, and learning adaptation) corresponding to the three stages of disaster conception, disaster formation, and post-disaster are organized, respectively, and the results are shown in Figure 3.

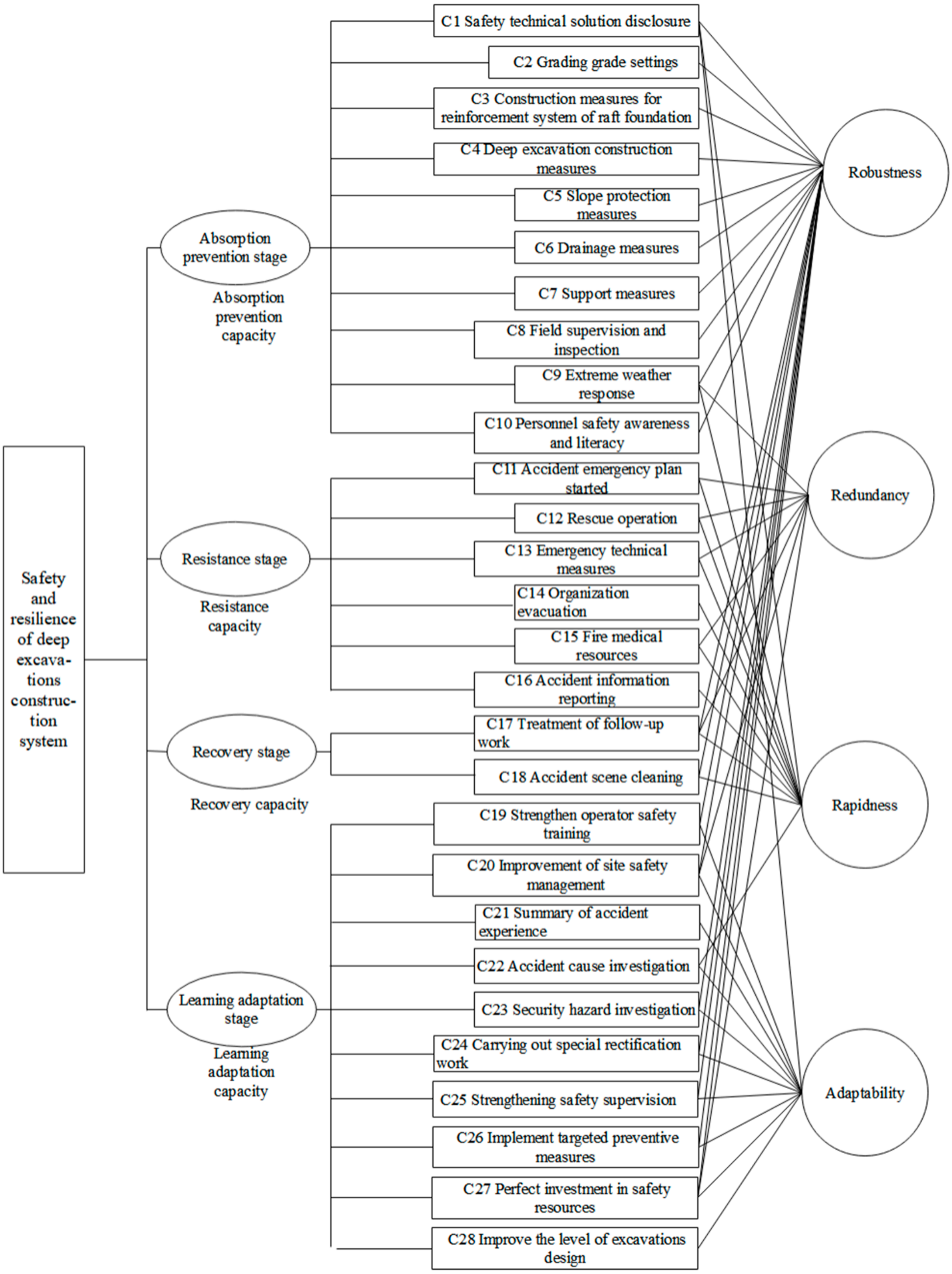

Figure 3. Impact factors of resilience based on accident process analysis.

4.2. Construction of the Initial Index System

Taking the four capabilities of prevention absorption (A), resistance (R), recovery (r), and learning (L) adaptation characterized by the process of resilience as the guideline dimensions, Technical Specification for Construction Safety of Deep Foundation Pit Engineering (hereinafter referred to as "Technical Specification") and the Specification for

Construction Project Management (hereinafter referred to as "Management Specification") are used as references. Combined with the relevant academic papers, the previous screened resilience influencing factors are analyzed, refined, summarized, and categorized through word frequency statistics, and the results of the initial evaluation indexes are shown in Table 2.

Table 2. Initial resilience evaluation index system of DFPCSS.

First-Level Indicator	Secondary Indicator (Measurement Indicators)	Subsystem	Index Source	Including Influencing Factors
Preventive absorptive capacity	Survey of construction environment Ac1	Technology	Technical specifications [2,19]	a7/b20
	Soil quality of foundation Ac2	Environment	The literature [2,20]	a9/a25/a27/b35
	Rationality of design and construction scheme Ac3	Technology	The literature [1,20]	a28/a29/a30/a43/a44/b22/b23/b21/b25
	Safe and civilized construction measures Ac4	Personnel organization	Management specification The literature [21]	a5/a16/a38/b19/b17
	Construction behavior compliance Ac5	Technology	The literature [1,22]	a20/a46/b24/b14
	Surface and ground drainage measures Ac6	Technology	Technical specifications	a4/a10/a26/a33/b26/c6
	Earth–rock excavation measures Ac7	Technology	Technical specifications	a1/b28/a2/b29/a3/b30/a6/b18/a8/a11/c4/c2/c5
	Supporting structure construction measures Ac8	Technology	Technical specifications	a12/a31/a35/a36/a48/b27/c7
	Reinforcement system construction measures Ac9	Technology	Accident process	c3
	Monitoring level of deep excavations Ac10	Technology	Technical specifications Technical standard	a32/b31
	Safety resource input Ac11	Material	The literature [13,21]	a13/b15/a17/a22/a40/b10/a37
	The perfection and implementation of construction safety management system Ac12	Personnel organization	The literature [1,19]	a39/a45/b7/b6/b8/a19/b13
	Safety supervision and check Ac13	Personnel organization	Technical specifications The literature [21]	a49/a50/a51/b9/c8
	Implementation of security technology disclosure Ac14	Technology	Technical specifications The literature [10,13,23]	b1/c1
	Personnel safety awareness and literacy Ac15	Personnel organization	The literature [1]	a15/a41/b4/a18/b11/c10
	Personnel position qualification Ac16	Personnel organization	The literature [1,2,21]	a14/a21/b3
	Safety publicity and education Ac17	Personnel organization	The literature [1,23]	b2
	Supervision of construction industry supervision departments Ac18	Environment	Accident case	b34
Resistance ability	Hazardous source disposal measures Rc1	Technology	Technical specifications	b32/a23/a34/a42/b33/a24/c9/c13
	Availability of emergency supplies Rc2	Material	The literature [7,19,21]	b16
	Reasonableness of emergency management plan Rc3	Personnel organization	Technical specifications The literature [21]	c11/c12/c14/c16/b12
	Access to social firefighting medical resources Rc4	Environment	The literature [10,21]	c15
	Emergency management and control capabilities of managers Rc5	Personnel organization	The literature [2,10,23,24]	/
	Personnel escape ability Rc6	Personnel organization	The literature [21,25]	b5

Table 2. *Cont.*

First-Level Indicator	Secondary Indicator (Measurement Indicators)	Subsystem	Index Source	Including Influencing Factors
Recover ability	Restoring resource-allocation capabilities rc1	Material	The literature [21,25]	/
	Psychological recovery of personnel rc2	Personnel organization	The literature [13,24]	The literature
	Disposal of follow-up work rc3	Personnel organization	The literature [10,21]	c17/c18
	Construction element redundancy rc4	Material	The literature [10,13,25]	/
Learning and adapting capability	Increased security input Lc1	Material	The literature [1,2,25,26]	c27
	Accident investigation and experience summary Lc2	Personnel organization	The literature [1,2,13,26]	c21/c22
	Improvement of safety and emergency management system Lc3	Personnel organization	The literature [13,19]	c20/c25
	Safety education training and drills Lc4	Personnel organization	The literature [10,21]	c19
	Elimination of security risks Lc5	Personnel organization	Accident process	c23/c24/c26
	Design and construction level improvement Lc6	Technology	The literature [21]	c28/d9

4.3. Establishment of Evaluation Index Based on Fuzzy Delphi Method

4.3.1. Overview of Fuzzy Delphi Method

(1) Theoretical basis

The traditional Delphi method uses a non-meeting method to conduct opinion inquiry, which can make full use of the professional knowledge and experience reserves of the experts under investigation, while still maintaining the relative independence of the feedback questionnaire [27]. However, if the results of the questionnaire do not converge, it needs to be repeated. Survey feedback is very costly and time-consuming. Ishikawa et al. used the triangular fuzzy number to realize the combination of traditional Delphi method and fuzzy theory phase, forming the fuzzy Delphi method. The principle is to use triangular fuzzy numbers to judge the importance of indicators instead of discourse variables, thus transforming the subjective judgments of experts into figurative data values [14]. Referring to the research results of Reference [28] and other scholars, this paper uses the "double triangle fuzzy number method" to optimize the initial indicators.

(2) Implementation steps

1. Questionnaire distribution and opinion collection

The evaluation score of this questionnaire is an integer from 0 to 10. The selected research objects are mainly experts and professors in the fields of resilience, safety management, and project management; relevant staff of the quality supervision department of the construction industry, and those with deep foundation pits or building construction. For experienced technical management personnel, a total of 21 questionnaires were distributed in this survey, and 5 invalid questionnaires were excluded for reasons such as missing answers, poor consistency, and failure to answer according to the rules. Finally, 16 valid questionnaires were recovered. Since this method requires about 15 experts, this survey meets the data-capacity requirements.

According to the design of the initial index questionnaire, the surveyed experts scored 0–10 on the basis of "importance degree". The data were counted according to the three evaluation dimensions of "single value of importance degree D^i", "most pessimistic assignment of importance degree C^i", and "most optimistic assignment of importance degree O^i", and the invalid scoring data with double standard deviation were excluded.

2. Calculation of double triangular fuzzy numbers

According to the results of data aggregation, the maximum value of "a single value of importance D^i", the minimum value and geometric mean value of D^i_L, D^i_U, and D^i_M; the maximum value of "most pessimistic assignment of importance C^i"; the minimum value and geometric mean value of C^i_L, C^i_U, and C^i_M; the maximum value of "most optimistic assignment of importance O^i", and the minimum value and geometric mean value of O^i_L, O^i_U, and O^i_M are calculated, respectively. Then the pessimistic assignment triangular fuzzy number, $C^i = (C^i_L, C^i_M, C^i_U)$, and optimistic assignment triangular fuzzy number, $O^i = (O^i_L, O^i_M, O^i_U)$, are thus established.

3. Expert opinion convergence judgement

In this study, the convergence of indicators is judged based on the gray zone test, and if the indicators do not converge, it means that there is a difference in the recognition of the importance of the part of the indicators by the experts. When $M^i - Z^i > 0$ and $Z^i > 0$, it indicates that the convergence of expert opinions; otherwise, it indicates that the expert opinions are not unified, and a second questionnaire is needed for the second opinion collection. Among them, $M^i = O^i_M - C^i_M$, and $Z^i = C^i_U - O^i_L$.

4. Calculation of expert consensus

When the expert opinion converges, the index should be filtered and eliminated, mainly based on the expert consensus degree value, G^i, with G^i mainly based on D^i_M, C^i_M, and O^i_M of the geometric mean processing. If G^i is larger, the higher the importance of the index, the stronger the relative priority. In order to eliminate the index according to importance, it is necessary to set the threshold value, S^i. The calculation method is to process all of the G^i geometric averages at a time, and if the consensus value of the index is greater than S^i, it is retained; otherwise, it is eliminated, and then the final index evaluation system is constructed. The specific formula is as follows:

$$G^i = \sqrt[3]{D^i_M C^i_M D^i_M} S^i = \sqrt[n]{G^1 G^2 G^3 \cdots G^n} \tag{1}$$

4.3.2. Questionnaire Consultation and Analysis

(1) First round questionnaire

In addition to evaluating the importance of the primary screening indicators, this questionnaire also invites experts to provide opinions on the rationality of the indicator setting, which mainly includes the definition boundary of the indicator, the name of the indicator, the correlation degree of the indicator, etc.; deletes the indicators lacking rationality; and improves the indicators that need to be modified. According to expert opinion analysis, this questionnaire deleted the initial indicators Ac2, Ac5, Ac12, Ac18, Rc4, and Lc5; modified Ac4, Ac17, rc3, and Lc1; supplemented Rc1; and merged Ac17.

In this paper, SPASSAU was used to analyze the reliability of the questionnaire, and the Cronbach's coefficient alpha was 0.864, which was greater than 0.7. In addition, by calculating the geometric averages of the three assignments and judging the convergence of the indexes according to the gray zone test method, it is found that seven indexes, namely Ac3, Ac9, Ac10, Ac12, Rc3, rc1, and rc3, do not meet the convergence requirements, thus indicating that there are differences in the recognition of the importance of these indexes by experts. According to the requirements of the fuzzy Delphi method, only when all indicators meet the convergence can the indicators be screened and eliminated according to the consensus degree value and the index system is finally constructed. Therefore, in the second questionnaire, with the exception that the indicator Ac12 is deleted after accepting experts' opinions, the remaining six indicators need to be collected twice for the same group of experts through the questionnaire.

(2) Second round questionnaire

The six indicators that did not reach the convergence in the first round of questionnaire were collected through the questionnaire form and combined with the results of the first data analysis, and the opinions of 16 experts were again consulted. Through the feedback of the second questionnaire results and data analysis, in terms of reliability analysis, the Cronbach's coefficient alpha is 0.821, which is greater than 0.7 to meet the reliability requirements, and the six indicators Z^i and $M^i - Z^i$ are greater than 0 to meet the convergence requirements. The consensus value, G^i, of all indicators is calculated according to Formula (1) and the geometric average value of all consensus values is calculated to obtain the threshold value, S^i, and finally S^i = 5.91. Since the consensus values of Ac3, Ac9, rc1, and Lc6 are less than 5.91, they are eliminated.

4.3.3. Construction and Interpretation of Final Index System

Through two rounds of expert questionnaires, based on double triangular fuzzy numbers, the optimization and elimination of indicators were carried out to finally complete the construction of deep foundation pit construction safety system resilience evaluation index system, with 23 indicators in 4 dimensions. According to the meaning of the indexes, they were classified into the corresponding subsystems. We renumbered the final indexes and explained their meanings as shown in Table 3.

Table 3. Resilience evaluation index system of deep excavations construction safety system.

Dimension	Evaluating Indicator	Indicator Meaning	Subsystem
Prevent absorption capacity	Construction environment survey Ac1	The ability to investigate the geological and hydrological natural conditions of the area where the deep foundation pit project is located, the layout of the underground water pipe network, and the condition of the surrounding existing buildings.	Technique
	Surface and ground drainage measures Ac2	Power performance of drainage equipment, drainage ditch, dewatering well point arrangement, drainage settings, and reinjection water settings to meet water level control requirements.	Technique
	Earth–rock excavation measures Ac3	Whether earth excavation is strictly prohibited from disorderly and irregular excavation, whether the slope caving rate is reasonable, whether the high slope is graded, and whether effective slope protection measures are taken.	Technique
	Support structure construction measures Ac4	Whether the construction technology and procedure of supporting structure are complied with or not; and whether the control of dip angle, distortion, and displacement meet the requirements of structural stability and safety management.	Technique
	Monitoring level of deep excavations Ac5	Whether the intelligent level of monitoring and data analysis can meet the needs of safety control, whether the monitoring scheme is reasonable, and whether the construction monitoring emergency plan is set up for complex environmental projects.	Technique
	Safe production protection measures Ac6	Whether the safety measures for hazardous work are sound and reasonable.	Personnel
	Investment in security resources Ac7	Resource inputs for on-site safety protection and safety civilized construction facilities, safety equipment for special operators, safety education and training, and emergency drills.	Material
	Safety supervision and inspection Ac8	Supervision on the quality of construction materials and mechanical equipment, the degree of construction behavior norms, the perfection of site safety management mechanism, and the implementation of operational protection measures.	Personnel
	Implementation of security technology disclosure Ac9	Completion of records, completeness of content, and normalization of process.	Technique
	Personnel safety awareness and literacy Ac10	Safety awareness and literacy of field workers.	Personnel
	Personnel qualification management Ac11	Construction management and field worker permits.	Personnel

Table 3. *Cont.*

Dimension	Evaluating Indicator	Indicator Meaning	Subsystem
Resistance	Technical disposal measures of hazard sources Rc1	Whether the technical response measures to various emergencies are timely and reasonable.	Technique
	Availability of emergency supplies and facilities Rc2	Emergency materials and facilities meet the emergency management level.	Material
	Reasonableness of emergency management plan Rc3	Degree of emergency management plan meeting emergency control and accident response needs.	Personnel
	Emergency management and control capabilities of managers Rc4	Reasonable evacuation, personnel resources organization and deployment, organization of rescue, and disaster relief work ability.	Personnel
	Personnel safety aversion and escape ability Rc5	The operator's mastery of emergency escape, protection and self-rescue skills, and the degree of escape possibility given by on-site emergency response.	Personnel
Recovery capability	Psychological recovery ability of the personnel rc1	Worker's ability of panic emotion regulation and stress response mitigation in the late accident period.	Personnel
	The validity of the aftermath rc2	Disposal rate and overall arrangement ability of accident site cleaning, liability compensation, family pension of casualties, implementation of corrective measures, public opinion control, etc.	Personnel
	Redundancy of construction elements rc3	Construction site emergency water supply and power supply facilities, spare construction materials and equipment, spare monitoring and early warning system, and other elements to meet the degree of construction recovery and subsequent safety control.	Material
Learning and adapting capability	Optimization of resource allocation Lc1	Whether to improve the allocation of safety resources according to the accident investigation and summary, emergency drill situation.	Material
	Accident investigation and experience summary Lc2	Post-disaster cause investigation, accident-related data collection, experience summary, and reflection on the development of work.	Personnel
	Improvement of safety and emergency management system Lc3	Whether the daily safety management and emergency management deficiencies exposed in accident investigation and daily emergency drills should be effectively corrected and improved	Personnel
	Safety education training and drills Lc4	Safety education and emergency drills	Personnel

5. Construction of Resilience Evaluation Model for DFPCSS

5.1. Determine the Weight of the Resilience Evaluation Index

(1) Determination of influence relationship among evaluation indexes and construction of ANP network structure diagram

Determine the impact relationship between indicators based on DEMATEL. By judging the degree of mutual influence between the indicators, the interviewed experts used the 0–3 scale method to assign the degree of influence, and the results were arithmetically averaged to obtain the direct impact matrix, T. Standardize T to obtain the normative influence matrix, T^*; use MATLAB software to find the limit of T^*; and multiply and accumulate T^* continuously to obtain the comprehensive influence matrix, D. Set the threshold, λ, for the elements in D, and take 1 when the element value is greater than λ; otherwise, take 0 to construct the reachable matrix, F. Based on the obtained reachability matrix, F, the ANP network structure diagram is constructed.

(2) Judgment of the matrix construction

The correlation factors were compared in pairs, and based on expert questionnaires and group discussions, the relative dominance of indicators was assigned, and a judgment matrix of 54 indicators of dominance was constructed. The following shows only the judgment matrix of Rc1 under the dimension of preventive absorptivity and rc2 under the dimension of resistance, as shown in Tables 4 and 5.

Table 4. Judgment matrix based on RC1 index.

Rc1	Ac1	Ac2	Ac3	Ac4	Ac5	Ac9
Ac1	1	3	2	3	2	1/2
Ac2		1	1/2	1	1/2	1/3
Ac3			1	2	1	1/2
Ac4				1	1/2	1/3
Ac5					1	1/2
Ac9						1

Table 5. Judgment matrix based on rc2 index.

rc2	Rc2	Rc3	Rc4	Rc5
Rc2	1	1	2	1
Rc3		1	2	1
Rc4			1	1/2
Rc5				1

(3) Determination of the index weight

Super Decisions software is used to calculate the related hyper-matrices. The unweighted hyper-matrices weighted hyper-matrices, and limit hyper-matrices are calculated based on the "Unweighted Super Matrix", "Weighted Super Matrix" and "Limit Matrix" commands, respectively. The column vector of the limit hyper-matrices is the final comprehensive weight of each index. The specific results are shown in Table 6.

Table 6. Evaluation index weight of resilience of deep foundation pit construction safety system.

Dimension Index	Indicator Weight	Secondary Indicators	Indicator Weight	Secondary Indicators	Indicator Weight
Prevention absorption capacity (Ac)	0.296688	Construction environment survey Ac1	0.022060	Investment in security resources Ac7	0.077530
		Surface and ground descent and drainage measures Ac2	0.002329	Safety supervision and inspection Ac8	0.107226
		Earthwork excavation measures Ac3	0.021569	Safety technology disclosure and implementation degree Ac9	0.046752
		Construction measures of supporting structure Ac4	0.002369	Personnel safety awareness and literacy Ac10	0.075051
		Monitoring level of deep foundation pit Ac5	0.029576	Post personnel qualification management Ac11	0.057738
		Safety production protection measures Ac6	0.014683		
Resistance resilience (Rc)	0.466884	Technical disposal measures of hazard sources Rc1	0.012264	Emergency control ability of management personnel Rc4	0.050809
		Availability of emergency supplies and facilities Rc2	0.038983	Personnel safety aversion and escape ability Rc5	0.034080
		Rationality of emergency management plan Rc3	0.052287		
Recovery capability (rc)	0.138284	Psychological recovery ability of the personnel rc1	0.019455	Redundancy of construction elements rc3	0.064765
		The validity of the aftermath rc2	0.058015		
Learning and adapting capability (Lc)	0.098143	Optimization of resource allocation Lc1	0.031171	Improvement of safety and emergency management system Lc3	0.051236
		Accident investigation and experience summary Lc2	0.051921	Safety education training and drills Lc4	0.078132

5.2. Construction of Extension Cloud Resilience Evaluation Model

(1) Determine the matter element to be evaluated

Combining the extension theory and cloud theory, the eigenvalue (Ex, En, He) is used to replace the eigenvalue in the traditional matter–element model to construct the cloud matter–element to be evaluated. The main form is shown in Formula (2):

$$R = (N, C, V) = \begin{bmatrix} N & C1 & V1 \\ & C2 & V2 \\ & \dots & \dots \\ & Cn & Vn \end{bmatrix} = \begin{bmatrix} N & C1 & (Ex_1, En_1, He_1) \\ & C2 & (Ex_2, En_2, He_2) \\ & \dots & \dots \\ & Cn & (Ex_n, En_n, He_n) \end{bmatrix} \tag{2}$$

where (Ex_i, En_i, He_i) is the cloud representation of the matter–element eigenvalue, V, to be evaluated.

(2) Determine the boundary of the evaluation level

Based on the resilience connotation of deep excavations construction safety system, and according to the resilience evaluation indicators screened above, the disaster prevention and disaster relief performance and safety control level of construction site before, during, and after disasters in each accident case are analyzed. On the basis of ensuring the rationality and balance of the grading gradient of the resilience evaluation level, the resilience evaluation level of the safety system is divided into five levels, namely excellent (corresponding Level 1), good (corresponding Level 2), medium (corresponding Level 3), passing (corresponding Level 4), and poor (corresponding Level 5). According to the relevant literature research and expert opinions, the boundary value of the evaluation index grade constructed above is set. Each grade interval contains the corresponding boundary threshold and numerical span, as shown in Table 7.

Table 7. Evaluation grade limit value of resilience index of deep foundation pit construction safety system.

Evaluation Indicators	Resilience Evaluation Grade Limits				
	Level 1 (Excellent)	Level 2 (Good)	Level 3 (Medium)	Level 4 (Pass)	Level 5 (Poor)
Construction environment survey Ac1	(100,90]	(90,80]	(80,70]	(70,60]	(60,0]
Surface and ground drainage measures Ac2	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Earthwork excavation measures Ac3	(100,90]	(90,80]	(80,70]	(70,60]	(60,0]
Support structure construction measures Ac4	(100,90]	(90,80]	(80,70]	(70,60]	(60,0]
Monitoring level of deep foundation pit Ac5	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Safety production protection measures Ac6	(100,90]	(90,80]	(80,70]	(70,60]	(60,0]
Investment in security resources Ac7	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Safety supervision and inspection Ac8	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Safety technology disclosure and implementation degree Ac9	(100,90]	(90,80]	(80,70]	(70,60]	(60,0]
Personnel safety awareness and literacy Ac10	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Post personnel qualification management Ac11	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Technical disposal measures of hazard sources Rc1	(100,90]	(90,80]	(80,70]	(70,60]	(60,0]
Availability of emergency supplies facilities Rc2	(100,90]	(90,80]	(80,70]	(70,60]	(60,0]
Rationality of emergency management plan Rc3	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Emergency control ability of management personnel Rc4	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Personnel escape ability Rc5	(100,90]	(90,80]	(80,70]	(70,60]	(60,0]
Psychological recovery ability of personnel rc1	(100,90]	(90,80]	(80,70]	(70,60]	(60,0]
validity of aftermath rc2	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Redundancy of construction elements rc3	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Optimization of resource allocation Lc1	(100,90]	(90,80]	(80,70]	(70,60]	(60,0]
Accident investigation and experience summary Lc2	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Improvement of safety and emergency management system Lc3	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]
Safety education training and drills Lc4	(100,95]	(95,85]	(85,75]	(75,65]	(65,0]

The hierarchical boundaries of safety system resilience are treated as a dual constraint space $[c_{\max}, c_{\min}]$, and the hierarchical boundary cloud parameters are set according to Formula (3), where S is a constant, which can be fine-tuned according to the actual situation and the dual uncertainty of the corresponding index. This paper takes 0.1:

$$Ex_n = \frac{c_{\max} + c_{\min}}{2}, En_n = \frac{c_{\max} - c_{\min}}{6}, He_n = S = 0.1 \tag{3}$$

(3) Determination of membership and evaluation of safety resilience

1. Build a comprehensive evaluation matrix

Referring to the operation rules of the normal cloud generator, the score value of each index is regarded as a cloud droplet, and the cloud droplet is calculated according to the three characteristic values (Ex, En, He) obtained by the double-constrained space processing of the previous grades and boundaries, according to Formula (4). For the correlation degree of the resilience evaluation level, the cloud membership degree of each cloud droplet is obtained:

$$k_{il} = \exp\left[-\frac{(x_i - Ex)^2}{2En'^2}\right] \tag{4}$$

In order to reduce the influence of sample randomness on the evaluation results, based on MATLAB programming software, the above calculation steps are repeated N times to take the average value of each index, and finally the comprehensive evaluation matrix, K, is established by summary, as shown in Formula (5):

$$k = \begin{bmatrix} k_{11} & k_{12} & \cdots & k_{15} \\ k_{21} & k_{22} & \cdots & k_{25} \\ \cdots & \cdots & \cdots & \cdots \\ k_{n1} & k_{n2} & \cdots & k_{n5} \end{bmatrix} \tag{5}$$

2. Determination of membership matrix of resilience grade of first-level evaluation index

By weighting the membership degree of the secondary index corresponding to the dimension index in the comprehensive evaluation matrix, K, the membership degree matrix of the dimension index can be obtained (refer to Formula (6)):

$$M = \left[w_1{}^l, w_2{}^l, w_3{}^l \ldots w_n{}^l\right] \bullet \begin{bmatrix} k_{11} & k_{12} & \cdots & k_{15} \\ k_{21} & k_{22} & \cdots & k_{25} \\ \cdots & \cdots & \cdots & \cdots \\ k_{n1} & k_{n2} & \cdots & k_{n5} \end{bmatrix} = \begin{bmatrix} m_1{}^1 & m_1{}^2 & m_1{}^3 & m_1{}^4 & m_1{}^5 \\ m_2{}^1 & m_2{}^2 & m_2{}^3 & m_2{}^4 & m_2{}^5 \\ m_3{}^1 & m_3{}^2 & m_3{}^3 & m_3{}^4 & m_3{}^5 \\ m_4{}^1 & m_4{}^2 & m_4{}^3 & m_4{}^4 & m_4{}^5 \end{bmatrix} \tag{6}$$

$w_n{}^l$ means the nth secondary index under dimension index l, and $m_i{}^l$ represents the membership under dimension index L under resilience level i.

3. Resilience grade evaluation vector calculation

By weighting the membership degree of the resilience grade of the first-level evaluation index, the evaluation vector, P, of the resilience grade can be obtained, as shown in Formula (7):

$$P = [W_1, W_2, W_3, W_4] \quad M = [p_1, p_2, p_3, p_4, p_5] \tag{7}$$

4. Determination of the resilience evaluation level

When the resilience evaluation result has a higher membership degree than a resilience grade, it indicates that the actual resilience level matches the grade. According to the calculated resilience grade evaluation vector, the maximum membership degree principle is adopted to judge the resilience membership grade of the deep excavations construction safety system. The specific formula is as follows:

$$p_J = \max(p_1, p_2, p_3, p_4, p_5) \rightarrow \text{Resilience affiliation grade is } J$$

$$r = \frac{\sum\limits_{i=1}^{5} z_i \cdot p_i}{\sum\limits_{i=1}^{5} p_i}, \quad E_{rx} = \frac{r_1(x) + r_2(x) + r_3(x) + \cdots\cdots + r_n(x)}{n} \tag{8}$$

where P_J is the maximum membership of five evaluation grades of resilience; z_i is the score that corresponds to the membership grade, i.e., from the first level to the fifth level are 1~5 points; r is the comprehensive resilience evaluation score; E_{xr} is the expected score for comprehensive resilience evaluation; and $r_n(x)$ is the comprehensive resilience evaluation score for the first operation.

Combined with the expected value and the subordinate level of the comprehensive evaluation of the resilience of the deep excavations construction safety system, the safety resilience level can be judged.

5. Reliability test

Since the expected score, E_{xr}, of resilience comprehensive evaluation is the result of multiple calculations, it is necessary to introduce the index reflecting the discrete degree of multiple calculation results and the reliability factor, θ, to test the evaluation results. If the θ value is larger, the credibility is lower. Conversely, if the θ value is smaller, the credibility is higher. Formula (9) shows the specific formula:

$$E_{rn} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(r_i(x) - E_{rx})^2} \tag{9}$$

6. Case Study

6.1. Project Overview

The No. 01 civil construction project of the first phase of Metro Line 1 in a Chinese city is located in Tongzhou District and Gangzha District of the city. The main project includes two stations and three sections. There are two groups of wind pavilions and four entrances and exits in the study station, of which the No. 4 entrance and the No. 2 wind pavilion are jointly constructed. According to the overall technical requirements, the excavation depth of the auxiliary foundation pit of the station is 9~12 m, the safety grade of the auxiliary foundation pit is secondary, and the environmental protection grade is secondary. The requirements for the protection level of foundation pit deformation control are the maximum subsidence of the ground is $\leq$0.2%H, and the maximum horizontal displacement of the enclosure structure is $\leq$0.3%H.

6.2. Determination of Evaluation Grade Boundary Cloud Parameters

According to the boundary threshold and numerical span of each grade interval, Formula (6) is used to determine the boundary cloud parameters of evaluation grade. Take the evaluation index Ac1, the dimensional index Ac and the total target resilience index as examples and use MATLAB to draw the standard cloud diagram, as shown in Figures 4–7.

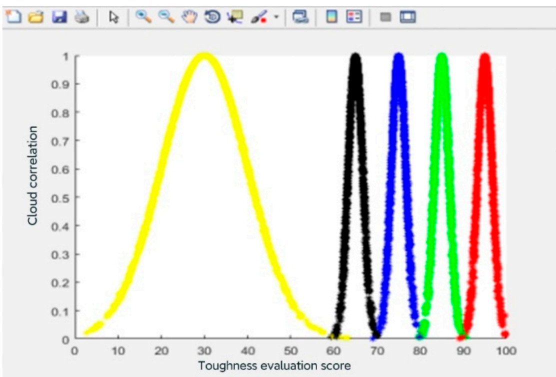

Figure 4. A_C1 index standard cloud chart.

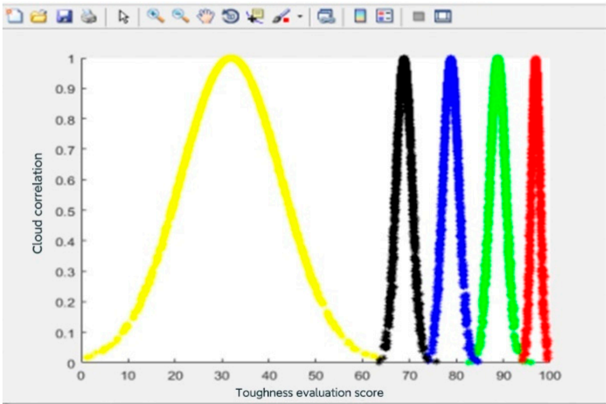

Figure 5. A_C index standard cloud chart.

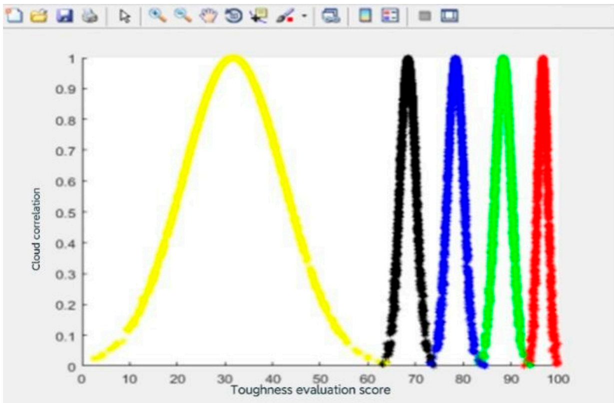

Figure 6. Standard cloud chart of total target resilience.

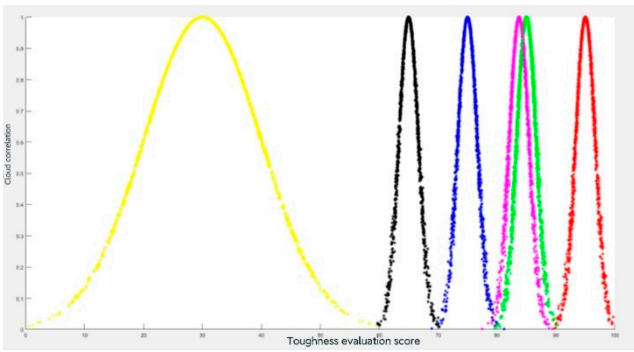

Figure 7. Cloud chart of overall target resilience evaluation level.

6.3. *Affiliation Calculation*

This study refers to the project unit's construction survey, safety management, emergency response, safety training, daily safety inspection records, and construction monitoring and then asks relevant questions of construction managers and site operators from the perspectives of personnel emergency organization capability, general knowledge of safety avoidance, and post-disaster dispatch and cleanup capability. Combined with expert recommendations and group discussions, the city's Metro Line 1 Phase I project study stations were scored and evaluated based on the deep foundation pit construction safety system resilience evaluation index system. Then the judging results were weighted average according to the expert level and substituted into the cloud model. Multiple calculations were performed by using MATLAB software to obtain the secondary resilience evaluation index level affiliation. The dimensional index affiliation was obtained by weighting, and the specific results are shown in Table 8.

Table 8. Secondary index grade membership degree of resilience evaluation of deep foundation pit construction safety system.

Evaluation Indicators	Weight	Score	Grade Membership					Judge
			Level 1	Level 2	Level 3	Level 4	Level 5	
Ac1	0.022060	88.34	0.0005	0.1379	0.0000	0.0000	0.0000	Good
Ac2	0.002329	78.94	0.0000	0.0000	0.8156	0.0000	0.0001	Medium
Ac3	0.021569	75.69	0.0000	0.0000	0.9172	0.0000	0.0000	Medium
Ac4	0.002369	83.65	0.0000	0.7204	0.0000	0.0000	0.0000	Good
Ac5	0.029576	69.35	0.0000	0.0000	0.0000	0.9266	0.0031	Pass
Ac6	0.014683	74.20	0.0000	0.0000	0.8905	0.0000	0.0001	Medium
Ac7	0.077530	93.63	0.0001	0.0957	0.0000	0.0000	0.0000	Good
Ac8	0.107226	95.36	0.0432	0.0068	0.0000	0.0000	0.0000	Excellent
Ac9	0.046752	81.47	0.0000	0.1095	0.0007	0.0000	0.0000	Good
Ac10	0.075051	82.21	0.0000	0.0000	0.4136	0.0000	0.0000	Medium
Ac11	0.057738	90.65	0.0000	0.9262	0.0000	0.0000	0.0000	Good
Rc1	0.012264	82.37	0.0000	0.2897	0.0001	0.0000	0.0000	Good
Rc2	0.038983	82.12	0.0000	0.2251	0.0002	0.0000	0.0000	Good
Rc3	0.052287	87.88	0.0000	0.4451	0.0000	0.0000	0.0000	Good
Rc4	0.050809	86.39	0.0000	0.0981	0.0009	0.0000	0.0000	Good
Rc5	0.034080	71.62	0.0000	0.0000	0.1294	0.0005	0.0002	Medium
rc1	0.019455	84.44	0.0000	0.9450	0.0000	0.0000	0.0000	Good
rc2	0.058015	89.56	0.0000	0.9655	0.0000	0.0000	0.0000	Good
rc3	0.064765	85.57	0.0000	0.0313	0.0044	0.0000	0.0000	Good
Lc1	0.031171	76.31	0.0000	0.0000	0.7330	0.0000	0.0000	Medium
Lc2	0.051921	88.34	0.0000	0.7802	0.0000	0.0000	0.0000	Good
Lc3	0.051236	78.94	0.0000	0.0000	0.3794	0.0000	0.0002	Medium
Lc4	0.078132	75.69	0.0000	0.0000	0.0000	0.0825	0.0078	Pass

6.4. Resilience Level Determination and Reliability Test

According to the membership degree of the secondary index, the membership degree of the dimension index is obtained by weighted calculation according to Formula (8). The membership grade is determined according to the principle of maximum membership degree, as shown in Table 9.

Table 9. Deep foundation pit construction safety system resilience evaluation dimension index grade membership.

Dimension Indicators	Weight	Dimension Index Resilience Evaluation Grade Membership					Judge
		Level 1	Level 2	Level 3	Level 4	Level 5	
Ac	0.296688	0.0046	0.0714	0.0659	0.0274	0.0001	Good
Rc	0.466884	0.0000	0.0405	0.0045	0.0000	0.0000	Good
rc	0.138284	0.0000	0.0764	0.0003	0.0000	0.0000	Good
Lc	0.098143	0.0000	0.0405	0.0424	0.0065	0.0006	Medium

According to Formula (8), the dimensional index evaluation level affiliation is weighted to obtain the target resilience evaluation level affiliation: $p_j = \max(p_1, p_2, p_3, p_4, p_5) = max(0.0014, 0.546, 0.0258, 0.0088, 0.0001) = p_2$. According to the principle of maximum affiliation, we know that the affiliation level of the resilience target is Level 2, as shown in Table 10.

Table 10. Membership degree of overall objective resilience evaluation grade.

Indicators	Total Target Resilience Evaluation Grade Membership					Judge
	Level 1	Level 2	Level 3	Level 4	Level 5	
Total target	0.0014	0.0546	0.0258	0.0088	0.0001	Good

According to the formula, E_{xr} = 3.5589, E_{rn} = 0.0190, and θ = 0.0054 can be calculated by MATLAB programming. It is generally believed that $\theta < 0.01$ indicates that the results are credible [29]. Therefore, the evaluation results of this paper meet the reliability requirements. Based on the subordinate level of the resilience target and the expectation of the evaluation score, the resilience level of the deep foundation pit project of the first-stage research station of Metro Line 1 in the city is finally determined to be Level 2 (good). After the three eigenvalues of the corresponding evaluation results are returned by the reverse cloud generator, the forward cloud generator is used to generate the cloud picture of the total target resilience evaluation level of the corresponding evaluation results. It can be seen from Figure 4 that the cloud droplet distribution on the normal cloud model is between the second level and the third level, but it is more inclined to the second level. Therefore, it can be explained that the cloud droplet distribution of the normal cloud model and the comprehensive evaluation results of the resilience evaluation results of the deep foundation pit construction safety system of the station are highly consistent.

6.5. Resilience Enhancement Strategies

(1) Preventive absorption capacity dimension

Attention needs to be paid to the safety training of the whole construction process and conduct post-job education and training for personnel with professional and technical requirements or more dangerous positions before and after entry, explain the consequences of illegal operations, help operators to clarify the safety situation, and improve safety literacy and awareness. The safety monitoring of deep foundation pit should pay attention to the application of intelligent and information technology, build an integrated intelligent monitoring platform and 3D visualization warning mechanism, share the monitoring data in real time, grasp the safety status of the main structure in time and accurately, and provide the basis for emergency management and hazard disposal.

(2) Resistance dimension

In daily emergency drills, focus on the targeted training of operators' escape ability to ensure their familiarity with safe escape paths and escape locations and mastery of emergency self-rescue skills is needed. Furthermore, the construction site should improve the resource allocation and investment of emergency equipment and facilities to meet the needs of personnel evacuation.

(3) Recovery ability dimension

Attention needs to be paid to the post-disaster recovery work and the organizational efficiency of the aftermath measures and the proper handling of the emotional comfort of the operators.

(4) Learning adaptation ability dimension

Based on the results of the accident investigation and feedback from emergency drills, optimize the deployment of material, machinery, and human resources in a timely manner. Modify ineffective regulations, improve site management organization structure, and make up for omissions and deficiencies in emergency management and resource input. Replace or repair protective equipment and facilities with low applicability and availability in a timely manner and clarify the emergency responsibilities and work content of each management personnel after the accident to meet the needs of emergency management and accident response.

7. Conclusions

With the change of safety management concept and the depth of theoretical research, the Safety-II system safety research paradigm with the concept of resilience as the core provides new ideas for the response to engineering disasters from the perspective of dynamics and development. In order to solve the problem of frequent safety accidents in deep foundation pit construction, it is necessary to establish a construction safety system resilience evaluation index system and evaluation model to evaluate the site safety condition and accident response capability.

Through theoretical and empirical analysis, this paper obtained the following research conclusions:

(1) The resilience evaluation index system should be based on the key factors affecting the resilience of deep foundation pit construction safety system play process, from the prevention of absorption, resistance, recovery, and learning adaptive capacity four dimensions systematically constructed.
(2) The evaluation of resilience should consider the objective correlation between evaluation indicators and the randomness and fuzzy characteristics of resilience evaluation itself. Using DEMATEL–ANP to calculate and analyze the relative weights of indicators can better circumvent the limitations and unreasonableness of conventional methods such as AHP. The resilience evaluation based on extension cloud model can better solve the problem of transforming the evaluation index from qualitative to quantitative, and also adapt to the characteristics of resilience evaluation.
(3) Resistance capability is the most significant capability representation that reflects the level of system resilience and has the highest importance and core degree compared to other dimensions. Therefore, maintaining the basic functions of the system in the face of disaster perturbations is the most critical stage of resilience emergence in the process of accident response; the weighting of prevention and absorption capability is also significant, indicating that successful prevention of safety accidents is a better state expression of the system, and paying attention to pre-safety risk identification can reduce the reliance on resistance and recovery capability in the late stage of accidents; post-disaster recovery and applicability learning capability can achieve internal safety system "evolutionary" enhancement.

Based on the proposed resilience evaluation index system and evaluation model, contractors or government construction safety management departments can evaluate the resilience of the safety systems of different deep foundation pit construction projects, thus providing a basis for ex ante prevention and ex post response to construction accidents.

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