buildings

MDPI

Article

Safety Resilience Evaluation of Deep Foundation Pit Construction Based on Extension Cloud Model

Xiaojian Guo, Jiayi Mao, Luyun Wang and Jianglin Gu *

School of Economics and Management, Jiangxi University of Science and Technology, Ganzhou 341000, China; 9120040023@jxust.edu.cn (X.G.); 6720230925@mail.jxust.edu.cn (J.M.); 6720221296@mail.jxust.edu.cn (L.W.)
* Correspondence: jianglingu@jxust.edu.cn

Abstract

Deep foundation pit construction faces significant safety challenges—including frequent accidents and severe disaster consequences—due to inherent complexity and uncertainty. Conventional risk assessment methods cannot adequately evaluate these complex engineering systems. This study introduces the concept of resilience to analyze safety issues during the deep foundation pits construction process and develops a safety resilience evaluation model based on the extension cloud model theory. First, based on the characteristics of the deep foundation pit construction process and the four stages of safety resilience, a safety resilience curve for deep foundation pit construction is plotted. Then, using multi-text analysis, an evaluation indicator list for deep foundation pit construction safety resilience is constructed, comprising 4 primary indicators and 24 secondary indicators. Next, based on the extension cloud model theory, the IF-AHP and entropy weight methods are combined to calculate the cloud membership degrees, systematically constructing a safety resilience evaluation model for deep foundation pit construction. Taking the Nanchang HH Center deep foundation pit project as an example, the model's effectiveness and accuracy are validated. The results indicate that the safety resilience level of this deep foundation pit project is Grade IV, consistent with the actual engineering conditions, thereby validating the scientific validity of this method. This study innovatively applies the concepts of safety resilience and the extension cloud model to deep foundation pit construction assessment, providing a suitable method for evaluating safety risks in deep foundation pit construction projects. The model assists decision-makers in appropriate risk classification and scientific risk prevention strategies, enhances the safety management system for deep foundation pit construction, and even promotes the sustainable development of the construction industry.

Keywords: deep foundation pit; IF-AHP method; entropy weight method; extension cloud; resilience evaluation

check for updates

Academic Editors: Erwin Oh and Cedric Payan

Received: 13 July 2025
Revised: 25 August 2025
Accepted: 3 September 2025
Published: 5 September 2025

Citation: Guo, X.; Mao, J.; Wang, L.; Gu, J. Safety Resilience Evaluation of Deep Foundation Pit Construction Based on Extension Cloud Model. *Buildings* **2025**, *15*, 3216. https://doi.org/10.3390/buildings15173216

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

As an essential component of underground transportation hubs, large-scale commercial complexes, and utility tunnels, foundation pit engineering has become a new trend in urban construction and development due to its efficient utilization of vertical space. However, the rapid growth of deep foundation pit projects also faces severe challenges, including high accident rates and difficulties in rescue and recovery, stemming from their inherent structural characteristics. Moreover, the current safety management systems for deep foundation pit construction primarily emphasize preemptive prevention, often neglecting the system's inherent resilience, coping capacity, and recovery enhancement

capabilities, making it difficult to meet the complex safety demands of modern deep foundation pit construction. During the critical and high-risk phases of urban construction, numerous challenges and uncertainties arise. These challenges include the following: the close proximity of existing building foundations and structures such as buildings, subway tunnels, municipal pipelines, and elevated bridges, which necessitate extremely stringent requirements for deformation control. Limited space at construction sites in urban centers further complicates the design of support structures and construction organization. Uneven soil layer structures, complex groundwater conditions (such as confined water), and unfavorable geological features may cause discrepancies between measurement data and actual conditions, thereby introducing significant uncertainty. These challenges indicate that relying solely on traditional methods emphasizing "absolute safety" and "risk avoidance" is insufficient to address the inherent complexity and uncertainty in modern deep foundation pit engineering. We need a new paradigm to manage these systemic risks. Therefore, integrating the concept of resilience into safety research for deep foundation pit construction and proposing targeted optimization strategies for construction safety are pressing issues that need to be addressed.

To further explore deep foundation pit construction safety, many scholars have conducted research. Jiang [1] argue that project construction safety is influenced by multiple factors such as time, space, events, characteristics, people, and object states, leading to the design of an efficient decision-making system for intrinsic safety risks based on CBR. Meng [2] study factors including geological conditions, surrounding environment, monitoring, construction, and management in deep foundation pit construction, introducing the MABAC method to identify high-risk factors and classify risk levels. Zhang [3] conducts dynamic analysis of leakage risks in water-rich sand layers, establishing a leakage risk evaluation index system that covers factors such as strata, recharge, structure, and deformation. Most of these studies focus primarily on pre-construction analysis and control of construction safety, without considering the full-process safety management in response to risk development or accident impacts.

Due to the suddenness and complexity of safety disasters or accidents in deep foundation pit construction, the demand for construction safety management throughout the development process is increasing. Some scholars have attempted to integrate the concept of resilience into deep foundation pit safety research. Ling et al. [4] constructed a deep foundation pit safety resilience model using DEMATEL-ANP-normal cloud from four aspects: people, materials, technology, and environment. Wang [5] identified indicators affecting the resilience of deep foundation pits in subway stations from three aspects: the foundation pit itself, construction, and support design, and used the Euclidean distance method for resilience assessment. Chen [6] combined the concept of resilience to construct a resilience evaluation system for subway construction safety from six systems: engineering organization, materials and equipment, construction process safety management, and construction work environment, and used the Analytic Hierarchy Process (AHP) multi-level fuzzy comprehensive evaluation method to quantitatively calculate resilience values. It can be observed that although these studies incorporate the definition of resilience, they have not linked actual resilience characteristics to build indicator bodies and conduct calculations and analyses.

Given this, this paper aims to construct a deep foundation pit construction safety resilience index system that spans the criteria layer from four dimensions: robustness, redundancy, efficiency, and adaptability. It also establishes an evaluation model based on Intuitive Fuzzy Analytic Hierarchy Process (IF-AHP) entropy weighted extended cloud, aiming to accurately assess the level of safety resilience, identify weak points in construc-

tion safety management, and optimize them, providing a reference for research on deep foundation pit construction safety.

2. Literature Review

2.1. Deep Foundation Pit Safety Management

Regarding the safety status of deep foundation pits, Yongcheng [7] identified several major factors causing safety risks in subway deep foundation pit construction using Bayesian network analysis: drilling collapse, mechanical injuries, shotcrete hazards, and surface/groundwater leakage. Jianliang [8] argued that project construction safety is influenced by multiple factors including time, space, events, characteristics, human factors, and object states, thus designing a BIM-based safety risk decision system emphasizing case similarity and correlation. Meng [9] conducted research on geological conditions, surrounding environment, monitoring, construction, and management factors in deep foundation pit construction, introducing the game cloud model to identify high-risk factors and classify risk levels for risk management guidance. Wang [10] found that pumping water from the confined aquifer of large deep foundation pit groups may lead to significant environmental deformation. Therefore, it is necessary to carry out on-site pumping and recharge tests to guide the design of groundwater and environmental deformation control schemes. Luo [11] evaluated the effectiveness of different pile row guardrail schemes in assessing the risks associated with deep foundation pit excavation in soft soil near existing tunnels through numerical research. Through numerical analysis, he gained an understanding of the main interaction mechanisms between excavation, guardrails, and tunnels. TuanPN [12] combined the analysis of variance with the finite element method (FEM) to simulate the stability of the column wall in deep foundation pit projects under different loads, and revealed the deformation law at the joint of the wall.

Wubo et al. [13] identified safety factors in deep subway foundation pit construction through hydrogeological analysis, excavation, and mechanical operations. They established an improved entropy-based DEMATEL-ISM model to explore dynamic relationships between these factors. Hu et al. [14] developed a BIM-knowledge graph framework for safety risk identification, assisting intelligent detection of key safety factors. Liu et al. [15] proposed a combined WBS-RBS method with G1 method for deep foundation pit excavation risk assessment. Through case studies, they identified Grade III risks in underground continuous wall construction, excavation, and main structure construction. Zhang et al. [16] analyzed safety supervision dimensions, emphasizing the need to prioritize preliminary exploration design, plan formulation, organizational management, quality control, technical management, and emergency response to ensure deep foundation pit construction safety.

2.2. Resilience Related Research

Huang et al. [17] studied the spatial distribution characteristics of resilience factors affecting 11 cities in Shanxi province from 2014 to 2023 by using the Moran index, exploratory regression analysis, and a geographically weighted regression (GWR) model. Liu et al. [18] proposed a different research method, and they developed an evaluation system with 29 indicators, focusing on the coordination of safety and efficiency. Zihan et al. [19], for problems such as poor building quality, aging infrastructure, and insufficient public services, optimized the adaptability, resilience, and transformation capacity of the community by renovation. Guan [20] evaluated the education level, resilience safety culture, safety learning ability, and safety performance of workers through a questionnaire survey. The results showed that the education level of construction workers had a significant positive impact on safety performance. Ying [21] systematically elaborated on the 19 dimensions of resilient safety culture across different maturity stages and probed into the practical

application of assessment frameworks and models. The research theoretically provides insights into the characteristics of resilient security culture maturity. Practically, it offers actionable guidance for benchmarking practices and enhancing organizations' capacity to manage security risks effectively. Chen [22] pioneered the application of resilience theory to engineering systems, developing a quantifiable model for metro project resilience using Bayesian networks, providing innovative approaches for risk resistance, adaptation, and recovery in subway infrastructure. Wang [23] established a comprehensive evaluation system for fire engineering resilience in historical and cultural districts through three dimensions: architectural resilience, site resilience, and road resilience, offering new perspectives on urban and district disaster prevention strategies. Ma [24] developed a risk resilience assessment framework for deep foundation pit construction in water-rich soft soils, focusing on resisting seepage, repairability, and preventing continuous failure, providing reference for risk management in urban underground space development. Chen [25] constructed a safety evaluation index system for prefabricated building construction from four resilience perspectives: stability, redundancy, efficiency, and adaptability.

2.3. Research Gap

(1) While safety management remains a critical focus in deep foundation pit construction, research on construction safety resilience requires further exploration. Current studies primarily concentrate on identifying risk factors, implementing preventive measures, and conducting safety assessments during the construction process. However, these efforts predominantly emphasize pre-construction and mid-construction phases while neglecting post-construction recovery capabilities and the development of rapid response mechanisms for emergency situations. This study establishes an indicator system across four dimensions of deep foundation pit resilience, conducting comprehensive analysis throughout the entire construction process. It specifically evaluates and addresses safety-related resilience challenges encountered during construction. By extending the scope of existing research through full-process analysis, the paper innovatively incorporates the entire construction cycle into unified safety resilience calculations and evaluations, ultimately deriving conclusive findings.

(2) The depth and breadth of the application of resilience theory in the field of deep foundation pit safety are insufficient. At present, although the concept of resilience is combined with the research on the safety of deep foundation pit construction, the index body is not constructed and calculated based on the actual resilience characteristics, and the many-to-many relationship between the index and the criterion layer is ignored. This study employs a research methodology that integrates subjective and objective approaches through the use of IF-AHP and entropy weighting, selecting indicators from existing research cases to calculate comprehensive weight values of indicator layers relative to the objective layer, thereby enhancing the applicability of the evaluation system. Through extensive quantification of indicators and alignment with practical scenarios, we establish a many-to-many relationship between indicators and the standard layer.

(3) In the research on the safety of deep foundation pit construction, the weighting methods are mainly concentrated in the entropy weighting method, analytic hierarchy process, G1 method (sequence relationship method), gray correlation analysis method, Delphi method, etc. The above methods are not comprehensive enough to reflect the safety and resilience management of deep foundation pit, so it is urgent to have a more comprehensive method for the safety evaluation of deep foundation pit. The extension cloud model effectively addresses the randomness and fuzziness of evaluation indicators, resolving contradictions and incompatibilities within assessment systems.

This study employs cloud membership functions to classify resilience indicators for deep foundation pits, significantly addressing multidimensional uncertainty issues in their indicator systems and enhancing the accuracy of research conclusions. While safety resilience emphasizes dynamic adaptability, our model provides robust support for comprehensive risk identification, enables quantitative quantification of resilience levels with inherent uncertainties, and dynamically reflects resilience evolution. These advancements effectively overcome limitations in existing studies, such as incomplete evaluations and static identification approaches.

3. Deep Foundation Pit Construction Safety Resilience

3.1. Security Resilience Connotation/Definition

Hughes [26] believes that resilience refers to the ability to return to a previously safe state after a disaster event. Trnka [27] defines resilience as the capacity of individuals and organizations to continuously adapt to changing needs and conditions during crises and disasters, handling dynamic and complex challenges. Liu et al. [28] argue that resilience has four major characteristics: adaptability, robustness, recover-ability, and redundancy, which enable comprehensive safety management throughout the process of prevention, response, coping, and recovery. It is evident that research on safety resilience differs from risk management, which focuses solely on pre-incident control. Resilience encompasses pre-incident resistance, mid-incident response and recovery, as well as post-incident enhancement, emphasizing the system's ability to sustain development throughout the entire process of facing safety incidents. Since Macaskill et al. [29] point out that the concept of resilience should be understood in the context of practical application fields, it is necessary to analyze the background of deep foundation pit engineering applications before defining the concept of resilience in deep foundation pit safety.

Deep foundation pit engineering is a systematic project that integrates geological engineering, geotechnical engineering, and structural engineering [30]. It often occurs in urban centers with complex surrounding buildings and underground pipelines, deep burials, and limited construction sites. Once local damage occurs, it can easily trigger a chain reaction, characterized by rapid accident development, severe consequences, and difficult rescue operations. Based on this, combining the inherent complexity of deep foundation pit engineering and the theory of resilience, the safety resilience of deep foundation pit construction is defined as: the system's ability to maintain structural safety through its inherent resilience when disturbed by disaster-causing factors or impacted by accidents; the ability to quickly take measures during an incident to prevent further damage; and the ability to recover to a safe state. Additionally, it includes the capability to optimize the construction safety system post-incident to prevent similar accidents from happening again [31].

3.2. Conceptual Curve and Characteristics of Security Resilience

The safety resilience of deep foundation pit construction is realized through the whole process of dynamic development of the safety system in four stages: resistance, response, recovery, and improvement. Based on this, the concept curve of safety resilience of a deep foundation pit construction is constructed, as shown in Figure 1.

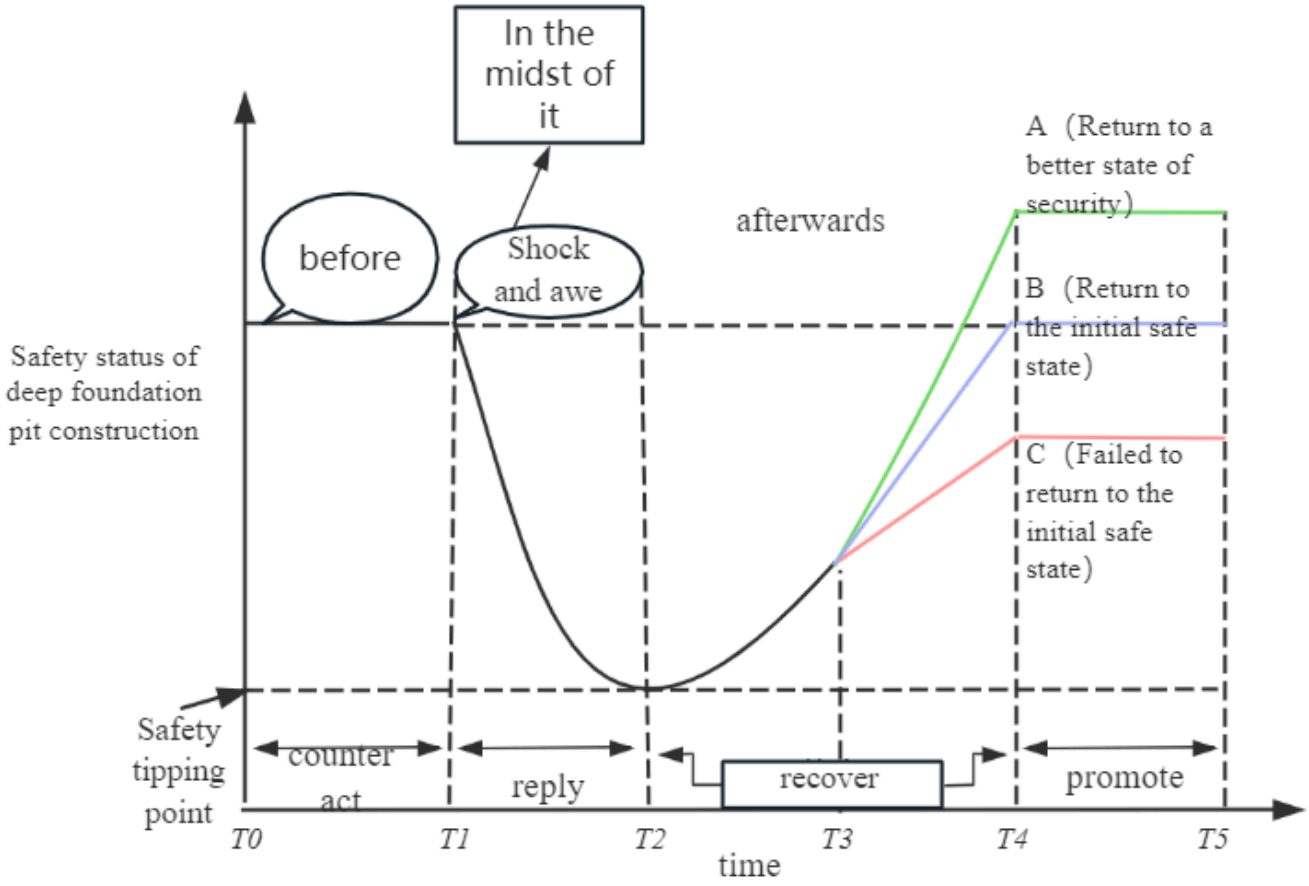


Figure 1. Conceptual curve of security resilience.

(1) During the T0 to T1 phase, the system is in the pre-event stage, free from risk disturbances and in a safe state. This phase corresponds to the inherent characteristic of resilience—robustness. Robustness is defined as the system's ability to resist disturbances caused by disaster factors, which means the system's capability to maintain structural stability and functional integrity when faced with external disturbances. Robustness forms the foundation for the system's resistance to external risks and directly determines the probability of safety incidents [32]. The higher the robustness, the more adequate the system's own safety redundancy, and the stronger its ability to remain safe after being disturbed, thereby significantly reducing the likelihood of safety accidents.

(2) During the T1~T2 phase, the system enters the mid-phase, where the risk impact has exceeded its capacity, leading to partial structural damage and a gradual decline in system safety. This phase corresponds to the core characteristic of resilience—redundancy. Redundancy is defined as the system ability to respond to external shocks, which involves setting up backup resources and emergency response mechanisms to ensure safety. It refers to the capability to promptly self-regulate and mitigate disasters, ensuring that the system can continue operating after partial damage and provide conditions for subsequent recovery. The higher the redundancy, the faster the system can regain self-control, reducing further impacts on safety and minimizing the decline in safety status, as well as the casualties and property losses caused by initial damage.

(3) In the T2~T4 phase, the system enters the post-incident stage, having already suffered a certain degree of damage. It is imperative to take measures to restore and repair the damaged structures and functions, gradually returning to a relatively stable and

safe state. This phase corresponds to the key characteristic of resilience—efficiency. Efficiency is defined as the system's ability to recover from an incident, meaning the speed and efficiency with which the system can gradually return to its initial safe state or reach a new equilibrium after being impacted by damage. The higher the efficiency, the more quickly the system can identify and repair damaged parts, prevent further losses and delays, and accelerate the recovery to a safe and controllable state [32].

(4) In the T4~T5 phase, if the system has strong recovery capabilities after an incident, it can quickly return to the initial safe state (B). If the system has extremely strong recovery and enhancement capabilities, it can recover to a better safe state (A). However, if the system's recovery and enhancement capabilities are weak, it cannot return to the initial safe state (C). This phase corresponds to the critical characteristic of resilience—adaptability, which is defined as the system's ability to improve after external shocks. It refers to the system's capacity to learn from incidents, continuously enhance construction safety resilience, and improve its long-term safety resilience capabilities, thereby significantly reducing the likelihood of similar accidents recurring [33].

4. Construction of Resilience Index System

4.1. Selection of Evaluation Indicators

The selection of indicators for this study is primarily based on the following four sources. (1) Four standards related to deep foundation pit construction: ① GB50202-2018 [34], Code for Acceptance of Construction Quality of Building Foundation and Substructure Engineering; ② JGJ311-2013 [35], Technical Specifications for Safety in Deep Foundation Pit Construction; ③ JGJ 59-2011 [36], Safety Inspection Standard for Building Construction; ④ JGJ120-2012 [37], Technical Regulations for Support of Building Foundation Pits. (2) Reviewing relevant books on deep foundation pit construction safety and resilience. (3) Conducting a type analysis of literature resources, using the Web of Science database to search for keywords—such as safety resilience; resilience assessment; resilience theory; and deep foundation pit construction—to screen out 424 valid documents from 2004 to 2025. (4) Statistical analysis of deep foundation pit construction accidents published by the national and local emergency management departments, identifying the main types of accidents as collapse, falls from height, lifting injuries, electric shock, and mechanical injuries, with the primary causes being as follows: lack of safety awareness, insufficient on-site protective measures, and inadequate safety management mechanisms. The main factors affecting safety resilience have been identified. To improve the accuracy of resilience assessment, in conjunction with the actual definition of resilience, there is an interrelated relationship between assessment indicators and characteristic elements. Based on this, the deep foundation pit construction safety resilience evaluation system is established as shown in Figure 2.

4.2. Reliability and Validity Analysis of Questionnaire

A total of 200 Likert five-point scale questionnaires were distributed in this study. Respondents scored 26 resilience indicators based on Figure 2, and the scores in the scale increased from 1 to 5, which intuitively mapped the importance degree from "low" to "high". After excluding invalid questionnaires, a total of 192 questionnaires were collected.

Table 1 presents the demographic data of respondents. Nearly half (46%) are over 46 years old, while more than 50% are under 46, indicating a balanced age distribution. Approximately 85% of respondents have worked in the construction industry for over six years (84.37%). Over half (68.23%) have experience working at both project developers

and contractors. The composition of these respondents demonstrates comprehensive diversity, which is advantageous for subsequent research.

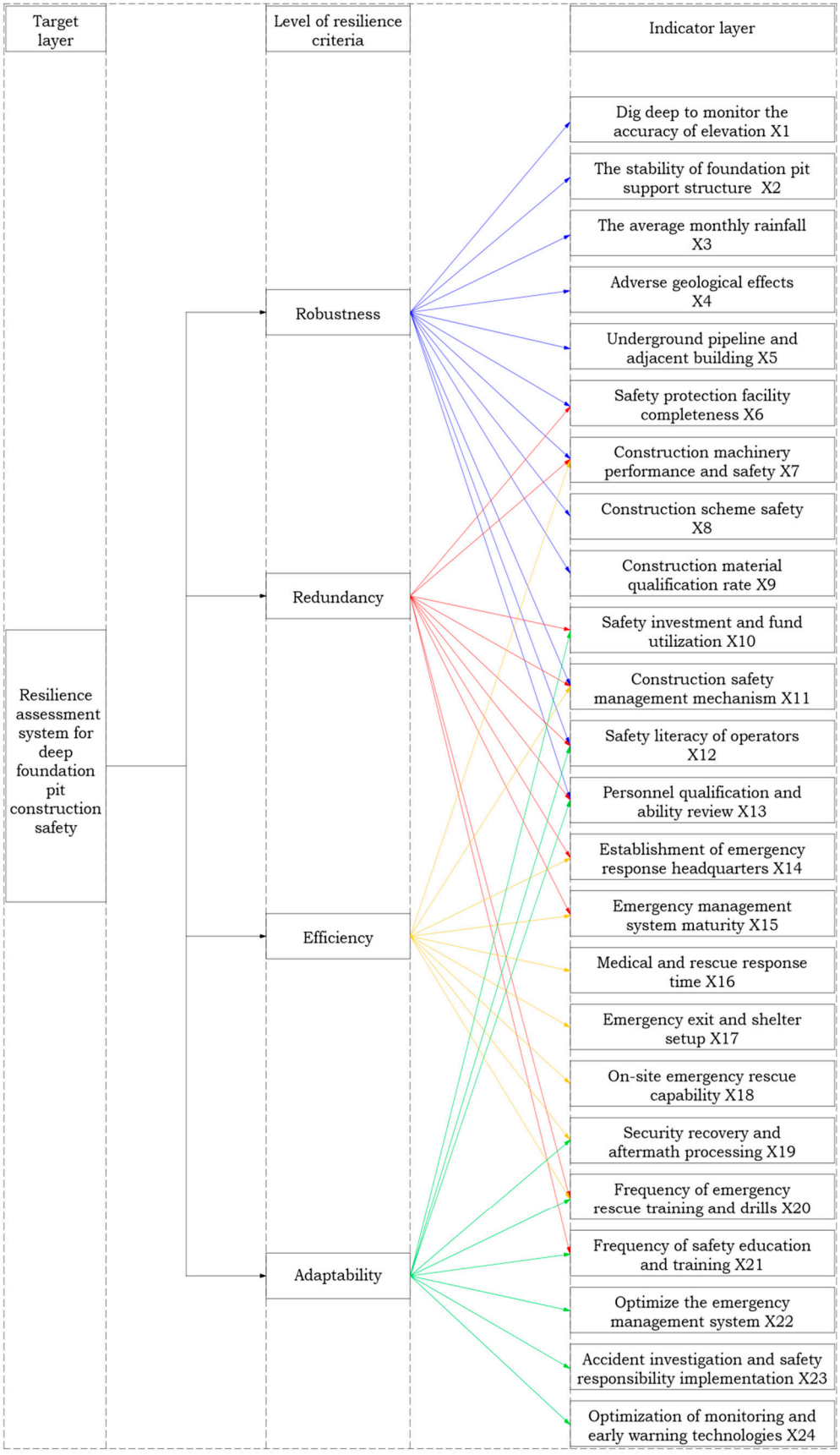


Figure 2. Safety resilience index system for deep foundation pit construction.

Table 1. Basic information of respondents.

Descriptive Indicators	Related Content	Number of Respondents	Percentage Point
Age	25 years old and under	22	11.46%
	26 to 30 years old	30	15.63%
	Age 31 to 45	50	26.03%
	Age 46 to 55	60	31.25%
	Age 56 and older	30	15.63%
Work experience	Under 6 years old	30	15.63%
	Six to 10 years	64	33.33%
	11 to 20 years	70	36.46%
	More than 20 years	28	14.58%
Type of affiliation	Developers	56	29.17%
	Contractors	75	39.06%
	Colleges	31	16.14%
	Other units	30	15.63%

Based on this Table 1, the SPSS 26.0 software was used to test the reliability and validity of the questionnaire to ensure the reliability of the data. The Cronbach's alpha coefficient for this survey questionnaire is 0.714 > 0.6, indicating good reliability. Moreover, the KMO values for each primary indicator are all greater than 0.6 (0.712, 0.658, 0.744, 0.797), suggesting that the overall validity is quite satisfactory and no modifications to the indicators are necessary.

5. Determination of the Weight of Resilience Indicators

5.1. Method Comparison and Selection

We analyze the strong point and weak point of various subjective and objective weighting methods to select the appropriate method for the research on the safety resilience evaluation of deep foundation pit construction.

Based on Table 2 above, IF-AHP is an enhanced method that integrates Analytic Hierarchy Process (AHP) with fuzzy set theory. Unlike traditional AHP approaches, it replaces conventional judgment matrices with fuzzy judgment matrices to convert expert subjective assessments into fuzzy numbers, thereby reducing the influence of subjective biases and better handling high-uncertainty decision-making scenarios. This method not only calculates weights for indicator layers relative to criterion layers but also further computes composite weights for indicator layers relative to objective layers, making it particularly suitable for the evaluation system proposed in this study. The entropy weighting rule quantifies each indicator's contribution through information entropy calculation, enabling objective assessment of their relative importance in decision-making processes. Combining IF-AHP with entropy weighting allows full utilization of both methods' strengths: IF-AHP compensates for entropy weighting's limitations in lacking expert subjective experience, while entropy weighting provides more objective data support for IF-AHP. This integration enhances the accuracy and reliability of resilience index weight calculations, ultimately improving the precision and dependability of resilience metric computations.

Table 2. Comparison of research methods.

	Weighting Method	Strong Point	Weak Point
Subjectivity	Delphi method	① Suitable for dealing with complex problems and consensus building when expert opinions are not consistent. ② Suitable for areas that are not easy to quantify. ③ Reduce bias through anonymous feedback.	① The process takes a long time and requires multiple rounds of feedback. ② It depends on the quality and quantity of experts, and the results may be limited. ③ Experts may be limited by their own experience and perspective.
	Brainstorming method	① Promote creativity and inspiration, open mind. ② Can quickly collect a large number of ideas.	① It is easy to produce disordered results and lack of structure. ② It may be dominated by individual participants and ignore the opinions of others.
	ANP law	① It is suitable for complex decision problems and can deal with multi-level and multi-objective relationships. ② Network hierarchical structure analysis can solve the problem of mutual dependence ignored in AHP method.	① Mathematical calculation is complex and requires a large amount of data support. ② Expert knowledge is needed for judgment, which may have subjective bias.
	AHP law	① The problem structure is directly decomposed and easy to understand. ② The subjective judgment of experts can be quantified by mathematical methods.	① The process is highly dependent on expert judgment and prone to bias. ② When the consistency of the judgment matrix is poor, the accuracy of decision results will be greatly affected.
	IF-AHP law	① The improvement based on AHP can deal with uncertainty and fuzzy information. ② It can solve the consistency problem in traditional AHP method.	① The subjective opinion of experts is still the core of decision-making, which may lead to bias in results. ② The reliability of results depends on the quality of input data.
	Entropy weight method	① Based on the data itself, it can automate the weight allocation and eliminate the subjective factors. ② It is suitable for the processing of information redundancy and can effectively quantify the contribution of each factor.	① The actual correlation between different indicators may be ignored. ② It is only suitable for use when the data is relatively clear, and the uncertainty is not handled well.
Objective	Principal component analysis	① It can reduce data dimensions, remove redundant information, and simplify analysis. ② It can provide an overall view of the data set.	① The results depend on the normality of the data, and it is difficult to capture the nonlinear relationship. ② It is difficult to explain the practical significance of the principal components.
	Maximum likelihood method	① It can provide accurate parameter estimation under large samples. ② It is suitable for in-depth data analysis and modeling.	① It is sensitive to the initial value and may fall into a local optimal solution. ② It has strong requirements on the model assumptions and the data distribution should conform to the assumptions.
	Factor analysis	① It can effectively reduce the dimension of data and reveal the potential variable structure. ② By extracting the implicit factors in the data, it can better understand the relationship between variables.	① It has high requirements on the sample size and requires more variables. ② The results of factor extraction are difficult to explain, especially when the relationship between variables is complex.
	Deviation method	① Easy to use and fast analysis and comparison of data. ② Can quickly evaluate and compare data.	① It ignores the relationship between factors. ② It cannot effectively deal with nonlinear problems and multiple relationships.

5.2. IF-AHP Method Is Used to Calculate Subjective Weights

IF-AHP is a significant extension of the traditional AHP, designed to address uncertainties and ambiguities in decision-making [38]. In complex real-world scenarios, decision-makers often struggle to make precise judgments due to limited knowledge, incomplete information, or inherent ambiguity in issues. IF-AHP effectively captures three psychological states—support, opposition, and uncertainty—while aligning with the complexity of human cognition. This method proves particularly suitable for intricate decision-making contexts involving incomplete data, ambiguous environments, and constrained knowledge, as exemplified by the risk assessment of deep foundation pit safety resilience discussed in this study.

(1) According to the resilience evaluation system mentioned above, opinions of many experts were collected, and the 5-point scale method from 0.1 to 0.9 was used to score the pairwise comparison of the first and second level indicators, respectively. After the weighted average, the judgment matrix AM = $(a_{ij})_{n\times n}$ was obtained, and the elements on the main diagonal were all 0.5, and $a_{ij} + a_{ji} = 1$.

(2) Based on the judgment matrix AM, a fuzzy consistency judgment matrix $B_M = (b_{ij})_{n\times n}$ was constructed, where B_{ij} is the element in the i-th row and j-th column of the judgment matrix AM, where ($b_{ij} = \frac{b_i - b_j}{2n} + 0.5$) represents the sum of the rows in the judgment matrix AM. Then, divide the two elements on the main diagonal of matrix BM to obtain an inverse matrix CM = $(c_{ij})_{n\times n}$, where cij is the element in the i-th row and j-th column of the inverse matrix CM, calculated as $c_{ij} = b_{ij}/b_{ji}$.

(3) The column vector $\overline{H} = [\sqrt[n]{\prod_{j=1}^{n} c_{ij}}\ \sqrt[n]{\prod_{j=1}^{n} c_{2j}} \cdots \sqrt[n]{\prod_{j=1}^{n} c_{nj}}]^T$ is obtained by using the square root method and normalized to obtain the single ranking weight vector $H = [\overline{H}_1 / \sum_{i=1}^{n} \overline{H}_j\ \overline{H}_2 / \sum_{i=1}^{n} \overline{H}_j \ldots \overline{H}_n / \sum_{i=1}^{n} \overline{H}_j]^T$ of the evaluation index layer.

(4) Assuming the indicator system has a total of i criterion levels (I_1, I_2, …, I_i), Level I1 has m indicators (I_{i1}, I_{i2}, …, I_{im}) with the hierarchical single-sorting weight being $\alpha_{11}, \alpha_{12}, \ldots, \alpha_{1m}$; Level I2 has *n* indicators (I_{21}, I_{22}, …, I_{2n}) with the hierarchical single-sorting weight being $\beta_{11}, \beta_{12}, \ldots, \beta_{1m}$; then the hierarchical total ranking indicator weight for the i-th indicator in Level L2 is $H_{2i} = \sum_{j=1}^{m} (\alpha_{1m}\beta_{ij})$.

5.3. Objective Weight Is Calculated by Entropy Weighting Method

The entropy weighting method, an objective weighting technique rooted in the concept of "entropy" from information theory, determines evaluation criteria weights. Its core principle states the following: A criterion with greater variation across different scenarios (sample cases) provides more valuable information for comprehensive assessments, thus warranting higher weighting. Conversely, smaller variations correspond to lower weights. As weights are entirely determined by data distribution, this entropy-based approach avoids human bias and ensures rigorous mathematical validity.

The entropy weight method is a commonly used approach in multi-criteria comprehensive evaluation. Its core idea is to determine the weight of each criterion by analyzing the information entropy of each evaluation indicator. The higher the entropy value, the greater the information uncertainty of that criterion, and thus its weight is relatively smaller; conversely, the lower the entropy value, the more concentrated the information of that criterion [38], and its weight is larger. Through the entropy weight method, the contribution of each criterion to the comprehensive evaluation can be objectively reflected, avoiding the subjectivity of manual weighting.

(1) Construct an m × n decision matrix X, where each row represents an evaluation sample and each column represents an evaluation index. That is, m experts are invited to score the n evaluation indexes, which can be expressed as follows:

$$X_{ij} = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ X_{m1} & X_{m2} & \cdots & X_{mn} \end{bmatrix} \quad (1)$$

X_{ij} represents the score of expert i on indicator j.

(2) The data is standardized to ensure dimensionless values, as required by the entropy weight method. In this study, the indicators are categorized into positive and negative indicators. For each indicator, the data is standardized using the following formulas:

$$x_{ij}^{*} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \quad (2)$$

$$x_{ij}^{*} = \frac{x_{ij} - \min x_j}{\max x_{ij} - \min x_j} \quad (3)$$

Min X_i is the minimum value of the i-th index. Max X_i is the maximum value of the i-th index. X_{ij} * is the j-th sample data of the i-th index.

(3) Calculate the information entropy of each index, process the standardized data, and calculate the proportion of each index in each scheme. If the standardized matrix is known, then the proportion of the j-th index in the i-th evaluation object can be calculated by counting the entropy value of the j-th index, which is based on the following:

$$E_j = -k\sum_{i=1}^{n} P_{ij} \ln P_{ij} \quad (4)$$

$$P_{ij} = \frac{x_{ij}^{*}}{\sum_{i=1}^{n} x_{ij}^{*}} \quad (5)$$

(4) Calculate the entropy weight of each index, where the entropy value is used to measure the information amount of the j-th index. The larger the entropy, the smaller the information amount of the index, and the smaller the weight. The weight is calculated according to the entropy value of each index, and the calculation formula of entropy weight is as follows:

$$W_j^{o} = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j} \quad (6)$$

where E_j represents the information utility value.

5.4. Calculate the Combination Weight Based on the Variable Weighting Theory

The theory of variable weights emphasizes adjusting the ratio between subjective and objective weights based on data changes or decision-making contexts in multi-criteria decision-making. In this paper, subjective weights are obtained through expert judgment, while objective weights are calculated using the entropy method. To effectively combine these two types of weights, the theory of variable weights introduces dynamic weighting

coefficients, which can flexibly adjust the weight ratios according to actual conditions, thereby optimizing the overall weight of the decision. The specific calculation process is as follows:

(1) Determine the subjective and objective weight coefficients, where the weights of subjective and objective weights are α and β, respectively. These represent the manager's preference for these two types of weights, with α + β = 1. The higher the value of α, the more the manager prefers subjective judgment; when α = 0.5, it indicates that both weights are equal. In practical applications, α and β can be dynamically adjusted according to decision-making needs, making the weight calculation better suited to specific decision contexts [39].

(2) This paper has given the calculation method of subjective and objective weights based on IF-AHP and entropy weighting method. Let the subjective weight of the j-th index be, and the objective weight be. When these weights are brought into the formula, the constant weight of the index can be calculated.

$$W_i^c = \alpha W_i^s + \beta W_i^o \tag{7}$$

(3) When calculating the weighted combination weight for more complex hierarchical structures with the integration of the weights of indicators at each level, the difference between the weights at the same level may be reduced, thus affecting the accuracy of the evaluation results. To solve this problem, the weighted combination weight can be calculated as follows: To adjust the weight of the constant weight combination and highlight the importance of key indicators. The variable weight coefficient for the i-th indicator is found here, reflecting its importance. When managers place greater emphasis on the balance between indicators, $0 < \partial_i < 0.5$; if managers do not pay attention to the balance between indicators, then set $0.5 < \partial_i < 1$; at this point, if = 1, the formula will revert to the constant weight model.

$$\omega_i = \frac{W_i^c (x_i^*)^{\partial_i - 1}}{\sum_{i=1}^{n} W_i^c (x_i^*)^{\partial_i - 1}} \tag{8}$$

6. Build a Resilience Evaluation Model

6.1. Extensional Cloud Model Theory

The cloud model is a framework that facilitates the transformation between qualitative and quantitative approaches, describing the relationship between randomness and fuzziness in the uncertainty of objective phenomena through expectation (Ex), entropy (En), and hyper-entropy (He). The extendable cloud model integrates two classic models: the extendable theory for quantitative calculations and the cloud model for qualitative analysis [40]. It replaces the V in the extendable model with the three numerical characteristics of the cloud model (Ex, En, He), combining the fuzzy and uncertain reasoning of cloud model theory with the qualitative and quantitative indicators of extendable theory, thus ensuring the accuracy of resilience assessment. Therefore, this paper establishes an extendable cloud model for safety and resilience evaluation in deep foundation pit construction, as shown in Figure 3.

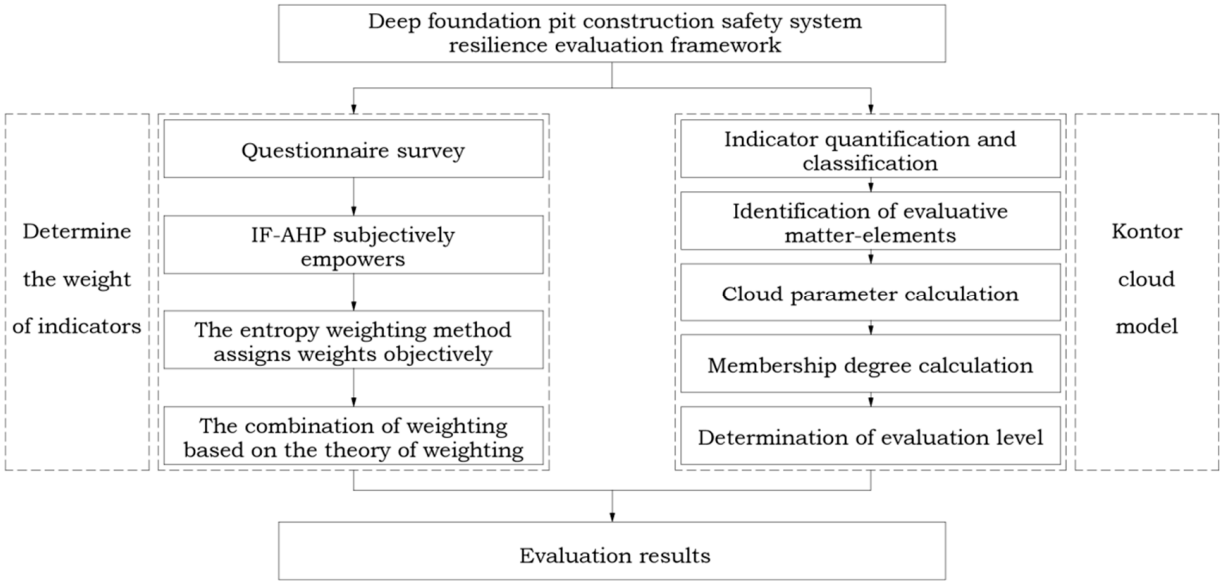


Figure 3. Evaluation process of construction safety resilience.

6.2. Rupture Grade Classification

(1) Construction safety resilience classification.

At present, there is no clear definition of the safety resilience level of deep foundation pit construction. This paper refers to relevant literature and standards to divide the resilience level into five levels from Level I to Level V, as shown in Table 3.

Table 3. Safety and resilience classification table.

Rigidity Grade	Resilience	Descriptive Grade
Level I	Lower resilience	The system's resistance is extremely weak. In the face of external shocks or risks, it has almost no capacity for proactive defense and cannot effectively prevent accidents from occurring or spreading; its response capability is poor, lacking effective emergency measures and response capabilities, making it unable to quickly identify and respond to emergencies; recovery ability is very weak, and once a fault or accident occurs, the system takes a slow and difficult time to return to normal; improvement capability is virtually zero, with a lack of targeted enhancement and optimization measures, preventing the system from learning from past events and making improvements.
Level II	Low resilience	The system has weak resistance and can respond to external shocks to a certain extent, but it is easily disturbed and lacks adequate prevention when events occur; the response ability is weak, although risks can be identified, but the emergency response is not fast enough, and the response measures may be delayed or incomplete; the recovery ability is weak. The recovery process is relatively slow, and may be restricted by many parties, so it is difficult to return to normal operation in a short time; the improvement ability is weak, the system is difficult to effectively summarize experience after the event, the improvement measures lag behind, and the improvement is difficult.
Level III	General resilience	The system's resistance is average, capable of handling medium-scale impacts. However, it still has certain limitations when facing more complex emergencies; its response capability is average, able to conduct initial emergency responses, but the methods for dealing with emergencies are limited and not always implemented in a timely manner; its recovery capability is average, the system can return to normal status, but the recovery speed is slow, requiring a considerable amount of time to address subsequent issues; its improvement capability is average, although the system can learn some lessons from incidents, the measures for enhancement and optimization are not systematic or efficient enough, making it difficult to rapidly improve response capabilities.
Level IV	High resilience	The system has strong resistance capabilities, capable of handling most emergencies and effectively preventing their escalation or causing greater losses; it also has robust response capabilities, able to quickly identify risks and take appropriate emergency measures, with a relatively complete response mechanism that can swiftly activate emergency plans; it has strong recovery capabilities, allowing the system to rapidly return to normal operation after encountering risk events, minimizing the impact on construction progress; it has strong enhancement capabilities, enabling the system to optimize based on post-event summaries and analyses, improving its ability to handle future risks, and continuously strengthening safety resilience.

Table 3. *Cont.*

Rigidity Grade	Resilience	Descriptive Grade
Level V	Higher resilience	The system has an extremely strong resistance capability, effectively blocking most external disturbances and promptly identifying and addressing potential risk sources to prevent problems from occurring; it also possesses an exceptionally strong response capability, able to quickly identify and handle complex or changing risks, taking effective measures to resolve issues with high flexibility and adaptability; the recovery capability is also very strong, allowing the system to rapidly return to normal operation after emergencies, ensuring that construction progress and safety management are not long-term affected; the enhancement capability is extremely strong, enabling continuous optimization of emergency response mechanisms and management systems through post-event evaluation and summary, progressively improving preparedness for complex risks, and possessing robust self-improvement and optimization mechanisms.

(2) Classification of resilience indicators

Based on relevant research literature and expert opinions (basic information detailed in Table 4) in related industries, the second-level index level of safety resilience evaluation system for deep foundation pit construction is quantified, as shown in Table 5.

Table 4. Basic information of experts.

Specialist	Work Unit	Working Life	Academic Title	Number of Deep Foundation pit Engineering Projects Participated in
1	Colleges	14	Inculcation	9
2	Colleges	9	Adjunct professor	5
3	Design unit	10	Design Director	6
4	Design unit	11	Design Director	5
5	Builder	12	Project Director	7
6	Builder	12	Technical Director	8
7	Supervision unit	10	Supervising engineer	6
8	Supervision unit	14	Supervising engineer	8
9	Real estate agency	15	Project manager	11
10	Real estate agency	14	General Manager of Engineering	10

Table 5. Secondary index resilience level interval division.

Secondary Indicators	I	II	III	IV	V
X1	[0, 20)	[20, 40)	[40, 60)	[60, 80)	[80, 100]
X2	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]
X3	[80, 100]	[60, 80)	[40, 60)	[20, 40)	[0, 20)
X4	[80, 100]	[60, 80)	[40, 60)	[20, 40)	[0, 20)
X5	[0, 20)	[20, 40)	[40, 60)	[60, 80)	[80, 100]
X6	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]
X7	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]
X8	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]
X9	[0, 20)	[20, 40)	[40, 60)	[60, 80)	[80, 100]
X10	[0, 20)	[20, 40)	[40, 60)	[60, 80)	[80, 100]
X11	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]
X12	[0, 20)	[20, 40)	[40, 60)	[60, 80)	[80, 100]
X13	[0, 20)	[20, 40)	[40, 60)	[60, 80)	[80, 100]
X14	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]
X15	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]
X16	[90, 100]	[80, 90)	[60, 80)	[30, 60)	[0, 30)
X17	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]
X18	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]
X19	[80, 100]	[60, 80)	[40, 60)	[20, 40)	[0, 20)
X20	[0, 20)	[20, 40)	[40, 60)	[60, 80)	[80, 100]
X21	[0, 20)	[20, 40)	[40, 60)	[60, 80)	[80, 100]
X22	[0, 20)	[20, 40)	[40, 60)	[60, 80)	[80, 100]
X23	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]
X24	[0, 30)	[30, 60)	[60, 80)	[80, 90)	[90, 100]

As can be seen from Table 4, most of the experts have more than 10 years of working experience, and the experts are evenly distributed in each unit. They have rich relevant

work experience and participate in a large number of deep foundation pit projects, which is conducive to the development of this study.

6.3. Determination of Items to Be Evaluated

Set the corresponding matter element to be evaluated R_i, where i represents the number of corresponding first-level indicators; N is the object to be evaluated, namely the safety resilience of deep foundation pit construction; C represents the indicator set, with *n* denoting the number of corresponding second-level indicators; (Ex_*n*, En_*n*, He_*n*) represents the cloud parameters of the matter element.

$$R_i = \begin{bmatrix} N & C_1 & (Ex_1, En_1, He_1) \\ & C_2 & (Ex_2, En_2, He_2) \\ & \vdots & \vdots \\ & C_n & (Ex_n, En_n, He_n) \end{bmatrix} \tag{9}$$

6.4. Cloud Parameter Calculation

The values of the resilience index levels are converted into cloud parameters. In this paper, Ex represents the expected value of security resilience capability, reflecting the central point of the assessment for different levels of security resilience capability; the entropy value En reflects the dispersion of the security resilience capability assessment; the super-entropy He is the entropy of En, indicating the fuzziness of the security resilience capability assessment [41]. The formula for calculating the digital characteristics of the cloud is as follows.

$$Ex = \frac{c_{min} + c_{max}}{2} \tag{10}$$

$$En = \frac{c_{max} - c_{min}}{6} \tag{11}$$

In the formula, c_{max} and c_{min} represent the upper and lower limits of the grade limit; σ is a constant, which can be adjusted according to the characteristics of the index, and σ = 0.1 is taken in this paper.

6.5. Cloud Membership Degree Calculation

Each secondary indicator value in the safety and resilience evaluation system for deep foundation pit construction is treated as a cloud droplet. Using MATLAB R2024a software, normal random numbers En′ are generated with En as the mean and He as the variance [42]. The process is repeated 2000 times, and the median is taken as the membership degree u_{jk} to form the comprehensive judgment matrix U for the safety and resilience evaluation of deep foundation pit construction.

$$\mu_{jk} = \exp\left[\frac{(x_j - Ex^2)}{2En'^2}\right] \tag{12}$$

In Formula (12), u_{jk} is the cloud membership degree of the index evaluation value x_j belonging to the K (1, 2, . . ., 5) level.

$$U = \begin{bmatrix} u_{11} & u_{12} & \dots & u_{1k} \\ u_{21} & u_{22} & \dots & u_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ u_{j1} & u_{j2} & \dots & u_{jk} \end{bmatrix} \tag{13}$$

In Formula (13), k is the number of secondary indicators, and k = 24.

6.6. Evaluation Level Determination

The combination weight vector H is multiplied by the comprehensive evaluation judgment matrix U to obtain the correlation degree D = HU of the comprehensive cloud. According to the principle of maximum membership degree, the resilience level D = max {d1, d2, . . ., d5} is determined.

7. Case-Based Verification

The analysis focuses on the deep foundation pit project of HH Center, a large commercial complex in Nanchang City. The total construction area is approximately 160,405.99 m^2, with a perimeter of 551 m for the foundation pit support. The standard section of the foundation pit has an excavation depth of about 11.6 m, and the stable water head is buried at a depth of 5.7~9.35 m. Within the excavation range of the foundation pit, there are seven soil layers, each with its thickness and related physical properties listed in Table 6. The design of the deep foundation pit support structure adopts φ850@600 mm triple-axis mixing piles with inserted φ800 PRC pipe piles. The bracing system incorporates a combination of sloping, jet-mixing stiffening piles, and prestressed fish-bellied steel struts. The project is located in the core area of Honggutan, Nanchang, directly 560 m from the Gan River, surrounded by towering super-high buildings, basements, and residential areas, making the surrounding environment quite complex. In the event of disaster disturbance, it can easily trigger a chain reaction, leading to severe consequences [43]. Therefore, it is necessary to study the safety resilience of this project to reduce the accident rate of similar projects, minimize accident losses, and enhance the safety status of deep foundation pit construction.

Table 6. Introduction of soil layers.

Stratum	Unit Weight γ (kN/m^3)	Peak Strength Indicators (Direct Shear, Consolidated Quick Shear)		Saturated Uniaxial Compressive Strength Standard Value (MPa)
		Cohesion C (kPa)	Friction Angle Φ (°)	
Miscellaneous Fill	18.0	5	5.0	
Silty Clay	19.2	23	8.0	
Medium Sand	19.5	0	20.0	
Coarse Sand	19.5	0	30.0	
Gravelly Sand	19.5	0	35.0	
Highly Weathered Sandy Conglomerate				1.97
Moderately Weathered Sandy Conglomerate				4.71

7.1. Determine the Characteristic Parameters of the Extendable Cloud

Experts were invited to classify the grade limits of each evaluation index according to the actual situation of deep foundation pit process and the Technical Code for Construction Safety of Deep Foundation Pit Engineering in Building [40] and to calculate the cloud parameters of each resilience grade limit. The results are shown in Table 7.

Table 7. Index level boundary cloud parameters.

Evaluating Indicator	I	II	III	IV	V
X1	(10, 3.33, 0.1)	(30, 3.33, 0.1)	(50, 3.33, 0.1)	(70, 3.33, 0.1)	(90, 3.33, 0.1)
X2	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)
X3	(90, 3.33, 0.1)	(70, 3.33, 0.1)	(50, 3.33, 0.1)	(30, 3.33, 0.1)	(10, 3.33, 0.1)
X4	(90, 3.33, 0.1)	(70, 3.33, 0.1)	(50, 3.33, 0.1)	(30, 3.33, 0.1)	(10, 3.33, 0.1)

Table 7. *Cont.*

Evaluating Indicator	I	II	III	IV	V
X5	(10, 3.33, 0.1)	(30, 3.33, 0.1)	(50, 3.33, 0.1)	(70, 3.33, 0.1)	(90, 3.33, 0.1)
X6	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)
X7	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)
X8	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)
X9	(10, 3.33, 0.1)	(30, 3.33, 0.1)	(50, 3.33, 0.1)	(70, 3.33, 0.1)	(90, 3.33, 0.1)
X10	(10, 3.33, 0.1)	(30, 3.33, 0.1)	(50, 3.33, 0.1)	(70, 3.33, 0.1)	(90, 3.33, 0.1)
X11	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)
X12	(10, 3.33, 0.1)	(30, 3.33, 0.1)	(50, 3.33, 0.1)	(70, 3.33, 0.1)	(90, 3.33, 0.1)
X13	(10, 3.33, 0.1)	(30, 3.33, 0.1)	(50, 3.33, 0.1)	(70, 3.33, 0.1)	(90, 3.33, 0.1)
X14	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)
X15	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)
X16	(95, 1.67, 0.1)	(85, 1.67, 0.1)	(70, 3.33, 0.1)	(45, 5, 0.1)	(15, 5, 0.1)
X17	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)
X18	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)
X19	(90, 3.33, 0.1)	(70, 3.33, 0.1)	(50, 3.33, 0.1)	(30, 3.33, 0.1)	(10, 3.33, 0.1)
X20	(10, 3.33, 0.1)	(30, 3.33, 0.1)	(50, 3.33, 0.1)	(70, 3.33, 0.1)	(90, 3.33, 0.1)
X21	(10, 3.33, 0.1)	(30, 3.33, 0.1)	(50, 3.33, 0.1)	(70, 3.33, 0.1)	(90, 3.33, 0.1)
X22	(10, 3.33, 0.1)	(30, 3.33, 0.1)	(50, 3.33, 0.1)	(70, 3.33, 0.1)	(90, 3.33, 0.1)
X23	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)
X24	(15, 5, 0.1)	(45, 5, 0.1)	(70, 3.33, 0.1)	(85, 1.67, 0.1)	(95, 1.67, 0.1)

7.2. Determination of Index Weight

Based on the actual project, and using the scoring data from experts on various indicators of the deep foundation pit at Huahao Center, we constructed judgment matrices for each criterion layer and indicator layer from four dimensions: robustness, redundancy, efficiency, and adaptability. Considering that both subjective and objective weights are equally important in this paper, parameter = 1 is set in Section 5.3, and the calculation is performed using a constant weight model. The results are shown in Table 8.

Table 8. Weight of construction safety resilience index.

Level II Indicators	Level I Indicator				Weight
	Robustness 0.295	**Redundancy 0.262**	**Efficiency 0.233**	**Adaptability 0.209**	
X1	0.115	-	-	-	0.034
X2	0.134	-	-	-	0.040
X3	0.079	-	-	-	0.023
X4	0.096	-	-	-	0.028
X5	0.058	-	-	-	0.017
X6	0.083	0.124	-	-	0.057
X7	0.038	0.075	0.061	-	0.045
X8	0.129	-	-	-	0.038
X9	0.067	-	-	-	0.020
X10	-	0.122	-	0.093	0.052
X11	0.068	0.134	0.091	-	0.077
X12	0.077	0.097	-	0.114	0.072
X13	0.056	0.069	-	0.085	0.052
X14	-	0.110	0.099	-	0.052
X15	-	0.154	0.118	-	0.068
X16	-	-	0.167	-	0.039
X17	-	-	0.135	-	0.031
X18	-	-	0.188	-	0.044
X19	-	-	0.050	0.067	0.026
X20	-	0.102	0.091	0.087	0.066
X21	-	0.062	-	0.112	0.040
X22	-	-	-	0.170	0.036
X23	-	-	-	0.110	0.023
X24	-	-	-	0.161	0.034

7.3. Determination of Resilience Grade

To determine the actual state of safety and resilience in deep foundation pit construction, questionnaires were distributed to relevant personnel in the deep foundation pit field, all with a bachelor degree or higher or more than five years of experience. This included

three construction workers and safety officers from construction units, two professional supervisors, two from the construction entity, and two scholars specializing in deep foundation pit research. The average score given by experts was used as the resilience index for the deep foundation pit. The cloud membership degree was calculated using the formula in Section 6.5. Specific resilience evaluation results are shown in Tables 9 and 10.

Table 9. Secondary index score, weight, and degree of membership.

Secondary Indicators	Rating Value	Weight	I	II	III	IV	V	Grade
X1	80.7	0.034	0.0000	0.0000	0.0000	0.0057	0.0203	5
X2	79.2	0.04	0.0000	0.0000	0.0221	0.0023	0.0000	3
X3	34.2	0.023	0.0000	0.0000	0.0000	0.4514	0.0000	4
X4	52.2	0.028	0.0000	0.0000	0.8040	0.0000	0.0000	3
X5	82.8	0.017	0.0000	0.0000	0.0000	0.0006	0.0964	5
X6	80.3	0.057	0.0000	0.0000	0.0083	0.0190	0.0000	4
X7	80.7	0.045	0.0000	0.0000	0.0057	0.0370	0.0000	4
X8	81.2	0.038	0.0000	0.0000	0.0035	0.0754	0.0000	4
X9	80.2	0.02	0.0000	0.0000	0.0000	0.0091	0.0130	5
X10	76.1	0.052	0.0000	0.0000	0.0000	0.1868	0.0002	3
X11	78.7	0.077	0.0000	0.0000	0.0330	0.0008	0.0000	3
X12	78.3	0.072	0.0000	0.0000	0.0000	0.0449	0.0021	4
X13	80.9	0.052	0.0000	0.0000	0.0000	0.0046	0.0239	5
X14	78.9	0.052	0.0000	0.0000	0.0281	0.0013	0.0000	3
X15	77.2	0.068	0.0000	0.0000	0.0965	0.0000	0.0000	3
X16	70.5	0.039	0.0000	0.0000	0.9888	0.0000	0.0000	3
X17	76.8	0.031	0.0000	0.0000	0.1241	0.0000	0.0000	3
X18	79.4	0.044	0.0000	0.0000	0.0187	0.0037	0.0000	3
X19	26.6	0.026	0.0000	0.0000	0.0000	0.5933	0.0000	4
X20	73.4	0.066	0.0000	0.0000	0.0000	0.5938	0.0000	4
X21	78.3	0.04	0.0000	0.0000	0.0000	0.0447	0.0021	4
X22	74	0.036	0.0000	0.0000	0.0000	0.4867	0.0000	4
X23	80.1	0.023	0.0000	0.0000	0.0100	0.0135	0.0000	4
X24	75.2	0.034	0.0000	0.0000	0.2959	0.0000	0.0000	3

Table 10. Evaluation results of construction safety resilience.

	Weight	I	II	III	IV	V	Grade
Robustness	0.295	0.0000	0.0000	0.0813	0.0805	0.0198	3
Redundancy	0.262	0.0000	0.0000	0.0346	0.2185	0.0072	4
Efficiency	0.233	0.0000	0.0000	0.1624	0.2260	0.0000	4
Adaptability	0.209	0.0000	0.0000	0.0311	0.3402	0.0072	4
Objective level		0.0000	0.0000	0.0774	0.2048	0.0092	4

7.4. Evaluation Result Analysis

(1) Through the IF-AHP entropy weight method, the combined weights were calculated, revealing the impact on safety resilience ranks as follows: robustness (0.295) > redundancy (0.262) > efficiency (0.233) > adaptability (0.209) (as can be seen in Table 10). To enhance the safety resilience of deep foundation pit construction, it is crucial to strengthen the inherent disaster resistance of deep foundation pits while improving their ability to respond to risk impacts or accidents. According to the overall ranking results in Table 5, emphasis should be placed on construction safety management mechanisms, worker safety awareness, and the maturity of emergency management systems during deep foundation pit construction, with the aim of enhancing the safety resilience of the deep foundation pit system.

(2) According to the maximum membership principle of Cantor Cloud, the final determination of the safety resilience of this deep foundation pit construction is Level IV, indicating that the safety resilience of this deep foundation pit project is relatively high. The robustness of the first-level indicator is Level III, while the redundancy, efficiency, and adaptability resilience levels are Level IV. Therefore, there is considerable room

for improvement in the robustness of this project, and further progress is needed in redundancy, efficiency, and adaptability.

(3) The secondary indicators of the project, including the stability of the foundation pit support structure and the resilience to adverse engineering geological impacts, are relatively low. The construction site is adjacent to a river, and the engineering geology and surrounding environment are complex. It is necessary to reduce the loading on the foundation pit slopes and set up monitoring points to fully control safety conditions. The resilience of the construction safety management mechanism, safety investment amount and usage, emergency command center set up, and the completeness of the emergency management system are also relatively low. There are deficiencies in the safety system, and greater emphasis should be placed on safety management, with improved emergency response plans, clear responsibility assignments, and reasonable budgeting for safety costs. The resilience of monitoring and early warning technology is relatively low, as the project uses manual monitoring methods, which are inefficient and may result in errors. Intelligent monitoring technologies should be strengthened.

8. Discussion

8.1. Theoretical Implications

(1) This study has made significant contributions to the safety theory of deep foundation pit construction by supplementing and refining existing frameworks. While previous research predominantly focused on risk management during construction processes—identifying, evaluating, and controlling individual risk factors—it overlooked the inherent interconnections between these elements and failed to examine construction safety management as an integrated system undergoing dynamic changes. Innovatively adopting a systemic resilience perspective, this research comprehensively identifies multiple factors influencing construction safety management. By establishing a robust indicator system, it injects fresh perspectives into the theoretical framework of deep foundation pit construction safety.

(2) The resilient theory has been effectively applied in deep foundation pit construction safety. While its current applications in construction engineering primarily focus on fire protection and earthquake resistance, research on its implementation in deep foundation pit construction remains limited. This study establishes a scientific and systematic resilience index system and evaluation model for construction safety, enabling quantitative assessment of resilience indicators and precise classification of resilience levels. These advancements provide robust theoretical support and practical references for enhancing safety management in deep foundation pit construction.

(3) The introduction of resilience theory has provided a new perspective for safety assessment in deep foundation pit construction, emphasizing the system's ability to resist, respond to, recover from, and adapt to risk impacts. By thoroughly investigating how construction safety management systems perform under adverse risks or accidents, and focusing on the manifestation of system resilience throughout the entire accident process, we can achieve comprehensive dynamic control over construction safety.

8.2. Practical Implications

(1) During deep foundation pit construction, due to the inherent engineering characteristics of such projects, even minor oversights may lead to major safety accidents including pit collapse, settlement and tilting of surrounding structures, and rupture of underground pipelines. These incidents can severely impact both public safety and property protection as well as the normal operation of urban infrastructure. This study provides practical guidance to effectively prevent such accidents from occurring.

(2) By comparing various safety assessment methodologies and modeling approaches, this study developed an evaluation framework that effectively identifies critical factors affecting safety resilience in deep foundation pit construction. The model enables precise classification of resilience levels. These findings are crucial for enhancing the system's construction safety recovery capabilities and risk resistance capacity, which significantly contributes to reducing major accidents and mitigating potential hazards.
(3) This paper systematically integrates construction safety management and explores the resilience changes in the system throughout the accident development process. The study on the safety resilience of deep foundation pit construction can improve the system's ability to resist and respond to risks, and enhance the ability to quickly restore the safety state after the accident.

8.3. Limitation and Future Research Directions

(1) This study primarily relies on qualitative indicators when constructing a safety resilience evaluation system for deep foundation pit construction, which results in a lack of quantitative basis for practical applications. While qualitative indicators help assess system resilience at the macro level, their limitation lies in the difficulty of conducting detailed analyses. Therefore, future research could incorporate more quantitative indicators and employ precise numerical methods to analyze safety resilience during construction processes, thereby enhancing the accuracy and operability of evaluations.
(2) This study primarily investigates the resilience of construction safety systems when exposed to risk disturbances or accidents, though it does not restrict specific risk types or accident categories. Given that different risk scenarios may exert varying impacts on system resilience, future research could adopt targeted risk scenarios or accident types as case studies for specialized security resilience assessments. Such approaches would enhance the model's applicability and practical value through evidence-based analysis.
(3) Given the significant variations in geological conditions and project contexts across deep foundation pit engineering, developing targeted safety resilience assessment systems tailored to distinct geological characteristics and engineering types has become an urgent challenge. Future research should focus on different deep foundation pit engineering categories and geological environments, integrating specific project scenarios to conduct in-depth safety resilience studies. This approach will gradually establish replicable evaluation standards and methodologies, ultimately providing more precise resilience management solutions for practical engineering projects.

9. Conclusions

(1) In light of China's current research status on deep foundation pit engineering and the characteristics of such projects, this paper highlights the necessity for evaluating the resilience of safety systems in deep foundation pit construction. It systematically reviews relevant literature on resilience assessment, defines the resilience of safety systems in deep foundation pit construction, and clarifies key resilience characteristics and common safety conditions, thereby laying a solid foundation for advancing theoretical research in safety management of deep foundation pit construction.
(2) Based on the accident analysis and literature research, 24 resilience influencing factors are identified from the four characteristics of robustness, redundancy, efficiency, and adaptability and resilience. Through the IF-AHP entropy weight method, the combined weights were calculated, revealing that the impact on safety resilience ranks as follows: robustness (0.295) > redundancy (0.262) > efficiency (0.233) > adaptability (0.209). Additionally, a cross-criterion layer index system suitable for the safety of

deep foundation pit construction is constructed, and the connotation of each resilience index is explained in detail.

(3) This study employs a combined subjective–objective weighting method integrating entropy weighting and IFAHP to quantify the weights of resilience indicators. Based on relevant standards, specifications, expert opinions, and practical case studies, the evaluation metrics were transformed into cloud maps through membership degree calculations, ultimately determining the resilience levels for deep foundation pit construction safety. The system categorizes safety resilience into five distinct tiers, providing clear quantitative benchmarks for practical assessments. To address the inherent ambiguity and randomness in deep foundation pit safety evaluations, this research introduces an expandable cloud model. According to Tables 9 and 10, through cloud map generation and membership degree calculations, the resilience levels for deep foundation pit construction safety are systematically established.

Author Contributions: Conceptualization, X.G., J.M., and L.W.; methodology, X.G., J.M., and L.W.; software, J.M. and L.W.; validation, J.M. and L.W.; formal analysis, X.G. and L.W.; investigation, J.M. and L.W.; resources, J.M. and L.W.; data curation, J.M. and L.W.; writing—original draft preparation, J.M. and L.W.; writing—review and editing, X.G., J.M., and J.G.; visualization, J.M. and L.W.; supervision, X.G.; project administration, J.G.; funding acquisition, X.G. and J.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research and project supported by Jiangxi Provincial Natural Science Foundation (grant number 20252BAC200337).

Data Availability Statement: The original data presented in the study are openly available in Github at https://github.com/MJY123295/MJY (accessed on 26 May 2025).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Jiang, X.; Wang, S.; Wang, J. A decision method for construction safety risk management based on ontology and improved CBR: Example of a subway project. *Int. J. Environ. Res. Public Health* **2020**, *17*, 3928. [CrossRef]
2. Meng, G.; Li, X.; Liu, H. Risk identification and assessment during the excavation of the deep foundation pit. *Adv. Mater. Sci. Eng.* **2021**, *2021*, 4291356. [CrossRef]
3. Zhang, S.; Li, J.; Wang, Q. Dynamic risk analysis of deep foundation pit leakage in water-rich sand layer based on Bayesian network. *J. Hohai Univ. Nat. Sci.* **2024**, *52*, 60–68.
4. Shen, L.; Xue, Z.; Tang, L.; Ge, H. Research on Resilience Evaluation and Enhancement of Deep Foundation Pit Construction Safety System. *Buildings* **2022**, *12*, 1922. [CrossRef]
5. Wang, J.; Zhao, F.; Wang, B.; He, X. Resilience evaluation for deep foundation pit of metro station under influence of multiple factors. *China Saf. Sci. J.* **2019**, *29*, 154–159.
6. Chen, Z.; Wang, Y.; Lai, R. Safety risk management of subway project under toughness concept. *Constr. Technol.* **2023**, *52*, 103–109.
7. Zhang, Y.; Xing, X.; Antwi-Afari, M.F. A hybrid approach for optimizing deep excavation safety measures based on Bayesian network and design structure matrix. *Adv. Eng. Inform.* **2023**, *58*, 102223. [CrossRef]
8. Chen, D.; Zhou, J.; Duan, P.; Zhang, J. Integrating knowledge management and BIM for safety risk identification of deep foundation pit construction. *Eng. Constr. Archit. Manag.* **2023**, *30*, 3242–3258. [CrossRef]
9. Wu, B.; Wei, Y.; Meng, G. Multi-Source Monitoring Data Fusion Comprehensive Evaluation Method for the Safety Status of Deep Foundation Pit. *Sustainability* **2023**, *15*, 11809. [CrossRef]
10. Wang, S.; Wang, W.; Xu, Z. Field Pumping and Recharge Test Study for Confined Aquifers in Super-Large Deep Foundation Pit Group Sites. *Buildings* **2025**, *15*, 1383. [CrossRef]
11. He, X.; Zuo, C.; Luo, X. Efficiency of pile barriers to mitigate supported excavation effects on existing tunnels. *Tunn. Undergr. Space Technol.* **2025**, *159*, 106447. [CrossRef]
12. Tuan, P.N.; Xuan, T.D.; Nguyen, T. Overall assessment of deformation and force of diaphragm wall joints during the stages of deep excavation construction. *Int. J. Comput. Civ. Struct. Eng.* **2024**, *20*, 163–176.
13. Wu, B.; Du, J.; Wen, X.; Zhao, Y. Safety risk assessment of deep foundation pit construction in water-rich soft soil layers based on improved entropy-weighted DEMATEL-ISM. *China Sci. Technol. Work. Saf.* **2023**, *19*, 106–114.

14. Hu, Y.; Liu, J.; Wang, X. Research on safety risk identification of deep foundation pit construction based on BIM and knowledge graph. *Met. Mines* **2023**, *2023*, 180–186.
15. Liu, B.; Liu, Z.; Long, R. Risk identification and evaluation of deep foundation pit excavation based on WBS-RBS-G1 method. *Highw. Traffic Technol.* **2021**, *37*, 119–125.
16. Zhang, X.; Yu, W. Analysis of safety supervision ideas for deep foundation pit construction in urban rail transit engineering. *Mod. Tunn. Technol.* **2021**, *58* (Suppl. S2), 197–200.
17. Huang, R.; Han, Y. Differentiated Optimization Policies for Water–Energy–Food Resilience Security: Empirical Evidence Based on Shanxi Province and the GWR Model. *Water* **2025**, *17*, 1540. [CrossRef]
18. Huang, R.; Liu, H. Evaluation and External Driving Factors Analysis of Water–Energy–Food Resilience Security—Based on Spatial Durbin Model and Four Provinces Along the Yellow River. *Sustainability* **2024**, *16*, 10126. [CrossRef]
19. Zhou, X.; Liu, Z.; Sun, Z.; Yang, P. Renewal Needs and Solutions for Urban Old Communities under the Guidance of Resilient Security. *J. Landsc. Res.* **2024**, *16*, 15–18, 26.
20. Chan, C.P.A.; Guan, J.; Choi, Y.N.T. Moderating Effects of Individual Learning Ability and Resilient Safety Culture on the Relationship between the Educational Level and Safety Performance of Construction Workers. *Buildings* **2023**, *13*, 3026. [CrossRef]
21. Trinh, M.T.; Feng, Y. A Maturity Model for Resilient Safety Culture Development in Construction Companies. *Buildings* **2022**, *12*, 733. [CrossRef]
22. Chen, Q.; Huang, Q.; Chen, Z.; Wang, Z. Resilience evaluation of subway engineering system based on Bayesian network. *J. Saf. Sci. China* **2018**, *28*, 98–103.
23. Wang, J.; Zhi, T.; Na, J.; Guo, Y.; Han, M.; Zhao, Z. Research on Resilience Evaluation Methods for Fire Engineering in Historical and Cultural Districts: A Case Study of Nanjing Lotus Pond. *J. Saf. Environ. Sci.* **2023**, *23*, 317–325.
24. Ma, B.; Li, J.; Miao, C. Risk management strategies for deep foundation pit construction in water-rich soft soil based on the concept of resilience. *Constr. Econ.* **2023**, *44* (Suppl. S2), 127–130.
25. Chen, W. Research on Construction Safety Evaluation of Prefabricated Buildings Based on Elasticity Perspective. Ph.D. Thesis, Lanzhou University of Technology, Lanzhou, China, 2024.
26. Hughes, L. The effects of event occurrence and duration on resilience and adaptation in energy systems. *Energy* **2015**, *84*, 443–454. [CrossRef]
27. Trnka, J.; Lundberg, J.; Jungert, E. Design and evaluation of a role improvisation exercise for crisis and disaster response teams. *Int. J. Inf. Technol. Manag.* **2016**, *15*, 251–271. [CrossRef]
28. Liu, K.; Liu, Y.; Kou, Y. Study on construction safety management in mega projects from the perspective of resilient governance. *Saf. Sci.* **2024**, *173*, 106442. [CrossRef]
29. Macaskill, K.; Guthrie, P. Multiple interpretations of resilience in disaster risk management. *Procedia Econ. Financ.* **2014**, *18*, 667–674. [CrossRef]
30. Pan, H.; He, J.; Chen, M.; Miao, W. Research on the construction risk of metro station foundation pit based on mutation level method. *J. Undergr. Space Eng.* **2017**, *13*, 840–845.
31. Tao, L.; Hu, G.; Jiao, B. Research on the Interaction and Deformation Control of the Adjacent Deep Foundation Pits Excavation. *J. Munic. Technol.* **2024**, *42*, 81–88, 98.
32. Zhou, B.; Ren, Y. Modeling and Application of Project Construction Management Based on BIM. *Constr. Technol.* **2017**, *46*, 143–150.
33. He, J.; Ding, J.; Wang, Y. Deep foundation pit construction technology for silty soil areas. *Archit. Eng. Technol. Des.* **2024**, *12*, 20–22.
34. *GB 50202-2018*; Standard for Acceptance of Construction Quality of Building Foundation. Ministry of Housing and Urban-Rural Development: Beijing, China, 2018.
35. *JGJ 311-2013*; Technical Code for Construction Safety of Deep Building Foundation Excavations. Ministry of Housing and Urban-Rural Development: Beijing, China, 2013.
36. *JGJ 59-2011*; Standard for Construction Safety Inspection. Ministry of Housing and Urban-Rural Development: Beijing, China, 2011.
37. *JGJ 120-2012*; Technical Specification for Retaining and Protection of Building Foundation Excavations. Ministry of Housing and Urban-Rural Development: Beijing, China, 2012.
38. Gong, Y.; Lu, W.; Tao, H. Research on construction risk of subway deep foundation pit based on CIM-AHP model. *J. Hefei Univ. Technol. Nat. Sci.* **2022**, *45*, 1422–1427.
39. Li, D.; Liu, C. Study on the Universality of the Normal Cloud Model. *Eng. Sci.* **2004**, *6*, 28–34.
40. Sun, C.; Liu, P.; Guo, Y. Implementing Large-diameter Well Dewatering Systems for Deep Excavation Construction. *Constr. Mech.* **2025**, *46*, 99–102.
41. Zhou, Y.-G. Application Analysis of Deep Foundation Pit Construction Technology in Iron Related Building Construction Projects. *Value Eng.* **2025**, *44*, 135–138.

42. Han, A. Study on Deformation Control of Deep Foundation Pit Construction Adjacent to Subway in Soft Soil Area. *Build. Constr.* **2024**, *46*, 1072–1075.
43. Sun, L.; Xie, H.-P.; Yu, Y.-Z. Influencing Factors of Engineering Construction Safety Management Based on Resilience. *J. Civ. Eng. Manag.* **2020**, *37*, 60–65.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.