Comprehensive Safety Evaluation of Emergency Training for Building Ruins Scenario Based on Analytic Hierarchy Process-Grey Fuzzy Evaluation

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ABSTRACT The quality of emergency training determines the professional ability of emergency personnel. To evaluate the safety of emergency training for building collapse ruin training scenarios, an approach combining analytic hierarchy process (AHP) and gray-fuzzy evaluation is proposed. According to the characteristics of building collapse ruin training scenarios and the principle of index selection, a safety evaluation index system for this training is constructed from four aspects: human, machine, environment, and management. AHP is used to determine the weight of each evaluation index, and the evaluation model is established base of the gray-fuzzy evaluation method. Based on the combination of the two methods, the quantitative results on training safety was obtained and the most important factor that have the greatest impact on training safety was found. Using this presented assessment method, the safety of an building collapse ruin training scenario for a domestic emergency training facility are assessed, the defects in its emergency capacity are determined, and measures and suggestions are recommended to provide scientific and effective basis for improving emergency capacity.

INDEX TERMS Building collapse ruins, emergency training, whiten weight function, grey fuzzy evaluation, safety assessment.

NOMENCLATURE

T	The target layer
Pi	First-level indicators
Mi	Secondary-level indicators
Ni	Tertiary-level indicators
M_i	Weight of the secondary-level indicators relative to the upper level
N_i	Weight of the tertiary-level indicators relative to the upper level
W_{Pi}	Weight of the first-level index
W_{Mi}	Weight of the secondary-level indicators relative to the target level
W_{Ni}	Weight of the tertiary-level indicators relative to the target level
K	Tertiary-level indicators set
V	The gray category set
C	The evaluation level set

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D	The safety risk assessment sample matrix
d_{ij}	Element of matrix D
n_{ij}	The sum of gray statistics number
r_{ij}	The gray assessment weight vector of evaluation
f	Albino weight function
B	Gray-fuzzy judgment matrix
Q	The results of secondary-level fuzzy judgment
Z	The result of the evaluation object
F	The comprehensive evaluation value

I. INTRODUCTION

Presently, people's cognition of new technology and new materials is insufficient. To a certain extent, this has caused frequent emergencies and introduced difficulties and challenges to the work of emergency rescue personnel [1], [2]. To improve the fighting level and professional ability of firefighters and respond to the country's need for actual combat fire simulation training, a variety of simulated disaster fire protection training scenarios came into being, including training scenarios that simulate the ruins of buildings that collapsed due to earthquakes or renovations. At present, the construction of building collapse ruin training scenarios in China is still in its infancy. During personnel training, a variety of uncertain factors [1], [3], [4] can cause fatal accidents, which will seriously affect the quality and effectiveness of the training [5]–[7]. For example, the scenario design and construction may be unreasonable, the corresponding safety plans may be lacking, the reward and punishment system and some other systems may not be perfect, and adequate supervision and safety measures may not be in place. Therefore, to ensure the safety and reliability of the training scenario, it is particularly important to conduct an effective scientific safety assessment of that training scenario.

At present, simulation training for building collapse accident scenarios is mainly used to simulate obstacles (e.g., cement walls, stones, and steel bars) for training, enable personnel climbing training, and facilitate personnel (dummy) search-rescue training. Some scholars in China have previously studied the collapse of buildings. Xiaojun Xu used the analytic hierarchy process to conduct a quantitative safety assessment of the risk of building collapse during a fire [8]. Ning Dong analyzed the trapped form and rescue methods of personnel in a collapsed building during an earthquake [9]. Xiangming Yu analyzed the main factors of building collapse during a fire without obvious signs and proposed new ideas for corresponding preventive measures [10]. In terms of safety and emergencies, Yue Ge combined AHP and grey theory to evaluate emergency management [11]. Chenglin Miao proposed a multi-level fuzzy comprehensive evaluation model based on the analytic hierarchy process and fuzzy mathematics method to study the emergency capacity of coal enterprises [12]. Yilin Tian *et al.* considered early warning capabilities, disaster preparedness, and recovery after a disaster, establishing an evaluation index system of emergency response ability [13].

Chen *et al.* [14] construct a method based on data from the testing of food-waste feed with comprehensive evaluation of its product safety by integrating fuzzy mathematics effectively, i.e., the entropy method (EM), and the model of the analytic hierarchy (AHP) process. A three-level model of fuzzy mathematics is applied to evaluate the product safety. Li *et al.* [15] proposed a two-stage solution methodology by combining multi-objective optimization using the q-DEA with an integrated decision-making technique FCM-GRP. Wang *et al.* [16] proposed a hybrid FMEA framework that combines the TODIM (an acronym in Portuguese of Interactive and Multi-criteria Decision Making) method and the Choquet integration method. This aggregation method can take into account different types of risk evaluation information. Wu *et al.* [17] proposed a multiple attribute group decision making method based on the extended hesitant Pythagorean fuzzy VIKOR under the HPFSs environment. They also proposed an integrated methodology to address MCGDM problems based on the best-worst method (BWM) [18]. The analytic hierarchy process (AHP) proposed by Tomas Saaty in 1970 is a well-known method for making decisions in many fields, including engineering [19]–[21]. It can help decision makers find the most important factors. For uncertain fuzzy information, the gray clustering method can quantitatively divide that information into the correct categories by establishing a whitening function. Practice has proven that the combined application of fuzzy mathematics methods and gray clustering methods in structural assessment is not only objective but also quantitative [22], [23]. Therefore, this study combines AHP with the gray fuzzy evaluation method and applies both to a training scenario of building collapse and ruins for the first time according to the expert survey method and brainstorming method. Moreover, measures are proposed to effectively solve the aforementioned personnel emergency training safety problems.

Compared with these studies, scholars to date have conducted preliminary research on the causes of building collapse and on-site emergency rescue. However, there is no comprehensive safety assessment study on emergency training sites for building collapse scenarios; there is a lack of identification and analysis of the influencing factors that affect the safety of trainers and no complete index system and assessment model. By the combination of AHP and grey fuzzy comprehensive evaluation, index weight analysis and quantitative safety assessment of emergency rescue training safety in building collapse accident scenarios can be carried out, then the training safety level can be obtained, and safety recommendations can be provided accordingly.

A safety evaluation index system for emergency rescue training of building collapse ruin training scenarios is established in this study based on the above research results and the characteristics of emergency training scenarios for building collapse accidents, combined with the national standards and standards for emergency training scenario construction and training. Combining the analytic hierarchy process and the gray fuzzy evaluation method, a safety risk assessment

indicator system for building collapse and ruin fire training scenarios is established. The weight of each factor is determined, and a comprehensive safety evaluation model is constructed. Finally, an example analysis is presented to verify the rationality of the model.

The main contributions of this work are the following threefold:

(1) A safety evaluation index system: To evaluate the training safety in building collapse ruin training scenarios, a safety evaluation index system is established.

(2) A safety assessment approach: Using AHP combined with gray fuzzy comprehensive evaluation, the safety evaluation of the building collapse accident emergency rescue training base was carried out, and suggestions for improvement were provided based on the evaluation results.

(3) A novel safety assessment model: With the safety index system and the assessment approach, a novel safety assessment model aims at emergency rescue training safety of building collapse ruin training scenario is proposed.

II. CONSTRUCTION OF THE SAFETY ASSESSMENT INDEX SYSTEM FOR A TRAINING SCENARIO OF BUILDING COLLAPSE RUINS

Safety assessment involves qualitatively or quantitatively analyzing the risk factors and hazards that cause accidents in a system [24]. The establishment of a safety evaluation index system for the training scenario of building collapse ruins should follow the principles of scientificity, comprehensiveness, systematization, comparability, and feasibility [25]–[27]. According to the brainstorming method and expert survey method, we consulted experts and senior practitioners in the field by email, interviews, meetings, etc. to gather expert opinions. Then, combined with a ''human-machine-loop-tube'' theoretical analysis of the principles of safety and the domestic and foreign emergency training regulations and standards, the classification is divided into three stages the safety risk index P_1 before training, the safety risk index P_2 during training, and the safety risk index P_3 after training) to establish a hierarchical safety assessment index system from the perspective of a time sequence. The hierarchical safety assessment index system is shown in Fig. 1.

A. SAFETY RISK INDICATORS BEFORE TRAINING P_1
1) QUALIFICATION RATE OF RELEVANT PERSONNEL A_1
The qualification rate of relevant personnel includes two aspects: personnel health A_{11} and degree of safety education A_{12}.

The physical health of the staff refers to the physical conditions required by the staff: a. It mainly inspects the number of sick days of the staff per year and whether the physical examination is qualified. The physical and health conditions of the trainees should meet the ''GB/Z 221-2009 Occupational Health Standards for Firefighters'' And specific training requirements (such as those with abnormal blood pressure and heart rate are not suitable for high-altitude training);
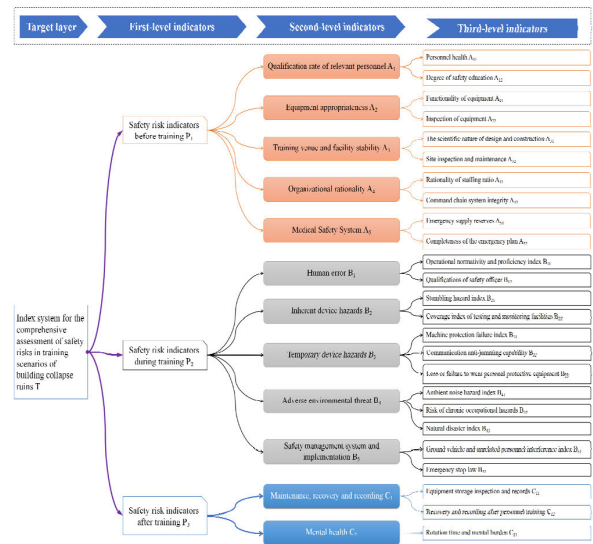

FIGURE 1. Index system of safety assessment for the training scenarios of building collapse ruins.

b. Doctors and psychologists should be regularly organized to conduct tests and visits to trainees. Group trainers should follow the requirements of GB/Z 221- ''2009 Fire Fighters Occupational Health Standards'' establishes the physical and mental health files of relevant personnel.

The degree of safety education is: a. The level of the trainee. The trainees are divided into three levels: elementary class, intermediate class, and advanced class. They have different levels of safety knowledge, safety awareness and operating experience. The trainees required to actually operate must be in the intermediate or advanced class; b. Instructor's Qualifications. The instructor's own professional abilities should be qualified, with a professional certification certificate issued by an officially recognized or authoritative organization; c. The integrity of the trainee's safety manual. The trainee should receive a trainee's handbook before training, which includes all the information required for the trainee to successfully complete the course (management and introduction, safety, structural engineering system, equipment lectures and exercises, support, dismantling, lifting and Equipment, field exercises, instructor evaluation form, appendix).

2) EQUIPMENT APPROPRIATENESS A_2
The equipment appropriateness includes two aspects: functionality of equipment A_{21} and inspection of equipment A_{22}.

The functionality of equipment refers to: a. Training equipment should meet the requirements of corresponding national standards or industry standards; b. Equipment without national standards and industry standards should be inspected by relevant national statutory inspection agencies.

Inspection of equipment refers to: a. Training equipment should be regularly inspected, tested, maintained, and registered; b. Training equipment should be inspected for

safety before being shipped out of the warehouse, and the equipment should reach 100 %. Personal protective equipment appropriate to the training course should be selected.

3) TRAINING VENUE AND FACILITY STABILITY A_3

The training venue and facility stability includes two aspects: the scientific nature of design and construction A_{31}, and site inspection and maintenance A_{32}.

The scientific nature of design and construction means that the design and construction of training venues, training facilities and training devices must meet the safety requirements of GA/T 623-2006, GB/T 29177-2012 and other related standards.

Site inspection and maintenance means: a. Sites and facilities should be inspected, tested, and maintained regularly, and records should be kept; b. Sites and facilities should be inspected before training; c. Sites and facilities should be safe before training. The unstable parts and supporting points that have been checked out shall be supported and reinforced, or the dangerous components shall be removed in advance to avoid secondary collapse.

4) ORGANIZATIONAL RATIONALITY A_4

The Organizational rationality includes two aspects: rationality of staffing ratio A_{41} and Command chain system integrity A_{42}.

Rationality of staffing ratio refers to: a. The number of trainees, instructors and medical rescue personnel. Instructors: trainees = 1:8 or 1:10; internal medicine and surgery or general practitioners ≥ 2 (see "GB/Z 221-2009 Occupational Health Standards for Firefighters"), the number of professional physicians and health personnel varies; group b. The trainer should formulate corresponding training safety management regulations and implement the training safety inspection and supervision system; c. Each training group should have a safety officer; d. The intermediate group training mode should be group work with separate positions and involve rotation.

Command chain system integrity refers to: a. A complete chain of command can convey information faster. b. There should be corresponding communication hardware technical means to improve the reporting mechanism, and attention should be paid to flattening the organization of emergency reports.

5) MEDICAL SAFETY SYSTEM A5

The Medical Safety System mainly refers to the reserve emergency supply reserves A_{51} and completeness of the emergency plan A_{52}.

Emergency supply reserves refers to: a. The area of health rooms or sanitary rooms, basic medical rescue equipment and commonly used drugs shall meet the requirements of "GBZ 221-2009"; b. The professional assessment results of full-time doctors and part-time doctors shall be qualified.

Completeness of the emergency plan refers to: a. Traffic congestion index: the route arrangement when using ambu-lances to the hospital should be reasonable, fully considering the shortest time required for unobstructed roads and traffic jams; b. The plan should include various injury handling procedures (GAT 967-2011), which is convenient for fully coping with emergencies during training.

B. SAFETY RISK INDICATORS DURING TRAINING P_2

1) HUMAN ERROR B_1

Human error indicators mainly refer to two aspects: operational normativity and proficiency index B_{11}, and qualifications of safety officer B_{12}.

Operational standardization and proficiency index can be considered from the following two aspects: a. Unskilled operation and insufficient knowledge and experience. Intermediate class students are more likely to be dangerous than junior and advanced classes because they combine theory with practice for the first time; b. The deviation between the actual operation steps of the trainees and the steps specified in the operating procedures, the greater the deviation The greater the risk of smashing, falling, and scalding (such as wrong rope specification selection, wrong knotting method, lack of safety rope and protective pad, etc.).

The meaning of the qualifications of safety personnel mainly refers to: a. Be able to accurately grasp the operation of the trainees; b. Be proficient in the information issued by the trainers and coaches, timely and accurately convey the emergency evacuation orders issued by the trainers, and be responsible for emergency check and count personnel after retreat and training; c. They should have the ability to identify and control the hazards of the training environment.

2) INHERENT DEVICE HAZARDS B_2

The inherent device hazard indicators include two aspects: stumbling hazard index B_{21} and coverage index of testing and monitoring facilities B_{22}.

The stumbling hazard index refers to the danger of people facing falling wires, cables, pits, uneven roads, protruding steel bars, etc., bumps in narrow spaces, cement and stone gaps or sharp corners.

The coverage index of testing and monitoring facilities the following three aspects, namely: a. The number of surveillance cameras, the monitoring angle and the duration, all relevant trained personnel are included in the monitoring angle, and there are no blind spots and blind spots; b. The air quality should be tested. The equipment is configured as a portable equipment, especially for air quality testing in confined spaces; c. Monitoring equipment used to monitor the stability of the building structure should be installed to monitor the stability of the building structure at any time.

3) TEMPORARY DEVICE HAZARDS B_3

The temporary device hazards include three aspects: machine protection failure index B_{31}, communication anti-jamming capability B_{32}, and loss or failure to wear personal protective equipment B_{33}.

Machine protection failure mainly refers to the failure of the machine's protection device, resulting in electric shock or debris splash injury.

The communication anti-jamming capability includes the following two aspects: a. The signal of the communication tool is interfered and its own damage; b. The lack of communication between teammates, or each step of the operation is not correctly understood.

The loss or failure to wear personal protective equipment refers to the protective equipment required for training

subjects such as respiratory protection, hearing protection, visual protection, helmet/headlights, spare batteries, gloves, rescue suits, and rescue boots.

4) ADVERSE ENVIRONMENTAL THREATS B_4

The index of adverse environmental threat can be comprehensively considered from three aspects: ambient noise hazard index B_{41}, risk of chronic occupational hazards B_{42} and natural disaster index B_{43}.

The ambient noise hazard index refers to the decibel level of the noise of the person's surrounding environment. Pay attention to the decibel level of the machine, such as cutting machine, to provide hearing protection, avoid noise (greater than 85dB) injury.

The risk of chronic occupational hazards should be paid attention to, such as dust factor, physical factor (high temperature, low temperature, high altitude, vibration injury, etc.).

The natural disaster index refers to the possibility of debris flow, earthquake, landslide, volcanic eruption and other geological disasters occurring in and around the training site.

5) SAFETY MANAGEMENT SYSTEM AND IMPLEMENTATION B_5

Safety management system and implementation indicators include ground vehicle and unrelated personnel interference index B_{51}, and emergency stop law B_{52}.

The interference index of ground vehicles and irrelevant personnel shall be considered from the following three aspects: a. Driver's driving qualification: drivers shall pass the assessment of the business departments above the detachment, and can participate in the composite training after obtaining the driving license of the corresponding vehicle type; b. There should be restrictions on the driving speed and driving range; c. The individual activities of irrelevant personnel (such as observers) shall not be affected by training and shall be limited in scope.

The emergency stop law mainly means that the ''stop'' emergency stop law should be set in the training regulations, and the implementation of the emergency situation in daily training should be analyzed.

C. SAFETY RISK INDICATORS AFTER TRAINING P_3

The safety risk indicators after training mainly include two aspects: maintenance, recovery and recording C_1, and mental health C_2.

1) MAINTENANCE, RECOVERY AND RECORDING C_1

Maintenance, recovery and recording can be considered from two aspects: equipment storage inspection and records C_{11}, and recovery and recording after personnel training C_{12}.

Equipment storage overhaul and recording refer to: a. After the training, check the training equipment and equipment, record the inspection status, clean and maintain the equipment after the training, such as using soap with low acid and alkaline, etc.; b. Repair or label training damaged equipment. The quality of equipment maintenance directly affects the safe use of mechanical equipment and its normal performance. Poor equipment maintenance is the main manifestation of equipment insecurity. To control the unsafe state of mechanical equipment, the most important thing is to do regular inspection and maintenance of mechanical equipment and daily maintenance of equipment.

The meaning of recovery and recording after personnel training is as follows: a. Whether to organize trainees to carry out restorative activities after training; b. After the training, fill in training records, establish training files, and implement the training safety evaluation system.

2) MENTAL HEALTH C_2

Mental health mainly refers to the work pressure or mental burden of the trainers C_{21}.

The working pressure can be considered through the working rotation time. The appropriate working hours should be worked out, the working rotation system should be earnestly implemented, and the appropriate rotation time should be determined.

Due to the influence of personal psychological pressure, if there is fear during the training, the training should be finished, and psychological experts should be invited to do a good job of psychological counseling after the training.

III. ESTABLISHMENT OF THE GREY FUZZY COMPREHENSIVE EVALUATION MODEL

The AHP can help decision makers to identify the most important factors. The combined application of the fuzzy mathematics method and the gray clustering method in structure evaluation is both objective and quantitative. The analytic hierarchy process is a decision-making method that decomposes the relevant elements of decision-making into goals, criteria, plans and other levels, and performs qualitative and quantitative analysis on this basis. The characteristic of this method is that on the basis of in-depth analysis of the nature, influencing factors and internal relations of complex decision-making problems, it uses less quantitative information to mathematicize the thinking process of decision-making, so as to provide a simple decision making method for complex decision problems with multi-objective, multi-criteria or no structure characteristics. First, according to the nature and requirements of the problem, a general goal is proposed; then the problem is divided into levels, and the factors at the same level are compared to determine their

respective weights relative to the goals of the previous level. In this way, layer by layer analysis, until the last layer, all factors (or programs) can be given a sort of importance (or preference) relative to the overall goal.

The grey fuzzy evaluation method can handle fuzzy information that other methods cannot handle. It is a method of making a decision or comprehensive judgment on a certain evaluation object for a certain evaluation target under a fuzzy environment, comprehensively considering multiple influencing factors. It is very effective for processing fuzzy information. Based on the degree of membership in fuzzy mathematics and the gray scale in gray theory, the basic principle of gray fuzzy evaluation is to evaluate risk factors that cannot be quantified or are difficult to quantify based on the degree of membership in fuzzy mathematics and the gray scale in gray theory [28]–[30]. Based on the hierarchical structure of the safety assurance ability of the collapsed building ruin training scenario, the weight of each evaluation index was determined by AHP. At present, research on the safety assurance of fire training for collapsed buildings is still in its infancy and involves many factors. Moreover, there is a great deal of fuzzy information [31]–[34]. In this study, fuzzy risk comments such as "low", "relatively low", "general", "relatively high", and "high" will be used for evaluation. The grey fuzzy evaluation method will be used to quantitatively express the grey fuzzy and difficult factors in the evaluation process to increase the credibility of the evaluation results.

A. INDEX WEIGHT DETERMINATION BASED ON THE ANALYTIC HIERARCHY PROCESS

Expert questionnaires were selected to obtain data statistics using the 1~9 scale method [35]–[37]. The importance score of each first-level indicator (P_1, P_2, P_3), second-level indicator (A_1,..., A_5, B_1,..., B_5, C_1, C_2), and third-level indicator (A_{11}, ..., A_{52}, B_{11}, ..., B_{52}, C_{11}, C_{12}, C_{21}) is obtained, a judgment matrix is constructed, and then the index weight is calculated by AHP. The weight of each level of indicator relative to the target layer is the product of the weights of all levels. Let the weights of the first-level indicators be w. Then, the weights of the second- and third-level indicators relative to the indicators of the previous layer are, respectively, recorded as w_i and w_{ij}, and the weights relative to the target layer are recorded as α and β; then, $\alpha = w \cdot w_i$, $\beta = \alpha \cdot w_{ij}$.

B. SAFETY ASSESSMENT BASED ON GREY FUZZY EVALUATION

1) SET FACTOR SETS AND COMMENT SETS AND DETERMINE THE GRADING STANDARD FOR THE RISK ASSESSMENT INDICATORS

Set the factor as $K = \{k_1, k_2, \ldots, k_s\}$ and the comment rating as $V = \{v_1, v_2, \ldots, v_l\}$. According to the relevant risk level classification scheme and actual experience, this study divides the risk indicators of this scenario into five levels: "low, relatively low, general, relatively high, and high". Next, assuming that the risk comment set is $C = (c_1, c_2, \ldots, c_l)$,

TABLE 1. Classification of risk comments.

score	1	2	3	4	5	1.5, 2.5, 3.5, 4.5
Degree of risk	low	relatively low	general	relatively high	high	between two adjacent levels

quantify the risk level and assign values accordingly: i.e., $c_1 = 1$, $c_2 = 2$, $c_3 = 3$, $c_4 = 4$, $c_5 = 5$. When the level of the risk index is between two adjacent levels, it is recorded as 1.5, 2.5, 3.5, and 4.5.

2) ESTABLISH THE EVALUATION SAMPLE MATRIX

Suppose there are m experts. Using the expert scoring method to score the third-level indicator K_{ij} according to Table 2, the nth expert scores the indicator K_{ij} as d_{ij}^n (n=1, 2, ..., m), which constitutes sample matrix D for the safety risk assessment of the scenario.

$$D = \begin{bmatrix} d_{11}^1 & d_{11}^2 & \cdots & d_{11}^m \\ d_{12}^1 & d_{12}^2 & \cdots & d_{12}^m \\ \vdots & \vdots & \vdots & \vdots \\ d_{ij}^1 & d_{ij}^2 & \cdots & d_{ij}^m \end{bmatrix} \qquad (1)$$

3) DETERMINATION OF THE GRAY CATEGORY FOR THE EVALUATION INDEX

The estimate given by the expert is actually a whitening value of a gray number. To accurately reflect the degree to which the evaluation index belongs to a certain category, it is necessary to determine the evaluation gray category (i.e., to determine the grade number of the gray category, the gray number of the gray category, and the whitening weight function of the gray number). Because the determination of the evaluation gray category depends on the actual evaluation problem, this study uses five gray categories: low, relatively low, general, relatively high, and high. The grade number of the gray category is represented by e (e=1, 2, 3, 4, 5), and its corresponding gray number and whitening weight function are as follows.

The first type (e=1) indicates that the risk level is low; the gray number is $\otimes \in [0, 1, 2]$, and the corresponding whitening weight function is f_1.

$$f_1\left(d_{ij}^n\right) = \begin{cases} 1, & d_{ij}^n \in [0, 1] \\ \dfrac{2 - d_{ij}^n}{1}, & d_{ij}^n \in [1, 2] \\ 0, & d_{ij}^n \notin [0, 2] \end{cases} \qquad (2)$$

The second type (e=2) indicates that the risk level is relatively low; the gray number is $\otimes \in [0, 2, 4]$, and the corresponding whitening weight function is f_2.

$$f_2\left(d_{ij}^n\right) = \begin{cases} \dfrac{d_{ij}^n}{2}, & d_{ij}^n \in [0, 2] \\ \dfrac{4 - d_{ij}^n}{2}, & d_{ij}^n \in [2, 4] \\ 0, & d_{ij}^n \notin [0, 4] \end{cases} \qquad (3)$$

The third type (e=3) indicates that the risk level is general, the gray number is $\otimes \in [0, 3, 6]$, and the corresponding whitening weight function is f_3.

$$f_3\left(d_{ij}^n\right) = \begin{cases} \dfrac{d_{ij}^n}{3}, & d_{ij}^n \in [0, 3] \\ \dfrac{6 - d_{ij}^n}{3}, & d_{ij}^n \in [3, 6] \\ 0, & d_{ij}^n \notin [0, 6] \end{cases} \qquad (4)$$

The fourth type (e=4) indicates that the risk level is relatively high, the gray number is $\otimes \in [0, 4, 8]$, and the corresponding whitening weight function is f_4.

$$f_4\left(d_{ij}^n\right) = \begin{cases} \dfrac{d_{ij}^n}{4}, & d_{ij}^n \in [0, 4] \\ \dfrac{8 - d_{ij}}{4}, & d_{ij}^n \in [4, 8] \\ 0, & d_{ij}^n \notin [0, 8] \end{cases} \qquad (5)$$

The fifth type (e=5) indicates that the risk level is high, the gray number is $\otimes \in [0, 5, 10]$, and the corresponding whitening weight function is f_5.

$$f_5\left(d_{ij}^n\right) = \begin{cases} \dfrac{d_{ij}^n}{5}, & d_{ij}^n \in [0, 5] \\ \dfrac{10 - d_{ij}^n}{5}, & d_{ij}^n \in [5, 10] \\ 0, & d_{ij}^n \notin [0, 10] \end{cases} \qquad (6)$$

4) CALCULATE GRAY STATISTICS

According to the results of the expert scoring, the gray statistics method can be used to calculate the gray statistical number n_{ij}^e of the evaluation index K_{ij} belonging to the e (e=1, 2, 3, 4, 5) evaluation gray category. Summarizing the results, the total gray statistical number n_{ij} of the evaluation indicator K_{ij} belonging to each evaluation gray category is obtained. This calculation is shown in Equation 7 and Equation 8.

$$n_{ij}^e = \sum_{n=1}^{m} f_e\left(d_{ij}^n\right) \qquad (7)$$

$$n_{ij} = \sum_{e=1}^{5} n_{ij}^e \qquad (8)$$

5) GREY EVALUATION WEIGHT AND GREY FUZZY WEIGHT MATRIX CALCULATION

For the evaluation index K_{ij}, the gray evaluation weight value belonging to the e-th evaluation gray category is recorded as r_{ij}^e. This calculation is shown in Equation 9:

$$r_{ij}^e = \frac{n_{ij}^e}{n_{ij}} \qquad (9)$$

Then, the gray evaluation weight vector of the evaluation index K_{ij} for each gray category is set as $r_{ij} = \left(r_{ij}^1, r_{ij}^2, r_{ij}^3, r_{ij}^4, r_{ij}^5\right)$, which represents the fuzzy membership degree of the risk index subset K_{ij} relative to the comment grade set V.

Then, we comprehensively calculate K_{ij} to obtain the gray evaluation weight matrix relative to each gray category, namely the gray fuzzy membership weight matrix, which is recorded as R_i. This calculation is shown in Equation 10:

$$R_i = \begin{bmatrix} r_{i1} \\ r_{i2} \\ \vdots \\ r_{in} \end{bmatrix} = \begin{bmatrix} r_{i1}^1 & r_{i1}^2 & \cdots & r_{i1}^5 \\ r_{i2}^1 & r_{i2}^2 & \cdots & r_{i2}^5 \\ \vdots & \vdots & \ddots & \vdots \\ r_{in}^1 & r_{in}^2 & \cdots & r_{in}^5 \end{bmatrix} \qquad (10)$$

6) CALCULATE THE GREY FUZZY EVALUATION MATRIX OF EACH LEVEL INDEX

The first-level fuzzy evaluation and the second-level fuzzy evaluation are made for each level of the evaluation object. Then, the gray fuzzy evaluation set is obtained, and the gray fuzzy judgment matrix is constructed for calculation. The result of the first-level fuzzy evaluation is recorded as B_i, and the relative calculation is shown in Equation 10. The second-level fuzzy evaluation result is recorded as Q_s.

$$\begin{aligned} B_i &= (b_{i1}, b_{i2}, \cdots, b_{i5}) \\ &= W_i \cdot R_i \\ &= (w_{i1}, w_{i2}, \cdots, w_{in}) \begin{bmatrix} r_{i1}^1 & r_{i1}^2 & \cdots & r_{i1}^5 \\ r_{i2}^1 & r_{i2}^2 & \cdots & r_{i2}^5 \\ \vdots & \vdots & \ddots & \vdots \\ r_{in}^1 & r_{in}^2 & \cdots & r_{in}^5 \end{bmatrix} \end{aligned} \qquad (11)$$

Then, we synthesize Bi to construct a new gray fuzzy judgment matrix B_s and subsequently perform a two-level fuzzy judgment on this basis. The results are sequentially recorded as Q_s, and the relative calculation is shown in Equation 12:

$$\begin{aligned} Q_s &= (Q_1, Q_2, \ldots, Q_S) \\ &= W_s \cdot B_s \\ &= (w_1, w_2, \ldots, w_s) \cdot \begin{pmatrix} B_1 \\ B_2 \\ \vdots \\ B_S \end{pmatrix} \end{aligned} \qquad (12)$$

7) CALCULATE THE COMPREHENSIVE EVALUATION VALUE OF THE INDEX SET

Synthesize Qs to obtain the gray evaluation weight matrix of the evaluation target K_i included in each evaluation's gray category. The result is then recorded as Q (see Equation 13):

$$Q = \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_l \end{bmatrix} \qquad (13)$$

The gray fuzzy comprehensive evaluation is conducted on the evaluation object, and the result is recorded as Z (see

TABLE 2. Judgment matrix and weight analysis of the first-level indicators.

T-P_i	P_1	P_2	P_3	Index Weight w
P_1	1	1/5	4	0.2141
P_2	5	1	7	0.7093
P_3	1/4	1/7	1	0.0766

λ_{max}=3.1268，C.I.= 0.0634，C.R.= 0.0944 <0.10，Consistency can be accepted

TABLE 3. Judgment matrix and weight analysis of the safety index before training.

P_1-A_i	A_1	A_2	A_3	A_4	A_5	Index Weight w_i
A_1	1	1/7	1/5	1	2	0.0799
A_2	7	1	4	5	4	0.4800
A_3	5	1/4	1	6	5	0.2923
A_4	1	1/5	1/6	1	2	0.0849
A_5	1/2	1/4	1/5	1/2	1	0.0629

λ_{max}=5.4214，C.R.= 0.0941<0.10; consistency can be accepted

Equation 14):

$$Z = W \cdot Q = (w_1, w_2, \ldots, w_l) \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_l \end{bmatrix} \quad (14)$$

8) CALCULATE THE COMPREHENSIVE ASSESSMENT VALUE OF RISK

Different values are assigned according to the different gray grades evaluated. Because the evaluation vector of the comment Rating Set V is, the comprehensive evaluation value F of the safety risk of the evaluated object is rendered as below:

$$F = Z \cdot C^T \quad (15)$$

According to the above steps, the system can be comprehensively evaluated.

IV. CASE ANALYSIS

Next we use the above method to conduct an example analysis on a training scenario involving a building collapse ruin in an emergency training base in China to determine the overall safety risk level of the scenario and the impact of various assessment indicators on safety risk and propose the appropriate measures. In this study, we use Matlab for programming and calculation on the Windows platform.

A. INDEX WEIGHT DETERMINATION

According to the scoring results of the experts, a corresponding judgment matrix is established using AHP to calculate the weights of the evaluation indicators. The calculation results are shown in Table 2 to Table 16, where λ_{max} represents the maximum eigenvalue, C.I. represents the consistency index, and C.R. represents the consistency ratio.

TABLE 4. Judgment matrix and weight analysis of the safety index in training.

P_2-B_i	B_1	B_2	B_3	B_4	B_5	Index Weight w_i
B_1	1	3	4	4	5	0.4481
B_2	1/3	1	3	4	3	0.2496
B_3	1/4	1/3	1	3	3	0.1521
B_4	1/4	1/4	1/3	1	2	0.0870
B_5	1/5	1/3	1/3	1/2	1	0.0632

λ_{max}=5.3205，C.R. = 0.0715<0.10, consistency can be accepted

TABLE 5. Judgment matrix and weight analysis of the secondary indexes under the safety index after training.

P_3-C_i	C_1	C_2	Index Weight w_i
C_1	1	4	0.8000
C_2	1/4	1	0.2000

λ_{max} = 2.0000，C.I.= 0，C.R.= 0

TABLE 6. Judgment matrix and weight analysis of a related person.

A_1-A_{1j}	A_{11}	A_{12}	Index Weight w_{ij}
A_{11}	1	2	0.6667
A_{12}	1/2	1	0.3333

TABLE 7. Judgment matrix and weight analysis of equipment appropriateness.

A_2-A_{2j}	A_{21}	A_{22}	Index Weight w_{ij}
A_{21}	1	1/3	0.2500
A_{22}	3	1	0.7500

TABLE 8. Judgment matrix and weight analysis of the training site and facility stability.

A_3-A_{3j}	A_{31}	A_{32}	Index Weight w_{ij}
A_{31}	1	1	0.5000
A_{32}	1	1	0.5000

TABLE 9. Judgment matrix and weight analysis of the organizational structure's rationality.

A_4-A_{4j}	A_{41}	A_{42}	Index Weight w_{ij}
A_{41}	1	1	0.5000
A_{42}	1	1	0.5000

TABLE 10. Judgment matrix and weight analysis of the medical safety system.

A_5-A_{5j}	A_{51}	A_{52}	Index Weight w_{ij}
A_{51}	1	1	0.5000
A_{52}	1	1	0.5000

TABLE 11. Judgment matrix and weight analysis of human error.

B_1-B_{1j}	B_{11}	B_{12}	Index Weight w_{ij}
B_{11}	1	2	0.6667
B_{12}	1/2	1	0.3333

1) CALCULATION OF THE WEIGHTS OF THE FIRST- AND SECOND-LEVEL INDICATORS

If the judgment matrix is a first-order matrix or a second-order matrix, λ_{max} = 2.0000, and no consistency test is required.

TABLE 12. Judgment matrix and weight analysis of inherent device danger.

B_2-B_{2j}	B_{21}	B_{22}	Index Weight w_{ij}
B_{21}	1	1/3	0.2500
B_{22}	3	1	0.7500

TABLE 13. Judgment matrix and weight analysis of temporary device danger.

B_3-B_{3j}	B_{31}	B_{32}	B_{33}	Index Weight w_{ij}
B_{31}	1	3	2	0.5247
B_{32}	1/3	1	1/3	0.1416
B_{33}	1/2	3	1	0.3338
λ_{max}=3.0538，C.R.=0.0464<0.10，Consistency can be accepted				

TABLE 14. Judgment matrix and weight analysis of adverse environmental threats.

B_4-B_{4j}	B_{41}	B_{42}	B_{43}	Index Weight w_{ij}
B_{41}	1	3	6	0.6393
B_{42}	1/3	1	4	0.2737
B_{43}	1/6	1/4	1	0.0869
λ_{max}=3.0540，C.R.=0.0466<0.10，Consistency can be accepted				

TABLE 15. Judgment matrix and weight analysis of the safety management system and implementation.

B_5-B_{5j}	B_{51}	B_{52}	Index Weight w_{ij}
B_{51}	1	1/5	0.1667
B_{52}	5	1	0.8333

TABLE 16. Judgment matrix and weight analysis of maintenance, restoration, and recording.

C_1-C_{1j}	C_{11}	C_{11}	Index Weight w_{ij}
C_{11}	1	3	0.7500
C_{12}	1/3	1	0.2500

2) WEIGHT CALCULATION OF THE THIRD-LEVEL INDICATORS

The weight of the third-level index of the mental health index relative to the second-level index is $W_{C2} = (w_{C21}) = (1.000)$.

3) THE COMBINED WEIGHT OF EACH LEVEL OF THE INDICATORS RELATIVE TO THE TARGET LAYER

The results are shown in Table 17.

Table 17 shows that the indexes with a large weight are the focal aspects for improving safety. For example, the proportion of human error B_1 reaches 0.3, which is much higher than the proportion of remaining indicators at the same level, followed by the inherent device risk B_2, both of which are key factors affecting the safety of training in this scenario. The operational normativity and proficiency index B_{11}, safety personnel qualification B_{12}, inspection and monitoring facility coverage index B_{22}, and equipment and equipment inspection A_{22} in the third-level index layer with a

TABLE 17. Relative weight of the indicators at various levels.

First-level indicators	w	Second-level indicators	w_i	α	Third-level indicators	w_{ij}	β
P₁	0.2141	A₁	0.0799	0.0171	A₁₁	0.6667	0.0114
					A₁₂	0.3333	0.0057
		A₂	0.4800	0.1028	A₂₁	0.2500	0.0257
					A₂₂	0.7500	0.0771
		A₃	0.2923	0.0626	A₃₁	0.5000	0.0313
					A₃₂	0.5000	0.0313
		A₄	0.0849	0.0182	A₄₁	0.5000	0.0091
					A₄₂	0.5000	0.0091
		A₅	0.0629	0.0135	A₅₁	0.5000	0.0067
					A₅₂	0.5000	0.0067
P₂	0.7093	B₁	0.4481	0.3178	B₁₁	0.6667	0.2119
					B₁₂	0.3333	0.1059
		B₂	0.2496	0.1770	B₂₁	0.2500	0.0443
					B₂₂	0.7500	0.1328
		B₃	0.1521	0.1079	B₃₁	0.5247	0.0566
					B₃₂	0.1416	0.0153
					B₃₃	0.3338	0.0360
		B₄	0.0870	0.0617	B₄₁	0.6393	0.0395
					B₄₂	0.2737	0.0169
					B₄₃	0.0869	0.0054
		B₅	0.0632	0.0448	B₅₁	0.1667	0.0075
					B₅₂	0.8333	0.0374
P₃	0.0766	C₁	0.8000	0.0613	C₁₁	0.7500	0.0460
					C₁₂	0.2500	0.0153
		C₂	0.2000	0.0153	C₂₁	1.0000	0.0153

sum of weight ratio more than 0.52 should be given attention. Although the weight ratio of the other indicators is relatively small, such indicators will also affect safety and should be considered to enhance the overall safety of the scenario.

B. GREY FUZZY EVALUATION

1) DIVIDE THE EVALUATION LEVEL AND EVALUATE THE SAMPLE MATRIX

According to the risk rating scoring standard, 10 experts were invited to score the third-level indicator k_{ij} to obtain the safety evaluation sample matrix D for the training scenario of building collapse ruins, as shown in Table 18.

2) CALCULATE GRAY STATISTICS

According to the evaluation sample matrix and the whitening weight function determined in Section 2.2, the gray statistics can be calculated according to Equation 7. Then, the total gray statistics nij for the evaluation index K_{ij} belonging to each evaluated gray category can be calculated by Equation 8. Take the evaluation index A_{11} as an example:

When e=1,

$$
\begin{aligned}
n_{A11}^1 &= \sum_{n=1}^{10} f_1\left(d_{11}^n\right) = f_1\left(d_{11}^1\right) + f_1\left(d_{11}^2\right) + \cdots + f_1\left(d_{11}^{10}\right) \\
&= f_1(2) + f_1(3) + f_1(4) + f_1(2) + f_1(2) \\
&\quad + f_1(3) + f_1(3) + f_1(3) + f_1(2) + f_1(3) \\
&= 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 \\
&= 0
\end{aligned}
\tag{16}
$$

TABLE 18. Evaluation sample matrix.

Index k_{ij}	Expert serial number									
	1	2	3	4	5	6	7	8	9	10
A_{11}	2	3	4	2	2	3	3	3	2	3
A_{12}	2	1	3	3	4	3	2	3	1	3
A_{21}	2	3	3	4	2	1	3	2	3	3
A_{22}	4	3	5	4	3	2	3	4	3	2
A_{31}	2	3	1	2	2	3	2	2	3	1
A_{32}	3	3	2	4	3	3	3	2	2	3
A_{41}	2	3	2	1	4	3	2	3	2	1
A_{42}	2	4	1	2	3	2	3	2	1	2
A_{51}	2	3	2	2	4	2	3	4	1	2
A_{52}	3	2	1	2	4	5	4	2	3	1
B_{11}	3	3	3	2	5	2	4	3	5	3
B_{12}	4	5	3	3	2	3	4	5	3	4
B_{21}	1	2	4	1	2	2	3	2	1	2
B_{22}	2	3	2	3	1	2	2	2	1	1
B_{31}	2	2	3	4	4	3	3	3	4	3
B_{32}	3	2	2	3	1	2	2	1	2	1
B_{33}	4	2	4	2	4	3	5	3	2	4
B_{41}	2	5	3	1	2	5	3	2	1	3
B_{42}	5	2	3	2	4	3	3	4	1	3
B_{43}	4	2	3	3	2	3	3	2	3	2
B_{51}	2	2	1	1	2	2	3	3	2	4
B_{52}	4	3	2	2	4	5	3	5	3	4
C_{11}	3	3	2	1	1	2	4	1	2	3
C_{12}	2	1	1	2	1	2	2	2	3	1
C_{21}	2	1	3	2	3	3	3	2	2	2

TABLE 19. Gray statistics of each evaluation index and total gray statistics.

Index K_{ij}	Gray statistics					Total gray statistics
	n_{ij}^1	n_{ij}^2	n_{ij}^3	n_{ij}^4	n_{ij}^5	n_{ij}
A_{11}	0.00	6.50	8.33	6.75	5.40	26.98
A_{12}	2.00	5.50	7.67	6.25	5.00	26.42
A_{21}	1.00	6.00	8.00	6.50	5.20	26.70
A_{22}	0.00	4.00	7.67	7.75	6.60	26.02
A_{31}	2.00	7.50	7.00	5.25	4.20	25.95
A_{32}	0.00	6.00	8.67	7.00	5.60	27.27
A_{41}	2.00	6.50	7.00	5.75	4.60	25.85
A_{42}	2.00	7.00	6.67	5.50	4.40	25.57
A_{51}	1.00	6.50	7.00	6.25	5.00	25.75
A_{52}	2.00	5.00	6.33	6.25	5.40	24.98
B_{11}	0.00	4.50	7.67	7.25	6.60	26.02
B_{12}	0.00	3.00	7.33	8.00	7.20	25.53
B_{21}	3.00	7.00	6.00	5.00	4.00	25.00
B_{22}	3.00	7.50	6.33	4.75	3.80	25.38
B_{31}	0.00	4.50	8.33	7.75	6.20	26.78
B_{32}	3.00	7.50	6.33	4.75	3.80	25.38
B_{33}	0.00	4.00	7.00	7.75	6.60	25.35
B_{41}	2.00	5.50	6.33	5.75	5.40	24.98
B_{42}	1.00	4.50	7.33	7.00	6.00	25.83
B_{43}	0.00	6.50	8.33	6.75	5.40	26.98
B_{51}	2.00	7.00	6.67	5.50	4.40	25.57
B_{52}	0.00	3.50	7.00	7.75	7.00	25.25
C_{11}	3.00	6.00	6.67	5.50	4.40	25.57
C_{12}	4.00	7.50	5.67	4.25	3.40	24.82
C_{21}	1.00	7.50	7.67	5.75	4.60	26.52

When e=2, $n_{A11}^2 = \sum_{n=1}^{10} f_2\left(d_{11}^n\right) = 6.50$; when e=3, $n_{A11}^3 = \sum_{n=1}^{10} f_3\left(d_{11}^n\right) = 8.33$; when e=4, $n_{A11}^4 = \sum_{n=1}^{10} f_4\left(d_{11}^n\right) = 5.40$; when e=5, $n_{A11}^5 = \sum_{n=1}^{10} f_5\left(d_{11}^n\right) = 5.40$.

Then, the total gray statistics nA_{11} of the evaluation index A_{11} belonging to each evaluation gray category are:

$$n_{A11} = \sum_{e=1}^{5} n_{A11}^e = n_{A11}^1 + n_{A11}^2 + n_{A11}^3 + n_{A11}^4 + n_{A11}^5$$
$$= 0 + 6.50 + 8.33 + 6.75 + 5.40$$
$$= 26.98 \qquad (17)$$

The gray statistics of the remaining indicators can be calculated similarly. The results are shown in Table 19.

3) CALCULATE GRAY EVALUATION WEIGHT VECTOR AND WEIGHT MATRIX

For the evaluation index A_{11}, the gray evaluation weight belonging to the gray category of the e-th evaluation is recorded as r_{A11}^e:

When e=1, $r_{A11}^1 = \frac{n_{A11}^1}{n_{A11}} = 0$; when e=2, $r_{A11}^2 = \frac{n_{A11}^2}{n_{A11}} = \frac{6.50}{26.98} = 0.2409$; when e=3, $r_{A11}^3 = \frac{n_{A11}^3}{n_{A11}} = \frac{8.33}{26.98} = 0.3087$; when e=4, $r_{A11}^4 = \frac{n_{A11}^4}{n_{A11}} = \frac{6.75}{26.98} = 0.2502$; when e=5, $r_{A11}^5 = \frac{n_{A11}^5}{n_{A11}} = \frac{5.40}{26.98} = 0.2001$.

Therefore, the gray weight vector of the evaluation index A_{11} can be expressed as $r_{A11} = \left(r_{A11}^1, r_{A11}^2, r_{A11}^3, r_{A11}^4, r_{A11}^5\right) = (0.0000, 0.2409, 0.3087, 0.2502, 0.2001)$. The fuzzy weight vector of the remaining index factors can be calculated similarly. The gray fuzzy membership matrix R_{A1} of the evaluation index A_1 is:

$$R_{A1} = \begin{pmatrix} r_{A11} \\ r_{A12} \end{pmatrix}$$
$$= \begin{pmatrix} 0.0000, 0.2409, 0.3087, 0.2502, 0.2001 \\ 0.0757, 0.2082, 0.2903, 0.2366, 0.1893 \end{pmatrix} \quad (18)$$

The gray clustering weight matrix of the other indexes for each evaluated gray category can be obtained in the same way:

$$R_{A2} = \begin{pmatrix} r_{A21} \\ r_{A22} \end{pmatrix}$$
$$= \begin{pmatrix} 0.0375, 0.2247, 0.2996, 0.2434, 0.1948 \\ 0.0000, 0.1537, 0.2948, 0.2978, 0.2537 \end{pmatrix} \quad (19)$$

$$R_{A3} = \begin{pmatrix} r_{A31} \\ r_{A32} \end{pmatrix}$$
$$= \begin{pmatrix} 0.0771, 0.2890, 0.2697, 0.2023, 0.1618 \\ 0.0000, 0.2200, 0.3179, 0.2567, 0.2054 \end{pmatrix} \quad (20)$$

$$R_{A4} = \begin{pmatrix} r_{A41} \\ r_{A42} \end{pmatrix}$$
$$= \begin{pmatrix} 0.0774, 0.2515, 0.2708, 0.2224, 0.1779 \\ 0.0782, 0.2738, 0.2609, 0.2151, 0.1721 \end{pmatrix} \quad (21)$$

$$R_{A5} = \begin{pmatrix} r_{A51} \\ r_{A52} \end{pmatrix}$$

$$= \begin{pmatrix} 0.0388, 0.2524, 0.2718, 0.2427, 0.1942 \\ 0.0801, 0.2002, 0.2534, 0.2502, 0.2162 \end{pmatrix} \quad (22)$$

$$R_{B1} = \begin{pmatrix} r_{B11} \\ r_{B12} \end{pmatrix}$$

$$= \begin{pmatrix} 0.0000, 0.1729, 0.2948, 0.2786, 0.2537 \\ 0.0000, 0.1175, 0.2871, 0.3134, 0.2820 \end{pmatrix} \quad (23)$$

$$R_{B2} = \begin{pmatrix} r_{B21} \\ r_{B22} \end{pmatrix}$$

$$= \begin{pmatrix} 0.1200, 0.2800, 0.2400, 0.2000, 0.1600 \\ 0.1182, 0.2955, 0.2494, 0.1872, 0.1497 \end{pmatrix} \quad (24)$$

$$R_{B3} = \begin{pmatrix} r_{B31} \\ r_{B32} \\ r_{B33} \end{pmatrix}$$

$$= \begin{pmatrix} 0.0000, 0.1680, 0.3111, 0.2894, 0.2315 \\ 0.1182, 0.2955, 0.2494, 0.1872, 0.1497 \\ 0.0000, 0.1578, 0.2761, 0.3057, 0.2604 \end{pmatrix} \quad (25)$$

$$R_{B4} = \begin{pmatrix} r_{B41} \\ r_{B42} \\ r_{B43} \end{pmatrix}$$

$$= \begin{pmatrix} 0.0801, 0.2202, 0.2534, 0.2302, 0.2162 \\ 0.0387, 0.1742, 0.2838, 0.2710, 0.2323 \\ 0.0000, 0.2409, 0.3087, 0.2502, 0.2001 \end{pmatrix} \quad (26)$$

$$R_{B5} = \begin{pmatrix} r_{B51} \\ r_{B52} \end{pmatrix}$$

$$= \begin{pmatrix} 0.0782, 0.2738, 0.2609, 0.2151, 0.1721 \\ 0.0000, 0.1386, 0.2772, 0.3069, 0.2772 \end{pmatrix} \quad (27)$$

$$R_{C1} = \begin{pmatrix} r_{C11} \\ r_{C12} \end{pmatrix}$$

$$= \begin{pmatrix} 0.1173, 0.2346, 0.2609, 0.2151, 0.1721 \\ 0.1612, 0.3022, 0.2284, 0.1712, 0.1370 \end{pmatrix} \quad (28)$$

$$R_{C2} = (r_{C21})$$

$$= (0.0377, 0.2828, 0.2892, 0.2168, 0.1735) \quad (29)$$

4) CALCULATE THE FIRST-LEVEL GRAY FUZZY EVALUATION MATRIX

The first-level fuzzy evaluation of the indicator A_1 results in a gray fuzzy evaluation matrix. The result is recorded as B_{A1} using Equation 11:

$$B_{A1} = W_{A1} \cdot R_{A1}$$

$$= (0.6667, 0.3333)$$

$$\cdot \begin{pmatrix} 0.0000, 0.2409, 0.3087, 0.2502, 0.2001 \\ 0.0757, 0.2082, 0.2903, 0.2366, 0.1893 \end{pmatrix}$$

$$= (0.0252, 0.2300, 0.3026, 0.2456, 0.1965) \quad (30)$$

The gray fuzzy judgment matrix B_i (i = A_1, A_2, ..., A_5, B_1, ..., B_5, C_1, C_2) for the remaining indicators can be obtained similarly.

5) CALCULATE THE SECOND-LEVEL GRAY FUZZY EVALUATION MATRIX

Synthesize B_i to construct a new gray fuzzy judgment matrix B_s (s = A, B, C) as follows:

$$B_A = \begin{pmatrix} B_{A1} \\ B_{A2} \\ B_{A3} \\ B_{A4} \\ B_{A5} \end{pmatrix}$$

$$= \begin{pmatrix} 0.0252, 0.2300, 0.3026, 0.2456, 0.1965 \\ 0.0094, 0.1715, 0.2960, 0.2842, 0.2389 \\ 0.0385, 0.2545, 0.2938, 0.2295, 0.1836 \\ 0.0778, 0.2626, 0.2658, 0.2188, 0.1750 \\ 0.0594, 0.2263, 0.2626, 0.2465, 0.2052 \end{pmatrix} \quad (31)$$

$$B_B = \begin{pmatrix} B_{B1} \\ B_{B2} \\ B_{B3} \\ B_{B4} \\ B_{B5} \end{pmatrix}$$

$$= \begin{pmatrix} 0.0526, 0.2350, 0.2657, 0.2452, 0.2015 \\ 0.1187, 0.2916, 0.2471, 0.1904, 0.1523 \\ 0.0167, 0.1524, 0.2376, 0.2216, 0.1795 \\ 0.0618, 0.2094, 0.2665, 0.2431, 0.2192 \\ 0.0130, 0.1611, 0.2745, 0.2916, 0.2597 \end{pmatrix} \quad (32)$$

$$B_C = \begin{pmatrix} B_{C1} \\ B_{C2} \end{pmatrix}$$

$$= \begin{pmatrix} 0.1283, 0.2515, 0.2528, 0.2041, 0.1633 \\ 0.0377, 0.2828, 0.2892, 0.2168, 0.1735 \end{pmatrix} \quad (33)$$

On this basis, a two-level fuzzy judgment is made, and the results are sequentially recorded as Q_{P1}, Q_{P2}, Q_{P3}:

$$Q_{P1} = W_A \cdot B_A$$

$$= (0.0799, 0.4800, 0.2923, 0.0849, 0.0629)$$

$$\cdot \begin{pmatrix} 0.0252, 0.2300, 0.3026, 0.2456, 0.1965 \\ 0.0094, 0.1715, 0.2960, 0.2842, 0.2389 \\ 0.0094, 0.1715, 0.2960, 0.2842, 0.2389 \\ 0.0778, 0.2626, 0.2658, 0.2188, 0.1750 \\ 0.0594, 0.2263, 0.2626, 0.2465, 0.2052 \end{pmatrix}$$

$$= (0.0281, 0.2116, 0.2912, 0.2572, 0.2118) \quad (34)$$

$$Q_{P2} = W_B \cdot B_B$$

$$= (0.0619, 0.2297, 0.2574, 0.2307, 0.1911) \quad (35)$$

$$Q_{P3} = W_C \cdot B_C$$

$$= (0.1102, 0.2578, 0.2600, 0.2067, 0.1653) \quad (36)$$

C. IMPACT ANALYSIS OF THE COMPREHENSIVE EVALUATION OF VARIOUS INDICATORS

1) OBTAIN THE GRAY EVALUATION WEIGHT MATRIX OF EACH EVALUATION GRAY CATEGORY AND RECORD IT AS Q

$$Q = \begin{pmatrix} Q_{P1} \\ Q_{P2} \\ Q_{P3} \end{pmatrix}$$

$$= \begin{pmatrix} 0.0281, 0.2116, 0.2912, 0.2572, 0.2118 \\ 0.0619, 0.2297, 0.2574, 0.2307, 0.1911 \\ 0.1102, 0.2578, 0.2600, 0.2067, 0.1653 \end{pmatrix} \quad (37)$$

The gray fuzzy comprehensive evaluation of the first-level indicators includes

$$Z = W \cdot Q = (W_{P1}, \ W_{P2}, \ W_{P3}) \cdot \begin{pmatrix} Q_{P1} \\ Q_{P2} \\ Q_{P3} \end{pmatrix}$$

$$= (0.2141, 0.7093, 0.0766)$$

$$\cdot \begin{pmatrix} 0.0281, 0.2116, 0.2912, 0.2572, 0.2118 \\ 0.0619, 0.2297, 0.2574, 0.2307, 0.1911 \\ 0.1102, 0.2578, 0.2600, 0.2067, 0.1653 \end{pmatrix}$$

$$= (0.0584, 0.2280, 0.2648, 0.2345, 0.1936) . \quad (38)$$

According to the analysis, the training scenario of the building collapse ruins is 5.84%, with a low risk level; 22.80%, with a relatively low risk level; 26.48%, with a general risk level; and 23.45%, with a relatively high risk level. The degree of the high risk level is 19.36%.

2) CALCULATE THE COMPREHENSIVE RISK EVALUATION VALUE

The comprehensive evaluation value F of the safety risk of the evaluation object is

$$F = Z \cdot C^T$$

$$= (0.0584, 0.2280, 0.2648, 0.2345, 0.1936) \cdot \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix}$$

$$= 3.2147 \quad (39)$$

Comparing the comprehensive evaluation value F=3.2147 with Table 2, it can be seen that in the whole process of personnel training in the fire training scenario of building collapse ruins, the training risk lies between the general risk level and the higher risk level, although the risk is more inclined toward the general level. Therefore, when a person engages in training under this scenario, the risk is at a general level.

Similarly, the evaluation value of the first-level indicators can be calculated as follows: $F_{P1} = 3.4130$, $F_{P2} = 3.1717$, and $F_{P3} = 3.0592$. The order of the comprehensive evaluation value of the first-level indicator risk is $3.5 > F_{P1} > F_{P2} > F_{P3} > 3$; here, the risk is more inclined toward the general level. However, special attention should be paid to the preparations before the fire training. Moreover, all the factors involved must be dealt with, and the risk response measures should be formulated in advance.

The score matrix for the evaluation values of the secondary indicators $F_i = B_s \cdot (1, 2, 3, 4, 5)^T = (3.3582, 3.5719, 3.2651, 3.1506, 3.3116, 3.3081, 2.9660, 2.8186, 3.3482, 3.6238, 3.0226, 3.2055)$, $i = A_1, A_2, \ldots, A_5, B_1, \ldots, B_5, C_1, C_2$. Thus, it can be seen that the risk levels of F_{A1} to F_{C2} are close to general. The risk of the safety management system and implementation is the largest followed by the risk value of the goodness of the equipment.

It can be seen that the overall risk of the training scenario of the example lies at a general level and that the main safety hazards exist before and during the training. The safety index is slightly higher after the training, but it remains only at a general level (in a critical state) and needs to be improved.

Timely measures should be taken to improve indicators with a low score performance, such as the safety management system and implementation status B_5, equipment appropriateness A_2, related personnel A_1, etc., especially the evaluation value of the safety management system and implementation status $4 > F_{B5} > 3.5$, which is far higher than the evaluation value scores of the other indicators. Thus, the risk is the greatest. Considering existing problems, the following measures are recommended:

For the safety management system and implementation B_5, measures should be taken from the perspective of the ground vehicle and unrelated personnel interference index B_{51} and emergency stop rule B_{52}. First, the driver should pass his or her assessment by the business department above the detachment and obtain a driver's license for the corresponding vehicle model before participating in synthetic training. The validity of the driver's qualification certificate should be checked (e.g., an overdue inspection), and there should be restrictions on the driving speed and driving range. The scope of activities of personnel who have nothing to do with the training should also be strictly controlled, and the emergency stop rule should be set up in the training regulations and strictly implemented during the training process.

For equipment appropriateness A_2, the training equipment should be regularly inspected, tested, maintained, and registered; personal protective equipment suitable for the training subject should be selected, and the pre-training equipment inspection and storage process should be strictly implemented. Training equipment and apparatuses that do not meet the necessary standards, are defective, or have expired should be sent for repairs or scrapped to prevent training accidents.

For related personnel A_1, detailed physical and mental health examinations should be conducted among the trainers. The physical and health statuses of the trainers should comply with China "GB/Z 221-2009 Firefighter Occupational Health Standard" and the specific training scenario. For training personnel who do not meet these training standards, measures such as degrading or prohibiting training should be taken. The technical level of the training personnel and their degree of mastery of the safety regulations should also be assessed. Those who fail the assessment should be subject to technical and safety education and should only participate

in training after passing an assessment in a later stage. The above measures, to a certain extent, can improve the overall safety assurance capabilities under the studied context.

V. CONCLUSION

Focusing on the emergency training scenarios of building collapse ruins, this study used AHP and grey fuzzy evaluation methods for the first time to conduct a comprehensive evaluation of safety risks. This evaluation method can provide a reference for the safety evaluation of other emergency training scenarios.

(1) From the perspective of time series development, the whole training process was divided into three stages: before training, during training, and after training. Combined with the "man-machine-ring-tube" theory of safety principles, each stage was subdivided into detailed secondary index factors. The brainstorming method and expert investigation method were used to establish a safety assessment index system for emergency training scenarios of building collapse and ruins.

(2) Based on the AHP-gray fuzzy evaluation theory, a comprehensive evaluation model for emergency training scenarios of building collapse ruins was constructed. The single ranking weight and total ranking weight of the safety evaluation index system were determined through calculations, and a preliminary judgment was made on the importance of each index in the index system. In the second-level indicator layer, the weight ratio of human error B_1 reached 0.3, which is a leading position, and the inherent device risk B_2 ranked second. Both are key factors that affect the training safety in this scenario.

(3) A domestic training base was selected to conduct an example analysis of the evaluation method. Finally, it was determined that the method's overall risk is at a general level; the main safety hazards exist in two stages: before and during training. According to the evaluation results, the safety management system and implementation status B_5, equipment appropriateness A_2, and related personnel A_1 all performed poorly. In particular, the safety management system and implementation status B_5 were the riskiest, and timely measures should be taken to enhance the safety performance to improve the safety assurance capabilities of personnel at the base during emergency training.

(4) This method combines AHP and gray-fuzzy evaluation so that it is possible to get quantitative results and find the most influential factor on training safety. In future research, it could be considered to be applied to training safety assessment in other scenarios, and the indicator system needs to be adjusted accordingly.

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