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Analysis of the Causes of Falling Accidents on Building Construction Sites in China Based on the HFACS Model

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Abstract: In order to explore the causative factors of falling accidents at high-rise building construction sites, this study collected 207 reports of these accidents from 2014 to 2024. We used the Human Factor Analysis and Classification System (HFACS) during sample collection, from the four perspectives of organizational impact, unsafe supervision, prerequisites for unsafe behavior, and unsafe behavior. In total, 21 important causal factors were identified, and the samples were classified according to these factors. Descriptive statistics, chi-square testing, and limit matrix analysis were mainly used. SPSS 27.01 was used to analyze the samples, and Super Decisions software was used to normalize the limit supermatrix and calculate the weight. Subsequently, innovative and comprehensive application of chi-square testing and correlation coefficients was applied to determine the correlation of factors, and ANP was used to determine the weight of the factors. According to the weight, we determined the key factors, levels, and paths, and the relationship between the causes of falling accidents in building construction was systematically studied. Finally, based on the key causal path and key factors, a corresponding pre-control strategy was proposed. The results show that the key factors are a lack of awareness of personnel safety, safety education and training, and on-site safety management and an absence of safety inspections and routine maintenance. The key causes are that labor companies are not qualified, there is a lack of on-site safety oversight, and personnel do not have a permit to work at significant heights and do not wear safety protection equipment properly. This study explores the shortcomings of safety management in the construction industry. In order to reduce the accident rate, it is very important to improve the level of decision-making regarding safety management by the government and construction industry. This study has the following limitations: firstly, the information obtained from the investigation report of high-rise building construction accidents is not adequate to fully reflect the situation of workers on-site, which inevitably leads to some deviations. Secondly, due to the high mobility of construction workers, it is very difficult to investigate psychological or physiological states that may have a potential impact on unsafe behavior.

Keywords: human factors analysis and classification system; construction enterprise; falling accidents; analytic network process (ANP); critical path

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1. Introduction

According to statistics from the Ministry of Emergency Management and the Ministry of Housing and Urban-Rural Development of China (MHURDC), in the first three quarters of 2024, there were 14,402 safety accidents and 13,412 deaths in China, a decrease of 24.5% and 18.4%, respectively, compared with the previous year [1]. Among them, the number of accidents and deaths in the construction industry decreased year-on-year. In 2019, there were 415 accidents involving falls from a great height, accounting for 53.69% of the total. In 2020, among the production safety accidents in housing and municipal engineering in China, there were 407 accidents involving falls from a significant height, accounting for 59.07% of the total number of production safety accidents, which is the highest proportion among accident types. In 2022, the proportion of falling accidents in China's construction industry was still high, and falling accidents accounted for 47.8% of all types of accidents. In the first half of 2024, there were 9229 work safety accidents and 8507 deaths across the country, a decrease of 3276 and 2035, respectively, compared with the same period in 2023. This clearly indicates the high frequency of falling-related accidents in building construction. Building construction has become the second-most accident-prone sector, and in this field, the number of falls and the number of deaths have always been highest in the field of construction. The results are shown in Figure 1.

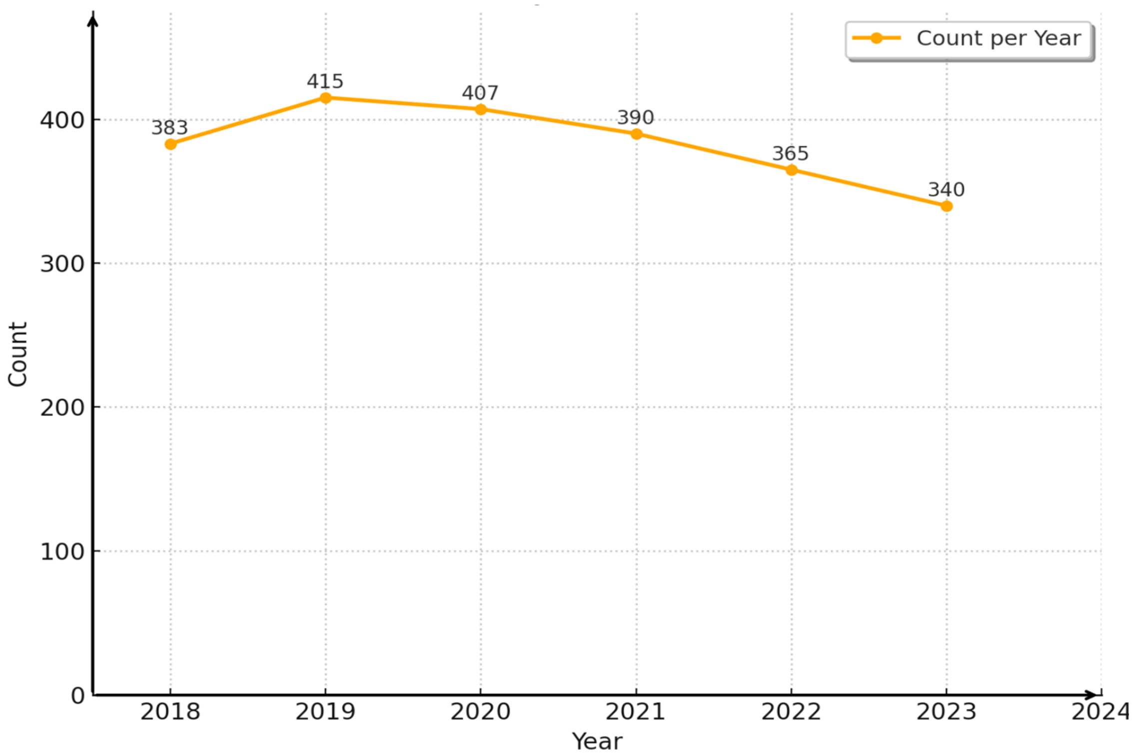

Figure 1. Statistics of safety accidents involving falls from a significant height in construction. Source: Work Safety Law Enforcement and Industry and Trade Safety Supervision and Administration Bureau.

Taking Hubei Province as an example, from January to October 2024, there were 63 accidents and 67 deaths in the construction industry (including housing and municipal engineering and railway engineering construction), which was 21 and 23 fewer than those in the same period of 2023, down 25.0% and 25.6%, respectively [2]. In general, although the safety production situation in the construction industry has improved, the total number of accidents is still high, and the safety production situation is still grim [3]. The most frequent causes of accidents include falling from heights, building collapses, being struck by an object, and injuries incurred during lifting or due to electric shock. Among these, falling from heights accounts for a high proportion of accidents and is the focus of accident prevention [4]. The results are shown in Figure 2.

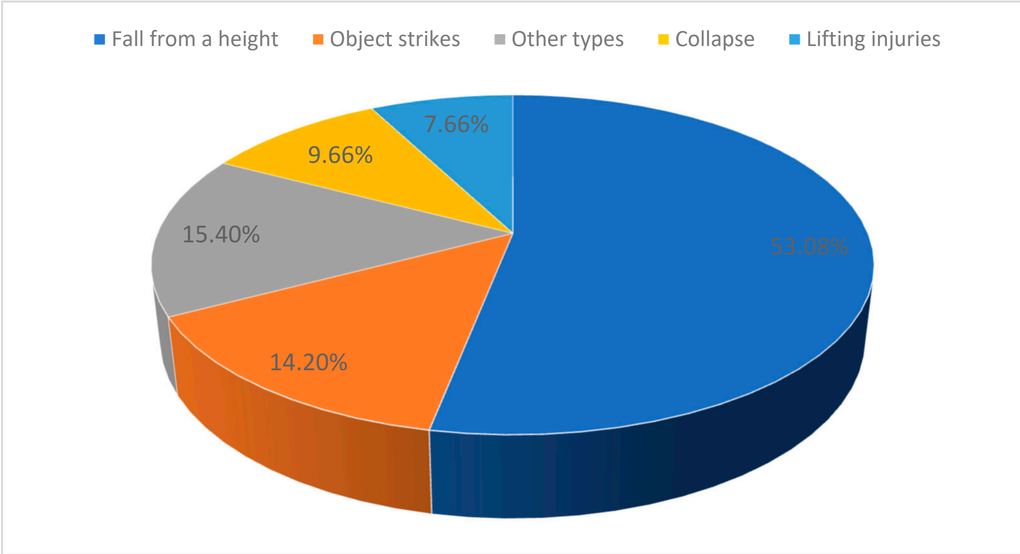

Figure 2. Distribution of main accident types in high-rise building construction from 2014 to 2024. Source: Ministry of Housing and Urban-Rural Development of China (MHURDC).

In China, the construction industry has made unremitting efforts in promoting safety management. According to statistics, in 2019, there were 415 deaths caused by falls from a great height in construction, and in 2023, there were 340. There was a significant downward trend in the number of falls from great heights that resulted in death, but the number of safety accidents resulting in deaths remained distressing, and the safety situation in China's construction industry is still very serious.

The purpose of this study is to systematically identify and analyze the key causal pathways of high-rise fall accidents in building construction. Based on the HFACS model, the logical relationship of human factors is constructed, and the relative weight of each factor in the process of accident formation is quantified to provide a theoretical basis and method support for the formulation of high-rise fall accident prevention strategies. In order to achieve the above objectives, this paper will focus on the following issues: What are the common causes of falling accidents in construction? What are the key paths and interrelationships between these causal factors? What factors play a major role in the occurrence of the accident? How much of a role do each of these factors play (in other words, what is their weight)?

The types of falling accidents in high-rise building construction include falls from scaffolding and falls from aerial work platforms. Falling accidents refer to an accident involving a personal injury or equipment damage caused by falling from a high place (usually referring to a position more than 2 m higher than the base level), when the operator is working at a high place (usually referring to a position more than 2 m higher than the base level), and due to causes such as loss of footing, unstable support, or inadequate protection.

To this end, this paper establishes a HFACS model to analyze the causal factors of fall accidents from great heights in building construction. Then, through chi-square testing, the correlation coefficient is calculated, and the ANP weight is determined to analyze the relationship between the causal factors of these falls; then, a strategy to prevent these falls is proposed [5]. Through the study of the correlation between the factors, correlation analysis between the two causal factors of the adjacent levels identified a total of 20 groups of relationships. The correlation between the weak safety awareness of personnel and the inadequate implementation of safety management systems was the strongest. The correlation analysis between the two factors of non-adjacent levels identified a total of seven groups of associations. Correlation analysis between the two factors at the same level identified 11 groups of correlations. Finding the most influential path and key factors, and taking measures against these, will greatly reduce the probability and severity of accidents.

2. Literature Review

2.1. Accident Cause Analysis Model

Some studies have used the HFACS framework to analyze the causes of construction accidents in order to identify and classify human factors and systemic problems that lead to accidents. At present, the models and methods for analyzing the causes of various accidents include the 2–4 model, HFACS model, FRAM model, accident tree analysis method, and causal analysis method. The HFACS framework defined by Wiegmann and Shappell (2001) [6] is the most widely used model or method in various fields. The general HFACS consists of four layers: the unsafe behavior layer, preconditions for unsafe behavior, unsafe supervision layer, and organizational impact layer. HFACS provides a structure to review and analyze historical accident and safety data.

Some studies have used the HFACS framework to analyze the causes of accidents in the construction industry to identify and classify the human factors and systemic problems that lead to accidents. It is well known that human factors are a key causal factor in many accidents, which may lead to varying degrees of accident injuries (Huang Zihan, 2024) [7]. Human factors are the dominant factors. Mechanical factors, environmental factors, and management factors also have a great impact on the occurrence of accidents. Li Huishan et al. conducted a human factors analysis on construction safety accidents involving steel structures based on the modified HFACS model (Li Huishan and Hui Limin, 2024) [8]. Li Yisong established a causal factor analysis framework based on the HFACS and system dynamics (SDs) to analyze the causal factors of unsafe behavior of construction workers, which provides a basis for the simulation of specific construction projects (Li Yisong et al., 2023) [9]. Based on the modified HFACS, Ma Shumei et al. carried out a cause analysis of residential engineering quality defects. They used the ISM model to analyze the relationship between the cause factors and used the MICMAC method to verify the research results (Ma Shumei et al., 2023) [10]. Chen Xiaoyong et al. [11] analyzed the human factors of construction safety qualitatively and quantitatively through the modified HFACS model combined with SPA and formulated more effective safety measures.

2.2. Fall Accidents in the Construction Industry

In order to study the key causal factors of falling accidents from significant heights, Mistikoglu et al. [12] used C5.0 and CHAID algorithms to construct a decision tree model and determined that factors such as fall distance, injury cause, and safety training had a significant impact on accident mortality. Dong et al. [13] conducted a statistical and descriptive analysis of 768 fall accidents in the United States and found that factors such as the age of the victims, the type of work, the type of enterprise, and the height of the victims were related to the occurrence of such accidents, emphasizing the importance of personal protection systems in the prevention of falls from heights. The findings of Kine [14] showed that the specific causes of serious injuries and deaths caused by construction workers falling from heights varied depending on the workplace, personal protection, and time. This finding suggests the need for appropriate precautions depending on the situation, such as deploying safety measures in specific workplaces to reduce the occurrence of falls from heights. In addition, safety training and guidance for workers should be strengthened at different time periods, making it easier to take the right actions when they are aware of the danger. It is important to note that in order to ensure the safety of construction workers, the use of personal fall arrest equipment plays a vital role. Therefore, it is important to encourage and ensure that all workers wear and use these devices correctly, while improving their quality and reliability.

Based on the above analysis of the literature, many causality models applied to accident analysis tend to have their own emphasis. For example, the HFACS model mainly emphasizes the analysis of human factors [15], while the 2–4 model emphasizes accidents caused by management errors [16]. The modularization of the HFACS model is divided into four aspects: [17] the organizational impact layer, unsafe supervision layer, prerequisites for unsafe behavior layer, and unsafe behavior layer. This classification enables rapid analysis of the causes of multiple accidents [18]. In addition, we combine ANP with HFACS methods to more effectively identify the key factors that lead to accidents [19].

At present, the safety management model of construction enterprises has gradually matured. Hallowell [20] summarized the current situation of safety management in the construction industry and analyzed the challenges and strategies of construction enterprises in terms of safety management. However, there are few studies on the analysis of the causes of fall accidents in building construction. Li Yu et al. [21] pointed out that the causes of falls from heights are more prominently noted in analyses of falls from heights and include such factors as inadequate protective facilities, weak safety awareness, and poor supervision, but the countermeasures of key factors have not been analyzed. The research on the causes of accidents at home and abroad [22] mainly focuses on coal mines and construction and chemical industries. Studies have shown that accidents are usually not caused by a single factor but are the result of a combination of multiple unsafe factors. Compared with industries such as coal mines and machinery, the types of accidents in the construction industry are mostly high falls, mechanical injuries, and collapses, but there are similarities in the causes of accidents in different fields. These studies provide a valuable reference for the analysis of the causes of accidents in building construction. Through the construction of the system and related data research, the key causal factors, key levels, and key paths are determined so that relevant organizations can take targeted measures.

2.3. The Innovation Point of This Article

Based on the analytical process and results of this study, several novelties and innovations can be identified: firstly, the research adopts the HFACS model as an analytical framework, enabling an in-depth exploration, from a human factors perspective, of the causal mechanisms of accidents involving falls from heights. This expands the depth of attention to human-related causes in current construction safety research. Secondly, the study innovatively integrates frequency analysis with association analysis to effectively identify key causal pathways among contributing factors. In addition, ANP is employed to calculate the weights of each causal factor, enhancing the scientific rigor and systematic nature of the causality ranking. Furthermore, the analysis is grounded in a large number of real accident reports, ensuring the practical relevance and applicability of the results. The identified key causal paths and critical control points can provide targeted improvement strategies for construction enterprises, offering strong practical value for enhancing safety management.

3. Materials and Methods

3.1. Data Collection and Research Methods

3.1.1. Data Collection

The research sample data come from the construction fall accident report of the safety management network, which mainly includes all kinds of safety accidents that occur when the construction enterprises carry out high-rise operations. The screening criteria included the following: the accident type was clearly identified as a fall from height, the accident description was complete, and information on casualties was provided. By screening and collecting 207 valid accident report samples, combining these with the basic framework of the HFACS model, and referring to its application in the fields of the chemical industry, aviation, etc. (and according to the characteristics of falling [23] accidents in building construction), these samples were classified and sorted; finally, the causes [24] and manifestations of falling accidents on building construction sites, based on the HFACS model, were obtained.

3.1.2. Research Methods

Chi-square test: the chi-square test is a commonly used statistical test method that is mainly used to test whether there is a significant correlation or independence between two or more categorical variables. Its basic principle is to compare the difference between the observed frequency and the expected frequency and calculate the size of the difference to determine whether there is a significant relationship between the variables.

Null hypothesis (H_0): *The two variables are independent; there is no association between them.*

Alternative hypothesis (H_1): *The two variables are not independent; there is an association between them.*

The basic principle of calculating the OR (odds ratio) is used to assess the association or relative risk between two variables, especially between two categorical variables.

- OR = 1: exposure is not associated with the disease (no association);
- OR > 1: exposure may be a risk factor for the disease;
- OR < 1: exposure may be a protective factor against the disease.

The basic principle of calculating the *p*-value is based on hypothesis testing, which is used to evaluate whether the observed results are consistent with the null hypothesis (usually no effect or no difference hypothesis) or whether the observed results are caused by random errors.

- $p < 0.05$ (commonly used significance level): the result is statistically significant; the null hypothesis is rejected, and the result is unlikely to be due to chance;
- $p \geq 0.05$: the result is not statistically significant; the null hypothesis cannot be rejected, and the observed difference may be due to random error.

The correlation degree of each pair of causal factors was calculated by SPSS. A total of 22 contingency tables were established using this software, and the chi-square, OR, and *p*-values were calculated on this basis to lay the foundation for determining the key factors, key levels, and key paths.

The basic principle of using Super Decisions software 2.10.0 to calculate the weight of cause factors is based on ANP. The network analytic hierarchy process is a structured decision-making method which is often used to solve complex decision-making problems, especially in the case of multiple criteria or factors. Its basic principle is to determine the weight by comparing the relative importance of each factor. In Super Decisions, the network relationship between the cause factors is constructed, and the importance of each pair of cause factors is compared by expert scoring. By calculating the supermatrix, the weighted matrix and unweighted matrix of the cause factors in the system regulating accidents involving falls from significant heights system are finally obtained.

3.2. Research Ideas and Data Analysis

The purpose of this study is to comprehensively apply the chi-square test, correlation coefficient, and ANP [25] method to determine the weight of each causal factor in falls from the reports of building construction accidents involving falls and to comprehensively analyze the key causal factors [26], levels, and paths [27] in building construction site falls. Then, we aim to propose a prevention and control strategy for building construction site falls. Figure 3 shows the research flowchart of this paper.

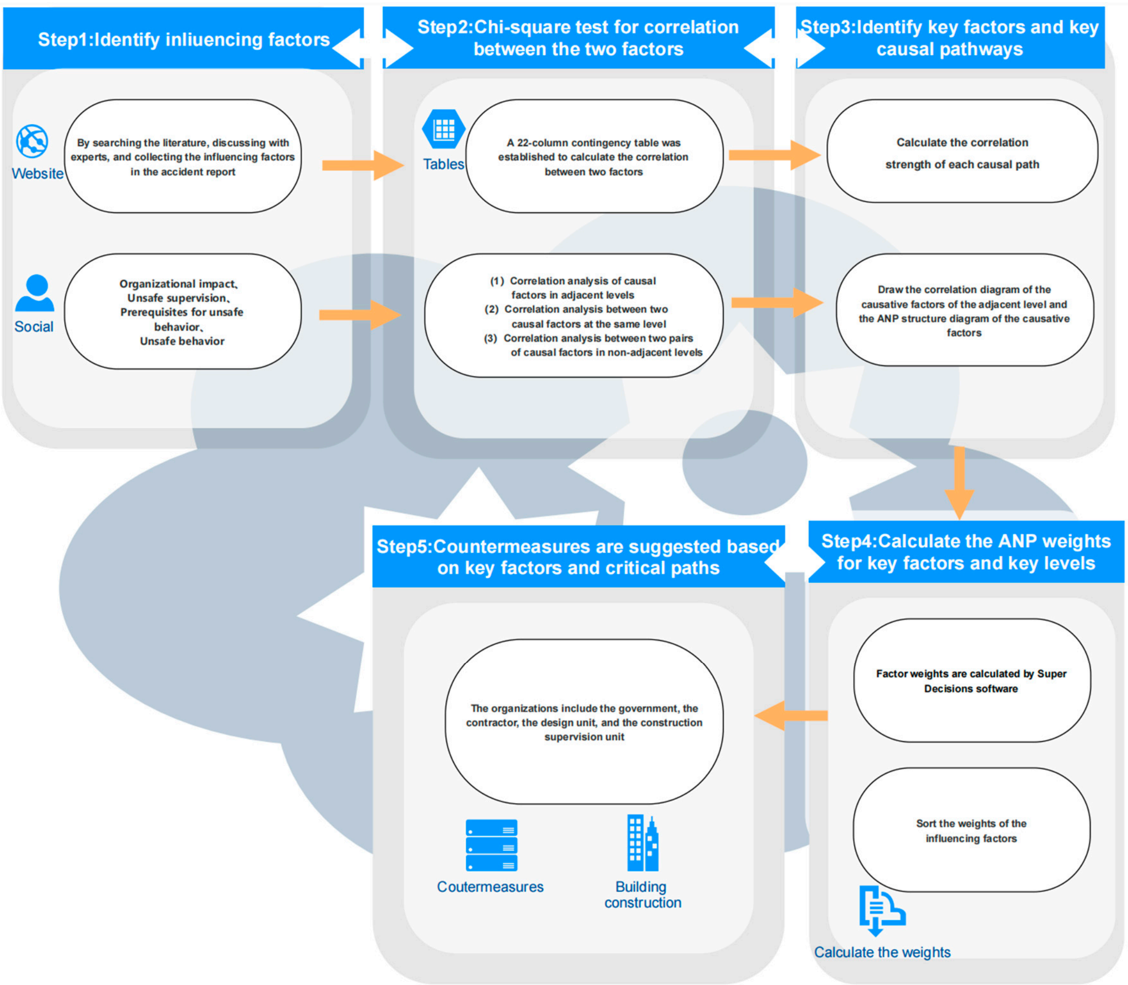

Figure 3. Research flowchart.

The HFACS model is an accident cause model applied to analyze complex systems. The causal factors of the accident can be analyzed on four levels, taking into account the correlation between the various factors [28]. In order to further strengthen the analysis, we use SPSS software for chi-square testing and OR analysis and combine the network analytic hierarchy process to comprehensively analyze the causes of accidents and identify key factors, key cause paths, and key levels.

The specific idea is as follows:

Step 1: establish the cause factor system (the HFACS method is used to establish the cause factor system of falling accidents [29] in building construction).

The causes of the accidents in 207 reports were analyzed and summarized. The causes of the falling accidents in building construction were as follows: 4 kinds of primary cause factors were identified, and 17 types of secondary cause factors were identified. According to the cause of the accident, the frequency of the accident was determined.

Step 2: analyze the relationship between the cause factors (including adjacent-level analysis, non-adjacent-level analysis, and same-level analysis).

Based on the four levels of cause factors in the HFACS model, we carried out frequency analysis, correlation analysis, and key cause path identification. Firstly, correlation analysis based on the level is carried out between the cause factors of adjacent levels. Secondly, correlation analysis based on the level is carried out between the cause factors of the same level. Finally, correlation analysis between the cause factors of non-adjacent levels is carried out.

Data are used to establish a 22-column contingency table, also known as a cross table, to show the relationship between two variables. It is usually used to explore the correlation between data distribution and variables. Through a 22-cross table, a chi-square (χ^2) test [30] was performed on each pair of causative factors to determine the correlation between them.

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i} \tag{1}$$

where O_i is the observation frequency, and E_i is the expected frequency.

$$E_i = \frac{(\text{Total number of rows}) * (\text{Total number of columns})}{\text{Overall}} \tag{2}$$

The assumption can be expressed as follows: causal factors between two different levels are independent, recorded as H_0. Another assumption is that the causal factors between two adjacent levels are dependent or correlated, recorded as H_1. In the χ^2 test, since each causal factor is a binary datum, the degree of freedom (df) is equal to 1. At the 5% significance level, the critical value of the χ^2 statistic was 3.84. If $\chi^2 \geq 3.84$, the null hypothesis is rejected.

The χ^2, OR, and *p*-value of Pearson, Kruskal, and Ronald A. Fisher were used to analyze the correlation between the factors [31]. OR is a statistic which is an eigenvalue used to measure the correlation between attributes A and B in a specific group. Let OR be m:

$$m = \frac{P_A(1 - P_A)}{P_B(1 - P_B)} \tag{3}$$

which indicates the probability of the existence of causal P_A when causal P_A occurs. This equation denotes the probability that causal P_B exists when causal P_A does not occur. The *p*-value is a probability value used to measure the consistency between the observed sample data and the hypothesis in statistical hypothesis testing. In short, the *p*-value is used to determine whether the sample data support the null hypothesis (usually with the null hypothesis indicating "invalid" or "no difference"). The calculated χ^2 is combined with the degree of freedom (df) to find the corresponding *p*-value according to the chi-square distribution table. The degree of freedom is usually calculated as follows:

$$df = (r - 1)(c - 1) \tag{4}$$

where r is the number of rows, and c is the number of columns.

If and only if $p < 0.05$, the value of OR is meaningful. When the OR value is greater than 1, the two causal factors A and B have a strong correlation. When the OR value is less than 1, the correlation between the two causal factors A and B is weak.

Step 3: through ANP, the weight of causative factors is calculated as follows:

- Determine the unweighted supermatrix (through the pairwise judgment matrix [32], the normalized feature vector is obtained by the feature vector method, and it is entered in the column vector of the supermatrix);
- Determine the weight of each element group in the hypermatrix (ensure the normalization of each column) [33].

Normalization is accomplished by dividing the elements in each column by the sum of all the elements in the column, so that each column adds up to 1. That is, for the elements in column j, there is the following:

$$\sum_{i} \omega_{ij} = 1 \tag{5}$$

- Calculate the weighted supermatrix;
- Calculate the limit supermatrix (use the power method to find the n-th power of the supermatrix until each column vector is stable) [34].

The limit super matrix is to perform multiple power operations (i.e., multiplication) on the normalized super matrix until convergence:

$$\text{Limit Supermatrix} = \lim_{k \to \infty} W^k \tag{6}$$

where W is the normalized super matrix, which means to multiply it by k power.

Step 4: finally, based on the results of the correlation analysis between levels, according to the analysis of key factors, key causal paths, and key levels, targeted prevention and control measures are formulated.

4. Results

4.1. Distribution of Causative Factors at All Levels

According to the actual operation of China's construction projects [35], the cause analysis model is divided into the organizational impact layer, the unsafe supervision layer, the prerequisites for unsafe behavior layer, and the unsafe behavior layer. In building construction, the Swiss cheese model is often used to explain and analyze the accident mechanism in safety management. This model was originally proposed by James Reason when studying the causes of accidents in the aviation and medical industries and was later widely used in construction, industry, and other high-risk industries. The cause analysis model is combined with the Swiss cheese model, as shown in Figure 4.

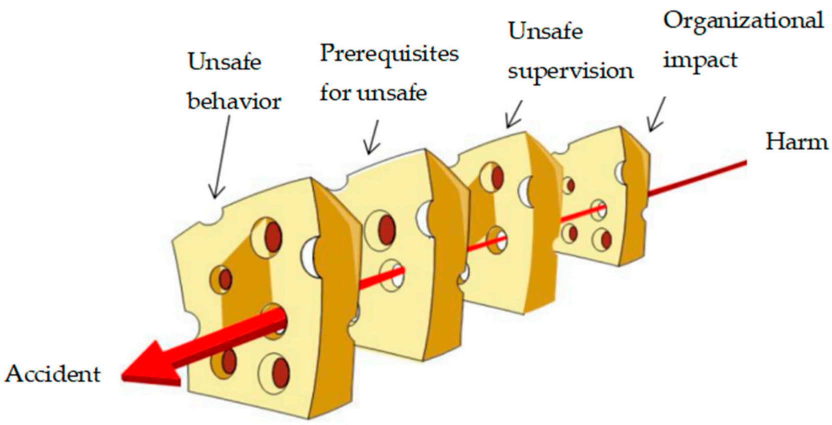

Figure 4. Swiss cheese model.

The Swiss cheese model was proposed by James Reason, a scholar of human factors, to analyze and understand the causes of accidents, especially in the interaction between human errors and systemic problems. This model can be applied to the analysis of accidents, such as falling from heights in building construction, to help identify potential risk factors and loopholes. The application of the Swiss cheese model, in the context of falling from a height in construction, usually includes the following points:

- Multiple protective layers (cheese slices): in the Swiss cheese model, each piece of cheese represents a protective layer or control measure (such as safety education and training, equipment inspection, monitoring during construction, and personnel protection measures). The purpose of these protective layers is to prevent accidents;

- Holes in the protective layer: there are some holes in each protective layer, representing potential risks, defects, or system vulnerabilities (such as inadequate safety education and training, imperfect safety management systems, and weak awareness of personnel safety). These holes usually do not exist intentionally but due to human error, organizational impact, or other factors;
- The condition of the accident: when the holes in multiple protective layers are aligned, it means that the risk factors overlap through different levels of defects, which leads to the occurrence of the accident. In the scenario of a fall from a high place in construction, the fall may be due to the joint action of multiple factors, such as the operator's failure to wear a seat belt, a lack of on-site safety oversight, or the fact that the labor company involved is not qualified, which eventually led to the occurrence of the falling accident.

The HFACS model is composed of 21 types of causative factors and has a secondary structure. According to the 207 reports of construction accidents involving falls from high places [36], it can be concluded that the factors that belong to the influence level of the organization are as follows: the supervision company failed to perform its supervision responsibilities, safety education and training were not in place, the safety management system was not perfect, hazard identification was insufficient, and the labor companies were not qualified.

Unsafe supervision is a second-level causative factor, including a lack of on-site safety oversight, failure to implement safety inspections and routine maintenance, a lack of on-site safety oversight, failure to detect and stop violations in a timely manner, a lack of obvious warning signs, and inadequate implementation of safety management systems.

The lack of on-site safety supervision means that during the construction process [37] there was a failure to carry out the necessary dynamic supervision of the safety status, operation behavior, and equipment operation of the operation site in accordance with the regulations, resulting in the risks in the construction project not being identified and resolved in time. In these cases, safety inspections and routine maintenance are not in place; the safety status of the equipment, facilities, and working environment on the construction site is not regularly and systematically verified; or problems are not found due to maintenance and treatment being delayed, resulting in long-term hidden dangers. Lack of inadequate implementation of safety management systems refers to the failure to establish, improve, or implement relevant rules and regulations to ensure construction safety in construction enterprises or projects, resulting in the lack of safety management work or a mere formality, thus eliminating potential safety hazards.

The preconditions for unsafe behavior are a third-level causative factor, and the preconditions for unsafe behavior [38] include the various reasons or factors that lead to behavior of personnel that does not meet the safety requirements, including weak awareness of personnel safety, safety technology disclosure that is not in place, personnel who do not have a permit to work at heights, and failure to take effective safety precautions. Weak awareness of personnel safety reflects a lack of awareness of safety risks by staff and occurs when staff have not taken the initiative to carry out necessary protective measures. When safety technology disclosure is not in place, the staff is not clearly informed of the potential risks and countermeasures in the construction process before the operation, or the disclosure is formalized and superficial. When personnel do not have a permit to work at heights, this indicates that the staff engaged in high-rise building operations have not obtained legal qualifications and have not received relevant professional training.

Unsafe behavior is a fourth-level causative factor for falling accidents in construction. Unsafe behavior can be further divided into employees carrying out their work in violation of safety regulations and failing to wear safety protective equipment correctly. A weak awareness of personnel safety refers to a lack of awareness of potential risks, relying too much on "experience", and ignoring basic safety requirements [39]. For example, operating mechanical equipment without permission, failure to implement safety measures in accordance with the requirements of technical disclosure, and the failure of experienced workers to pay attention to details due to their overconfidence or fixed ideas. Unsafe behavior [40] includes violations of the regulations imposed by those who ensure safety on construction sites. For example, this is the case when workers are not wearing seat belts or are wearing non-standard seat belts when working on high ground. In some cases, construction began before companies obtained approval documents such as construction project planning licenses. The results are shown in Figure 5.

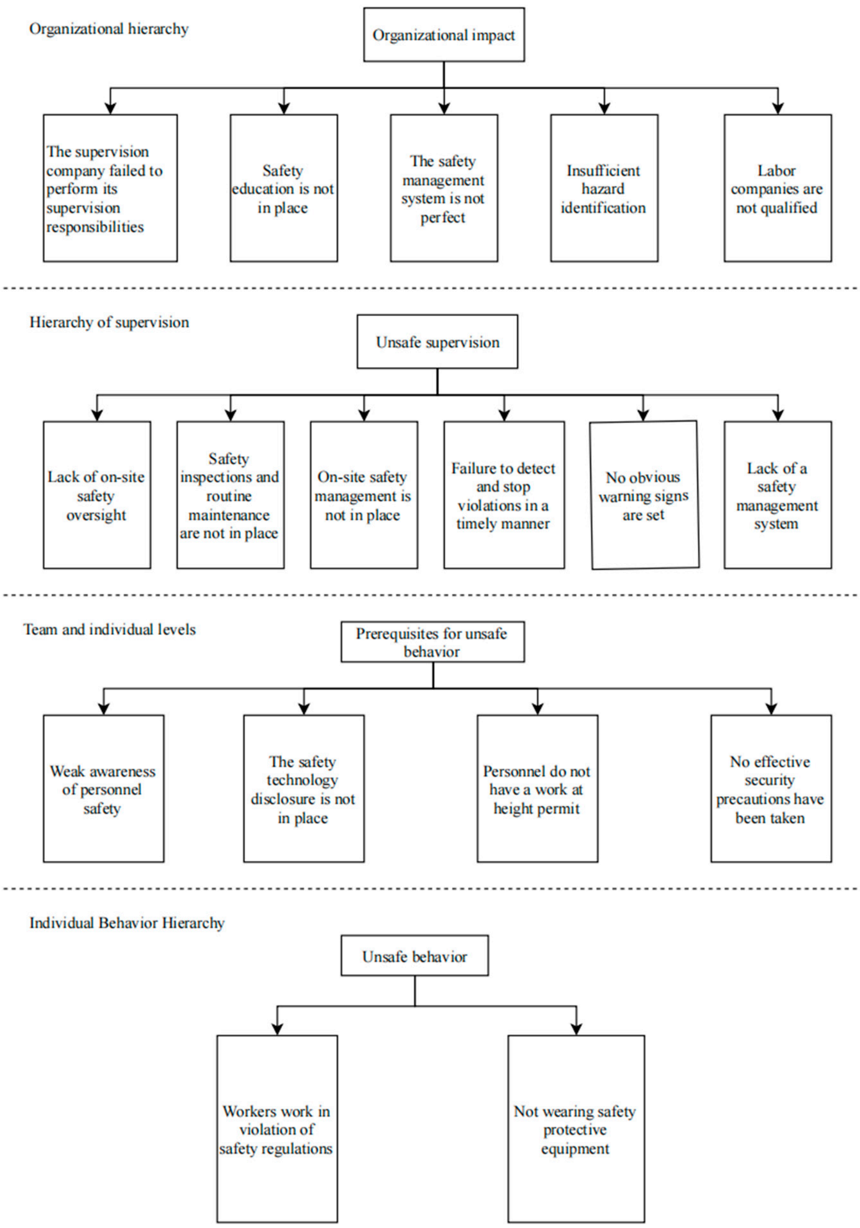

Figure 5. HFACS model based on falls from heights.

4.2. Chi-Square Test and Correlation Coefficient Calculation

Through the analysis of 207 accident reports, the causal factors and corresponding frequencies of accidents involving falls from heights are summarized in Table 1.

Table 1. Frequency and frequency analysis results of causal factors of falls from heights.

Level	Causal Factors	Frequency	Relative Frequency
Organizational impact	Labor companies/contractors are not qualified	14	0.0733
	Insufficient hazard identification	14	0.0733
	The supervision company failed to perform its supervision responsibilities	23	0.1204
	Safety education and training are not in place	106	0.5550
Unsafe supervision	The safety management system is not perfect	34	0.1780
	Lack of on-site safety oversight	41	0.1494
	Safety inspections and routine maintenance are not in place	78	0.2847
	On-site safety management is not in place	86	0.3139
	Failure to detect and stop violations in a timely manner	23	0.0839
	No obvious warning signs are set	15	0.0547
	Inadequate implementation of safety management systems	31	0.1131
Prerequisites for unsafe behavior	Weak awareness of personnel safety	109	0.3907
	The safety technology disclosure is not in place	34	0.1219
	Personnel do not have a permit to work at heights	44	0.1577
	Misjudgment of climatic conditions	6	0.0215
	There is no lighting in the environment	10	0.0358
	Physical fatigue/sudden illness	9	0.0323
	Mental illness/sudden accidents	7	0.0251
	No effective security precautions have been taken	51	0.1828
	Not equipped with standard protective tools	9	0.0323
Unsafe behavior	Workers work in violation of safety regulations	46	0.4423
	Failure to wear safety protective equipment correctly	58	0.5577

As can be seen from Table 1, the causal factor of "Safety education and training are not in place" is the most frequent in terms of organizational impact. Among the unsafe supervision factors, the frequencies of "Safety inspections and routine maintenance are not in place" and "On-site safety management is not in place" were the highest. Among the prerequisites for unsafe behaviors, the frequency of "Weak awareness of personnel safety" was the highest. Among the factors of unsafe behavior, there was no significant difference in the frequency of workers violating regulations, on the one hand, and those not wearing safety protective equipment correctly. Therefore, "Safety education and training are not in place", "Safety inspections and routine maintenance are not in place", "Lack of on-site safety oversight", "Weak awareness of personnel safety", "Workers work in violation of safety regulations", and "Failure to wear safety protective equipment correctly" are common factors leading to falls from heights in the construction industry at all levels.

In terms of factors related to organizational impact, "Safety education and training are not in place" accounted for 55.5% of the causal factors of accidents involving falls from heights in construction—a significant proportion—and safety production accidents in the construction industry are closely related to the safety education and training work of the organization. The lack of safety awareness in the preconditions for unsafe behaviors accounted for 39.1% of the accidents in building construction involving falls from heights, and these data showed that these falls were related to weak awareness of personnel safety and ineffective safety education and training by external organizations. External organizations generally include supervision companies, labor service companies, and contractors. The fact that there are fewer types of accidents that occur due to the physical condition of the workers themselves can be explained by the fact that there is little information about the condition of the workers at the site in the accident investigation reports; this finding is consistent with previous research. Taking workers violating regulations and failing to wear safety protective equipment correctly as examples, a 2 × 2 column table is listed separately; see Table 2.

Table 2. "Workers work in violation of regulations" and "Failure to wear safety protective equipment correctly" 2 × 2 contingency table.

Factor		Failure to Wear Safety Protective Equipment Correctly		Line Sum
		Yes	No	
Workers work in violation of regulations	Yes	20 (f_1)	26 (f_2)	46
	No	38 (f_3)	123 (f_4)	161
Column sum		58	149	207

Note: f_1~f_4 is the actual observation of four cells; n is the sum of rows or columns.

$$\chi^2 = \frac{n(f_1 f_4 - f_2 f_3)^2}{(f_1+f_2)(f_3+f_4)(f_1+f_3)(f_2+f_4)} \quad (7)$$

$$m = \frac{f_1 f_4}{f_2 f_3} \quad (8)$$

SPSS 27.01 software was used to calculate the χ^2 and m value and 95% confidence interval between the two factors at the upper and lower levels. $p < 0.05$, $m > 1$ is a significant correlation between the two factors, and the factors that meet $p < 0.05$, $m > 1$ are sorted out, as shown in Table 3.

Calculating χ^2 and m values [41] can enhance the accuracy of factor correlation analysis and effectively judge the interaction between factors [42]. The HFACS model [43] starts from the level of organizational influence to determine influence layer by layer. Firstly, χ^2 testing and OR analysis of the cause factors of the upper and lower adjacent levels are carried out, and then, the correlation between the cause factors of the same level and the non-adjacent level is further analyzed. SPSS 27.01 software was used to calculate χ^2, the upper and lower limits of p-value, m, and 95% confidence interval between the two causal factors at the upper and lower levels. When $p < 0.05$ and m > 1, there is a significant correlation between the two factors. We organized and presented the factors that satisfy $p < 0.05$ and m > 1 in Table 3.

It can be seen from Table 3 that there are 15 groups of relationships among the factors that satisfy $p < 0.05$ and m >1. The maximum m value between "Safety technology disclosure is not in place" and "No obvious warning signs are set" is 6.016, indicating that the correlation between the two is the strongest among the causal factors of adjacent levels. The minimum m value between "Weak awareness of personnel safety" and "Safety inspections and routine maintenance are not in place" is 1.784, indicating that there is a correlation between the two in the cause factors of adjacent levels, but the correlation strength is small. Based on Table 3, the relationship between the causal factors of adjacent levels is obtained, as shown in Figure 6.

Table 3. Correlation analysis results of causal factors in adjacent levels.

Causal Factors	Chi-Square Test		m	95% Confidence Interval	
	χ^2	p		Lower Limit	Upper Limit
Organizational Impact And Unsafe Supervision					
"On-site safety management is not in place" and "Labor companies/contractors are not qualified"	3.197	0.074	2.712	0.875	8.399
"No obvious warning signs are set" and "Insufficient hazard identification"	4.493	0.034	4.114	1.010	16.748
"Lack of on-site safety oversight" and "Safety education and training are not in place"	4.389	0.036	2.124	1.040	4.336
"On-site safety management is not in place" and "Safety education and training are not in place"	9.566	0.002	2.435	1.378	4.302
"Failure to detect and stop violations in a timely manner" and "Safety education and training are not in place"	5.339	0.021	3.024	1.414	8.015
"Inadequate implementation of safety management systems" and "Safety education and training are not in place"	7.710	0.005	3.221	1.367	7.591
Unsafe Supervision and Prerequisites for Unsafe Behavior					
"Weak awareness of personnel safety" and "Lack of on-site safety oversight"	12.693	0.001	3.239	1.666	6.296
"The safety technology disclosure is not in place" and "No obvious warning signs are set"	12.443	0.001	6.016	2.000	18.091
"Weak awareness of personnel safety" and "Safety inspections and routine maintenance are not in place"	3.960	0.047	1.784	1.006	3.161
"Weak awareness of personnel safety" and "On-site safety management is not in place"	4.749	0.029	1.864	1.062	3.272
"Weak awareness of personnel safety" and "Inadequate implementation of safety management systems"	3.888	0.049	1.955	0.998	3.829
"Personnel do not have a permit to work at heights" and "On-site safety management is not in place"	4.904	0.027	2.501	1.090	5.734
Prerequisites for Unsafe Behavior And Unsafe Behavior					
"Failure to wear safety protective equipment correctly" and "Weak awareness of personnel safety"	4.008	0.045	1.884	1.009	3.518
"Failure to wear safety protective equipment correctly" and "Personnel do not have a permit to work at heights"	8.422	0.004	2.741	1.367	5.496
"Workers work in violation of safety regulations" and "Weak awareness of personnel safety"	6.782	0.009	2.494	1.238	5.002

Figure 6 shows that there are 10 complete accident causation paths between the adjacent level causation factors [44]. Among them, there are 10 main cause paths:

1. "Safety education and training is not in place"–"On-site safety management is not in place"–"Weak awareness of personnel safety"–"Failure to wear safety protective equipment correctly";
2. "Safety education and training is not in place"–"On-site safety management is not in place"–"Workers work in violation of safety regulations"–"Workers work in violation of safety regulations";
3. "Safety education and training is not in place"–"On-site safety management is not in place"–"Personnel do not have a permit to work at heights"–"Failure to wear safety protective equipment correctly";
4. "Safety education and training is not in place"–"Inadequate implementation of safety management systems"–"Weak awareness of personnel safety"–"Failure to wear safety protective equipment correctly";

5. "Safety education and training is not in place"–"Inadequate implementation of safety management systems"–"Weak awareness of personnel safety"–"Workers work in violation of safety regulations";
6. "Safety education and training is not in place"–"Lack of on-site safety oversight"–"Weak awareness of personnel safety"–"Failure to wear safety protective equipment correctly";
7. "Safety education and training is not in place"–"Lack of on-site safety oversight"–"Weak awareness of personnel safety"–"Workers work in violation of safety regulations";
8. "Labor companies/contractors are not qualified"–"On-site safety management is not in place"–"Weak awareness of personnel safety"–"Failure to wear safety protective equipment correctly";
9. "Labor companies/contractors are not qualified"–"Lack of on-site safety oversight"–"Weak awareness of personnel safety"–"Workers work in violation of safety regulations";
10. "Labor companies/contractors are not qualified"–"On-site safety management is not in place"–"Personnel do not have a permit to work at heights"–"Failure to wear safety protective equipment correctly".

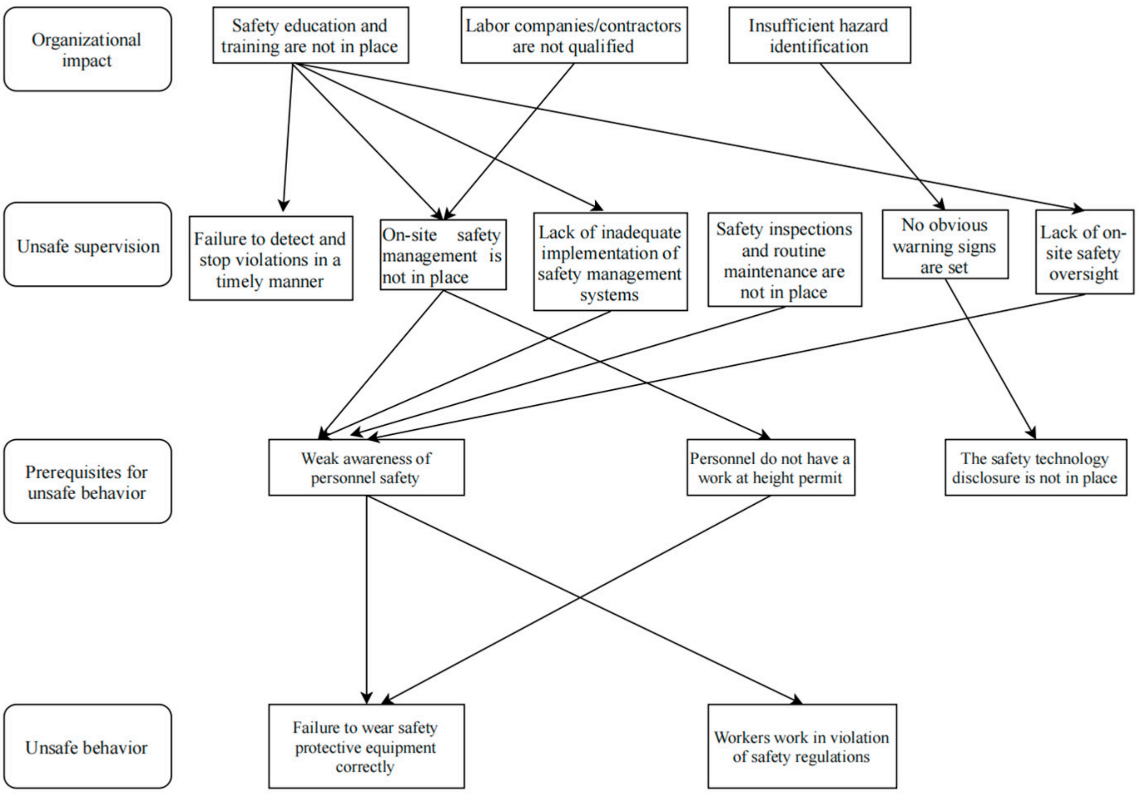

Figure 6. Correlation between causal factors at adjacent levels.

Among them, the 10th path has the largest sum of correlation strength, and the correlation strength is 7.954; thus, this is the key causal path [45].

In the HFACS model, there are also correlations between non-adjacent-level factors [46] and internal factors at the same level in the HFACS model. There is also a correlation between the factors. Chi-square testing and OR analysis were performed to meet the factors of $p < 0.05$ and $m > 1$, as shown in Tables 4 and 5.

Table 4. Correlation analysis results between two causal factors at the same level ($p < 0.05$, $m > 1$).

Causal Factors	Chi-Square Test		m	95% Confidence Interval	
	χ^2	p		Lower Limit	Upper Limit
Organizational Impact					
"Safety education and training are not in place" and "Insufficient hazard identification"	4.500	0.034	3.782	1.023	13.982
Unsafe Supervision					
"Lack of on-site safety oversight" and "Failure to detect and stop violations in a timely manner"	6.130	0.013	2.903	1.215	6.939
"Safety inspections and routine maintenance are not in place" and "Inadequate implementation of safety management systems"	6.451	0.011	2.677	1.229	5.831
"Safety inspections and routine maintenance are not in place" and "No obvious warning signs are set"	8.754	0.003	5.131	1.573	16.734
"On-site safety management is not in place" and "Failure to detect and stop violations in a timely manner"	5.970	0.015	2.984	1.204	7.398
Prerequisites for Unsafe Behavior					
"The safety technology disclosure is not in place" and "No effective security precautions have been taken"	4.051	0.044	2.199	1.008	4.796
"Weak awareness of personnel safety" and "The safety technology disclosure is not in place"	5.247	0.022	2.485	1.121	5.506
Unsafe Behavior					
"Workers work in violation of safety regulations" and "Failure to wear safety protective equipment correctly"	7.008	0.008	2.490	1.252	4.950

Table 5. Correlation analysis results between two pairs of causal factors in non-adjacent levels ($p < 0.05$, $m > 1$).

Causal Factors	Chi-Square Test		m	95% Confidence Interval	
	χ^2	p		Lower Limit	Upper Limit
Organizational Impact					
"Safety education and training are not in place" and "Insufficient hazard identification"	4.500	0.034	3.782	1.023	13.982
Unsafe Supervision					
"Lack of on-site safety oversight" and "Failure to detect and stop violations in a timely manner"	6.130	0.013	2.903	1.215	6.939
"Safety inspections and routine maintenance are not in place" and "Inadequate implementation of safety management systems"	6.451	0.011	2.677	1.229	5.831
"Safety inspections and routine maintenance are not in place" and "No obvious warning signs are set"	8.754	0.003	5.131	1.573	16.734
"On-site safety management is not in place" and "Failure to detect and stop violations in a timely manner"	5.970	0.015	2.984	1.204	7.398
Prerequisites for Unsafe Behavior					
"The safety technology disclosure is not in place" and "No effective security precautions have been taken"	4.051	0.044	2.199	1.008	4.796
"Weak awareness of personnel safety" and "The safety technology disclosure is not in place"	5.247	0.022	2.485	1.121	5.506
Unsafe Behavior					
"Workers work in violation of safety regulations" and "Failure to wear safety protective equipment correctly"	7.008	0.008	2.490	1.252	4.950

From Table 4, it can be seen that the correlation analysis between the two causal factors at the non-adjacent levels of the HFACS model conforms to a total of eight groups of associations of $p < 0.05$, m > 1 [47]. The maximum m value between "Safety inspections and routine maintenance are not in place" and "No obvious warning signs are set" is 5.131, indicating that the correlation between the two is the strongest among the non-adjacent-level causal factors. The minimum m value between "Weak awareness of personnel safety" and "The safety technology disclosure is not in place" is 2.485, indicating that there is a correlation between the two in the non-adjacent-level causative factors, but the correlation strength is small.

It can be seen from Table 5 that in the correlation analysis between the two factors at the same level of the HFACS model, a total of eight groups of correlations consistently satisfied $p < 0.05$ and $m > 1$. The maximum m value between "Safety inspections and routine maintenance are not in place" and "No obvious warning signs are set" is 5.131, indicating that the correlation between the two is the strongest in the same level of cause factors. The minimum m value between "The safety technology disclosure is not in place" and "No effective security precautions have been taken" is 2.199, indicating that there is a correlation between the two factors at the same level, but the correlation strength is small.

4.3. Determine the Weight of the Cause Factors of the High Fall Accident

We invited seven experts to score the influence intensity of 21 factors and constructed the corresponding scoring matrix. By analyzing the correlation of cause factors between adjacent levels, the cause path with the largest sum of correlation intensity in falling accidents in building construction is determined, and the weight of each cause factor in the HFACS model is calculated based on this. The HFACS model is similar to the ANP [48,49] model at the structural level. The four levels and 21 causal factors of the HFACS [50] model correspond to the four element groups of the criterion layer and the network layer of the ANP [51] model, respectively. Therefore, the ANP structure diagram of the cause factors of falling accidents in high-rise building construction is generated, and the weight calculation is carried out by ANP [52], as shown in Figure 6. It can be seen from Figure 6 that the structure diagram includes the target layer, the criterion layer, and the network layer. The criterion layer includes four levels of the HFACS model, and the network layer includes 17 specific accident-causing factors corresponding to each level of the HFACS model. In the network layer, the relationship between factors is determined by the m value in the correlation analysis and the specific meaning of each cause factor. The results are shown in Figure 7.

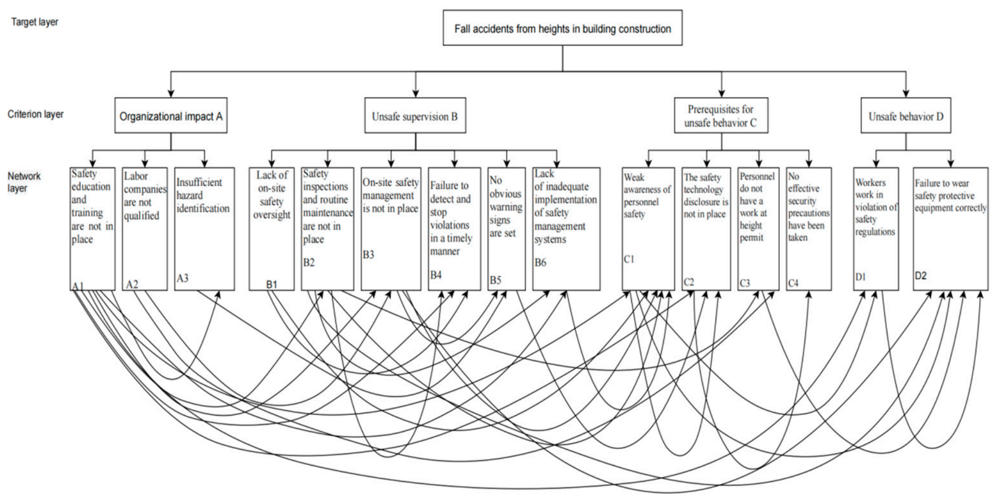

Figure 7. ANP structure of causal factors of accidents involving falls from heights in building construction.

When using Super Decisions software 2.10.0 to calculate the weight of cause factors, experts are usually invited to score the relative importance of each index. However, expert evaluation is subjective and may be biased. In contrast, frequency value and correlation strength value are objective results based on sample calculation, which can be used as the basis for judging the importance of factors. Therefore, the frequency value and the correlation strength value can be used as the basis for judging the importance of the factors, and then, the mutual influence between the factors can be determined. The weights of each level and the weights and rankings of each cause factor are calculated by Super Decisions software 2.10.0, as shown in Table 6.

Table 6. The weights and rankings of each causative factor.

Level	Weight	Causal Factors	Local Weights	Global Weights	Sort
Organizational impact	0.121128	Labor companies/contractors are not qualified	0.02080	0.002519	15
		Insufficient hazard identification	0.13776	0.016686	10
		Safety education and training are not in place	0.84145	0.101923	4
Unsafe supervision	0.45024	Lack of on-site safety oversight	0.08182	0.036837	9
		Safety inspections and routine maintenance are not in place	0.20454	0.092092	6
		On-site safety management is not in place	0.26800	0.120665	3
		Failure to detect and stop violations in a timely manner	0.13630	0.061369	7
		No obvious warning signs are set	0.21948	0.098821	5
		Inadequate implementation of safety management systems	0.08986	0.040457	8
Prerequisites for unsafe behavior	0.397937	Weak awareness of personnel safety	0.57950	0.230604	1
		The safety technology disclosure is not in place	0.36539	0.145402	2
		Personnel do not have a permit to work at heights	0.02904	0.011558	13
		No effective security precautions have been taken	0.02607	0.010373	14
Unsafe behavior	0.030694	Workers work in violation of safety regulations	0.48316	0.014830	12
		Failure to wear safety protective equipment correctly	0.51684	0.015864	11

From Table 6, it can be seen that among the four types of causes leading to mechanical injury accidents in manufacturing enterprises, the highest weight among those related to unsafe supervision is 0.45024, indicating that it is the key factor leading to mechanical injury accidents in manufacturing enterprises; the weight of the preconditions for unsafe behavior is 0.397937, which has a relatively high weight, and the weight of "Weak awareness of personnel safety" in the category of "Unsafe behavior" is 0.230604, which indicates that "Weak awareness of personnel safety" is the key factor leading to the occurrence of falling accidents in building construction. The weight of the influence of organizational impact is 0.121128, but the weight value of "Safety education and training are not in place" is 0.101923, which is the key factor leading to accidents involving falls from heights and the factor that cannot be ignored in the prevention of safety accidents. The unsafe behavior factor has the lowest weight, 0.030694.

5. Discussion

The purpose of this paper is to comprehensively apply HFACS, chi-square testing, correlation coefficients, and ANP to deeply analyze the causes of accidents involving falls from heights and to provide a scientific basis and effective suggestions for these falls for the building construction industry. This study found that the key factors leading to these falls mainly include inadequate safety training at the organizational level and weak awareness of personnel safety or unsafe behavior. The specific key causal path is as follows: "Labor companies/contractors are not qualified"–"Lack of on-site safety oversight" –"Personnel do not have a permit to work at heights"–"Failure to wear safety protective equipment correctly".

The traditional accident-causing theory attributes the causes of falling accidents in building construction to four aspects: people, equipment, environment, and management. Domestic and foreign scholars have studied the causes of accidents involving falls from heights from multiple perspectives. Based on the N-K model and fuzzy DEMATEL, He Jiabin [53] et al. carried out a coupling analysis of the causes of falls from significant heights. Based on frequency statistics and χ^2-PCC, Xu et al. [54] analyzed the characteristics of these accidents in construction. Based on the "2–4" model, Sun Shimei [55] et al. studied the tendencies of falling accidents. Compared with other publications in the literature, this study classifies the causal factors of high-rise falling accidents based on the HFACS model and identifies the key causal factors and their key causal paths more logically. Construction companies can formulate more specific and effective prevention and control measures based on these factors and paths.

When using Super Decisions software 2.10.0 to calculate the weight of cause factors, experts are usually invited to score the relative importance of each index. However, expert evaluation is subjective and may be biased. In contrast, frequency value and correlation strength value are objective results based on sample calculation, which can be used as the basis for judging the importance of factors. Therefore, the frequency value and the correlation strength value can be used as the basis for judging the importance of the factors, and then, the mutual influence between the factors can be determined. According to the analysis in Section 4.2, the non-independent characteristics between factors are not suitable for the use of the analytic hierarchy process (AHP) for weight calculation, while ANP considers the non-independent characteristics between factors. By constructing the network structure, the influence relationship between indicators can be intuitively displayed, and the degree of importance can be calculated. The results of correlation analysis revealed the correlation between factors, which was helpful in the construction of the ANP model. These results were combined with the m value to judge the relative importance of factors.

Through statistical analysis and data research on accident reports, it is found that safety education and training are often not in place or are not available. Weak awareness of position and safety is often the key factor leading to an accident. Among the factors, "Safety education and training are not in place" was commonly noted in the working environment, and many workers are not familiar with safety operation procedures and emergency disposal methods. The weak safety awareness of construction personnel is the result of many factors. It is necessary to take comprehensive measures on the individual, organizational, and social levels to effectively improve the safety awareness of construction personnel and reduce accidents. In the prevention and control of falls on building construction sites, it is necessary to comprehensively consider the factors at all levels.

From the perspective of these organizations [56], it is important to propose targeted prevention and control measures. Construction projects are usually affected by contractors, owners, government departments, third parties, and other organizations. The research results of this paper aim to prevent the occurrence of accidental falls from great heights [57]. The critical prevention and control measures proposed in this paper can more effectively reduce accident losses, help construction enterprises prevent accidents, improve safety management systems, and improve the overall safety management level [58].

This study has the following limitations: firstly, the information obtained from the investigation report on high-rise building construction accidents does not adequately reflect the situation of workers on the construction site, which inevitably leads to some deviations. Secondly, due to the high mobility of construction workers, it is very difficult to investigate the psychological or physiological states that may have a potential impact on unsafe behavior.

6. Conclusions

Based on the investigation report of 207 typical accidents involving falls in construction, in this study, we adopt the HFACS model and extract the cause of the accident from four levels: the organizational impact level, unsafe supervision level, prerequisites for unsafe behavior level, and unsafe behavior level. By collecting accident reports, analysis of the literature, and consulting relevant experts, 21 factors leading to accidents in construction involving falls from significant heights were finally determined. In order to deeply analyze the relationship between the cause factors, chi-square testing, correlation coefficients, and the ANP method were used to determine the weights of each causative factor. This study found that the deep-seated causes of accidents from significant heights are mainly related to safety education and training not being carried out at the organizational level and to a lack of safety awareness among personnel (among factors in the ”unsafe behavior” level). The key factors (in terms of unsafe behavior) in accidents involving falls from great heights mainly include weak awareness of personnel safety and disclosure of safety technology not being carried out; in terms of unsafe supervision, these factors mainly include a lack of on-site safety oversight; and in terms of organizational impact, these factors mainly include safety education and training not being carried out. The key cause path with the strongest correlation strength is “Labor companies/contractors are not qualified”–“Lack of on-site safety oversight”–“Personnel do not have a permit to work at heights”–“Failure to wear safety protective equipment correctly”.

In order to reduce the occurrence of such accidents, the government should strengthen supervision, improve relevant regulations and standards, strengthen public supervision and reporting mechanisms, improve project quality supervision, and require construction personnel and management personnel to undergo professional safety training and obtain relevant qualification certificates before taking office. The contractor should establish a sound safety management system for operations carried out at significant heights, strictly review the qualifications of subcontractors, ensure that they meet the requirements of relevant laws and regulations, formulate a scientific and reasonable operation plan for work carried out at significant heights before construction, carry out special safety technology disclosure, and equip the elevated operation area with the necessary safety protection facilities. The design unit should reasonably design and optimize the construction plan, provide the design of safety protection facilities, clarify the safety technical measures, and ensure that the construction organization design conforms to the national regulations and standards. The construction supervision unit should regularly carry out safety inspection and investigation of hidden dangers, supervise the safety technical disclosure and training, supervise the construction personnel to ensure that they wear safety protection equipment correctly, and audit the construction organization design and special safety plan to ensure that it meets the safety specifications. The occurrence of falling accidents is often the result of the interaction of multiple factors. The measures formulated by the organizations according to the key factors and the cause path will reduce the damage caused by the accident to a great extent and reduce losses incurred in the accident.

When using Super Decisions software 2.10.0 to calculate the weight of causal factors, experts are usually invited to score the importance of each index. However, expert evaluation is subjective and may be biased. In contrast, the frequency value and the correlation strength value are objective results based on the sample calculation, which can be used as the basis for judging the importance of each factor. Therefore, this study uses frequency value and correlation strength value to determine the mutual influence between the factors.

Researchers and safety managers commonly use several analytical methods to identify the root causes of accidents and develop targeted prevention strategies. The HFACS model allows for a comprehensive analysis of human behavior and its underlying causes from a systemic perspective. Cause-and-effect diagrams (fishbone diagrams) offer a clear structure and are suitable for team-based discussions. Fault Tree Analysis (FTA) combines qualitative and quantitative approaches and is ideal for analyzing complex system accidents. Root Cause Analysis (RCA) is simple and practical, often used in on-site accident investigations. Compared to other methods such as fishbone diagrams, FTA [59], RCA, or STAMP [60], applying the HFACS model to analyze accident causation offers several distinct advantages: it provides a systematic framework for analyzing human factors. HFACS adopts a four-level structure, progressing from surface behaviors to deeper systemic causes, forming a hierarchical chain of causation. Methods like fishbone diagrams and RCA tend to focus on individual errors or linear cause–effect chains, without emphasizing the structural factors behind human error. HFACS is particularly well-suited for analyzing construction accidents from a human-and-system combined perspective, enabling multi-level, systematic causation analysis and supporting a shift from accident investigation to root cause prevention.

Based on the conclusions and limitations of this study, future research can be further expanded and deepened in the following aspects:

- Expanding the applicability of the HFACS model: this study adopts the standard HFACS framework to analyze accidents involving falls from heights. In the future, the model can be localized or further developed according to the characteristics of the construction industry, thereby enhancing its adaptability and explanatory power in construction scenarios;
- Introducing dynamic causal analysis methods: the current research focuses on static path analysis. Future studies may consider incorporating methods such as Bayesian networks or system dynamics to construct dynamic evolution models of accident causation, which can better capture the temporal sequence and chain reactions in accidents;
- Expanding data sources and data structures: at present, data mainly come from textual accident reports. In the future, integrating multiple sources such as video surveillance, sensor data, and on-site records could help build a more comprehensive and structured causation database, thereby improving data quality and analytical accuracy.

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