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AUTOMATIC IDENTIFICATION AND QUANTIFICATION OF SAFETY RISKS EMBEDDED IN DESIGN STAGE: A BIM-ENHANCED APPROACH

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Abstract. Design stage plays a decisive role in safety risk management of the whole life cycle for construction projects. However, existing research mostly pay attention to post-accident management and lack pre-management consciousness. Based on the concept of design for safety (DFS), this paper explains how design optimization can enhance the safety performance for construction projects. Firstly, use accident causality theory and trajectory crossing theory to clarify the logical relationship between safety accidents and design process. Then, identify risk sources of safety accidents in deep foundation pit of subway projects and form a safety management knowledge base. Thirdly, based on design and review rules in the knowledge base and improved FEC risk quantification method, quantify the design oriented subway construction safety risks. Finally, use BIM secondary development technology to realize automatic examination and visualization of safety risks. A case study was conducted to verify this research framework. This paper can be a supplement to the existing risk management theoretical research.

Keywords: design for safety (DFS), safety risks quantification, FEC method, knowledge management, BIM.

Introduction

Urban infrastructure projects usually involved with some distinct characteristics such as large investment, big scale and management complexity. Due to these explicit features, they are always faced with various kinds of safety accidents. In 2008, during the collapse of Xianghu Station of Hangzhou Metro Line 1 in China, there were hidden defects in the early planning and design stage, and finally exposed in the construction stage, resulting in 21 deaths. In 2015, Nanjing Metro Line 4 in China failed to predict the geological conditions sufficiently, and the ground surface suddenly collapsed during the construction process, resulting in temporary traffic paralysis and economic losses. There are a lot of such accidents need our further research. From the perspective of risk management, reasons for the occurrence of these accidents are usually attributed to the weak awareness of pre-management and insufficient attention to design stage (Liu et al., 2018a). Currently, metro safety management has certain achievement (Jiang et al., 2020; Jin et al., 2020; Pan et al., 2019; Zhou et al., 2014), but mostly focused on post-control, namely to take remedial measures after the accident occurred (Chan et al., 2019), there are few research caring about risk prevention from design stage (Yuan et al., 2019), but in fact design plays a decisive role in safety management. Therefore, the concept of design for safety (DFS) is proposed, which means the health and safety state of workers, operation and maintenance safety are considered from the design stage, and risks are eliminated or reduced by standardizing and improving the design results, so as to reduce the occurrence of accidents (Abueisheh et al., 2020; Hossain et al., 2018; Liu et al., 2020; Xiahou et al., 2018).

Every kind of construction projects need to be built according to the design drawings. Due to this important attribution, subway projects can effectively reduce construction risks and enhance the ability to handle risks by optimizing design schemes in early stage. Most of the traditional studies focus on identifying and evaluating the risks in the construction stage, and then put forward a control plan (Chao et al., 2014; Zhou et al., 2020). However, previous research only focuses on monitoring and controlling of the construction site, ignoring the leading role of design schemes. Current engineering safety theory has changed from ex post control to prevention (Su et al., 2019), and the prevention process has also changed from passive to active (Ezisi & Issa, 2019). The core content of risk control is quantification, while traditional quantifi-

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cation ways mainly depend on expert reviewing or FEC methods (Siu et al., 2018), relying too much on expert experience, lacking automatic ways. Risk management still remains in the stage of strong arbitrariness and poor reliability. There is no advance control method applicable to the design stage, so it can no longer meet the requirements of newly subway safety management. In addition, the current risk identification process is still through 2D drawings and the design scope considered in the current design specifications are far from being able to cover all kinds of safety problems in the construction and operation phases (such as the safety of employees during construction (Xia et al., 2020; Zhou & Guo, 2020), the safety of staff and passengers during normal operation (Danfeng & Jing, 2019; Shin, 2020), the safety of public evacuation of large passenger flow under emergencies (Chen et al., 2020; Chen, 2020; Cheng et al., 2020; Li et al., 2017, etc.), lack of visually risk identification and quantification methods, can no longer meet the increasingly complex needs of projects. The rapid development of BIM technology provides a new idea for construction safety risk quantification (Kim et al., 2020; Lee et al., 2020; Providakis et al., 2019). This paper uses BIM secondary development and knowledge management technology to improve the existing FEC risk quantification method, in the aim to enhance the automatic level for safety risk quantification. FEC is abbreviation of frequency, exposure and criticality, normally be used to conduct risk quantification.

This paper firstly reveals the transmission mechanism of how hidden defects in design schemes can turn to subway construction safety accidents (SCSA) and then use improved FEC method and numerical model to research the risk identification and quantification. Finally, taking a deep foundation pit project as example to verify the validity of this research framework. The mainly contributions are as below:

(1) Based on the concept of DFS, this paper attempts to carry out the risk warning of construction process from the design stage of the whole life cycle of engineering construction, and use BIM as a display form to realize the intelligence and visualization of risk management.

(2) This study can be used for the optimization of construction safety and construct ability of design schemes. It emphasizes the control in advance, which is an important improvement of the traditional passive management mode of construction safety.

The overall structure of this paper is as follows: Section 1 summarizes the latest research progress of DFS and risk management; Section 2 explains the research method and logic structure for this paper in detail; Section 3 analyzes the relationship between safety accidents and design schemes, and also explains the form mechanism of accidents; Section 4 takes a deep foundation pit project as an example to identify the risk factors and control measures of construction accidents and build a knowledge base for risk sources; Section 5, based on the improved FEC method, carries out risk evaluation of a certain deep foundation pit and verifies the calculation results by BIM secondary development. Section 6 provides an overall discussion. Conclusions are provided at the end of the paper.

1. Literature review

The construction process of subway project is complicated and safety accidents occur frequently, which is mainly attributed to weak control in advance and lagging risk management. With the large-scale development of subway projects, there have many theoretical and practical achievements in the field of construction safety research. This section summarizes the frontier theories and information technology in construction management, highlight the advantages of existing research and clarifies the future research directions, try to provide reference for researchers.

1.1. DFS theory for construction management

As a key point in the whole life cycle, the unsafe factors in design stage inevitably affect the safety conditions in the downstream construction, operation and maintenance stages. The concept of design for safety (DFS) was first formed in United States, and there are many similar expression terms in the theoretical field, such as design for construction safety (DFCS), prevention through design (PTD) and so on (Hallowell & Hansen, 2016; Hardison & Hallowell, 2019).

Safety design (DFS) is an effort to reduce safety accidents from the design stage of the whole life cycle of a project; the American institute of occupational safety and health believes that preventive design (PTD) is designed to minimize risk through taking occupational safety and health requirements into account at the design stage (Lingard et al., 2013).

The implementation of the concept DFS requires designers identify the later construction safety risks from the design stage, and take effective measures to reduce or even eliminate the safety risk, so as to achieve a better performance goal of the project. It requires that the design schemes should not only meet the requirements of final use, but also need to enhance the construction safety and construct-ability during the construction process.

Some risk management methods (risk list; risk assessment; risk review) are to review the implementation of safety design using a text-based checklist, it's inefficient and cumbersome to use. With the rapid development of information technology, how to apply advanced 3D/4D visualization technologies such as CAD, VDC (Andersen & Findsen, 2019; Shafiq & Afzal, 2020), BIM and so on to realize intelligent pre-control of construction safety accidents has become a hot topic.

1.2. Engineering risk assessment methods

Engineering risk assessment is a necessary means to measure operability and sustainability in the early stage of project and can effectively avoid loss in later stage. Currently, the widely used research methods for construction safety risk assessment including checklist method, expert investigation, AHP analysis, LEC quantification method and so on, we just illustrate some of these methods in detail.

Checklist method is a commonly used tool for risk identification. In essence, it lists out the experienced risk events and their sources to form a check table, trying to predict the possible risk factors unhappened under the guidance of past experience. Rey et al. (2021) used checklist method to design and implement a computational system to carry out smart inspections for construction sites. The advantage of this method is that risk identification process is relatively simple and easy to grasp critical risks; the disadvantage is that the interdependence between risk sources is not revealed and some risks not included in the checklist are prone to omission.

Expert survey is a method of judging, evaluating and predicting risks through expert investigation. This method relies on experts' knowledge and experience, especially suitable for long-term prediction in the situation of absence of objective information or data (Leontaris et al., 2019). Some certain methods used frequently in the identification of safety risk in subway construction, including: field investigation method (Li et al., 2020; Liu et al., 2018b) and Delphi method (Alomari et al., 2020).

LEC is a semi-quantitative assessment method for potential hazards. This method uses three factors related to the system risk to evaluate possibility of some certain risks. Three factors are likelihood (L), exposure (E) and criticality (C). This method is easy to understand and operate, so it has a lot of derivations. Based on the basically elements of LEC method, this paper made an improvement to the existing method, we use frequency (F) to replace (L) indicator, so it will be more in line with the realistic sceneries of the construction industry.

1.3. BIM application on safety management

The widely accepted definition of BIM is proposed by the facility information committee (FIC) of the national institute of building sciences. BIM is a new design mode, which integrates all kinds of relevant information in the whole life cycle of construction engineering, and it is an integrated management system of engineering project information. Marinho et al. (2021) used BIM to deal with the asymmetric information (AI) problem in construction projects and improve the contract management service. Olawumi and Chan (2019) developed an effective BIM-project information management framework for construction projects with a view to enhancing the functional management of project information. BIM can also play a positive role for safety management in construction. Using BIM, we can not only realize the function of construction safety accident simulation, but also carry out time-varying structural safety analysis, space-time conflict management, model inspection and so on, so as to further improve the safety level of construction site. Lin et al. (2016) used BIM to develop a tool for construction quality inspection and defect management. As an innovative way of production, BIM is a direct application of information technology in the construction industry in recent years, which is affecting the whole industry quickly and deeply.

BIM secondary development refers to the realization of new functions on the original platform by means of programming languages and plug-ins, which is a user-defined software development method. There is no formal method for BIM secondary development, therefore, using Revit platform to develop plug-in applications no doubt has a broad application space in construction management field. Using the concept of preventive design, Yuan et al. (2019) developed plug-ins in Revit software to automatically traverse the design documents of a frame structure building and realize the safety detection of some components. Esfahani et al. (2021) used scan to-BIM technology to scan and model the built environment of buildings, studies the accuracy and certainty of software modeling process, and provides support for decision makers in the operation and maintenance and reconstruction of existing buildings. Vignali et al. (2021) used existing I-BIM, namely infrastructure information management system, to optimize and upgrade a road construction scheme in Italy, generating a 3D parametric model of the complete road and visualizing it in a real environment. The results show that I-BIM method is not only a powerful tool to optimize and verify the project scheme according to the specifications before project construction, but also can simulate the synergy between project environment and the infrastructure.

Through literature review, it can be found that the existing research on subway engineering safety management mainly focuses on the construction stage, most papers made contribution on construction site monitoring, numerical simulation of construction method, optimization and update of process, equipment and facilities. Theoretical researches also concentrate on traditional project management theories and risk prevention strategies. There are few studies working on the influence of design stage on the safety performance of subsequent construction stage, and some do research on the design stage only focus on the design documents and specifications themselves, ignoring the effective connection between design stage and construction stage. Therefore, based on DFS theory, this paper emphasizes the great potential of optimized design scheme for improving construction safety performance, which is an important supplement to existing research.

2. Research framework and methodology

A knowledge base in this paper incorporates design regulations, related literature and best practices. Based on the improved FEC risk assessment method and BIM secondary development technology, we take a subway deep foundation pit project as an example and automatically identify the construction safety and construct-ability problems in design schemes under the guidance of safety design concept.

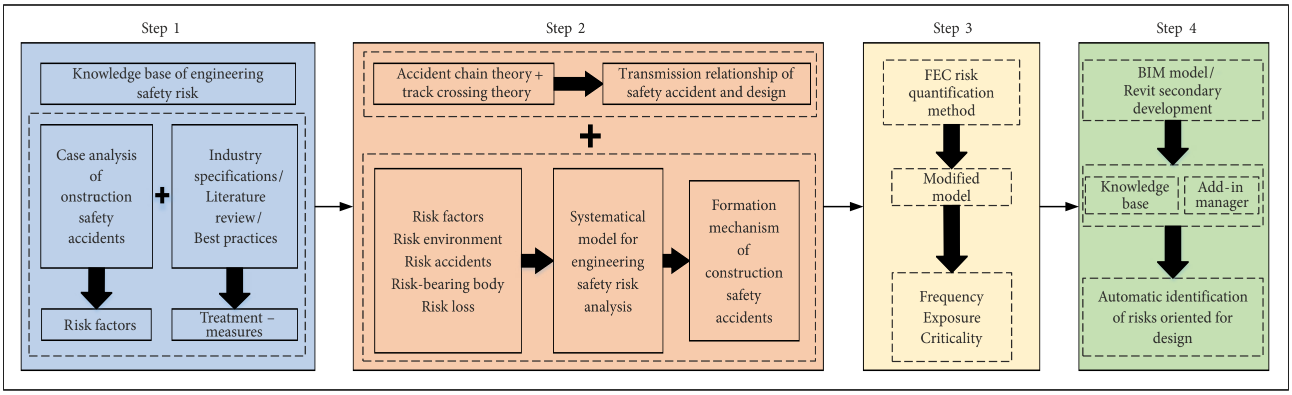

Figure 1. Research logic diagram

Figure 1 shows the whole research logic, from the creation of knowledge base, risk formation mechanism, risk quantification to BIM model verification. The purpose is to improve the construction safety and construct-ability from the design phase, address the importance of design stage in the whole process of construction, so that designers can use automatic ways to conduct safety design for engineering documents, and to realize the great potential of DFS to enhance the safety performance in the construction industry.

3. SCSA formation mechanism analysis

According to Symberski's theory, prior control in design stage plays a significant role in safety management (Szymberski, 1997). However, the mechanism of how construction safety accidents caused by design defects is still unclear, and the transmission relationship between design and accidents remains to be deeply studied. In this section, we use accident causality theory to reveal the correlation between design and accidents, and then deduce the formation mechanism of subway deep foundation pit collapse.

3.1. Transmission relationship between design and accidents

Heinrich (1980) classifies the causes of industrial accidents into five links: social environment, human mistakes, unsafe behavior or unsafe state, safety accidents and injuries, failure of any link will affect the normal operation. Heinrich (1980) also points out that the key to control accidents depend on eliminating the unsafe behavior of people and the unsafe state of objects, that is the third link of accident chain. Bird modified Heinrich's theory explains that the unsafe behavior of people and the unsafe state of objects are only concrete representations before accident occur, and the root cause of accident is management defect (Fu et al., 2020).

Bird's accident chain also contains five factors: first, root cause of accident is management defect; second, indirect reasons include personal reasons and working conditions; third, direct cause is unsafe behavior of people or unsafe state of objects; fourth, accident is regarded as the contact between people, structure, equipment and energy beyond their bearing threshold; fifth, the consequences include casualties and property losses.

Trajectory crossing theory synthesizes the positive aspects of accident chain theories and holds that accidents are the final result of many interrelated events. These events can be summarized into two categories of people and objects (including environment) (Niu et al., 2009). When the unsafe behavior and unsafe state intersect in a certain time and space, the energy will be transferred to human body, and safety accidents will occur immediately. The unsafe state of objects and unsafe behavior of people are direct causes of safety accidents, but the two are not completely independent and often affect each other: the unsafe state of objects can lead to the unsafe behavior of people, for example, the failure of warning lights may lead people to enter dangerous areas; similarly, the unsafe behavior of people can also lead to unsafe state of objects, for example, people remove the protective devices of facilities for convenience. The emergence and development of people's unsafe behavior and the unsafe state of objects are often caused by management defects. The accident causation logic is shown in Figure 2.

For the complex construction process of subway, safety design standards, designers' lack of safety awareness and backward management methods constitute a dangerous environment for subway construction. All kinds of risks are finally transmitted to the construction process in the form of design documents. Because the construction stage of subway project is a process of turning the planning into entity, if the construction safety risks in the risk environment are not effectively dealt with, these defect factors will eventually appear unsafe state in the construction stage, which intersects with the unsafe behavior of site workers in the construction stage, and may cause construction safety accidents.

3.2. Mechanism analysis of SCSA

Construction risk consists of five aspects: risk environment, risk-bearing body, risk factor, risk accident and risk loss. Risk environment is the external environment

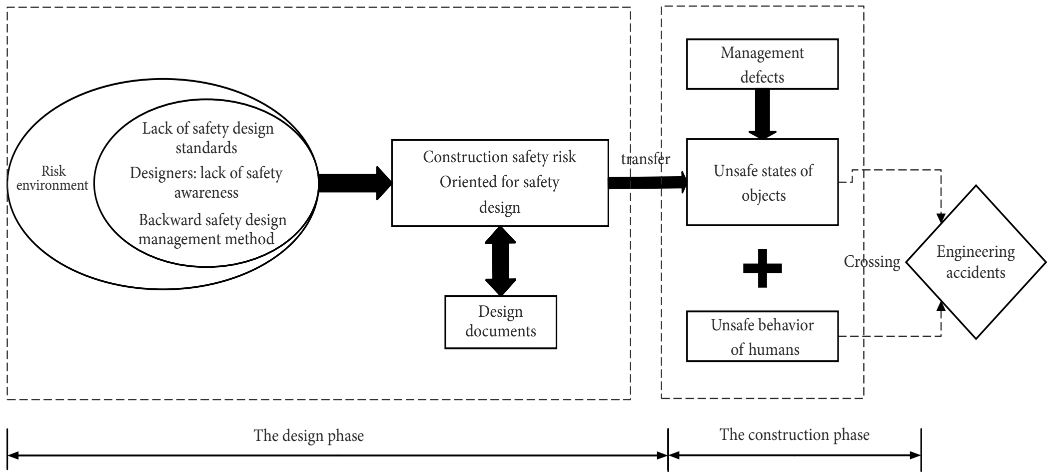

Figure 2. Relationship between safety accidents and design

in which risk is brewing and occurring. The risk-bearing body is a carrier to bear the risk loss, which may be personnel, machinery, environment, structure and so on. Risk factors are the trigger for risk. When a certain risk factor appears, it will cause a risk accident, resulting in damage to the risk-bearing body, and bringing in a certain risk loss.

In this paper, the main sources of risk are divided into two aspects: first, the construction safety risk caused by design parameters, which means these parameters are exceeding standard or the standard value itself is improper; second, the construction safety risk caused by the design scheme, which means that design schemes ignore the construct-ability.

The first kind of risk mainly involves the technical regulation, which directly relates to the construction safety. The key is properly control of the design parameters and set the standard value of safety risk. This paper divides the design parameters into two categories:

– Design parameters affecting the safety of structures, mainly include the load-bearing capacity of the components, the overall stability of the structure and the durability level of the structure, such as reinforcement ratio, anchor length, etc. For the prevention of this kind of safety risk, the construction safety risk caused by exceeding the standard value can be eliminated to a great extent by controlling all the design parameters within the allowable range, so long as the design strictly complies with the standards and specifications issued by the state and industry.
– Design parameters that do not affect the safety of structures but may affect the safety of construction process. Although such parameters do not affect the safety of structures, that is, the design documents made by the designer are safe. However, if the design scheme is measured from the point of DFS, it may also cause the unsafe state of the construction stage, thus causing the safety risk.

The second type of risk is mainly due to the safety risk which caused by ignoring the construct-ability of the project in the design work (such as the influence of the spacing of steel bar placement on the operation of the construction workers, the deep foundation pit slope does not consider the workers' protection measures, etc.). This kind of risk is not directly related to the construction safety accident, however, by studying the construct-ability and optimizing the design scheme, the difficulty of construction can be reduced, so that the construction workers can carry out various activities more conveniently and reasonably, and the construction safety can be effectively improved.

The subway construction scale is large and the investment is huge, not only the construction environment is more complex than the general project, but also the construction period is longer, involves more building materials, machinery equipment and operators. So, the design process is more demanding than other projects. The formation mechanism of different accident types is also different. Taking the collapse of subway deep foundation pit as an analysis case, this paper analyzes the formation mechanism of engineering construction safety accidents from five aspects of risk factors, risk environment, risk accident, risk-bearing body and risk loss according to the logical causation of risk, as shown in Figure 3.

All in all, the design content of subway project is mainly served for construction process, and the accuracy, rationality, construct-ability, effective management and safely protection measures of the design results in design stage are directly or indirectly related to the size of the construction safety risk. Set up the concept of DFS, so that designers will take the construction safety and construct-ability into account, it can effectively reduce the hidden defects in the design documents, eliminate the unsafe state of objects (environment). In this way, even if there is unsafe behavior in the construction process, it can effectively prevent the unsafe state of objects (environment) and the track of human unsafe behavior from crossing, so as to achieve the purpose of pre-control of construction safety accidents and ensure construction safety.

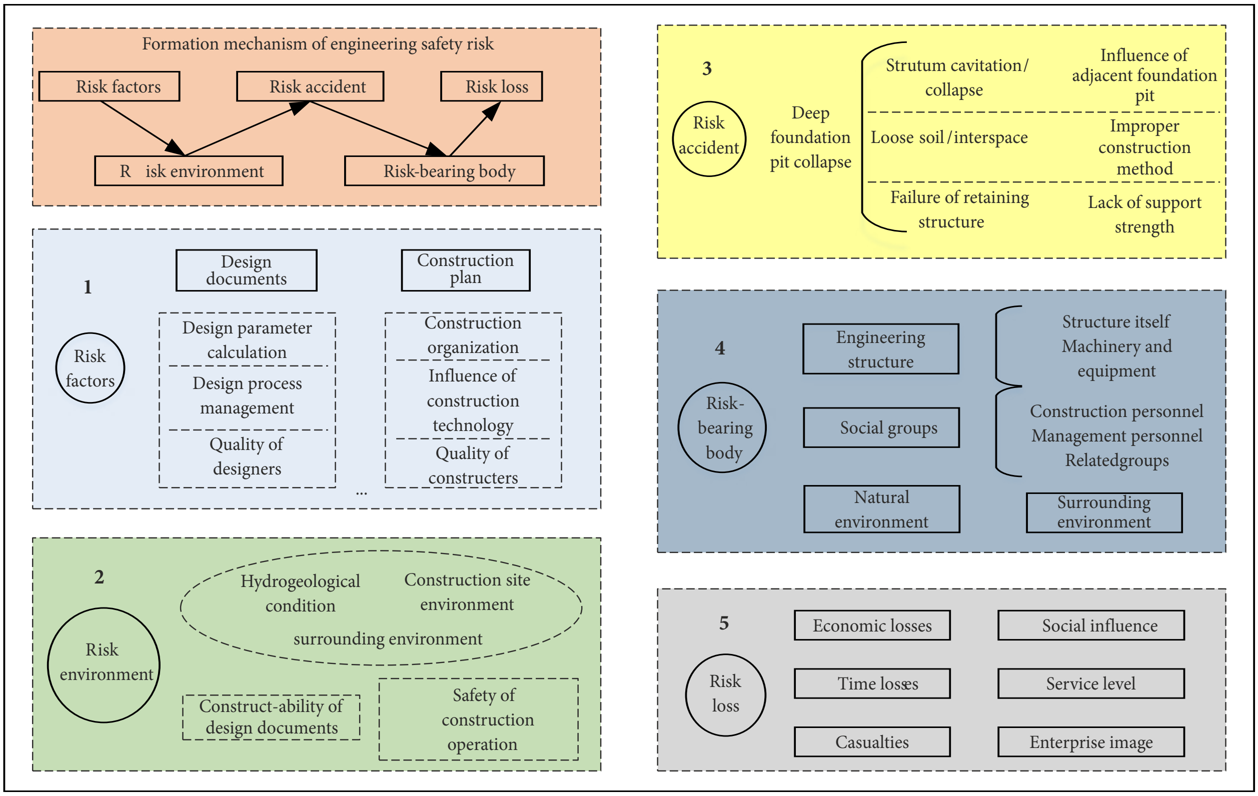

Figure 3. Causation mechanism of collapse accident for deep foundation pit

4. Risk management knowledge base of DFS

4.1. Identification method of subway construction safety risk

This paper aims at the safety risk of subway construction, takes the final design documents of subway engineering as the research object, trying to identify and express the various risk factors which directly or indirectly related to the safety accident in the form of list, and accurately reflect the construction safety risk contained in the design documents of subway engineering. Considering the lack of risk identification results of subway construction safety oriented to engineering design in China, based on the basic principles and methods of risk identification, from the perspective of affecting the construction safety and construct-ability, this paper carries out risk identification and summarizes the risk list.

The identification of risks and measures in this paper is mainly carried out through the following three ways:

(1) Analysis of normative regulations

At present, although various countries have not yet promulgated specifications, standards, guidelines or manuals specifically for identifying construction risks for subway projects, but through experience, some reference information for risk identification can be summarized. Although there is no explicit statement of risk in these normative standards or regulations, but by identifying the key words, such as "should", "should not", "must", "strictly prohibited", "appropriate", "inappropriate" and so on, possible risks can be inferred. As stipulated in the Technical Regulations for Foundation Pit Support of China, "the embedded depth of the double-row pile structure should not be less than 1.0h for muddy soil, 1.2h for silt and 0.6h for general cohesive soil and sandy soil (h is the depth of foundation pit)". According to the keyword reasoning method, this paper summarizes 36 design and technical regulations including subway engineering survey, design, construction, quality, safety and inspection, the identification results provide a rational basis for the establishment of the risk list.

(2) Literature analysis

A large number of experts and scholars are engaged in the research work on subway engineering safety at present, and have obtained a large number of research results such as monographs, papers, academic reports and so on. Different from the design specifications and standards, this kind of knowledge is a summary of experience in the actual construction process. Although it is not compulsory requested by the state, it can systematically and comprehensively analyze the important links in subway engineering project. In this paper, the special scheme of deep foundation pit construction in Nanjing Metro Line 2 is studied in detail. The expert scheme pays special attention to three points: bolt support method, foundation pit dewatering process and foundation pit fence setting. The special scheme of deep foundation pit construction is a further supplement to the specification rules.

(3) Case studies

Accident cases are the most powerful evidence in the process of risk analysis. According to the statistics, in 2002–2016, about 246 accidents occurred in subway construction, of which 43% were collapse accidents, and about 67% of them were deep foundation pit collapse. Our research team collected the detailed data of 52 SCSA in recent years, and found that a few of the direct causes of safety accidents are due to design reasons, such as Shanghai Metro Hailun Road Station, the design documents do not take the influence of confined water into account, resulting in insufficient insertion depth of the enclosure structure, and eventually lead to safety accidents caused by the damage of the foot line. Most of the direct risk factors of accidents are from the construction reasons, but behind the risk factors of construction there are still poor design schemes, which will lead to accidents. Case analysis provides a practical basis for the establishment of risk list.

4.2. Knowledge base of safety risk for deep foundation pit

The main results of risk identification are the risk list. The risk identification method mentioned in the above section is comprehensively used to form a design-oriented safety risk identification list for subway deep foundation pit engineering, and 10 kinds of important risks in the construction process are summarized, respectively, seepage failure of the envelope, deep foundation pit support instability, soil landslide in pit, foot failure of deep foundation pit envelope, sudden flood damage, flow soil (sand) of foundation pit bottom, water gushing on the side wall of foundation pit, foundation pit bottom uplift, excessive deformation of steel support, dumping of foundation pit. According to industry specifications, literature and best practice cases, the possible consequences and treatment measures of various risk factors are extracted. Only some of the risks are listed for reasons of limited space, as shown in Table 1.

After identifying the risk factors and countermeasures of the construction safety risk of subway deep foundation pit, the Access software is used to classify all kinds of risk information and assign the corresponding number to form the knowledge base of subway construction safety management.

5. Case study

5.1. Quantification of construction safety risks

FEC method is a relatively unified method of safety risk quantification at present. The main parameters of this method include: frequency (F), exposure (E) and criticality (C). Relations of these three parameters can be expressed by the following formula:

$$\textit{Safety risk} = \textit{frequency} \times \textit{exposure} \times \textit{criticality} \text{ (FEC quantification model).} \quad (1)$$

In the formula, frequency is the number of accidents occurred per unit time, criticality is the magnitude of the consequences of a certain accident, and exposure is the time exposed to potential hazards.

5.1.1. Improved FEC quantitative model

According to the definition of frequency, exposure and criticality, combining with the research frontier, this paper improves the traditional FEC quantification method, so that the research results can be used in the design-oriented safety risk management of subway engineering.

Table 1. Identification list of safety risk for deep foundation pit

Number	Risk events	Brief overview	Risk factors	Possible consequences	Treatment measures
1	Seepage failure of envelope	Failure of envelope structure leads to the infiltration of groundwater into working environment of deep foundation pit, resulting in destruction of supporting structure	Design error of precipitation scheme; Design strength of support structure is insufficient	The structure loses its bearing capacity and the foundation pit loses its overall stability	(1) Review of design scheme; (2) Structure strength checking
2	Deep foundation pit support instability	Due to improper design, construction defects or other external interference, the anchorage system of deep foundation pit support is not strong and stable enough to achieve the support effect, which causes the deep foundation pit envelope to dump and destroy to the interior	Design strength of support structure is insufficient; Insufficient spacing and depth of anchor; Excessive spacing of temporary columns	The instability of supporting structure can induce the failure of whole foundation pit	(1) Increasing design strength of support structure; (2) Optimizing the arrangement of temporary columns
3	Soil landslide in pit	The existing retaining and supporting structures in deep foundation pit are damaged due to steep slope, top load or heavy rain	Slope angle is bigger than safety value	Foundation overturned; Casualties	(1) Optimizing the design of slope; (2) Heap load cannot exceed allowable values

(1) For the frequency quantification, the concept of the frequency value is the number of accidents occurred per hour, which can be obtained by:

Frequency value of a specific safety risk accident type = the number of safety accidents occurred per hour of subway deep foundation pit × the proportion of a specific risk accident type of subway deep foundation pit ((number of accidents/hour) × *the proportion of accident types*).

The safety accidents of subway deep foundation pit occurred per hour can be obtained by the development curve of total safety risk accidents of subway deep foundation pit over years. In this paper, according to the statistics of safety accidents of deep foundation pit of subway in China since 2002, the distribution map of safety accidents in subway deep foundation pit construction is obtained as shown in Figure 4. From this picture, we can see that since 2003, 2008 and 2010 were the two years with the highest number of accidents in subway deep foundation pit construction. This is mainly because the number of subway lines under construction in these two years is 73 and 70, these two years were in the period of vigorous development of subway construction; after 2010, the number of safety accidents in subway deep foundation pit is obviously reduced, but the number of subway lines built every year has not decreased. This reflects the increasing emphasis on security issues over time during construction and continuously improved technical and managerial skills, the number of accidents has stabilized since 2010. Under the assumption that the subway safety management level has not changed qualitatively, taking the average of accidents after 2010 as the number of accidents used in this study, that is to say, it is assumed that 2.4 times underground deep foundation pit safety accidents occur per year.

The proportion of specific safety risk accident types in deep foundation pit of subway can be obtained by the existing safety accident statistics. For example, the author of this paper found that the proportion of leakage damage of enclosure structure, instability of support of deep foundation pit and landslide of soil in pit is the largest among all safety risk types. At the same time, proportion of specific causes of these three major safety risk accident types can also be obtained and analyzed, the results are shown in Figure 5.

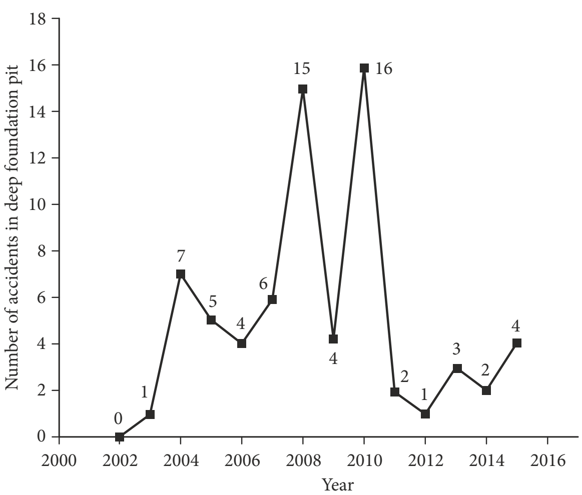

Figure 4. Statistics of safety accidents in deep foundation pit

According to the analysis of causes for risk accidents, the contribution value of each risk factor in the deep foundation pit safety accident can be obtained, that is the probability of its occurrence. Taking the insufficient embedded depth in the deep foundation pit support structure as an example, the proportion of support instability in the subway deep foundation pit safety accident is 13%, and the proportion caused by the insufficient embedded depth is 20%, then the proportion of the deep foundation pit safety accident caused by the insufficient embedded depth is 0.026 (13% × 20%).

(2) The criticality is defined as the death and injury degree of the construction workers caused by a safety risk accident; it is calculated by means of nonlinear quantification. The nonlinear quantization value was obtained by Hallowell (2012) through the analysis results of a large number of building construction safety risk events, which matches each accident with the specific loss of the construction enterprise. According to the corresponding relationship of these two data, they obtained a specific function and simulates for a nonlinear quantitative risk value. By analyzing statistics on the cases of deep foundation pit accidents in China's subway, Yang and Yu (2013) have formed a statistical data on the number of losses caused to construction enterprises by different types of safety risk accidents. The corresponding relationship between the number of losses and the score is shown in Table 2.

Yang and Yu (2013) carried out case analysis on the existing deep foundation pit engineering accident of subway and interviewed relevant personnel, then obtained direct economic losses caused by the classic subway deep foundation pit accidents in the past 10 years. Through the induction and processing of the data, the scores of economic losses for several different deep foundation pit instability accidents were calculated on average to form the corresponding relationship of the types and severity scores of subway safety risk events, as shown in Table 3.

(3) For the quantitative process of exposure, the meaning of exposure is the duration of a hazardous work performed by the construction worker. Because the duration is difficult to calculate, previous safety risk quantification is generally calculated by the experience value of the construction worker, but this method is too subjective. This paper calculates the exposure time according to the construction schedule of a specific subway construction design scheme. For example, when considering the safety risk exposure time caused by insufficient embedded depth, the duration of follow-up work after foundation pit support is calculated as the exposure time, and the time is calculated in hours.

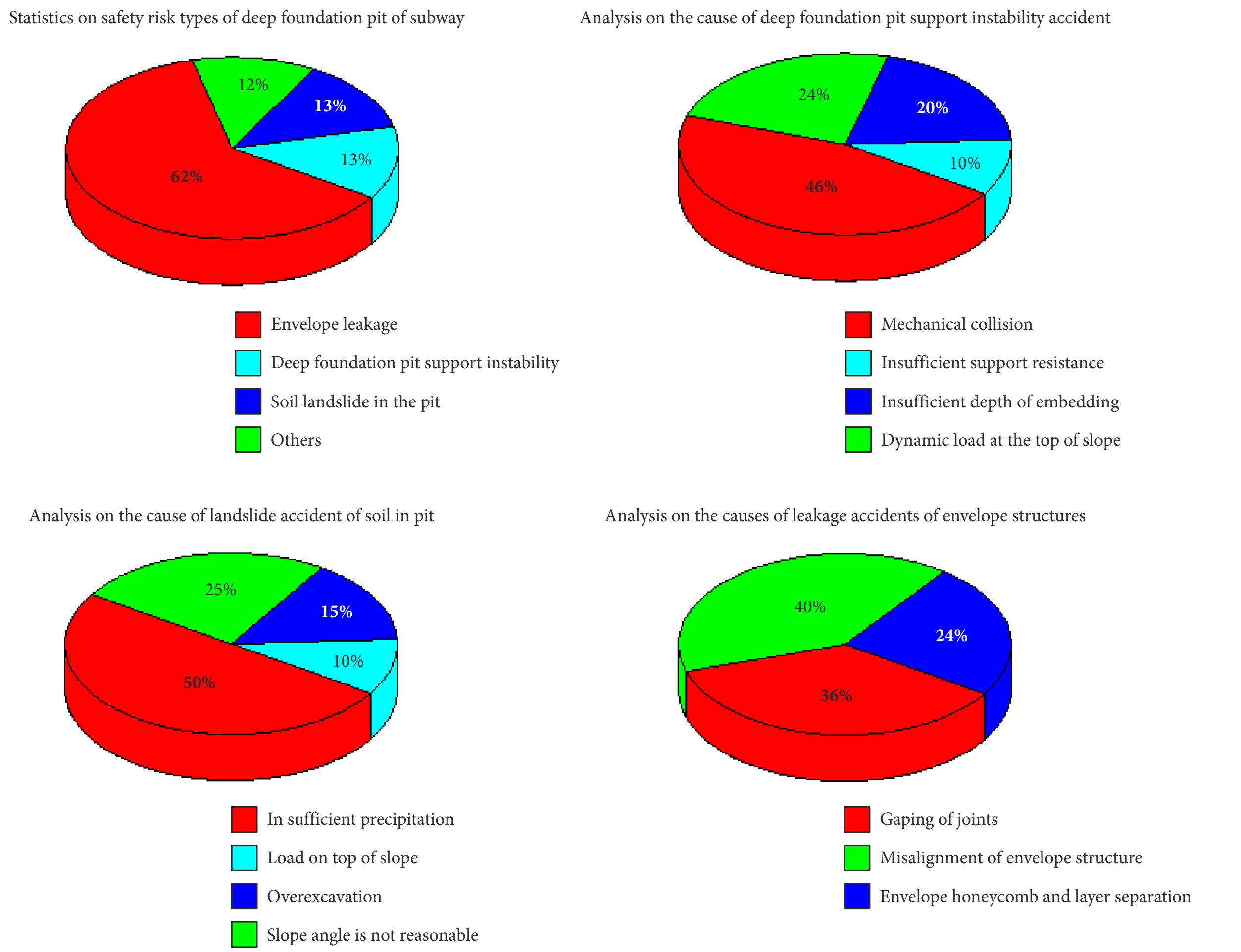

Figure 5. Statistics on safety risk types of deep foundation pit of subway

Table 2. Classification of safety accident severity

Consequences of the accident	Score
¥3 million ≤ direct economic losses	100
¥1 million ≤ direct economic losses < ¥3 million	40
¥0.3 million ≤ direct economic losses < ¥1 million	15
¥0.1 million ≤ direct economic losses < ¥0.3 million	7
¥0.01million ≤ direct economic losses < ¥0.1 million	5
¥1000 ≤ direct economic loss < ¥0.01 million	3
¥1000 > direct economic losses	1

Table 3. Severity degree of safety accidents

Types of safety risk accident	Score
Seepage failure of the envelope	54
Deep foundation pit support instability	56
Soil landslide in pit	55
Foot failure of deep foundation pit envelope	15
Sudden flood damage	27
Flow soil (sand) of foundation pit bottom	15
Water gushing on the side wall of foundation pit	15
Foundation pit bottom uplift	11
Excessive deformation of steel support	7
Dumping of foundation pit	40

5.1.2. safety risk quantitative evaluation case

The quantization process of safety risks is to multiply three risk indicators. For example, for a specific subway deep foundation pit construction case: the length is about 170 m, and this case is designed as an underground station, the main body and part of the subsidiary structure of the station are constructed by open excavation method, and the excavation depth of the foundation pit is about 16.5 m. Foundation pit soil layer is general clay soil, foundation pit support adopts double row pile structure, the standard width of foundation pit is 19.4 m, part of its construction schedule is shown in Table 4.

It is found that the embedded depth of anchor rod in the design scheme is insufficient, which can easily lead to the occurrence of construction safety risk. The quantified value of the construction safety risk is calculated as follows:

(1) Criticality: because the embedded depth is insufficient, the deep foundation pit support instability is easy to occur, based on the proposed method the risk quantification score is 56;

(2) Frequency: firstly, the proportion of underground deep foundation pit safety accidents caused by embedded depth insufficient is 0.026, and the annual number of underground deep foundation pit safety risk acci-

Table 4. Schedule of construction progress

Project	Duration	Start time	Completion time
Station	491 days	30 September 2016	2 February 2018
Digging pile and ring beam	60 days	30 September 2016	29 November 2016
Earthwork excavation	150 days	29 November 2016	28 April 2017
Soil nailing bolt support	150 days	8 December 2016	7 May 2017
...	...	...	...
Completion inspection	2 days	31 January 2018	2 February 2018

dents is 2.4, then the number of safety risk accidents caused by insufficient embedded depth are approximately 0.0624, assuming that working 9 hours a day, 5 days a week, 50 weeks a year, the safety risk accidents caused by this risk factor are 0.0624/2250 per hour;

(3) Exposure: according to the schedule calculated based on the proposed method, the total duration is 491 days, bolt support starts on the 69th day and ends on the 219th day, the construction period is 150 days. So the hidden hazards duration time from bolt support completion to insufficient embedded depth exists in the construction process for 272 days, that is, the working time is 2448 hours;

(4) Construction safety risk quantification: after multiplying the quantitative values of the above three indicators, the quantitative score of safety risk caused by insufficient embedded depth is 3.8;

(5) The meaning of the score 3.8: based on the proposed method , the score 3 shows that the direct economic loss caused to the construction enterprise is between 1000 yuan and 10,000 yuan, while the score 5 shows that the direct economic loss caused to the construction enterprise will be between 10,000 and 100,000. The value of the direct economic loss caused by the score 3.8 to the construction enterprise is 46,000 by the conversion of the proportional relationship.

5.2. Quantification of safety risks based on BIM

5.2.1. Application framework of safety risk quantification model

BIM is used to realize the visualization of safety risk quantification model. In essence, it is a process of reviewing the design scheme and automatically identifying construction safety risks based on the knowledge or rules in the safety design knowledge base. Firstly, we need to use the Revit software to build a construction model for research object, Secondly, use VS platform and C# language to program the knowledge base rules and FEC risk quantification process into the language that computer can recognize. Then we use the Add-in manager tool to connect the base files developed by VS platform with Revit software. After that, the research model will automatically be detected, specific data information will be extracted and judged, and then the modified software will identify corresponding construction safety risks and hazards, it can also show the identification and calculation results. The research results provide scientific basis for the design company to standardize and optimize the design documents, and the construction company can use this method to improve the construction technology.

5.2.2. Case verification of risk quantification

The underground deep foundation pit in Section 5.1.2 is selected as the research case, in which the excavation depth of foundation pit is about 16.5 m, the soil layer around the foundation pit is general clay soil, the support form adopts double row pile structure, and the standard width of foundation pit is 19.4 m. The Revit numerical model of foundation pit is established, as shown in Figure 6, and the soil anchor is enlarged as shown in Figure 7.

The DFS-oriented safety risk identification includes the dimensions, positions, materials, etc. Design parameters such as embedded depth, slope gradient, anchor diameter, anchor spacing, etc. can be identified through secondary development technology and add-in manager plug-in tool. According to the technical regulations for foundation pit support of construction of China, the embedded depth of double-row pile structure should not be less than 0.6 h (h

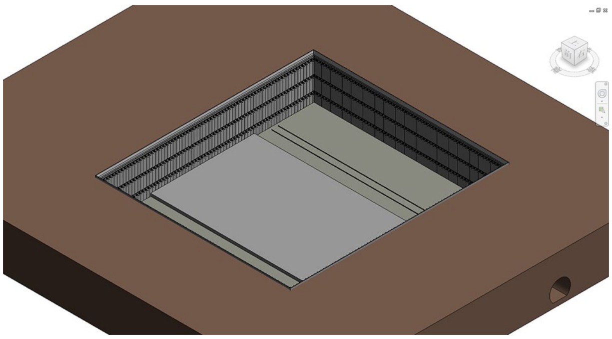

Figure 6. Revit model of deep foundation pit

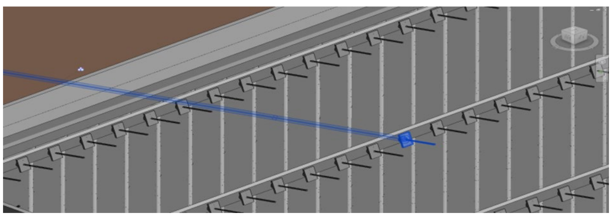

Figure 7. Soil anchor details

is the foundation pit depth) for general cohesive soil or sandy soil. According to the realization algorithm of specific data information extraction and judgment, through programming in the Visual Studio platform, the design scheme is traversed by using the way of external command to determine whether there is a construction safety risk of insufficient embedded depth.

The algorithm mainly includes the following steps: (1) identifying anchor module in deep foundation pit, and obtain its length and free end length; (2) identify the excavation depth of the deep foundation pit and the whole schedule of deep foundation pit, to clearly master the support completion time (calculate exposure); (3) calculate embedded depth value (total length minus free end length); (4) determine whether the depth of the embedding is in accordance with the design specifications; (5) if the embedded depth meets the requirements, then the window pops up , "the embedded depth is in accordance with the regulations"; if not, calculate the risk score according to the FEC formula, and pops up in the window.

When the code is written down, then runs on the VS platform, the base file will be loaded by the manual mode in the Add-In manager tool in the Revit, and the identification result of the construction safety risk of the deep foundation pit will obtained by running the plug-in, as shown in Figure 8.

The contents displayed in the program are consistent with the manual calculation results, indicating that the code and method are effective. By constantly expanding the code content and combining with the safety risk quantification model, the code can be used to identify different design factors and complete the comprehensive risk quantification.

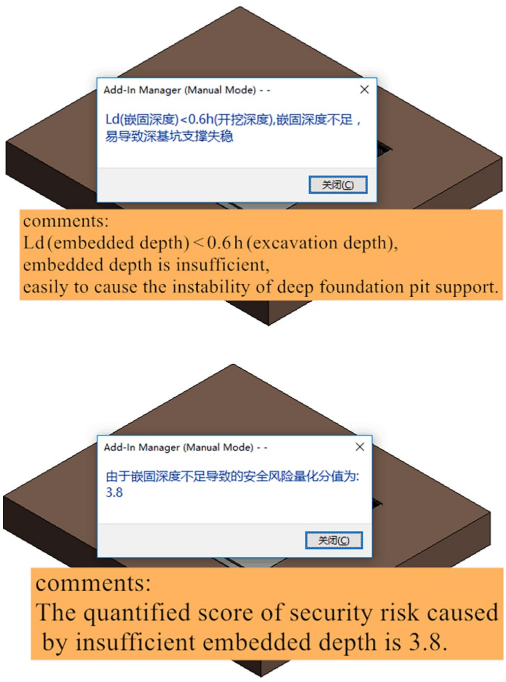

Figure 8. Results of construction safety risk identification

6. Discussion

Based on the concept of design for safety (DFS), this paper focuses on the identification and treatment of safety risks in construction process, which enriches the research on prior control for safety management and completes the design-oriented analysis of the causation mechanism of subway construction accidents. Secondly, through DFS risk identification method, taking one typical subway deep foundation pit project as research object, this paper forms a safety risk management knowledge base of deep foundation pit construction. Finally, based on BIM secondary development technology, we propose a method to transform safety design knowledge into a computer language that Revit can recognize, so that the design scheme can be automatically reviewed. The computational logic for risk quantification is embedded in Revit and finally form a design-oriented safety risk quantification method.

However, there are still some deficiencies of this paper, which requires further in-depth research in the future: (1) This paper mainly considers the construction safety management from the perspective of design people. In practice, there are also construction agent company, construction people, material and equipment supplier and other participants. It is worth further study to discuss how to build a risk management model that supports multi-party participation and collaborative work; (2) The safety risk identification list in this paper only takes the subway deep foundation pit project as research object, and identifies the construction safety risk of the deep foundation pit project. Other projects in the construction process still need to be further studied; (3) Based on BIM secondary development, this paper proposes a method that transform safety design knowledge into computer language which Revit can identify, so as to automatically identify the construction safety risk, the realization of information extraction and judgment function is not perfect. It is only roughly expressed for the relatively simple design regulation, and the collaboration between knowledge base and BIM model still needs to be improved; (4) In the process of safety risk quantification, the data sources all come from existing subway deep foundation pit projects, so the research data has certain limitations. In the future, the case base of subway construction projects will be more abundant and the quantitative results will be more reliable.

Conclusions

This paper analyzes the occurrence mechanism of subway construction safety accidents (SCSA), introduces the concept of design for safety (DFS), and advocates to consider the construction safety and construct-ability from design stage. Firstly, this paper introduces safety design, risk evaluation system and related theories of BIM; another contribution is that this paper identifies subway construction risks from design documents and forms a risk list for safety management; in addition, we proposed an improved FEC risk quantification method consists of frequency, exposure and criticality and finally put forward an automatic risk quantification model based on BIM. Some important results are as follows:

(1) This paper reveals the causative mechanism of safety accidents and analyzes the relationship between construction safety accidents and engineering design documents based on relative theories, it shows that deficiencies hidden in design documents will adversely affect the safety performance and operability of the subsequent construction stage;

(2) According to review of design specifications, literature review and best practices, from the perspective of construction safety and construct ability, this paper carries out the DFS oriented subway construction safety risk identification and form a risk list including 10 major security risk events for subway deep foundation pit;

(3) This paper promotes traditional risk qualitative evaluation to quantitative evaluation, based on LEC methods, propose three risk assessment indicators: frequency, exposure and criticality. In this paper, the product of these three values is taken as the risk value, and a deep foundation pit is taken as a case study to evaluate the risk status in the construction process of the project with FEC method;

(4) In this paper, BIM secondary development technology is used to realize the visualization and automatic calculation of FEC method: embedding the deep foundation pit construction safety knowledge base and FEC calculation logic into BIM software, taking one rule of anchorage length in design specifications of deep foundation pit as a research point to calculate the construction risk, which is a new attempt to solve the risk management problems by using BIM technology.

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