Research on vulnerability of subway deep foundation pit construction system based on N-K model

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Abstract. In order to analysis the vulnerability of underground deep foundation pit construction system and improve the safety level of underground deep foundation pit construction. Firstly, based on the vulnerability theory, the concept of vulnerability of underground deep foundation pit construction safety system is proposed; secondly, the three characteristic elements of vulnerability are used to construct a diagram of the recursive evolution process of vulnerability influencing factors; finally, a total of 107 underground deep foundation pit construction safety accidents are selected from 2010 to 2022, and the probability of each factor and its coupling value when coupling occurs in different cases are calculated using the N-K model to derive the key coupling factors affecting the vulnerability of subway deep foundation pit construction system. The key coupling factors affecting the vulnerability of metro deep foundation pit construction system. The study shows that: the probability of accidents and the number of factors involved in the coupling is positively correlated; through the vulnerability analysis can find the weak links of the underground deep foundation pit construction system, and provide certain theoretical support for improving the level of safety management of underground deep foundation pit construction.

Keywords: subway; Vulnerability; deep foundation pits of the subway; N-K model; coupling

1 Introduction

In the context of rapid economic development and increasing urbanisation level, the metro plays an important role as a travel mode to ease urban traffic. As the most critical part of underground construction, the deep foundation pit project of underground station is affected by the complex geological environment and site operation environment, which leads to its frequent occurrence of safety accidents.

Most of the current studies on the risk level of deep foundation pit construction in metro are based on numerical simulation and other methods, and few of them are conducted from the perspective of risk coupling. Therefore, some scholars in the field of safety engineering related fields began to study the underground deep foundation pit

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construction safety from the perspective of risk coupling. Yan Wenzhou et al [1]constructed an underground construction risk evaluation model based on multi-factor interaction through the interaction matrix method under the perspective of multi-factor coupling. Zhao Jinxian et al [2]determined the construction risk level by calculating the coupling degree between risk factors based on the risk coupling model of inverse cloud. Based on the risk coupling theory, Wang Qiankun et al[3] established an underground deep foundation pit construction risk evaluation model based on the interaction matrix method and C-OWA operator to derive the construction risk level.

The study of vulnerability first originated from the field of natural disasters, and then gradually penetrated into the field of safety science and other fields. Yue Rentian et al[4] analysed the recursive evolution process of vulnerability elements of air transport system by constructing a coupled model of vulnerability factors. Hou Gongyu et al [5]analysed the coupling between vulnerability factors in the metro construction process based on the N-K model. Vulnerability, as an inherent property of a system, exists in the elements that constitute the system. Therefore, the study of vulnerability can help to find the essential causes of accidents, and then propose corresponding measures to reduce the vulnerability of the system.

2 Vulnerability analysis of metro deep foundation pit construction system

2.1 Vulnerability concept and characteristic elements1

In 1981, Timmerman et al[6]defined vulnerability as "the degree of reaction of the system to cope with unfavourable responses when a disaster event occurs." Our scholars, Li He et al[7], consider vulnerability to be a property of a system that changes its internal structure and function when it is subjected to internal and external perturbation effects. According to the research on vulnerability by some scholars in the field of safety engineering, the vulnerability of a system only becomes apparent when it is subjected to the action of external perturbations. At present, the elements of vulnerability characteristics widely accepted by scholars include the degree of exposure, sensitivity and adaptability [8], the degree of exposure refers to the degree of damage suffered by the system when it is subjected to the action of external perturbations, sensitivity refers to the degree of response of the system when it is disturbed by the system itself, and the degree of adaptability refers to the ability of the system to restore the normal operation state after it is damaged by the perturbations [9-10]. Through the research of related scholars, it is found that the elements of vulnerability characteristics are not simply juxtaposed with each other, but exist in a certain logical order. Song Shouxin et al [11] pointed out that the three characteristic elements of vulnerability are not independent of each other, but there is a recursive evolutionary relationship, as shown in Figure 1.

In summary, the author defines the vulnerability of the underground deep foundation pit construction system as the ability of the system to continue to maintain normal work after the subway deep foundation pit construction safety system is subjected to the disturbing effects of internal and external risk factors, under the graded resistance effects of exposure, sensitivity and adaptability.

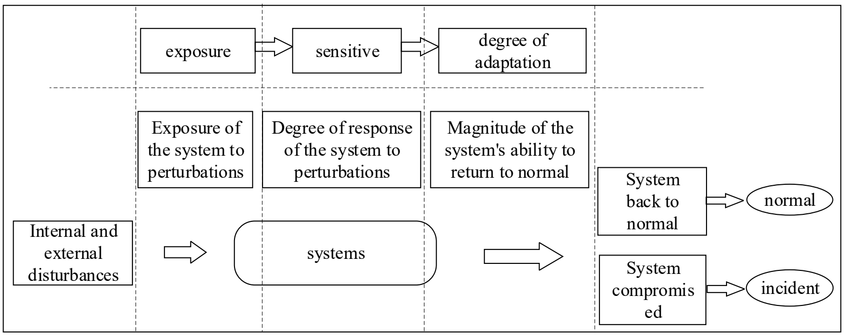

Fig. 1. Framework for the evolution of vulnerability analysis

Since the underground deep foundation pit construction will face the disturbance of many factors, in order to better find out the weakness of the system itself, it is necessary to identify the vulnerability factors affecting the safety of deep foundation pit construction. In this paper, five subsystems, namely personnel, equipment, internal and external environment, organisational management and technology, are taken as the research objects, and vulnerability characteristic elements, i.e., exposure, sensitivity and adaptability, are combined to classify the factors contributing to deep foundation pit construction accidents in metro, as shown in Table 1(H, M, E, M*, T， stand for personnel, equipment, environment, management, and technical factors respectively).

Table 1. Vulnerability factors of safety system for deep foundation pit construction of metro

first level	second	third	Vulnerability impact factors	
Vulnerability of safety systems for underground deep foundation pit construction	exposure	H	Failure to follow the construction programme	Inadequate geological surveys
		M	Poor equipment selection	Poor equipment placement
		E	Complex groundwater hydrological conditions	Complex underground pipelines
			High surrounding loads	
		M*	Inadequate technical safety briefings	Failure to implement responsibility for safety in production
			Security education and training	
		T	earthwork over-excavation	Inadequate pit excavation support
			Reasonableness of the drainage programme	
	sensitivity	H	Personnel fatigue	Weak security awareness
		M	Equipment safety hazard	

	E	Extreme weather	
	M*	Inadequate management of construction organisation Identification of potential safety hazards	Regularity of the security responsibility system
	T	Support system instability seepage damage	In-pit landslides
degree of adaptation	H	security measure	Accident response capacity
	M	Daily maintenance of equipment	
	E	Advanced geological forecasting	
	M*	Emergency Response Plan Formulation and Implementation	Emergency Response Measures
	T	Technical measures for site safety	

2.2 Coupled analysis of system vulnerability factors

The interaction of two or more vulnerability factors leads to changes in the system security state phenomenon called vulnerability factor coupling phenomenon[12]. Under the role of internal and external interference, the underground deep foundation pit construction system of the insecurity factors produce dynamic coupling effect, the size of the coupling effect to a certain extent determines the size of the system vulnerability.

3 Vulnerability analysis of metro deep foundation pit construction system based on N-K model

3.1 Principle of N-K model

The N-K model was initially proposed by biologist Kauffman[13] as a method to study the evolution of complex systems, and was later applied to study the interactions between elements within a system. In addition, the application of the N-K model in the fields of studying the coupling between risks such as road hazardous materials transport[14], underground construction[15] , and marine traffic safety [16] has been feasible. N in the N-K model stands for the number of elements in the system, and K stands for the number of elements in which coupling occurs between the systems, and the value of K is in the range of [0, N-1].If the sub-systems of the underground deep foundation pit construction safety system subsystem exists n states, then there are at most n^K coupling states [17].

3.2 Vulnerability factor coupling metric information interaction formula

In order to quantify the coupling relationship of human-machine-environment-pipe-technology vulnerability factors in metro deep foundation pit construction, the coupling information interaction formula (1) is usually used to calculate the coupling value T. The larger the value of T is, the greater the vulnerability of the system is, and the more likely to cause.

$$T(\mathrm{a,b,c,d,e}) = \sum_{h=1}^{H}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} P_{hijkl} \cdot \log_2\left[\frac{P_{hijkl}}{P_{h....} \cdot P_{.i...} \cdot P_{..j..} \cdot P_{...k.} \cdot P_{....l}}\right] \quad (1)$$

In the formula., a, b, c, d, represent personnel, equipment, environmental, organisational management and construction technology factors respectively; the status of each of the five categories of factors is represented by h, i, j, k and l respectively; included among these h=1, ···H； i =1, ···I； j=1,···J; k=1,···K; l=1,···L; $P_{h....}$, $P_{.i...}$, $P_{..j..}$, $P_{...k.}$, $P_{....l}$ Indicates the coupling probability of personnel, equipment, environment, organisational management and construction technology,, P_{hijkl} denotes the probability that coupling occurs with personnel in state h, equipment in state i, environment in state j, management in state k and construction technology in state i.

3.3 Double and multi-factor coupling calculation formula

According to equation (1): four-factor counting coupling calculation to personnel - equipment - environment - organisational management coupling as an example:

$$T(a,b,c,d) = \sum_{h}^{H}\sum_{i}^{I}\sum_{j}^{J}\sum_{k}^{K} P_{hijk.} \cdot \log_2\left[\frac{P_{hijk.}}{P_{h....} \cdot P_{.i...} \cdot P_{..j..} \cdot P_{...k.}}\right] \quad (2)$$

The two-factor coupling calculation is exemplified by the personnel-equipment coupling:

$$T(a,b) = \sum_{h=1}^{H}\sum_{i=1}^{I} P_{hi...} \cdot \log_2\left[\frac{P_{hi...}}{P_{h....} \cdot P_{.i...}}\right] \quad (3)$$

The three-factor coupling calculation is exemplified by the personnel-equipment-environment coupling:

$$T(a,b,c) = \sum_{h=1}^{H}\sum_{i=1}^{I}\sum_{j=1}^{J} P_{hij..} \cdot \log_2\left[\frac{P_{hij..}}{P_{h....} \cdot P_{.i...} \cdot P_{..j..}}\right] \quad (4)$$

4 Case studies

4.1 Data sources

Due to the complex and unpredictable environment of underground deep foundation pit construction, different types of safety accidents occur frequently. In order to take effective measures to reduce the probability of safety accidents during deep foundation pit construction, this paper collects and collates the investigation reports of a total of 107 underground deep foundation pit construction safety accidents from 2010 to 2022, and statistically calculates the number and probability of occurrence of vulnerability factors coupled with the accidents from the three aspects of the degree of exposure, sensitivity, and adaptability, as shown in Table 2.

Table 2. Number and probability of coupling of single, double, and multifactor

	Type of coupling	Frequency and probability				
exposure	Single Factor	N(10000)=4 $P_{10000}=0.037$	N(01000)=2 $P_{01000}=0.018$	N(00100)=5 $P_{00100}=0.046$	N(00010)=7 $P_{00010}=0.065$	N(00001)=1 $P_{00001}=0.009$
	Two-factor	N(11000)=0 $P_{11000}=0$	N(10100)=8 $P_{10100}=0.074$	N(10010)=13 $P_{10010}=0.121$	N(10001)=3 $P_{10001}=0.028$	N(01100)=0 $P_{01100}=0$
		N(01001)=0 $P_{01001}=0$	N(00110)=7 $P_{00110}=0.065$	N(00101)=10 $P_{00101}=0.093$	N(00011)=2 $P_{00011}=0.018$	N(01010)=0 $P_{01010}=0$
	Multi-factor	N(11100)=0 $P_{11100}=0$	N(11010)=5 $P_{11010}=0.046$	N(11001)=0 $P_{11001}=0$	N(10110)=7 $P_{10110}=0.065$	N(10101)=7 $P_{10101}=0.065$
		N(01110)=0 $P_{01110}=0$	N(01101)=1 $P_{01101}=0.009$	N(01011)=1 $P_{01011}=0.009$	N(00111)=8 $P_{00111}=0.074$	N(11110)=0 $P_{11110}=0$
		N(11011)=1 $P_{11011}=0.009$	N(10111)=8 $P_{10111}=0.074$	N(01111)=0 $P_{01111}=0$	N(11111)=0 $P_{11111}=0$	N(10011)=7 $P_{10011}=0.065$
sensitivity	Single Factor	N(10000)=9 $P_{10000}=0.084$	N(01000)=0 $P_{01000}=0$	N(00100)=1 $P_{00100}=0.009$	N(00010)=12 $P_{00010}=0.112$	N(00001)=10 $P_{00001}=0.093$
	Two-factor	N(11000)=1 $P_{11000}=0.009$	N(10100)=1 $P_{10100}=0.009$	N(10010)=25 $P_{10010}=0.233$	N(10001)=4 $P_{10001}=0.037$	N(01100)=0 $P_{01100}=0$
		N(01001)=0 $P_{01001}=0$	N(00110)=3 $P_{00110}=0.028$	N(00101)=3 $P_{00101}=0.028$	N(00011)=21 $P_{00011}=0.196$	N(01010)=2 $P_{01010}=0.018$
	Multi-factor	N(11100)=0 $P_{11100}=0$	N(11010)=4 $P_{11010}=0.037$	N(11001)=0 $P_{11001}=0$	N(10110)=2 $P_{10110}=0.018$	N(10101)=0 $P_{10101}=0$
		N(01110)=0 $P_{01110}=0$	N(01101)=0 $P_{01101}=0$	N(01011)=0 $P_{01011}=0$	N(00111)=1 $P_{00111}=0.009$	N(11110)=0 $P_{11110}=0$
		N(11011)=0 $P_{11011}=0$	N(10111)=1 $P_{10111}=0.009$	N(01111)=0 $P_{01111}=0$	N(11111)=0 $P_{11111}=0$	N(10011)=7 $P_{10011}=0.065$
degree of adaptation	Single Factor	N(10000)=12 $P_{10000}=0.112$	N(01000)=1 $P_{01000}=0.009$	N(00100)=2 $P_{00100}=0.018$	N(00010)=9 $P_{00010}=0.084$	N(00001)=9 $P_{00001}=0.084$
	Two-factor	N(11000)=0 $P_{11000}=0$	N(10100)=1 $P_{10100}=0.009$	N(10010)=19 $P_{10010}=0.177$	N(10001)=8 $P_{10001}=0.074$	N(01100)=0 $P_{01100}=0$
		N(01001)=0 $P_{01001}=0$	N(00110)=4 $P_{00110}=0.037$	N(00101)=2 $P_{00101}=0.018$	N(00011)=21 $P_{00011}=0.196$	N(01010)=2 $P_{01010}=0.018$
	Multi-factor	N(11100)=0 $P_{11100}=0$	N(11010)=2 $P_{11010}=0.018$	N(11001)=0 $P_{11001}=0$	N(10110)=0 $P_{10110}=0$	N(10101)=3 $P_{10101}=0.028$

	N(01110)=0	N(01101)=0	N(01011)=0	N(00111)=5	N(11110)=0
	$P_{01110}=0$	$P_{01101}=0$	$P_{01011}=0$	$P_{00111}=0.046$	$P_{11110}=0$
	N(11011)=0	N(10111)=0	N(01111)=0	N(11111)=0	N(10011)=7
	$P_{11011}=0$	$P_{10111}=0$	$P_{01111}=0$	$P_{11111}=0$	$P_{10011}=0.065$

4.2 Calculation of coupling degree of vulnerability factors

Before calculating the coupling degree, the coupling probability of each factor should be calculated first. For example, the single-factor coupling probability in the exposure degree is $P_{1....}=P_{10000}+P_{11000}+P_{10100}+P_{10010}+\cdots\ P_{11111}$=0.087; the two-factor coupling probability in the exposure degree is $P_{11...}=P_{11000}+P_{11100}+P_{11010}+\cdots P_{11111}$=0.056; similarly, we can obtain the single, two-factor and multi-factor coupling probability of the exposure degree, sensitivity, adaptation and vulnerability factors. Due to space constraints, this article will not show it in detail, as shown in Table 3.

Table 3. Exposure factor coupling probabilities (partial)

Type of coupling	Probability of coupling						
Single Factor	$P_{0....}=0.041$	$P_{1....}=0.588$	$P_{.0...}=0.906$	$P_{.1...}=0.093$	$P_{..0..}=0.429$	$P_{..1..}=0.570$	$P_{...0.}=0.383$
	$P_{...1.}=0.617$	$P_{....0}=0.542$	$P_{....1}=0.458$	—	—	—	—
Two-factor	$P_{11...}=0.056$	$P_{10...}=0.533$	$P_{01...}=0.037$	$P_{00...}=0.374$	$P_{1.1..}=0.280$	$P_{1.0..}=0.308$	$P_{0.1..}=0.290$
	$P_{0.0..}=0.121$	$P_{1..1.}=0.383$	$P_{1..0.}=0.205$	$P_{0..1.}=0.233$	$P_{0..0.}=0.177$	$P_{1...1}=0.242$	$P_{1...0}=0.345$
	$P_{0...1}=0.214$	$P_{0...0}=0.196$	$P_{.11..}=0.009$	$P_{.10..}=0.084$	$P_{.01..}=0.561$	$P_{.00..}=0.346$	$P_{.1.1.}=0.065$
	$P_{.1.0.}=0.028$	$P_{.0.1.}=0.551$	$P_{.0.0.}=0.355$	$P_{.1..1}=0.028$	$P_{.1..0}=0.065$	$P_{.0..1}=0.430$	$P_{.0..0}=0.477$
	$P_{..11.}=0.280$	$P_{..10.}=0.290$	$P_{..01.}=0.336$	$P_{..00.}=0.093$	$P_{..1.1}=0.318$	$P_{..1.0}=0.252$	$P_{..0.1}=0.140$
	$P_{..0.0}=0.290$	$P_{...11}=0.252$	$P_{...11}=0.364$	$P_{...11}=0.205$	$P_{...11}=0.178$	$P_{111..}=0$	$P_{110..}=0.056$
Multi-factor	$P_{101..}=0.280$	$P_{100..}=0.252$	$P_{011..}=0.009$	$P_{010..}=0.028$	$P_{001..}=0.280$	$P_{000..}=0.093$	$P_{11.1.}=0.056$
	$P_{11.0.}=0$	$P_{10.1.}=0.327$	$P_{10.0.}=0.065$	$P_{01.1.}=0.009$	$P_{01.0.}=0.028$	$P_{00.1.}=0.224$	$P_{00.0.}=0.149$
	$P_{11..1}=0.009$	$P_{11..0}=0.047$	$P_{10..1}=0.233$	$P_{10..0}=0.299$	$P_{01..1}=0.019$	$P_{01..0}=0.018$	$P_{00..1}=0.196$
	$P_{00..0}=0.177$	$P_{1.11.}=0.140$	$P_{1.10.}=0.140$	$P_{1.01.}=0.243$	$P_{1.00.}=0.065$	$P_{0.11.}=0.140$	$P_{0.10.}=0.149$
	$P_{0.01.}=0.093$	$P_{0.00.}=0.028$	$P_{1.1.1}=0.140$	$P_{1.1.0}=0.140$	$P_{1.0.1}=0.103$	$P_{1.0.0}=0.205$	$P_{0.1.1}=0.177$
	$P_{0.1.0}=0.112$	$P_{0.0.1}=0.037$	$P_{0.0.0}=0.084$	$P_{1..11}=0.149$	$P_{1..10}=0.233$	$P_{1..01}=0.093$	$P_{1..00}=0.112$
	$P_{0..11}=0.103$	$P_{0..10}=0.131$	$P_{0..01}=0.112$	$P_{0..00}=0.065$	$P_{.111.}=0$	$P_{.110.}=0.009$	$\cdots$..

4.3 Analysis of calculation results

According to the calculation of equation (1) to (4), the underground deep foundation pit construction system exposure, sensitivity, adaptability factor coupling value and ranking can be determined, as shown in Table 4. Due to space limitations, only the exposure coupling value ordering is shown

Table 4. Coupling values and ranking of exposure factors

coupling values	sorting	coupling values	sorting	coupling values	sorting
$T_2^1(a,b)=0.0003$	25	…	…	$T_4^1(a,b,c,d)=0.2430$	2
$T_2^2(a,c)=0.0382$	16	$T_3^5(a,c,e)=0.0053$	23	$T_4^2(a,b,c,e)=0.1793$	5
$T_2^3(a,d)=0.0053$	24	$T_3^6(a,d,e)=0.0264$	17	$T_4^3(a,b,d,e)=0.1076$	9
$T_2^4(a,e)=0.0088$	21	$T_3^7(b,c,d)=0.1478$	6	$T_4^4(a,c,d,e)=0.2089$	4
$T_2^5(b,c)=0.0728$	12	$T_3^8(b,c,e)=0.1237$	7	$T_4^5(b,c,d,e)=0.2134$	3
$T_2^6(b,d)=0.0025$	25	$T_3^9(b,d,e)=0.0211$	19	$T_5^1(a,b,c,d,e)=0.3618$	1
$T_2^7(b,e)=0.0081$	22	$T_3^{10}(c,d,e)=0.0616$	14	—	—

1) By the degree of exposure to the coupling value of the factors can be seen: five factors at the same time when the coupling value is the largest, at this time it is very easy to cause safety accidents; four factors, the human-machine-environmental-pipe coupling value is the largest, through the control of the occurrence of any of these factors can effectively reduce the degree of exposure of the system; three factors, the machine-environmental-pipe coupling value is the largest, the insecure state of the equipment, the complexity of the environment and the management of the lack of the system in place; two-factor coupling, machine-environmental coupling value is the largest, therefore, site staff should be detailed surveys and records before construction, according to different geological and hydrological conditions of scientific selection of external environment The exposure of the system will increase; two-factor coupling, machine-ring coupling value is the largest, therefore, the site staff should be in the construction of the external environment before the detailed investigation and records, according to different geological and hydrological conditions of scientific selection of machinery to meet the requirements of the construction.

2) By the sensitivity of the coupling value of the factors can be seen: five-factor coupling coupling value is the largest, the system's sensitivity is the highest; four factors, the human - ring - pipe - technology coupling value is the largest; three factors, the human - machine - technology coupling value is the largest, indicating that the personnel of equipment and other things such as high and low level of safety awareness to a certain extent affects the operating behaviour, making the system sensitivity increased; two factors, the human - technology coupling value is the largest. , so in the construction process, should focus on a series of accident hidden dangers due to personnel earth over-excavation, pit support is not in place, and poor precipitation and drainage measures. For example, in the pit excavation, it should be confirmed that the support concrete strength reaches the standard after taking the principle of excavation in layers and segments, so that the excavation of the deep pit should be matched with the support system to make the overall structure tends to be stable, if due to the earth over-excavation leads to the destruction of the pit support system, it should suspend the construction, and prevent the further destruction through the reinforcement or backfilling of the earth; after the excavation of the pit, it should be set up in time to drain the ditch and the collection of water wells, to prevent After excavation of the pit, drainage ditches and water collection wells should be set up in time to prevent the foundation bearing capacity from deteriorating due to water immersion in the pit, and to cause

gushing water and sand under the action of dynamic water pressure, slope instability and other phenomena.

3) It can be seen from the order of the coupling value of the adaptability factors; the coupling value is the largest when five factors occur at the same time, and the adaptability of the system is the lowest; among the four factors, the coupling value is the largest when human-environmental-pipe-technological coupling; among the three factors, the coupling value of human-environmental-technological coupling is the largest, which indicates that the personnel's ability to deal with the emergency when the accident occurs as well as the protective measures taken on the site are very important for the enhancement of the adaptability of the system; among the human-technological two-factor coupling, the system has the lowest adaptability and the fragility is relatively higher. When human-technology double factors are coupled, the system has the lowest adaptability and the relative vulnerability is greater. Therefore, for the dangerous factors that may occur in the process of deep foundation pit construction, firstly, the corresponding emergency plan should be formulated and perfected; secondly, based on the complexity of the construction site operation, the technology combining dynamic monitoring and information-based construction should be adopted, and the key construction parts and conditions should be monitored by instrumentation and on-site inspection, so that the personnel of all parties can be notified in time to take countermeasures once the monitoring value reaches the early-warning value.

5 Conclusion

Based on the 107 cases of underground deep foundation pit construction safety accidents collected in this paper, the following conclusions are drawn by constructing the N-K model based on the vulnerability theory:

(1) According to the coupling value of various types of risk factors and their ranking, it can be seen that: the degree of danger of underground deep foundation pit construction rises with the increase of vulnerability factors. Whether from the exposure, sensitivity, adaptability or the overall vulnerability of the system, it is in line with, indicating that the more vulnerability factors involved in the coupling in the construction process, the larger the coupling value, the higher the exposure, the higher the sensitivity, the lower the adaptability, and the higher the chances of the system vulnerability to be formed in turn.

(2) In summary, it can be seen that through the comparison of exposure, sensitivity and adaptability of the three stages of the coupling situation is slightly different, in order to reduce the vulnerability of the system, the need for a phased, targeted response to the weak links in the system, so that the underground deep foundation pit construction loss minimisation.

(3) The data collected in this paper come from incomplete statistics of relevant departments, and the results of the N-K model are easily affected by the quality of the sample, therefore, in future research should be selected from a variety of factors and increase the sample capacity to ensure that the results are more in line with the actual situation.

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