

Safety Assessment of Excavation with Fault Tree Analysis

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ABSTRACT: How to reduce the probability of failure during the excavation has caused an increasing concern in recent years in China. Fault tree analysis (FTA) is a systematic method of analyzing events that lead to the undesirable event and it may be a feasible way to analyze this probability. According to 342 actual excavation accidents presented in publications and reports in China, statistical analyses are reviewed based on different accident causes, different types of excavation supporting systems and different excavation depths and the frequency distributions are obtained. The fault trees of the soil nailing system and cement-soil retaining wall are established and the minimum cut sets are determined by qualitative analysis. A case study of safety assessment of soil nailing system for excavation with FTA is carried out as a validation.

1 INTRODUCTION

Excavation engineering is to provide a safe and sufficient space for the underground construction. In recent years, there has an increasing concern on the excavation because of its high frequency of accidents. Excavation accidents may cause huge losses both on underground structures and nearby structures. However, most excavation supporting systems are temporary structures. Their safety and importance are often ignored by owners (Bian and Huang 2006). Meanwhile, the soils and environmental conditions such as underground water conditions, adjacent structures and underground pipes and lines are complex. The cooperation and management in the excavation are very difficult because the construction of excavation supporting system, soil excavation, in-site monitoring and construction of the underground structures are usually done by different companies in China. As a result, many accidents have occurred during the excavations. So how to reduce the probability of failure during the excavation has become a very important task. Risk analysis theory may be a feasible way to analyze this probability. In recent years, probability risk analyses have been used for excavation supporting systems. The calculation of occurrence probability could provide corresponding measures and reduce the probability of failure (Goulielmos and Kostas 1997).

2 ACCIDENTS INVESTIGATION REVIEWED

Up till now, there are many types of excavation supporting systems, such as sheet pile supporting system including cantilever pile system, anchored pile system and strutted pile system, cement-soil retaining wall, soil nailing system, diaphragm wall, sloping and so on. Each excavation supporting system has its advantages and disadvantages. According to 342 actual excavation accident investigations in China (Bian 2006), accident frequencies of different excavation supporting systems are obtained, as shown in Fig.1 and Table 1. According to Fig.1, sheet pile supporting system (including cantilever pile, strutted pile and anchored pile system) is the most frequently used system

but the failure frequency is also highest, with a frequency 0.637. Coming next is soil nailing system with a failure frequency 0.105, then cement-soil retaining wall with a failure frequency 0.099. We should point out that the supporting system with a low failure frequency may not be the best system because its frequency of being used is also low. Meanwhile, the supporting system frequently used may not be the best system because its failure frequency is also high. In practical engineering, which is the best supporting system is determined by the actual conditions, such as soil properties, underground water conditions, excavation depth and deformation restrain criterion.

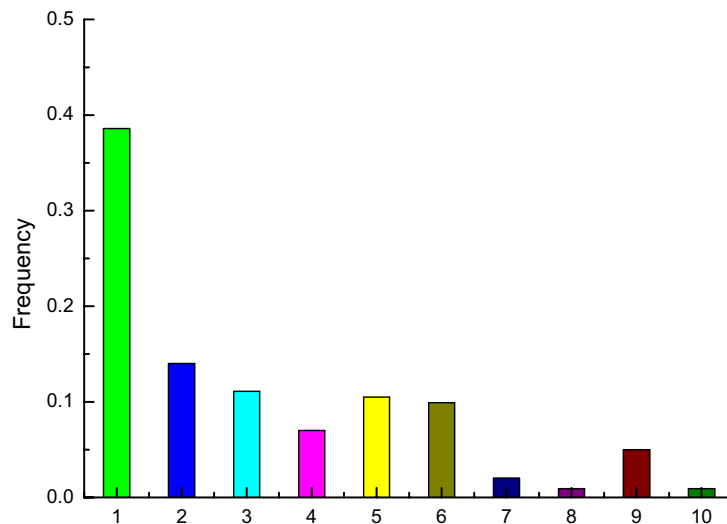


Fig.1 The accident frequencies of various excavation supporting systems

Table 1 Excavation supporting systems 1~10 and their frequencies

Supporting system	Quantity	Frequency	Supporting system	Quantity	Frequency
1-cantilever pile	132	0.386	6-cement-soil retaining wall	34	0.099
2- strutted pile	48	0.140	7-composite soil nailing system	7	0.020
3- anchored pile	38	0.111	8-caisson	3	0.009
4-diaphragm wall	24	0.070	9-sloping	17	0.050
5-Soil nailing system	36	0.105	10-others	3	0.009

Based on the statistical data, the causes of the accidents can be classified into 6 types, including investigation error, design error, construction error, monitoring error, supervisor error and owner error, as shown in Fig.2. Many accidents are caused by several causes. So the total number of the causes of 342 accidents is 530. Accidents caused by construction error is 270, 50.9% of the total. Accidents caused by design error is 180, 34.3% of the total. Construction error and design error are the most frequent causes of excavation accidents, together 84.2% of the total.

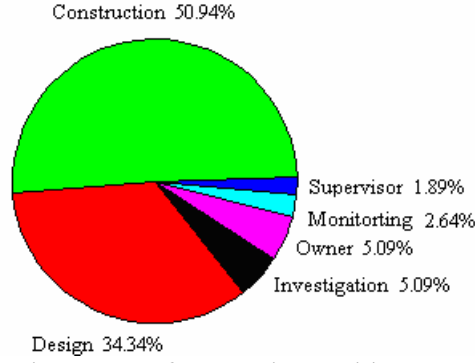


Fig.2 The causes of excavation accidents

282 in 342 accidents, except 60 accidents without excavation depth records, are also analyzed by the excavation depth h with 4 grades: $h \leq 6$ m, $6 \text{ m} < h \leq 10$ m, $10 \text{ m} < h \leq 14$ m, $h > 14$ m. The accident frequencies of different excavation is shown in Fig.3. According to Fig.3, 6~10 m is the depth region at which accidents are most frequently happened.

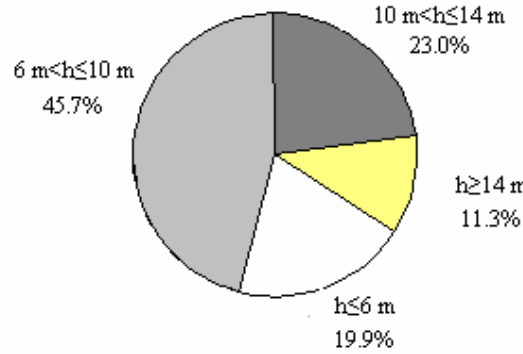


Fig.3 The accident frequencies of different excavation depth

3 FAULT TREE ANALYSIS THEORY

Fault tree analysis is a systematic method of analyzing events that lead to the undesirable event (top event). Fault trees can be used to assess the probability of failure of a system (or top event), to compare design alternatives, to identify critical events that will significantly contribute to the occurrence of the top event, and to determine the sensitivity of the probability of failure of the top event to various contributions of basic events (Johnson 1999). The process of applying FTA is shown in Fig.4. A fault tree is established by many basic events which are not needed to decompose anymore (Richard et al. 1975). A minimum cut set is a combination of the basic events that is sufficient to cause an occurrence of the top events (Sundararajan 1991; Ayyub and McCuen 1997). The minimum cut sets of the fault tree can be obtained by logical analysis, which is usually based on Boolean algebra. Each minimum cut set corresponds to a failure mode or a failure path. The occurrence probabilities of the minimum cut sets can be calculated when the occurrence probabilities of all the basic events, which are usually based on statistical data or experts' experience, are determined. Then the failure probability of the top event, F_s , can be back calculated based on the occurrence probabilities of the minimum cut sets as follows:

$$\begin{aligned}
 F_s = P(T) &= P(K_1 + K_2 + \dots + K_k) \\
 &= \sum_{i=1}^k P(K_i) - \sum_{i < j=2}^k P(K_i K_j) + \sum_{i < j < l=3}^k P(K_i K_j K_l) + \dots + (-1)^{k-1} P(K_1 K_2 \dots K_k)
 \end{aligned} \quad (1)$$

Where K_i is the occurrence probability of the i th minimum cut set.

Meanwhile, the importance of each basic event can also be calculated. Then, the dangerous events

can be identified. The importance of the i th basic event, $I_g(i)$, can be calculated as follows:

$$I_g(i) = \frac{\partial F_s}{\partial F_i} \cdot \frac{F_i}{F_s} \quad (2)$$

Where F_i is the occurrence probability of the i th basic event.

The larger the $I_g(i)$ is, the more dangerous the i th basic event is. The failure probability can be reduced after the dangerous events have been controlled or prevented by corresponding measures.

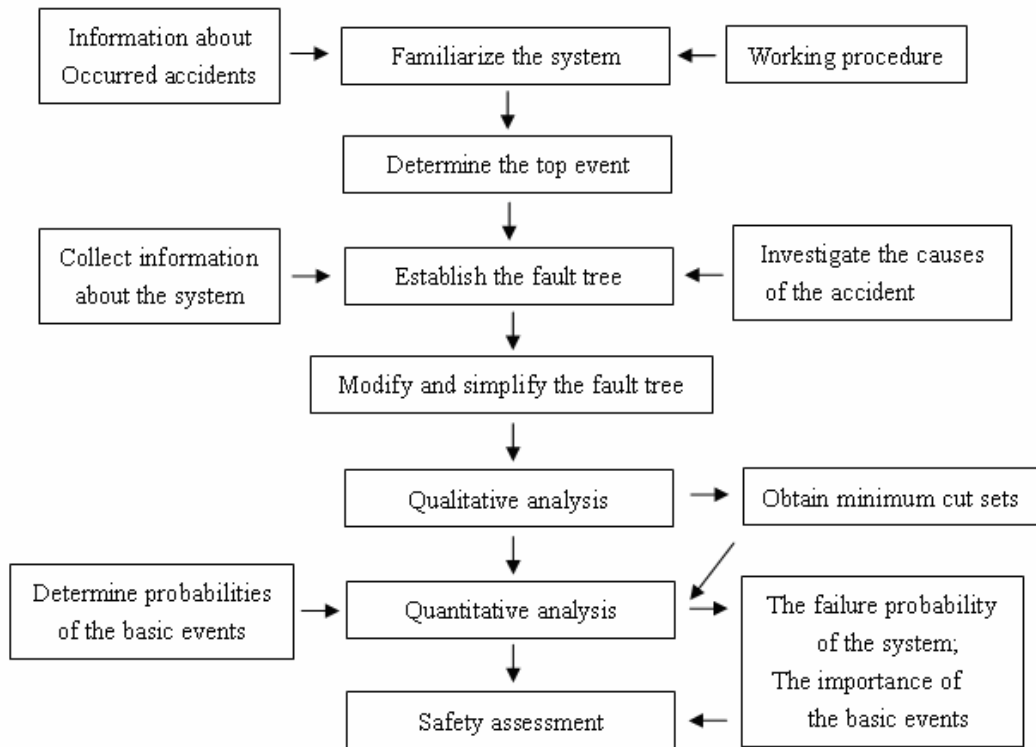


Fig.4 The process of applying FTA

4 SAFETY ASSESSMENT OF SOIL NAILING SYSTEM AND CEMENT-SOIL RETAINING WALL WITH FTA

The details about the fault tree diagramming can be found in Ang and Tang (1984), Lee et al. (1985), and Ayyub and McCuen (1997). Fault tree analysis is to find out all the possible failure modes of the system and the dangerous events. So, an analyst must be familiar with the excavation including past accidents, design theories, construction processes, working conditions and environmental impacting factors. The fault trees of soil nailing system and cement-soil retaining wall for excavation are shown in Fig.5 and Fig.6, respectively. The meanings of the symbols in Fig.5 and Fig.6 are indicated in Table 2 and Table 3, respectively.

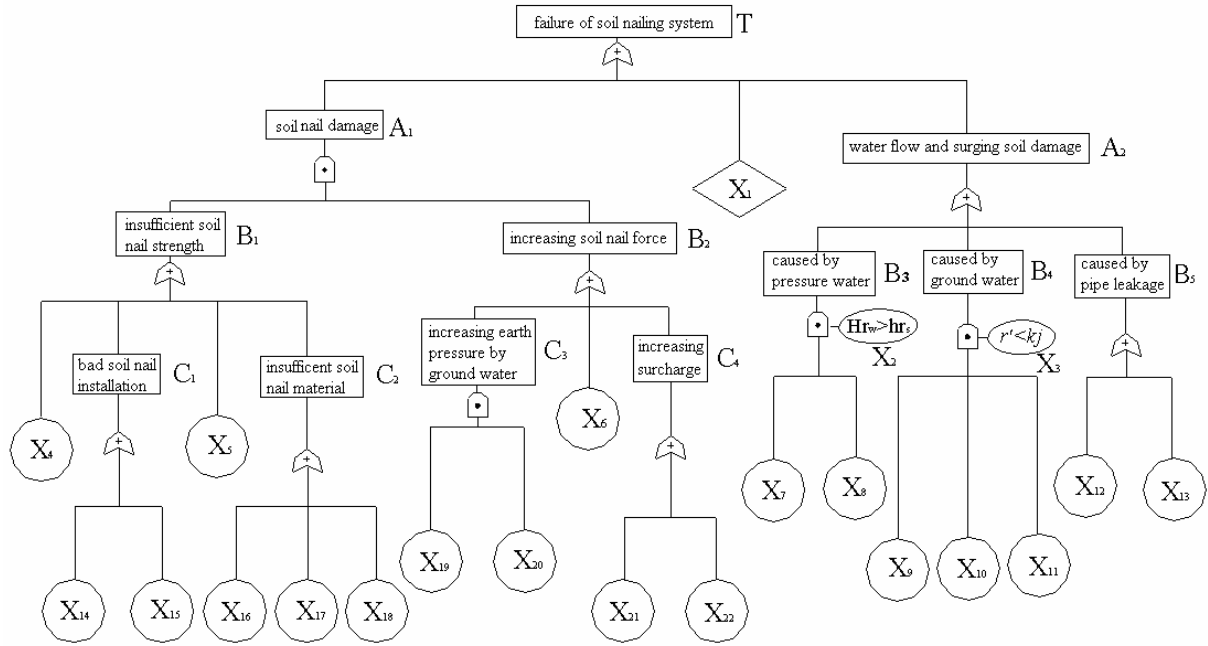


Fig.5 The fault tree of soil nailing system

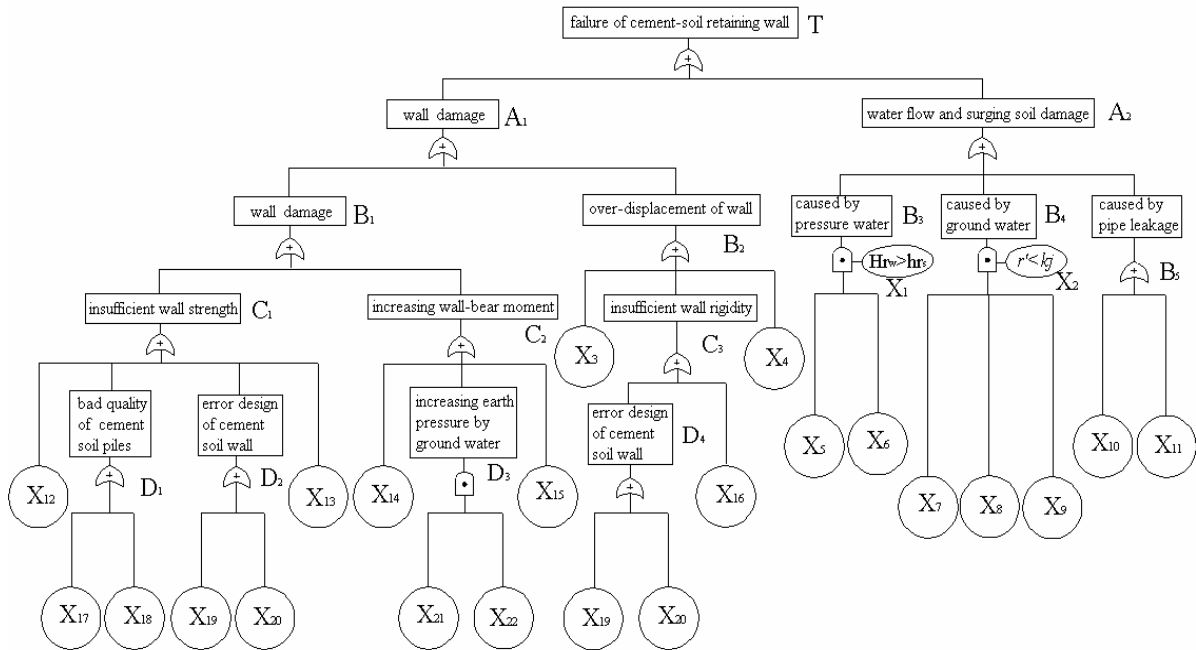


Fig.6 The fault tree of cement-soil retaining wall

Table 2 The symbol meanings in Figure 5 and the probabilities of the basic events in case study

Symbol	Meaning	Prob.	Symbol	Meaning	Prob.
X_1	Reinforced facing damage	0.01	X_{12}	Pipe leakage before excavation	0.01
X_2	$Hr_w > hr_s$	0.01	X_{13}	Pipe leakage caused by excavation	0.50
X_3	$r' < kj$	0.30	X_{14}	Insufficient strength of the joint of the soil nail and the concrete surface	0.01

X_4	Error design of soil nail strength	0.01	X_{15}	Insufficient grouting pressure or grouting depth	0.01
X_5	Insufficient anchor-holding force caused by leakage	0.30	X_{16}	Bad material quality of the soil nail	0.01
X_6	Over excavation	0.30	X_{17}	Insufficient length of the soil nail	0.01
X_7	High pressure head	0.01	X_{18}	Over space interval of the soil nail	0.01
X_8	Bad sealing	0.01	X_{19}	Bad drainage or water prevention	0.20
X_9	High static water head	0.01	X_{20}	Rain fall or pipe leakage	0.60
X_{10}	Sand clay located in pit	0.30	X_{21}	Error design of static load	0.01
X_{11}	Bad quality of sealing or water prevention	0.10	X_{22}	Surcharge or dynamic force	0.50

Table 3 The symbol meanings in Figure 6

Symbol	Meaning	Symbol	Meaning
X_1	$Hr_w > hr_s$	X_{12}	Insufficient cement quality
X_2	$r' < kj$	X_{13}	Too early excavation
X_3	Insufficient resistance of passive soil	X_{14}	Improper excavation
X_4	Over excavation	X_{15}	Surcharge or dynamic force
X_5	High pressure head	X_{16}	Bad quality of ring beam
X_6	Bad sealing	X_{17}	Bad verticality of piles
X_7	High static water head	X_{18}	Insufficient overlapping width between piles
X_8	Sand clay located in pit	X_{19}	Insufficient wall width
X_9	Bad quality of cemented soil piles	X_{20}	Insufficient inserting depth
X_{10}	Pipe leakage before excavation	X_{21}	Improper drainage
X_{11}	Pipe leakage caused by excavation	X_{22}	Rain fall or pipe leakage

The minimum cut sets of the fault tree in Figure 5 are easily obtained based on Boolean algebra as follows:

$$\begin{aligned}
T &= A_1 + X_1 + A_2 = B_1 + B_2 + X_1 + (B_3 + B_4 + B_5) \\
&= (X_4 + C_1 + X_5 + C_2) + (C_3 + X_6 + C_4) + X_1 + X_2 X_7 X_8 + X_3 X_9 X_{10} X_{11} + (X_{12} + X_{13}) \\
&= X_4 + X_{14} + X_{15} + X_5 + X_{16} + X_{17} + X_{18} + X_{19} X_{20} + X_6 + X_{21} + X_{22} + X_1 + X_2 X_7 X_8 + X_3 X_9 X_{10} X_{11} + X_{12} + X_{13}
\end{aligned} \tag{3}$$

So, the fault tree of the soil nailing system has 16 minimum cut sets, which are $\{X_4\}$, $\{X_{14}\}$, $\{X_{15}\}$, $\{X_5\}$, $\{X_{16}\}$, $\{X_{17}\}$, $\{X_{18}\}$, $\{X_{19}, X_{20}\}$, $\{X_6\}$, $\{X_{21}\}$, $\{X_{22}\}$, $\{X_1\}$, $\{X_2, X_7, X_8\}$, $\{X_3, X_9, X_{10}, X_{11}\}$, $\{X_{12}\}$, $\{X_{13}\}$. They indicate 16 failure modes. The soil nailing system would fail when any of 16 minimum cut sets occurs. The occurrence of a minimum cut set means the basic events of the minimum cut set occur simultaneously. For example, the minimum cut set $\{X_{19}, X_{20}\}$ occurs only when the basic events $\{X_{19}\}$ and $\{X_{20}\}$ occur simultaneously and the occurrence probability of the minimum cut set $\{X_{19}, X_{20}\}$ depends on the probabilities multiplication of the basic events $\{X_{19}\}$ and $\{X_{20}\}$.

The minimum cut sets of the fault tree in Fig.6 can also be obtained as follows:

$$\begin{aligned}
T &= A_1 + A_2 = (B_1 + B_2) + (B_3 + B_4 + B_5) = (C_1 + C_2) + (X_3 + C_3 + X_4) + (X_1 X_5 X_6) + (X_2 X_7 X_8 X_9) + (X_{10} + X_{11}) \\
&= (X_{12} + D_1 + D_2 + X_{13}) + (X_{14} + D_3 + X_{15}) + X_3 + (D_4 + X_{16}) + X_4 + X_1 X_5 X_6 + X_2 X_7 X_8 X_9 + X_{10} + X_{11} \\
&= X_{12} + X_{17} + X_{18} + X_{19} + X_{20} + X_{13} + X_{14} + X_{21} X_{22} + X_{15} + X_3 + X_{16} + X_4 + X_1 X_5 X_6 + X_2 X_7 X_8 X_9 + X_{10} + X_{11}
\end{aligned} \tag{4}$$

So, the fault tree of the cement-soil retaining wall also has 16 minimum cut sets, which are $\{X_{12}\}$, $\{X_{17}\}$, $\{X_{18}\}$, $\{X_{19}\}$, $\{X_{20}\}$, $\{X_{13}\}$, $\{X_{14}\}$, $\{X_{21}, X_{22}\}$, $\{X_{15}\}$, $\{X_3\}$, $\{X_{16}\}$, $\{X_4\}$, $\{X_1, X_5, X_6\}$, $\{X_2, X_7, X_8, X_9\}$, $\{X_{10}\}$, $\{X_{11}\}$.

5 CASE STUDY

In order to verify the feasibility of FTA for safety assessment of the excavation supporting system, a case study of soil nailing system is carried out. Fig.7 shows the schematic plane view of the excavation. The depth of the excavation is 11.5 m. The length and the width of the excavation are 70 m and 55 m, respectively. South of the excavation is a main road with a 6 m wide pavement. North of

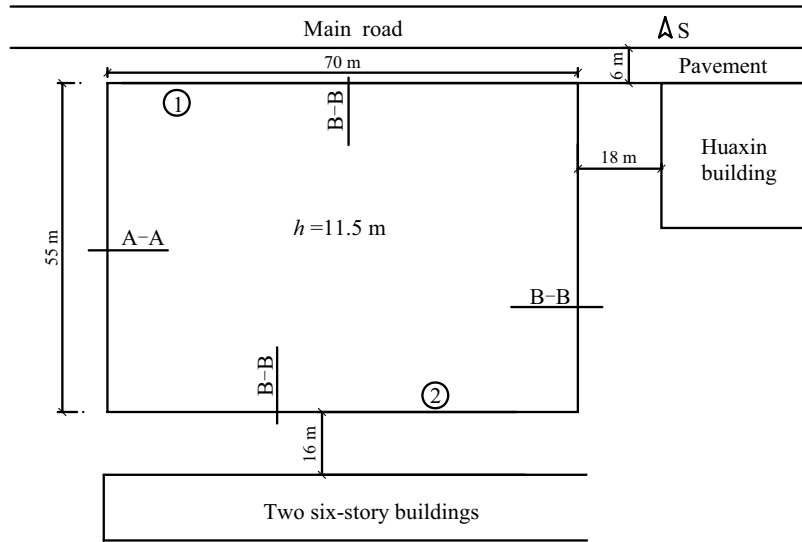


Fig.7 The schematic plane view of the excavation

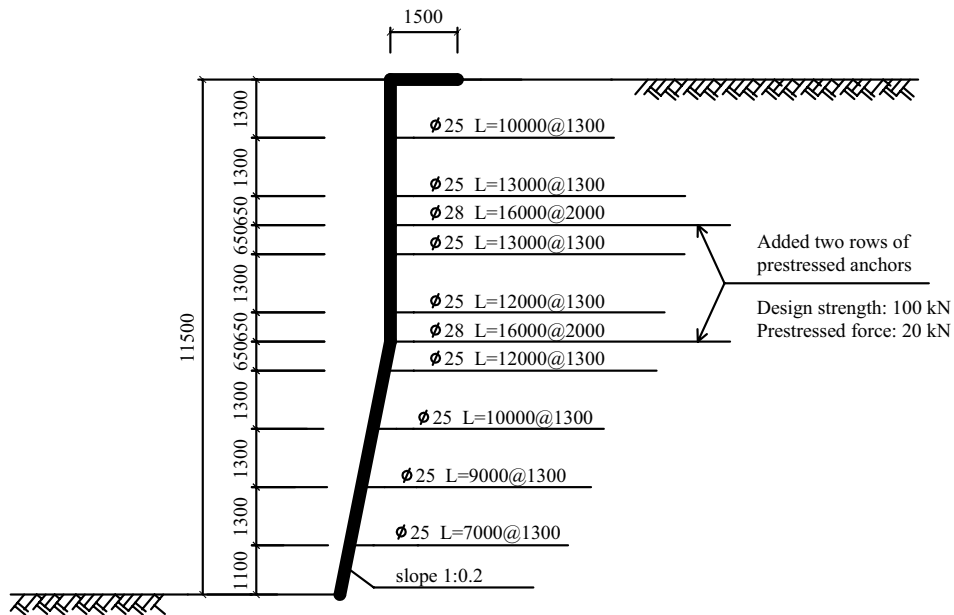


Fig.8 The B-B cross section of the soil nailing system

the excavation is two 6-story buildings with a distance of 16 m. West of the excavation is Huaxin Building with a distance of 18 m. The deformations at the points ① and ② in Fig.7 are monitored. Fig.8 is the B-B cross section of the soil nailing supporting system. The global factor of safety is 1.60. The depth and the width of each excavation step are about 1.3 m and 10 m, respectively. There is no measure for lowering the underground water except several drainage holes because the underground water table is low. Meanwhile, there is no investigation about the details of the pipes around the excavation, such as types, depths and directions.

According to the details mentioned above, the probabilities of the basic events $X_1 \sim X_{22}$ are determined by experts' experience, as shown in Table 1. Then probabilities of the minimum cut sets can be calculated, as shown in Table 4. The failure probability of the soil nailing system is calculated to be 0.9015 based on the Eq. (1). Table 5 shows the importance of the basic events.

Table 4 The probabilities of the minimum cut sets in case study

Minimum cut set	Probability	Minimum cut set	Probability
X_4	0.01	X_6	0.30
X_{14}	0.01	X_{21}	0.01
X_{15}	0.01	X_{22}	0.50
X_5	0.30	X_1	0.01
X_{16}	0.01	X_2, X_7, X_8	1.0e-6
X_{17}	0.01	X_3, X_9, X_{10}, X_{11}	9.0e-5
X_{18}	0.01	X_{12}	0.01
X_{19}, X_{20}	0.12	X_{13}	0.50

Table 5 The importance of the basic events in case study

symbol	$Ig(i)$	order	symbol	$Ig(i)$	order
X_1	1.103e-003	4	X_{12}	1.103e-003	4
X_2	1.092e-007	6	X_{13}	1.092e-001	1
X_3	9.831e-006	5	X_{14}	1.103e-003	4
X_4	1.103e-003	4	X_{15}	1.103e-003	4
X_5	4.681e-002	2	X_{16}	1.103e-003	4
X_6	4.681e-002	2	X_{17}	1.103e-003	4
X_7	1.092e-007	6	X_{18}	1.103e-003	4
X_8	1.092e-007	6	X_{19}	1.489e-002	3
X_9	9.831e-006	5	X_{20}	1.489e-002	3
X_{10}	9.831e-006	5	X_{21}	1.103e-003	4
X_{11}	9.831e-006	5	X_{22}	1.092e-001	1

Table 6 The corresponding measures to reduce the failure probability

Basic event	Corresponding measures
X_{13}	Add anchors to prevent the over deformation of the soil
X_{22}	Control the surcharge or the vehicles near the excavation
X_6	Avoid over excavation or backfill immediately when over excavation
X_5, X_{20}	Investigate the pipes and lines around the excavation and enhance the deformation monitoring during the excavation
X_{19}	Add drainage holes

According to the calculated $Ig(i)$, the most dangerous basic events are X_{13} (Pipe leakage caused by

excavation) and X_{22} (Surcharge or dynamic force), followed by X_5 (Insufficient anchor-holding force caused by water leakage) and X_6 (over excavation), then X_{19} (bad drainage or water prevention) and X_{20} (rain fall or pipe leakage). Because a minimum cut set corresponds to a failure mode of the fault tree, $\{X_{13}\}$, $\{X_{22}\}$, $\{X_5\}$, $\{X_6\}$ and $\{X_{19}, X_{20}\}$ which have the largest failure probabilities in Table 4 are the most dangerous failure causes, reasonably consistent with the importance of the basic events. So, we could take corresponding measures, such as shown in Table 6, to control these basic events to reduce the failure probability of the soil nailing supporting system.

For clarity, it should be mentioned that the importance of basic event not only depends on the probability of the basic event but also depends on its logical relationship with other basic events. For example, the occurrence probability of $\{X_{20}\}$ (0.60) is much higher than that of $\{X_6\}$ (0.30), but the importance of the former ($1.489\text{e-}02$) is smaller than that of the later ($4.681\text{e-}02$). Hence, establishing the fault tree and determining the probabilities of the basic events, both are very important for the safety assessment of excavation supporting system with FTA. The reliability of the assessment is based on their correctness.

The installation of the top three rows of the soil nail was successful at the B-B section. The excavation encountered a weak layer at the depth of 5 m. The designer required the excavation should be stopped before the reinforcement measures were implemented. But, the excavation went on without reinforcement and the depth and the width of this excavation step were 2.5 m and 28 m, respectively, not the designed 1.3 m and 10 m. Furthermore, the excavation was vertical rather than the designed slope 1:0.2. The in-site monitoring indicated that the deformation of the slope increased violently. Hence, the designer required to add two rows of 16 m long prestressed anchors to restrain the deformation. However, the reinforcement had not been carried out even half month later due to various reasons. Meanwhile, water began to flow out of the drainage holes and became clean with a constant quantity after several days. It indicated that the pipes were broken due to over deformation of the soils. At the same time, many heavy loaded trucks past the pavement when the main road was mending. As a result of above dangerous factors, the failure of the excavation happened at the B-B section near the pavement. The length and the width of the failure were 40 m and 17 m, respectively. The maximum settlement was 3 m. It caused the main road being closed for more than 40 hours. The accident investigation showed that the accident was caused by pipe leakage, dynamic force near the excavation, bad drainage and water prevention, strongly consistent with the result of the fault tree analysis.

6 CONCLUSIONS

The aim of safety assessment of the supporting system for excavation with FTA is to identify the probable risk resources and take corresponding measures to reduce the failure probability of the excavation. It is valuable of FTA for the safety assessment of the supporting system for excavation because FTA could identify the potential dangerous events which will help us avoid unsafe designs and construction procedures and propose the most important items to be monitored in the construction field. On the other hand, FTA helps us find out the causes of the failure and avoid similar accidents in the future.

The case study shows that the causes of the excavation accident obtained by FTA are pipe leakage, dynamic force near the excavation, bad drainage and water prevention, which is rather strongly consistent with the accident investigation.

The most important and difficult task is to establish the fault tree and determine the probabilities of the basic events correctly. The reliability of the safety assessment of the excavation is based on their correctness. An analyst must be familiar with the excavation including past accidents, design theories, construction processes, working conditions and environmental impacting factors.

It needs to note that FTA is partially based on statistical data and expert's experience. So, it is very important to collection sufficient actual accident information to extend the basic events and improve the correctness of their probabilities.

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