Risk analysis on cutter head failure of shield in composite ground

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ABSTRACT: All kinds of accident examples and their potential reasons were analyzed and summarized for cutter head failure of shield in composite ground. In order to research the mechanism of failure risk mode on cutter head, cutters and other different cutting components in shield, Fault tree analysis (FTA) was applied in establishing an analytical model on cutter head failure risk. Firstly, potential failure risk modes and effect factors were all analyzed and calculated by set theory in a qualitative way. Then, relevant control measures were proposed to reduce the cutter head failure risk of shield. The paper results would give some useful references for cutter head design and construction in composite ground by shield in China.

1 INTRODUCTION

With the manufacture technique development of shield, the strata scope in which shield works is more and more wide. Shield technology is not only used in relatively uniformity or single ground, but also used in composite ground that concludes alternant soft and hard rock. During the advance process in composite ground, the accidents rate of cutter head is one half of the total shield risk accidents. The main form accidents are cutter abrasion, cutter disc abrasion, cutter disc distortion and so on (L. Guo 2006). These accidents made the advance rate and cutter head life largely depressed. According to statistics, in domestic compound EPB (earth pressure balance) shield construction, the failure of cutter abrasion came forth in engineering at differently degree (W. B. Zhu, S. J. Ju, etc. 2006). In the 23 cutter head accident cases of non-cutter failure, the frequency of cutter disc accident was highly 69.7% (cake 34.8%, cutter disc deformation 17.4%, cutter disc blocked 8.7%, cutter disc abrasion or rupture 8.7%); the frequencies of bearing mangle, muck mend system accident, falling across underground eye-winker were separately 21.7%, 4.4% and 4.4%. these engineering risk accidents also occurred in other countries (J. Zhao, Q.M. Gong, Z. Eisensten 2007). Therefore, it is very important to research the failure risk of shield cutter head in composite ground.

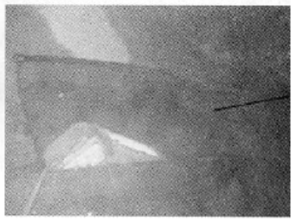
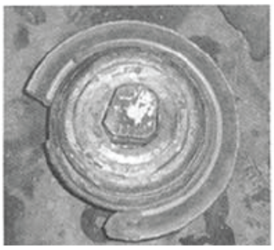
Adopting the FTA (Fault Tree Analysis) method, this paper would analysis the cutter head failure problem of shield in the composite ground, study its mechanism and influence factor, and evaluate the importance degree of every influence factor. Then the measures were put forward for reducing the occurrence of cutter head failure. The works of this paper could provide references for developing shield technology in composite ground.

2 THE ACTUALITY OF SHIELD CUTTER HEAD FAILURE IN COMPOSITE GROUND

There are three portions to be considered for shield cutter head failure that are cutter disc failure, cutter failure and other systems failure. The special engineering accidents cases are list in Table 1.

Table 1 the cases of cutter head failure

Failure name	Case examples	The description of case examples
Cutter	The section	Because of many times and seriously cake throughing

disc failure	between Haizhu square and Er-gong in Guangzhou subway No.2 line	river (Fig.for disc cutter to have already tore down), the average advanced rate per day was lack of 2m, and the cutting speed was only 0~0.5mm/min. 
	Xianfeng No.1 shield constructing at Shenzhen subway	From 497 to 498 ring, the advance distance was about 1.5m. Becauseof all the disc cutters in the scope from No.27~28 to No.36~38 damage, all of the bucket tool and its tool surpport, part of cutter disc were worn through seriously. 
Cutter failure	Some site of Shenzhen subway No.1 line	Because the weathering terrane and the total thrust couldn't provide the friction that made disc cutter rotation, disc cutters were not able to roll and flat wear. Advancing not enough 10m, it caused 25 disc cutters damage. 
	Chenglingji tunnel crossing Yangtze River	The damaged cutters in testing advance 300m included: 7 cutter rings rupture or falling off account for 77.8% of total amount, 1 flat wear account for 11.1%, 2 block rings and 1 axletreee damaged separatelyaccount for 22.2% and 11.1%. The Fig.showed the ruptured cutter ring. 
Other systems failure	Guangzhou subway No.1 line	The section between Front Park and the Martyr Cemetery, the big axletree was seriously damaged.
	Some site of Shenzhen subway No.1 line	Because the soil temperature inside the chamber was excessively high (achieving 100℃ at the centre of cutter head) that exceeded the highest temperature of cutter seal endured. So it leaded to axletree damage for the leakage of cutter lubricating oil, and also leaded to cutter ring flat-spotted or rupture.

3 FTA ANALYSIS OF THE CUTTER HEAD FAILURE RISK

3.1 Summarize of the FTA method

Fault Tree Analysis (FTA for short) is a method for evaluation complicated system reliability and failure (Richard E, Barlow, Jerry B, etc. 1975; D. H. Shi, S. R. Wang 1993; J. C. Jiang, Z. L. Guo 2004). Making use of FTA to carry on analysis, it can not only obtain the accident direct reasons, but also go deep into the accident latent occurrence mechanism and put forward the defending measures directly. Fig.1 shows the flowchart of FTA.

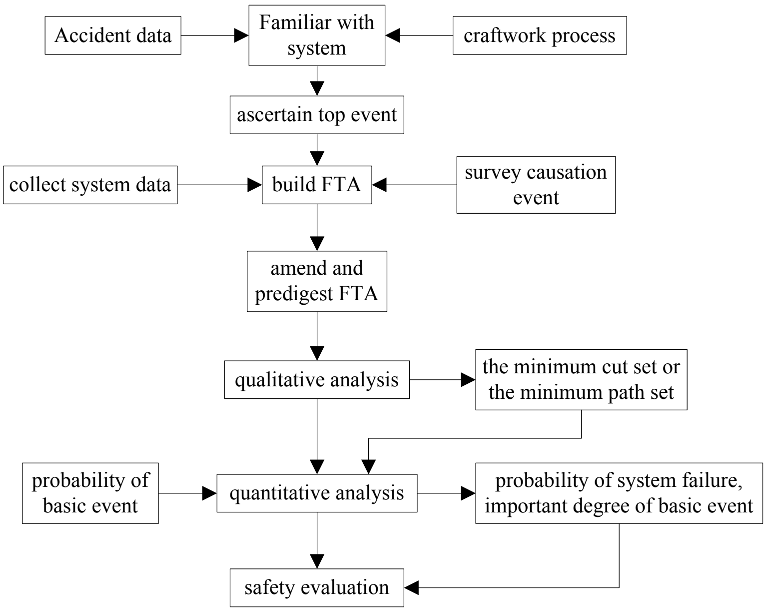


Fig.1 the Flowchart of FTA

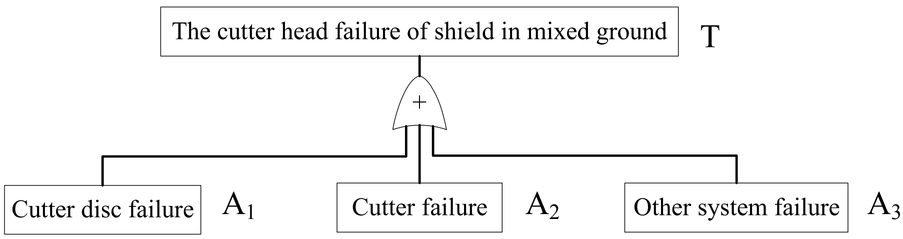
3.2 Fault tree model for the risk of shield cutter head failure

To investigate the failure risk of shield cutter head, some assumptions are made as follows:

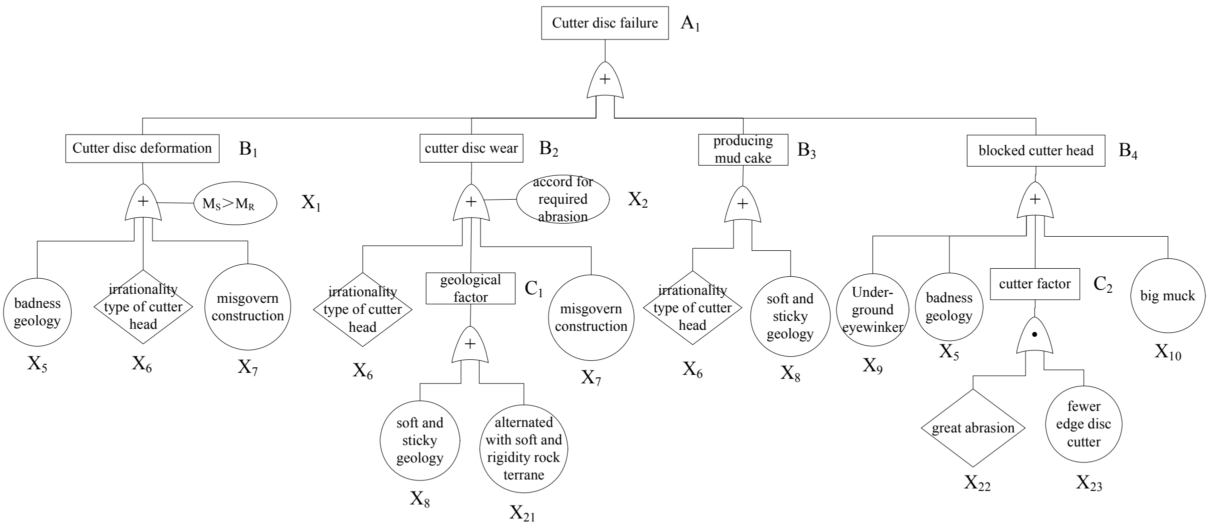
(1) It didn’t take account of the disadvantageous influence that the engineering construction brought to the surroundings building, road surface, underground pipeline etc.

(2) Drag bits and scrapers would often occur normal wear during the shield advance, so their abrasion was not considered.

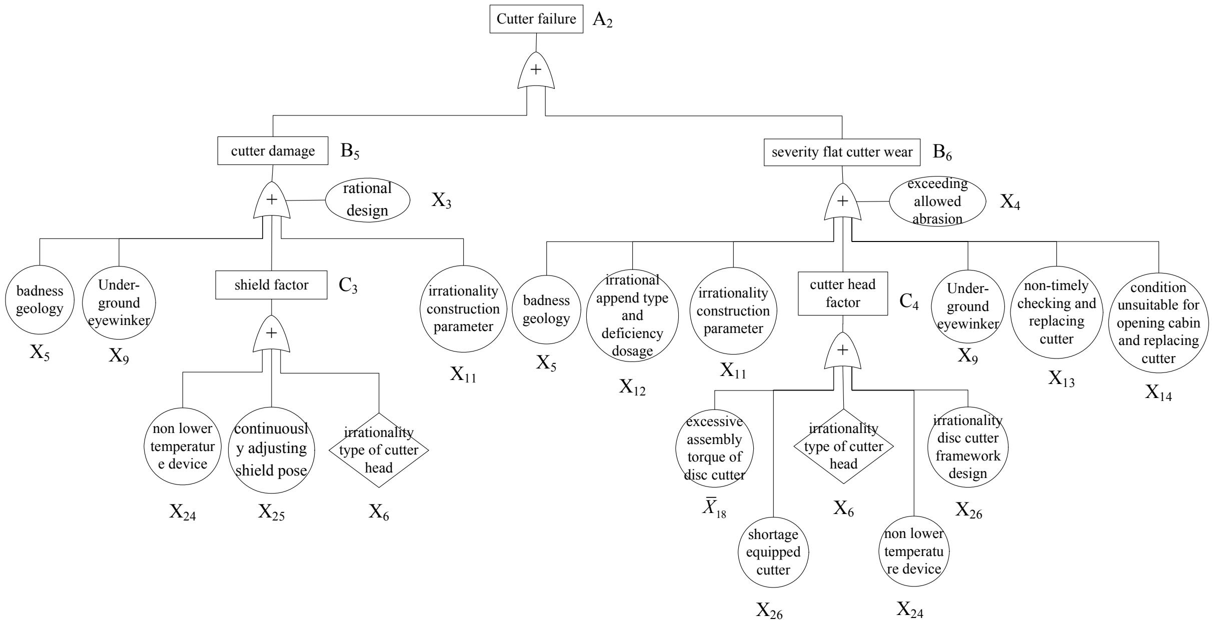
According to the above investigation accidents data, the failure risk model of shield cutter head in composite ground was set by means of the FTA method, shown in Fig.2.



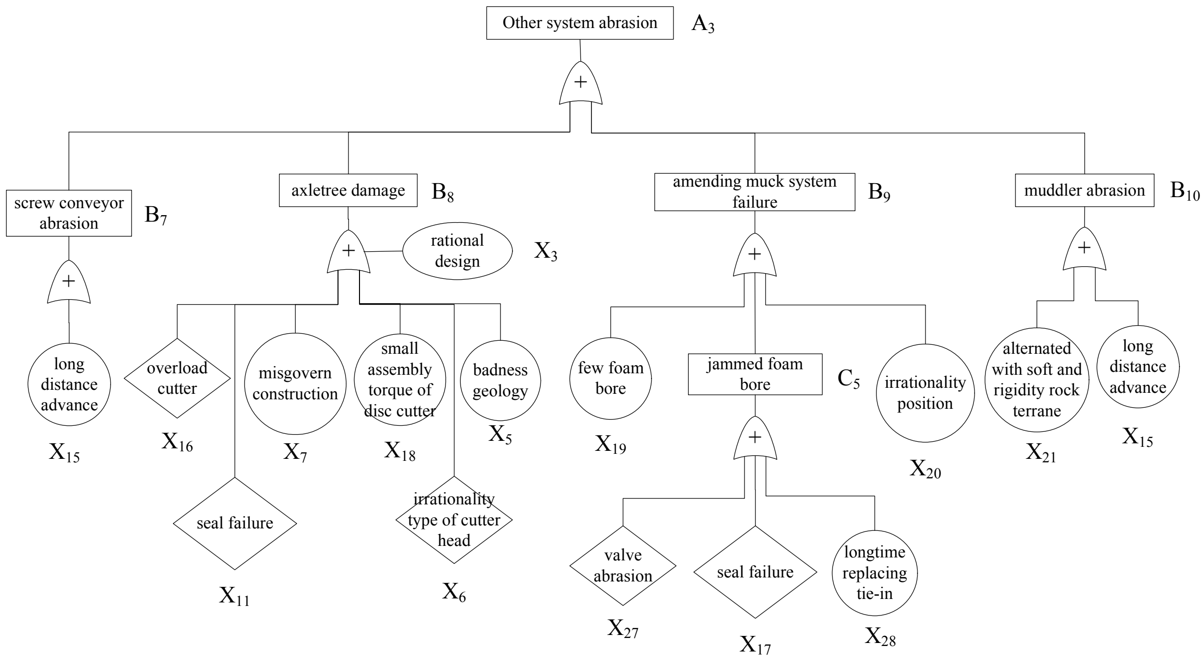
(A)



(B)



(C)



(D)

Fig.2 FTA Model for the Risk of Cutter Head Failure of Shield in Composite Ground

The systemic risk probability of cutter head is analyzed based on the established fault tree model. Firstly, the minimum basic event sets which cause the main event occurrence is solved, i.e. the minimum cut set of fault tree. Each minimum cut set corresponds to one accident type, and there are several minimum cut sets with different occurrence probability of one fault tree. The minimum cut set with the maximum occurrence probability is the most probably potential factor which may cause accident. According to Bull’s algorithm, the main event of risk accident during shield construction in composite ground is defined as:

$$
\begin{aligned}
T &= A_1 + A_2 + A_3 \\
&= (B_1 + B_2 + B_3 + B_4) + (B_5 + B_6) + (B_7 + B_8 + B_9 + B_{10}) \\
&= [X_1(X_5 + X_6 + X_7) + X_2(X_6 + C_1 + X_7) + (X_6 + X_8) + (X_9 + X_5 + C_2 + X_{10})] \\
&+ [X_3(X_5 + X_9 + C_3 + X_{11}) + X_4(X_5 + X_{12} + X_{11} + C_4 + X_9 + X_{13} + X_{14})] \\
&+ [X_{15} + X_3(X_{16} + X_{11} + X_7 + X_{18} + X_6 + X_5) + (X_{19} + C_5 + X_{20}) + X_{21} + X_{15}] \\
&= [X_1(X_5 + X_6 + X_7) + X_2(X_6 + X_8 + X_{21} + X_7) + (X_6 + X_8) + (X_9 + X_5 + X_{22}X_{23} + X_{10})] \\
&+ [X_3(X_5 + X_9 + X_{24} + X_{25} + X_6 + X_{11}) + X_4(X_5 + X_{12} + X_{11} + \bar{X}_{18} + X_{26} + X_6 + X_{24} + X_{26} + X_9 + X_{13} + X_{14})] \\
&+ [X_{15} + X_3(X_{16} + X_{11} + X_7 + X_{18} + X_6 + X_5) + (X_{19} + X_{27} + X_{17} + X_{28} + X_{20}) + X_{21} + X_{15}] \\
&= X_1X_7 + X_2X_7 + X_3X_7 + X_3X_{11} + X_3X_{16} + X_3X_{18} + X_3X_{24} + X_3X_{25} + X_4X_{11} + X_4X_{12} + X_4X_{13} + X_4X_{14} \\
&+ X_4\bar{X}_{18} + X_4X_{24} + X_4X_{26} + X_{22}X_{23} + X_5 + X_6 + X_8 + X_9 + X_{10} + X_{15} + X_{17} + X_{19} + X_{20} + X_{21} + X_{27} + X_{28}
\end{aligned}
\tag{1}
$$

Based on the Bull's algorithm, the top event T is the intersection of the 28 cut sets which are the minimum cut set of the fault tree, i.e. $\{X_1X_7\}$, $\{X_2X_7\}$, $\{X_3X_7\}$, $\{X_3X_{11}\}$, $\{X_3X_{16}\}$, $\{X_3X_{18}\}$, $\{X_3X_{24}\}$, $\{X_3X_{25}\}$, $\{X_4X_{11}\}$, $\{X_4X_{12}\}$, $\{X_4X_{13}\}$, $\{X_4X_{14}\}$, $\{X_4\bar{X}_{18}\}$, $\{X_4X_{24}\}$, $\{X_4X_{26}\}$, $\{X_{22}X_{23}\}$, $\{X_5\}$, $\{X_6\}$, $\{X_8\}$, $\{X_9\}$, $\{X_{10}\}$, $\{X_{15}\}$, $\{X_{17}\}$, $\{X_{19}\}$, $\{X_{20}\}$, $\{X_{21}\}$, $\{X_{27}\}$, $\{X_{28}\}$, which mean the 30 different risk accidents combination caused the main event. Therefore, the main event probability caused by the 28 minimum cut sets could be calculated based on fault tree theory.

According to the minimum cut sets, there are two types of basic events leading to the top event occurrence. They are sorted to be estimated.

(1)Single minimum cut set: That means a minimum cut set including one basic event. There are 12 single minimum cut sets in the FTA of cutter head failure, such as $\{X_5\}$、$\{X_6\}$、$\{X_8\}$、$\{X_9\}$、$\{X_{10}\}$、$\{X_{15}\}$、$\{X_{17}\}$、$\{X_{19}\}$、$\{X_{20}\}$、$\{X_{21}\}$、$\{X_{27}\}$、$\{X_{28}\}$. For example, $\{X_5\}$ means that the appearance of X_5 （badness geology） may lead to the failure of cutter head.

(2)Double minimum cut set: That means a minimum cut set including two basic events. There are 16 double minimum cut sets in the FTA of cutter head failure, such as $\{X_1X_7\}$、$\{X_2X_7\}$、$\{X_3X_7\}$、$\{X_3X_{11}\}$、$\{X_3X_{16}\}$、$\{X_3X_{18}\}$、$\{X_3X_{24}\}$、$\{X_3X_{25}\}$、$\{X_4X_{11}\}$、$\{X_4X_{12}\}$、$\{X_4X_{13}\}$、$\{X_4X_{14}\}$、$\{X_4\bar{X}_{18}\}$、$\{X_4X_{24}\}$、$\{X_4X_{26}\}$、$\{X_{22}X_{23}\}$. For example, $\{X_1X_7\}$ means that the basic events X_1 （$M_S > M_R$） and X_7 (misgovern construction) simultaneity may lead to the failure of cutter head.

4 QUALITATIVE ANALYSIS OF THE FAULT TREE

For many factors affecting the occurrence of shield cutter head in composite ground, it needs to analyze their affection. According to the established fault tree, it analyzes the sensitive degree of every factor, and makes the compositor of the basic events. At present, the method for obtaining the coefficient of structural importance often uses the minimum cut set or path set to approximately estimate the importance index. Their principles are as follows:

(1) The structural importance coefficient of the single cut set is the biggest. For example $\{X_5\}$, $\{X_6\}$, $\{X_8\}$, $\{X_9\}$, $\{X_{10}\}$, $\{X_{15}\}$, $\{X_{17}\}$, $\{X_{19}\}$, $\{X_{20}\}$, $\{X_{21}\}$, $\{X_{27}\}$, $\{X_{28}\}$. Where,

(2)

$$I_5 = I_6 = I_8 = I_9 = I_{10} = I_{15} = I_{17} = I_{19} = I_{20} = I_{21} = I_{27} = I_{28} \tag{2}$$

(2) The structural importance coefficients are the same for basic events together appearing in only one minimum cut set. For example $\{X_{22}X_{23}\}$, i.e. $I_{22}=I_{23}$, from structural, each basic event of great abrasion and fewer edge disc cutters is in the same degree of affecting the occurrence of the top event.

(3) The structural importance coefficient of basic event depends on appearing times in the minimum cut sets which have the same number of basic events. That is to say, the number is few, and the structural importance coefficient is small; in reverse is OK; the number is the same, and coefficient is equal. Where

$$I_4 > I_3 > I_7 > I_{11} = I_{24} > I_1 = I_2 = I_{12} = I_{13} = I_{14} = I_{16} = I_{18} = \overline{I}_{18} = I_{22} = I_{23} = I_{25} = I_{26} \tag{3}$$

(4)When basic events appear in the minimum cut sets having different number of basic events, the structural importance coefficient is determined as follows:

①If the appearance times are equal, the structural importance coefficient is larger which is in the cut set of fewer basic events. Where

$$\begin{aligned} &I_5 = I_6 = I_8 = I_9 = I_{10} = I_{15} = I_{17} = I_{19} = I_{20} = I_{21} = I_{27} = I_{28} > \\ &I_1 = I_2 = I_{12} = I_{13} = I_{14} = I_{16} = I_{18} = \overline{I}_{18} = I_{22} = I_{23} = I_{25} = I_{26} \end{aligned} \tag{4}$$

②If the basic event appears in the small cut set little and the large cut set much, even though more complicated circs, the coefficient can be calculated following discriminate below.

$$\sum I(i) = \sum_{X_{i \in K_j}} \frac{1}{2^{n_i - 1}} \tag{5}$$

Where, $I(i)$ is approximately calculated value of the basic event (X_i) structural importance coefficient; $X_i \in K_j$ denotes the basic event X_i belonging to the minimum cut set K_j; n_i is the number of basic events in the minimum cut set which includes X_i. For example:

$$I_5 = \frac{1}{2^{1-1}} = 1, \quad I_1 = \frac{1}{2^{2-1}} = \frac{1}{2} \tag{6}$$

Therefore, following above analysis, the taxis of basic event structural importance is educed.

$$\begin{aligned} &I_5 = I_6 = I_8 = I_9 = I_{10} = I_{15} = I_{17} = I_{19} = I_{20} = I_{21} = I_{27} = I_{28} > I_4 > I_3 > I_7 \\ &> I_{11} = I_{24} > I_1 = I_2 = I_{12} = I_{13} = I_{14} = I_{16} = I_{18} = \overline{I}_{18} = I_{22} = I_{23} = I_{25} = I_{26} \end{aligned} \tag{7}$$

The former fifteen basic events in the structural importance taxis are listed in the Table 2.

Table 2 the former fifteen basic events

Sign	Basic event	Sign	Basic event	Sign	Basic event
X_5	badness geology	X_{15}	long distance advance	X_{27}	valve abrasion
X_6	irrationality type of cutter head	X_{17}	seal failure	X_{28}	longtime replacing tie-in
X_8	soft and sticky geology	X_{19}	few foam bore	X_4	exceeding allowed abrasion
X_9	underground eyewinker	X_{20}	irrationality position	X_3	rational design

X_{10}	big muck	X_{21}	alternated with soft and rigidity rock terrane	X_7	misgovern construction

5 MAINLY INFLUENCE FACTOR AND IMPROVENMENT MEASURE

According to the taxis result, single minimum cut set X_5 , X_6 , X_8 , X_9 and so on easily cause the failure of cutter head; Secondly, the basic events X_4 , X_3 , X_7 which appear more times also easily cause the top event failure. They are the weakness parts of the system and the main risk factors arousing the failure of the shield cutter head in the composite ground. Therefore, during the tunnel construction, it aims at surveying and managing the basic events which greatly influents the top event occurrence to lower the risk accidents of cutter head failure.

(1) For lowering the risks X_5 (badness geology), X_8 (soft and sticky geology), X_{21} (alternated with soft and rigidity rock terrane) influences on the cutter head failure, it should strengthen to run the geology forecast, accurately certain the position of the badness geology and its distribute, and adopt corresponding measures in advance.

(2) For lowering the risk X_6 (irrationality type of cutter head) influence on the cutter head failure, it should accord to the geology and hydrology condition, structural design, construction advance request etc. factor, choose much adaptability cutter head, and make an adequacy adjustment of shield installation under concrete conditions during construction.

(3) For lowering the risks X_4 (exceeding allowed abrasion), X_7 (misgovern construction) influences on the cutter head failure, it should choose reasonable advance model and parameters, continuously accumulate the experience, and reduce man-made breakage; installing the cutter wear monitor system, it can accurately obtain the information of the cutter wear, then adopt corresponding measures; enhancing cutter’s replacing rate and quality.

6 CONCLUSIONS

From risk analysis of shield cutter head failure in the composite ground based on FTA, the conclusions are as follows:

(1) Having a directly view and simple character, the FTA is a valid method for analyzing the failure risk of shield cutter head in composite ground.

(2)It totally considered 28 basic events for the failure risk fault tree of shield cutter head in composite ground. Through the fault tree calculation, it can definite the weakness parts of cutter head failure, confirm the key factors of risk occurrence, and make a taxis for the importance of various influence factors.

(3) Through FTA of the cutter head failure, it made sure the mostly reason and mechanism of leading to the failure risk of shield cutter head in composite ground, brought forward the improved measures and suggestion. So it gave some useful conference for preventing or reducing the failure risk of shield cutter head in composite ground during construction.

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