Risk analysis for cutterhead failure of composite EPB shield based on fuzzy fault tree

Y.R. Yan & H.W. Huang
Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, P.R. China
Department of Geotechnical Engineering, Tongji University, Shanghai, P.R. China

Q.F. Hu
Shanghai Institute of Disaster Prevention and Relief, Shanghai, P.R. China

ABSTRACT: All factors and related hazards in the cutterhead of composite EPB shield were systematically analyzed, and then fuzzy Fault Tree Analysis (FTA) model of cutterhead failure was proposed. Main basic events affecting the occurrence probability of the top event were verified by a quantitative analysis, which could be applied in the risk analysis of EPB shield machine’s cutterhead. Compared with the traditional fault tree analysis, the fuzzy fault tree method can get the cutterhead failure possibility distribution of composite EPB shield. At last, the measures that help reducing the cutterhead failure occurrence were presented.

1 GENERAL INSTRUCTIONS

1.1 The actuality of composite EPB shield cutterhead failure

With the manufacture technique development of shield tunnelling, the scope of strata in which shields works becomes more and more widely. Shield technology is not only used in relatively uniformity or single ground, but also used in mixed ground that changes from hard rock to mixed face and soft ground (and vice versa) at the tunnel level. During the excavation, the highly abrasive and frequently changing mixed face ground causes high cutter wear, especially flat cutter wear; the accident rate of cutter disc to the total shield is highly to one half. The main forms of accidents are cutter abrasion, cutter disc abrasion, cutter disc distortion and so on (Lei Guo 2006). These accidents made the advance rate and cutterhead service life largely depressed. According to statistics, in domestic composite EPB (Earth Pressure Balance) shield construction, the failure of cutter abrasion came forth at differently degree (Weibin Zhu et al. 2006).

1.2 The introduction of fuzzy FTA

In the traditional fault tree, a failure event system (top event) is divided into many sub-events with a combination of series and parallel. Its failure probability can be back-calculated according to the logical relationship of the fault tree when the failure probability of each basic event is known. Fault tree analysis is based on Boolean algebra. A quantitative analysis needs probabilities of all basic events or the minimal cut set, which are mostly obtained by statistical data or subjective judgmental data based on experts’ experiences. These data have uncertainty because of various influence factors during statistical procedures and limitation of experts’ experiences. It is necessary to define a fuzzy value in the probabilistic space to represent a single probability. Basic concepts and methods of the fuzzy fault tree were proposed in 1980s (Tanaka et al.1983, Furuta 1984). At present, the study of the fuzzy fault tree is almost focused on algorithm and the integrated theory systems have not been established and verified in practice (Singer 1999). A fuzzy set is introduced in this paper and the failure probability of basic events is replaced by the fuzzy failure probability. A triangular fuzzy number is introduced to represent the failure probability of a basic event and the fuzzy failure probability of a top event is obtained by fuzzy number operation. Measures to reduce the cutterhead failure possibility of the EPB shield are verified by analyzing the importance of basic events.

2 FUZZY SET THEORY AND ITS OPERATIONS

2.1 Fuzzy set

Fuzzy set theory was introduced by Zadeh (1965) to deal with the problem in which the phenomena are
imprecise and vague. Let $X$ be a collection of objects, called the universe, whose elements are denoted by $x$. A fuzzy subset $A$ in $X$ is characterized by a membership function $f_A(x)$ which associates with each element $x$ in $X$ a real number in the interval $[0, 1]$. The function value $f_A(x)$ represents the grade of membership of $x$ in $A$. The larger the $f_A(x)$ is, the stronger the degree of belongingness for $x$ in $A$.

### 2.2 Fuzzy numbers and its operations

Switch between the fuzzy numbers are used to handle imprecise information such as 'close to 5', 'high reliability', 'low failure rate', etc. There are many forms of fuzzy numbers to represent the linguistic values. In here, triangular fuzzy numbers are applied. Let $x, a, m, b \in R$ (real line). A triangular fuzzy number is a fuzzy number $A$ in $R$, if its membership function $f_A$: $R \sim [0, 1]$ is

$$
\mu_A(x) = \begin{cases} 
0 & \text{for } x < a \\
\frac{(x-a)/(m-a)} & \text{for } a \leq x \leq m \\
\frac{(b-x)/(b-m)} & \text{for } m \leq x \leq b \\
0 & \text{for } x > b 
\end{cases}
$$

(1)

In this study, triangular fuzzy numbers are employed. A triangular fuzzy number can be defined by a triplet $\hat{A} = (a, m, b)$. The membership function is with $a \leq m \leq b$. The triangular fuzzy number can be denoted by a triplet $\hat{A} = (a, m, b)$. The parameter $m$ gives the maximal grade of $f_A(x)$, i.e. $f_A(m) = 1$, it is the most probable value of the evaluation data. $a$ and $m$ are the lower and upper bounds of the available area for the evaluation data.

For a given $\lambda$ in the interval $[0, 1]$, the arithmetic operations of fuzzy numbers can be defined by means of $\lambda$-cut operations according to the extension principle(Zadeh 1965):

$$
A_\lambda = \{x | x \in R, \mu_A \geq \lambda\} = [a_\lambda^*, b_\lambda^*] \\
B_\lambda = \{x | x \in R, \mu_B \geq \lambda\} = [a_\lambda^*, b_\lambda^*] 
$$

Then

$$
\tilde{A}(+)\tilde{B} = A_\lambda + B_\lambda = [a_\lambda^* + a_\lambda^*, b_\lambda^* + b_\lambda^*] 
$$

(2)

$$
\tilde{A}(--)B = A_\lambda - B_\lambda = [a_\lambda^* - a_\lambda^*, b_\lambda^* - b_\lambda^*] 
$$

(3)

$$
\tilde{A}(\cdot)B = A_\lambda \cdot B_\lambda = [a_\lambda^* \cdot a_\lambda^*, b_\lambda^* \cdot b_\lambda^*] 
$$

(4)

$$
(a_\lambda^* \geq 0, a_\lambda^* \geq 0) \\
(a_\lambda^* \geq 0, a_\lambda^* > 0)
$$

(5)

### 3 FTA OF CUTTERHEAD FAILURE

#### 3.1 Fault tree model for the risk of composite EPB shield cutterhead failure

The main purpose of the fault tree analysis is to find out all failure modes of the system and the event with a rather large failure probability. After weak sections have been enhanced, occurrence probabilities of these accidents are reduced so that the system reliability is improved. For researching the cutterhead failure risk of composite EPB shield, there were some supposition in the analysis 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 produce normal wear during the shield advance, so their abrasion was not considered.

According to the above investigation accidents data, the cutterhead failure risk of composite EPB shield in mixed face ground was set by means of the fuzzy FTA method, shown in Figure 1.

The systemic risk probability of cutterhead 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 (MCS for short) of fault tree. Each MCS corresponds to one accident type, and there are several MCSs with different occurrence probability of one fault tree. The MCS with the maximum occurrence probability is the most probably potential factor which may cause accident. Boolean algorithm is relatively simple in solving the MCS. The fault tree in Figure 1 is obtained from the Boolean algorithm as it shown in Eq. (6).

From the result obtained above, the top event $T$ is the union of 28 sets which are the MCS of the fault tree, i.e. $\{X_1X_7\}$, $\{X_2X_7\}$, $\{X_3X_7\}$, $\{X_4X_11\}$, $\{X_5X_16\}$, $\{X_6X_18\}$, $\{X_7X_24\}$, $\{X_8X_35\}$, $\{X_9X_35\}$, $\{X_4X_12\}$, $\{X_4X_{13}\}$, $\{X_4X_{14}\}$, $\{X_2X_{18}\}$, $\{X_4X_{34}\}$, $\{X_4X_{26}\}$, $\{X_2X_{23}\}$, $\{X_3\}$, $\{X_6\}$, $\{X_8\}$, $\{X_9\}$, $\{X_{10}\}$, $\{X_{15}\}$, $\{X_{17}\}$, $\{X_{19}\}$, $\{X_{20}\}$, $\{X_{21}\}$, $\{X_{27}\}$, $\{X_{28}\}$, which correspond to 28 accident modes.

#### 3.2 Quantitative analysis

Quantitative analysis includes evaluation of failure probability of the top event and important analysis of the basic events. In practice, the occurrence probability of a top event (PT) is obtained using approximate probability formula of independent events as shown in Eq.(7)

$$
P_T = 1 - \prod_{i=1}^{n} [1 - P(M_i)]
$$

(7)

Where $P(M_i)$ is the occurrence probability of the ith MCS. For example, $P(M_1)$ is the occurrence
Figure 1. Fault tree of the cutterhead failure risk of composite EPB shield.
probability of the first MCS \( \{X_1, X_7\} \), which depends on the probability multiplication of basic events \( X_1 \) and \( X_7 \).

Probabilities of the basic events must be known in advance, in order to evaluate failure probability of the top event and important analysis of the basic events. Expert elicitation and fuzzy set theory will be used to get the probabilities of the basic events in this paper. Because the experts cannot exactly evaluate the probability of events, and sometimes some of the events are vague, the experts tend to apply natural linguistic expression, such as ‘Impossible, Infrequent, Occasional, Possible and Frequent’, to describe the probability of events. According to the ‘Guidelines of Risk Management for Metro Tunnelling and Underground Engineering Works’ (2007), it ranks the occurrence probability of risk into 5 class, shown in Table 1. Conventional mathematical ways cannot handle natural linguistic expression efficiently because of its vagueness. Therefore, fuzzy set theory is used to cope with it. According to the triangular fuzzy number discussed above, it is assumed herein

\[
a_i = 0.95m_i \quad i = 1, 2, \ldots, n \quad (8)
\]
\[
b_i = 1.05m_i \quad i = 1, 2, \ldots, n \quad (9)
\]

The occurrence probabilities of random basic events using Eq.(8) and Eq.(9), and their fuzzy probabilities are shown in Table 2.

Figure 2 shows that the fuzzy probability of the top event can be expressed as triangular fuzzy numbers and the parameters are (0.9925, 0.9960, 0.9982). The corresponding occurrence probability is 0.9925 \( \sim \) 0.9982, however, the most possible probability is equal to 0.9960 with a membership grade equal to 1.

3.3 Sensitivity analysis

The main basic events affecting the occurrence probability of the top event can be determined and some effective measures are verified by sensitivity analysis to reduce occurrence probability of the basic events and the top event. According to the fuzzy number model defined in this paper, sensitivity evaluation index \( V_i \) is simply defined in Eq.(10) (Chen and Zhang 2002)

\[
V_i = \left. \frac{\partial g(x)}{\partial x_i} \right|_{x=g, \mu=g} \mu_{x_i} \quad \mu_{x_i}
\]

Where \( \mu_{x_i} \) is the occurrence probability of the top event, \( \mu_x \) is the average occurrence probability of the basic event \( x \).

If \( V_i \geq V_j \), it is more effective to minimize the occurrence probability of the top event by reducing the occurrence probability of the event \( i \) rather than the event \( j \).
Table 2. Fuzzy probability of the basic event in the fault tree.

<table>
<thead>
<tr>
<th>Basic event</th>
<th>Fuzzy probability value</th>
<th>Sensitivity index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>m</td>
</tr>
<tr>
<td>X1</td>
<td>0.000095</td>
<td>0.01%</td>
</tr>
<tr>
<td>X2</td>
<td>0.000475</td>
<td>0.05%</td>
</tr>
<tr>
<td>X3</td>
<td>0.095</td>
<td>10%</td>
</tr>
<tr>
<td>X4</td>
<td>0.8075</td>
<td>85%</td>
</tr>
<tr>
<td>X5</td>
<td>0.0855</td>
<td>9%</td>
</tr>
<tr>
<td>X6</td>
<td>0.0475</td>
<td>5%</td>
</tr>
<tr>
<td>X7</td>
<td>0.0095</td>
<td>1%</td>
</tr>
<tr>
<td>X8</td>
<td>0.76</td>
<td>80%</td>
</tr>
<tr>
<td>X9</td>
<td>0.000665</td>
<td>0.07%</td>
</tr>
<tr>
<td>X10</td>
<td>0.000475</td>
<td>0.05%</td>
</tr>
<tr>
<td>X11</td>
<td>0.0057</td>
<td>0.6%</td>
</tr>
<tr>
<td>X12</td>
<td>0.00076</td>
<td>0.08%</td>
</tr>
<tr>
<td>X13</td>
<td>0.095</td>
<td>10%</td>
</tr>
<tr>
<td>X14</td>
<td>0.0038</td>
<td>0.4%</td>
</tr>
<tr>
<td>X15</td>
<td>0.076</td>
<td>8%</td>
</tr>
<tr>
<td>X16</td>
<td>0.057</td>
<td>6%</td>
</tr>
<tr>
<td>X17</td>
<td>0.00855</td>
<td>0.9%</td>
</tr>
<tr>
<td>X18</td>
<td>0.00076</td>
<td>0.08%</td>
</tr>
<tr>
<td>X19</td>
<td>0.000665</td>
<td>0.07%</td>
</tr>
<tr>
<td>X20</td>
<td>0.000855</td>
<td>0.09%</td>
</tr>
<tr>
<td>X21</td>
<td>0.76</td>
<td>80%</td>
</tr>
<tr>
<td>X22</td>
<td>0.0855</td>
<td>9%</td>
</tr>
<tr>
<td>X23</td>
<td>0.00665</td>
<td>0.7%</td>
</tr>
<tr>
<td>X24</td>
<td>0.0057</td>
<td>0.6%</td>
</tr>
<tr>
<td>X25</td>
<td>0.0038</td>
<td>0.4%</td>
</tr>
<tr>
<td>X26</td>
<td>0.00057</td>
<td>0.06%</td>
</tr>
<tr>
<td>X27</td>
<td>0.00038</td>
<td>0.04%</td>
</tr>
<tr>
<td>X28</td>
<td>0.057</td>
<td>6%</td>
</tr>
</tbody>
</table>

Sensitivity indices of all basic events are obtained by sensitivity analysis of the fault tree of the cutterhead failure risk of composite EPB shield as shown in Fig. 1.

The basic event in which the sensitivity index is greater than 5% is chosen and arranged as follows: $V_4 = 95.32\%$, $V_5 = V_{21} = 80.35\%$, $V_{13} = 8.54\%$, $V_5 = 8.03\%$, $V_{28} = 6.03\%$, $V_{24} = 5.1\%$, $V_{13} = 5.02\%$.

4 MAINLY INFLUENCE FACTOR AND IMPROVEMENT MEASURE

According to the order result, single minimum cut set $X_5$, $X_6$, $X_5$, $X_9$, $X_{21}$ and so on easily cause the failure of cutterhead; Secondly, the basic events $X_4$, $X_7$, $X_{24}$ 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 cutterhead in the mixed face ground. Therefore, during the tunnel construction, it aims at surveying and managing the basic events which greatly influence the top event occurrence to lower the risk accidents of cutterhead 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 cutterhead 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 cutterhead) influence on the cutterhead failure, it should accord to the geology and hydrology condition, structural design, construction advance request etc. factor, choose much adaptability cutterhead, 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 cutterhead 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.

5 CONCLUSIONS

From risk analysis of composite EPB shield cutterhead failure in the mixed face ground based on fuzzy 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 composite EPB shield cutterhead in mixed face ground.

2. It totally considered 28 basic events for the failure risk fault tree of composite EPB shield cutterhead. Through the fuzzy fault tree calculation, it can definite the weakness parts of cutterhead failure, confirm the key factors of risk occurrence, and make an order for the importance of various influence factors.

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

REFERENCES


Zhu, W.B., Ju, S.J. etc. 2006. *Shield tunnelling technology in mixed face ground conditions*. Beijing: China Science and Technology Press.