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Cause Analysis of Sudden Water Pollution Accidents Based on Fuzzy Fault Tree: Taking the South-to-North Water Diversion Project in China as an Example

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ABSTRACT

This study aims to explore the causes of sudden water pollution accidents in the main canal of the South-to-North Water Diversion Project in China. Triangular fuzzy function and fault tree analysis method were combined, and qualitative and quantitative fuzzy fault tree analyses of sudden water pollution accidents in main canals of the South-to-North Water Diversion Project in China were conducted. Results show that the probability of sudden water pollution accident in the main canal of the South-to-North Water Diversion Project is 0.0205%, which is in accordance with the actual situation. The instantaneous deterioration of water quality, excessive water quality, artificial poisoning, and terrorist attacks have the greatest impacts on sudden water pollution accidents, followed by vessel traffic accidents and geological hazards, and finally by road traffic accidents. The conclusion provides a decision-making reference for the prevention and treatment of sudden water pollution accidents in the main canal of the South-to-North Water Transfer Project.

INTRODUCTION

The South-to-North Water Transfer Project has made tremendous contributions to the solution of the uneven distribution of water resources between the northern and southern parts of China, thereby realizing a rational strategy for allocating water resources and ensuring the sustainable development of economy and society in China. However, water quality is the key to the success or failure of the South-to-North Water Transfer Project to make the benefits of the project play a normal role. Sudden water pollution accidents should be avoided, and water quality safety should be guaranteed during water conveyance. That is, the quality of the source of water diversion and water conveyance channel should be guaranteed. Only in this way can the South-to-North Water Transfer Project promote the economic and social development of water-receiving areas and the well-being of the people.

In the South-to-North Water Transfer Project, the main canals along the Middle Route Project are long and comprise open canals and many crossing structures. Thus, sudden water pollution accidents may occur during water conveyance. Polluted water directly affects social stability and people's health, property, and economic security. Sudden water pollution incidents may be manifested in the following aspects: First, vehicles carrying oils, chemicals, and biological drugs on bridges and highways across water supply channels overturn when a traffic accident occurs, and these substances enter the channel. Second, a polluted river crossing an aqueduct rapidly spreads pollution to channel. Third, contaminants, including unused fertilizers, garbage, and aquaculture wastes in soil flows into open channels and cause water pollution. Fourth, the pipelines adjacent to the oil and gas pipeline of the South-to-North Water Transfer Project are prone to break and leak. Fifth, terrorist attacks or sabotage are likely.

Given that sudden water pollution accidents easily occur in the South-to-North Water Transfer Project, a series of studies on water quality safety and water pollution control has been performed on the site. For example, sudden water quality risks of the east and middle routes of the South-to-North Water Transfer Project have been assessed (Zhang et al. 2018). Notably, administrative division, government-led single-treatment mode (Li et al. 2014), lack of cooperative system, and lack of public participation (Zhang et al. 2004) were found to be the reasons for the inefficiency of water pollution prevention and control in the middle route of the South-to-North Water Transfer Project (Ren et al. 2008). Emergency control strategies (Fang et al. 2014) were also studied, although most of the results are from the technical point of view or are obtained through qualitative analysis, such as water dispatch. The causes of sudden wa-

ter pollution accidents are rarely investigated because insufficient statistical data, and relevant quantitative research is limited.

Fuzzy fault tree analysis (FTA) is a simple, clear, and logical method for analysing the risk of complex system engineering. In the absence of accurate statistical data, the probability of events can be estimated by expert experience. In this regard, to ensure the normal operation of the South-to-North Water Transfer Project, we use fault tree theory to gradually decompose the causes of sudden water pollution accidents in the main canal of the project, fuzzify the occurrence probability of basic events, replace fixed probability with triangular fuzzy function, and calculate the fuzzy probability of sudden water pollution accidents in the main canal of the project by fuzzy number calculation method. This study provides a basis for line and safety management.

MATERIALS AND METHODS

FTA Method

FTA is an important analysis method in safety system engineering. The objective of this method is to take the events (top events) that the system does not want to occur. This method enables the determination of the factors that may cause system accidents, analysis of logical relations among the factors; the relations are then expressed in the form of a fault tree for the prediction of the probability of system accidents by qualitative and quantitative methods and formulation of corresponding prevention measures; these processes ensure the effective prevention of accidents (Khakzad et al. 2011). The traditional FTA method requires comprehensive statistical data obtained through quantitative analysis for the deduction of the probability of basic events. However, statistical data are often difficult to obtain; thus, the probability of basic events can only be treated as fuzzy numbers by using fuzzy theory. The commonly used fuzzy numbers include triangular, normal, and trapezoidal fuzzy numbers, and triangular fuzzy numbers are useful in resolving fuzziness and definite meaning (Ozaki et al. 1998). Therefore, triangular fuzzy numbers are selected to represent the fuzzy probability of each basic event, and the membership functions of triangular fuzzy numbers can be expressed by linear functions.

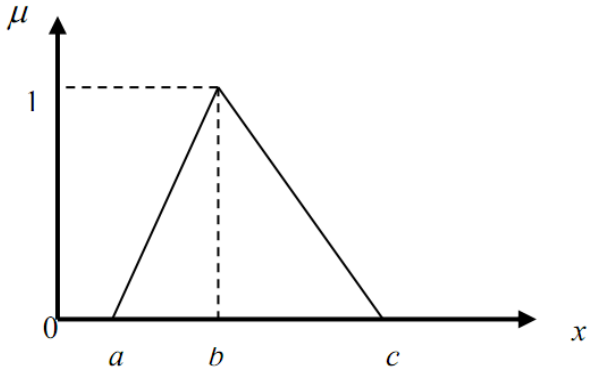

Fig. 1: Triangular fuzzy numbers.

$$\mu_A(X)=\begin{cases}\dfrac{x-a}{b-a}, x\in[a,b]\\ \dfrac{c-x}{c-b}, x\in[b,c]\\ 0, \quad others\end{cases} \qquad ...(1)$$

In Formula (1), b is the nucleus of $\mu_A(x)$, a and c are the left and right distributed parameters of fuzzy numbers that indicate the extent to which the function extends to the left and to the right, and c-a is the blind degree of $\mu_A(x)$. The triangular fuzzy number is obtained by using the following formula:

$$A=(a,b,c) \qquad ...(2)$$

Where, $a<b<c$, $\mu_A b=1$, as shown in Fig. 1.

Logic Operation

Operation of triangular fuzzy numbers: Two triangular fuzzy numbers $\tilde{q}_1$ and $\tilde{q}_2$ are represented by (a_1,b_1,c_1) and (a_2,b_2,c_2), respectively, and the algebraic operation of triangular fuzzy numbers is as follows:

1) "$\oplus$" operation: $\tilde{q}_1 \oplus \tilde{q}_2=(a_1,b_1,c_1)\oplus(a_2,b_2,c_2)$.

2) "$\ominus$" operation: $\tilde{q}_1 \ominus \tilde{q}_2=(a_1,b_1,c_1)\ominus(a_2,b_2,c_2)$.

3) "$\otimes$" operation: $\tilde{q}_1 \otimes \tilde{q}_2=(a_1,b_1,c_1)\otimes(a_2,b_2,c_2)$.

Fuzzy processing of fault tree doors: Traditional fault tree generally uses logical AND gate logical OR gate to express the logical relationship between the upper and lower two levels of events. The operators of the traditional fault tree logical AND gate are:

$$q_{and}=\prod_{i=1}^{n} q_i \qquad ...(3)$$

The operators of the traditional fault tree logical OR gate are:

$$q_{\text{or}} = 1 - \left(1 - \prod_{i=1}^{n} q_i\right) \quad ...(4)$$

In formulas (3) and (4), q_i is the exact probability of occurrence of event *i*.

Logical AND gate operators, such as those in formula (5), are used in fuzzy processing.

$$\tilde{q}_{and} = (a_{and}, b_{and}, c_{and}) = \left(\prod_{i=1}^{n} a_i, \prod_{i=1}^{n} b_i, \prod_{i=1}^{n} c_i\right) \quad ...(5)$$

Logical OR gate operators, such as those in formula (6), are also adopted in fuzzy processing.

$$\tilde{q}_{or} = (a_{or}, b_{or}, c_{or}) = \left\{\left[1 - \prod_{i=1}^{n}(1 - a_i)\right], \right.$$
$$\left.[1 - \prod_{i=1}^{n}(1 - b_i)], [1 - \prod_{i=1}^{n}(1 - c_i)]\right\} \quad ...(6)$$

Factors of Sudden Water Pollution Accidents

The main canal of the South-to-North Water Transfer Project spans many regions and watersheds and is a typical complex system with a high degree of social and ecological integration. Case studies that used field survey results show that the specific inducing factors are mainly concentrated on the following aspects:

Production water and live wastewater: Factors affecting the production of domestic wastewater along the line. The main canal of the South-to-North Water Transfer Project spans considerable industrial zones and produces a large amount of industrial wastewater. For safe water conveyace, several measures have been taken for the discharge of sewage from the diversion channel into other rivers through sewage interception and use of a diversion project. However, illegal discharge by enterprises remains due to the high cost of sewage treatment. Flow equipment failure and floods lead to the influx of wastewater into the channel.

Pollution factors of oil and harmful substances: Some of the main canals of the South-to-North Water Transfer Project have navigable functions and dense vessels. Once a ship leaks oil or loads harmful substances or a ship sinks because of the negligence of the crew or of accident, it causes water pollution accidents in local waters. Moreover, all kinds of industrial and mining enterprises are concentrated along the main canal of the project. Safety accidents in chemical factories, paper mills, acid mills, and alcohol factories result in the instantaneous leakage of chemical pollutants into the diversion channels, which will exert a fatal impact on the water body.

Factors of traffic accidents along bridges: Many roads and canals crossing bridges are installed along the South-to-North Water Transfer Project and often have busy traffic. Accidents involving vehicles carrying toxic and harmful substances cause leakage or explosion and other emergencies and rapid discharge of various pollutants, which easily cause water quality pollution.

Human malicious damage factors: Some dissatisfied people, desperate people, and people with mental disorders carry out malicious activities and terrorist attacks in the main canals to retaliate against society and vent their discontent.

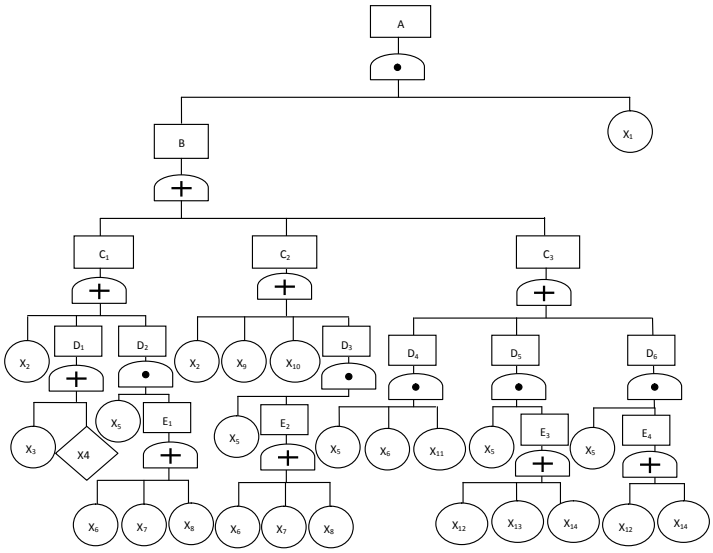

Fig. 2: Water pollution accident tree in the main canal of the South-to-North Water Diversion Project.

Table 1: Incident numbers and meanings in accident tree.

No.	Incident Meaning
A	Sudden water pollution accident in engineering main canal
B	Sudden water pollution
C_1	Oil pollution
C_2	Chemical pollution
C_3	Abnormal influx of sewage
D_1	Oil leakage on ship
D_2	Oil products flowing into the water along chemical enterprises along the line
D_3	Toxic chemicals flowing into the water along chemical enterprises along the line
D_4	Large quantities of agricultural sewage flow into the water body
D_5	Large quantities of industrial sewage flow into the water body
D_6	Large quantities of domestic sewage flow into the water body
E_1	Oil spill accidents along chemical enterprises along the route
E_2	Toxic chemicals leaked in chemical enterprises along the line
E_3	A large increase in industrial sewage
E_4	A large increase in domestic sewage
X_1	Instantaneous deterioration of water quality
X_2	Highway traffic accidents
X_3	Vessel traffic accident
X_4	Operation error
X_5	Failure of closure works
X_6	Meteorological disaster
X_7	Geologic hazard
X_8	Blast
X_9	Artificially poisoned
X_{10}	Terrorist attack
X_{11}	Extensive use of fertilizers and pesticides
X_{12}	Sewage treatment plant failure
X_{13}	Enterprise secret emissions
X_{14}	Sewage capacity exceeding sewage treatment capacity

These activities, including the release of chemical poisons and pathogenic bacteria and destruction of water supply equipment, also cause sudden water pollution accidents.

RESULTS AND ANALYSIS

After analyzing the inducing factors of sudden water pollution accidents in the main canal of the South-to-North Water Transfer Project and the hierarchical relationship among the factors, the fault tree is constructed, as shown in Fig. 2. The event numbers and meanings in the fault tree are shown in Table 1.

Qualitative Analysis of Fault Tree

The main task of qualitative analysis of fault tree is to determine all possible modes that lead to accidents, that is, to find all the minimum cut sets. The main methods for finding the minimum cut sets are Boolean algebra, determinant method, and matrix method. This study uses the Boolean algebra method. According to the fault tree shown in Fig. 2, the smallest cut set is 12 after the Boolean algebra operation, that is, (X_1, X_2), (X_1, X_3), (X_1, X_4), (X_1, X_5, X_6), (X_1, X_5, X_7), (X_1, X_5, X_8), (X_1, X_9), (X_1, X_{10}), (X_1, X_5, X_6, X_{11}), (X_1, X_5, X_{12}), (X_1, X_5, X_{13}), and (X_1, X_5, X_{14}).

Quantitative Analysis of Fault Tree

The statistical data of the basic events are difficult to obtain because of the short running time of the South-to-North Water Transfer Project and their limitation. Therefore, this study adopts expert scoring, which is conducted by a group of more than three experts. Each expert of the group estimates the probability of the occurrence of each basic event and finally takes each event. The mean *b* of the probability is estimated as the exact probability of the basic event. In the fuzzy processing of probability, the fuzzy probability value (Höhle et al. 2012) is usually obtained by 3σ representation. The probability value obeys the normal statistical law, and the standard deviation is σ. According to the rule of 3σ representation, the probability that its value falls into the interval $[b-3\sigma, b+3\sigma]$ is 99.7%. Therefore, this study lets $a=c=3\sigma$, and the probability values are fuzzy characterized as $(3\sigma, b, 3\sigma)$. The basic event expert scoring and 3σ representation fuzzy processing results are shown in Table 2.

According to formula (5), formula (6), and the minimum cut set that leads to sudden water pollution accidents in the main canal of the South-to-North Water Transfer Project, the fuzzy probability results of the accidents are as follows: $\tilde{q}_T = (0.0111\%, 0.0205\%, 0.0316\%)$. This result shows that the probability of sudden water pollution accident in the main canal of the South-to-North Water Transfer Project is 0.0205%, and the fluctuation range is 0.0111%-0.0316%. Although the possibility of an accident is small, it will cause serious consequences once it happens; hence, we should pay attention to it.

Fuzzy Importance Analysis

The fuzzy importance of basic events reflects the importance of their impacts on top events. The most commonly used methods are the median and centre-of-gravity methods, but the median method is less computational. Therefore, the median method for fuzzy importance analysis (Jindal et al. 2015) is used in this study. The order is

$$S_1 = \int_{b-a}^{b} m_A(x)dx \ , \ S_2 = \int_{b}^{c-b} m_A(x)dx, \quad S = S_1 + S_2 \qquad ...(7)$$

Where, S_1 and S_2 are the areas of the 12 small triangles in Fig. 1. A point Z exists, which makes the areas of the left and right parts of the fuzzy curve equal under the boundary of the point. Z is called the median of the triangular fuzzy number. When a=c is available, $T_z^1 = b$ exists.

For the fault tree with a structure function of

Table 2: Basic event expert scoring fuzzy processing data.

Symbol	Expert 1	Expert 2	Expert 3	b	∂	$\tilde{q}$
X_1	0.001	0.002	0.003	0.002	0.001	(0.003, 0.002, 0.003)
X_2	0.006	0.007	0.008	0.007	0.001	(0.003, 0.007, 0.003)
X_3	0.003	0.004	0.005	0.004	0.001	(0.003, 0.004, 0.003)
X_4	0.070	0.060	0.050	0.060	0.008	(0.024, 0.060, 0.024)
X_5	0.090	0.085	0.080	0.085	0.004	(0.012, 0.085, 0.012)
X_6	0.080	0.090	0.070	0.080	0.008	(0.024, 0.080, 0.024)
X_7	0.004	0.003	0.005	0.004	0.001	(0.003, 0.004, 0.003)
X_8	0.070	0.080	0.075	0.075	0.004	(0.012, 0.075, 0.012)
X_9	0.001	0.003	0.002	0.002	0.001	(0.003, 0.002, 0.003)
X_{10}	0.001	0.002	0.003	0.002	0.001	(0.003, 0.002, 0.003)
X_{11}	0.150	0.200	0.250	0.200	0.040	(0.120, 0.200, 0.120)
X_{12}	0.075	0.070	0.065	0.070	0.004	(0.012, 0.070, 0.012)
X_{13}	0.055	0.050	0.060	0.055	0.004	(0.012, 0.055, 0.012)
X_{14}	0.035	0.040	0.030	0.035	0.004	(0.012, 0.035, 0.012)

$f(x_1, x_2, ..., x_n)$, the median of the top event is T_Z, the median of the basic event is $T_{iZ}^{'}$, and the fuzzy importance of the basic event X_i is $I_i = T_Z - T_{iZ}^{'}$. The importance of the top event T_Z is the same; accordingly, as long as the comparison of $T_Z^{'}$, that is, the smaller the $T_Z^{'}$ is, the greater the I_i and the impact on the occurrence of the top event are; otherwise, the less the impact on the occurrence of the top event.

After calculation, the fuzzy importance of basic events is ranked as follows:

$$I_1 = I_9 = I_{10} > I_3 = I_7 > I_2 > I_{13} = I_{14} > I_{12} > I_8 > I_6 > I_5 > I_{11} \quad ...(8)$$

CONCLUSION

The causes of sudden water pollution accidents in the main canals of China's South-to-North Water Transfer Project are analysed. The calculation results of the fuzzy probability of tree top events show that the probability of sudden water pollution accidents in main canals of the South-to-North Water Transfer Project is 0.0205%, which is basically in line with the actual situation and verifies the feasibility of the method. Based on the fuzzy importance of basic events, we can determine that the water quality deteriorates instantaneously, exceeds the standard, and is poisoned artificially. Terrorist attacks are the most important causes of sudden water pollution accidents, followed by ship traffic accidents and geological disasters, and lastly by highway traffic accidents.

The above FTA calculates the fuzzy probability of accidents from the quantitative point of view and gives the importance of each factor to the sudden water pollution accident of the trunk canal. However, the consequences caused by each factor are disregarded. The probability of the basic event is determined by the experts' score because of limitation in data, and a certain degree of subjectivity exists. Therefore, further research can be performed by accurately measuring the impacts of basic events on the probability of occurrence of the top event, considering the different consequences of different triggers of water pollution accidents, and adopting targeted intervention strategies.

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