# Event Tree and Fault Tree Analysis in Tunneling with Imprecise Probabilities

Xiaomin You[1], PhD, M. ASCE and Fulvio Tonon[2], PhD, M. ASCE, P.E.

[1]Former Ph.D. student at The University Texas of Austin; currently at Parsons Brinckerhoff, 444 South Flower Street Suite 800, Los Angeles, CA 90071; youx@pbworld.com
[2]Assistant Professor, The University of Texas at Austin, Department of Civil Engineering, 1 University Station C1792, Austin, TX 78712; tonon@mail.utexas.edu

**ABSTRACT** This paper presents the methodologies of event tree analysis and fault tree analysis in tunneling by using imprecise probabilities. In traditional risk assessment and analysis, uncertainties are measured by precise probabilities. However, due to the limited information in geological and underground conditions, assigning a precise value as to the probability of an event may not be practical. Probability is often evaluated imprecisely in tunneling. The International Tunnelling Association has published guidelines for tunneling risk management, in which the likelihood of occurrence is recommended to be evaluated by several predefined intervals rather than a crisp probability. The goal of the methodologies proposed in this study is to deal with imprecise information without forcing the experts to commit to assessments that they do not feel comfortable with or the analyst to pick a single distribution when the available data does not warrant such precision. Several case histories of risk analysis in tunneling were revisited by using the methodologies developed in this study. All results obtained based on imprecise probabilities are discussed and compared with the results from precise probabilities.

## INTRODUCTION

In risk analysis, we often face the problem of evaluating the probability or the consequences of failure. Event-Tree Analysis (ETA) and Fault-Tree Analysis (FTA) are two common methodologies to deal with the problem. The International Tunnelling and Underground Space Association (ITA) published guidelines (Eskesen et al. 2004) for risk management in tunneling projects, which recommended ETA and FTA as risk analysis tools.

An event tree presents an inductive logical relationship, starting from a hazardous event, which is called as "initiating event" and followed by all the possible outcomes. A fault tree analysis is a deductive analytical technique. It starts from a specified state of the system as the "Top event", and includes all faults which could contribute the top event.

ETA and FTA are widely used in risk analysis in tunneling. Kohl et al. (2006) used Event-tree to analysis the frequencies of defined accident scenarios in a road tunnel. Šejnoha et al. (2009) used FTA to identify failure causes and failure types and then applied ETA to quantify the risk of cave-in collapse during excavation by using event-tree. Hong et al. (2009) applied event-tree analysis to the design of shield TBM. Detailed introduction about the application of ETA and FTA to civil engineering with precise probabilities could be found in Benjamin and Cornell (1970) and Ang and Tang (1984).

## IMPRECISE PROBABILITIES

In the conventional analysis, probabilities are usually treated as precise values (Whitman 1984). However, due to inherent uncertainty in ground and groundwater conditions, assigning precise probabilities may not be sensible on practical. For example, ITA guidelines for tunneling risk management (Eskesen et al. 2004) recommended using intervals instead of single values to evaluate the frequencies of occurrence when dealing with risk analysis. Risk analysis has to rely on the judgments from experienced engineers and experts. Any probability distribution compatible with the judgments should be considered in the risk analysis (Walley 1991).

The theory of Imprecise Probabilities constructs a general convex set of probability distributions based on decision maker's judgments (Walley 1991). To illustrate, consider a tunnel boring machine (TBM) advancing in soft ground as an example, often facing such problem: whether there are any existing obstructions or not. In this case, the set of possible states (also called *Possibility Space*) is $\Omega = \{\omega_1 =$ no obstructions, $\omega_2$ =small obstructions, $\omega_3$ =big obstructions$\}$. According to past experience and exploration data, following judgments can be made:

(1) Having obstructions ahead is more probable than no obstructions;
(2) Probability of big obstructions is between 0.1 and 0.5;
(3) The amount of big obstructions should be less than half amount of small obstructions.

The theory of imprecise probabilities interprets such information as inequalities, and then imprecise probabilities defined by the three piece of information or judgments can be written as a convex set $\Psi$:

$$\Psi = \Big\{P: P(\omega_2) + P(\omega_3) \geq P(\omega_1); 0.1 \leq P(\omega_2) \leq 0.5; P(\omega_3) < 0.5P(\omega_2);\ P(\omega_i) \geq 0;\ \sum P(\omega_i) = 1\Big\} \quad (1)$$

A convex set $\Psi$ can also be defined by extreme points, which are the points that cannot be expressed as a convex combination of any other points in set $\Psi$.

Insufficient information is the most important inducement for choosing imprecise probabilities. Imprecise probabilities can be applied to problems when information is limited, either because it is impossible to collect more or because it is not practical or economically feasible to do so. For example, we will never drill boreholes every meter along the tunnel alignment for a perfect geological investigation report. As experience is gained and information accumulates, upper and lower probabilities become close to one another and imprecision decreases.

This paper explains how the theory of imprecise probability may help tunnel engineers in carrying out risk analyses under conditions of uncertainty, partial information and ignorance without unwittingly adding information. For example, experts are not forced to provide more information than they are comfortable with just because the analyst has to use only one probability distribution. The degree of imprecision can reflect both the amount of information on which probabilities are based, and the extent of conflict between different types of information.

## ETA WITH IMPRECISE PROBABILITIES

To carry out the event-tree analysis with imprecise probabilities, we first start the analysis from the sub-trees at the bottom, determine the upper and lower expectations of the sub-trees, then continue to the upper part of the tree till the initiating event is reached, and finally achieve the bounds of the failure probability or the expected consequence. Detailed methodology for event-tree analysis within imprecise probabilities was presented by You and Tonon (2011). Let us start from an example in tunnel to illustrate how to perform the event-tree analysis with imprecise probabilities.

***Example 1***: Consider a leaking water-conveyance tunnel. The analysis is meant to evaluate the failure probability with the initiating event $S_{1,0}$: construction void behind the unreinforced concrete lining. Here 'failure' is defined as either structural collapse failure or service failure of the lining (i.e., wide cracks). Three states are considered for the construction void: (1) large void ($s_{1,1,0}$: Diameter $\varnothing > 3$ ft); (2) small void ($s_{1,2,0}$: Diameter $\varnothing \le 1$ ft); and (3) intermediate size void ($s_{1,3,0}$: Diameter 1 ft$<\varnothing\le 3$ ft). If the void is large ($s_{1,1,0}$), it is possible that structural collapse (Event $S_{1,1}$) occurs because of non-uniform load distribution on the lining. Thus, there are only two outcomes, Yes ($s_{1,1,1}$) or No ($s_{1,1,2}$).If the void is small ($s_{1,2,0}$), although the lining will not collapse, the void may cause some cracks (Event $S_{1,2}$), which may reduce the serviceability. Given the existence of small voids, there are three outcomes for crack development (Event $S_{1,2}$): (1) $s_{1,2,1}$: wide cracks; (2) $s_{1,2,2}$: small cracks; (3) $s_{1,2,3}$: no cracks. Here we assume that only wide cracks will cause leakage through the lining. If the size of the void is intermediate ($s_{1,3,0}$), structural collapse (Event $S_{1,3}$) is still possible, i.e., two outcomes are possible: Yes ($s_{1,3,1}$) or No ($s_{1,3,2}$).

The event tree is depicted in Fig. 1. We are interested in the probability of failure, and thus set those consequences leading to failure equal to 1 and all the others equal to 0: $a_{1,1,1} = a_{1,2,1} = a_{1,3,1} = 1$ , and all other $a_{i_1,i_2,i_3}$ are 0.

All available information on probabilities of events is imprecise, and thus sets of probability distributions may be constructed. In fact, one may show that sets of probability distributions are convex. The vertices of theses sets are also called extreme points or extreme distributions (Bernardini and Tonon 2010).

For the initiating event $S_{1,0}$, the information is given as follows: (1) 10% of voids are either large or intermediate; (2) 80% of voids are small; (3) the remaining 10% of voids is indeterminate. Set $\Psi_{1,0}$, the set of probability distributions of event $S_{1,0}$ has four vertices $\mathbf{p}^1_{EXT_{1,0}}$ = (0, 0.9, 0.1)$^T$, $\mathbf{p}^2_{EXT_{1,0}}$ = (0, 1, 0)$^T$, $\mathbf{p}^3_{EXT_{1,0}}$ = (0.1, 0.8, 0.1)$^T$, and $\mathbf{p}^4_{EXT_{1,0}}$ = (0.2, 0.8, 0)$^T$.

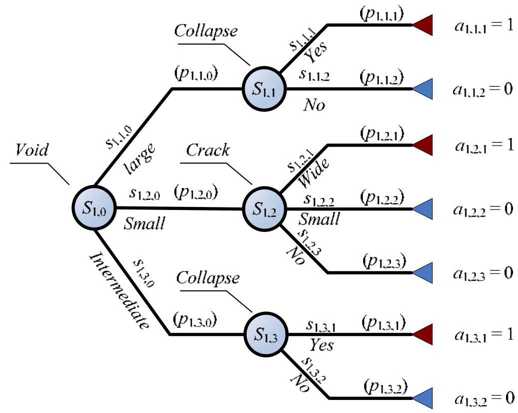


**FIG. 1. Event-tree for a leaking water-conveyance tunnel (You and Tonon 2011).**

At event $S_{1,1}$, information is given in terms of probabilities conditional to large voids ($s_{1,1,0}$), and evaluated as $0.8 \le P(s_{1,1,1}|s_{1,1,0}) \le 0.9$. Set $\Psi_{1,1}$ has two extreme points: $\mathbf{p}^1_{EXT_{1,1}}$ = (0.8, 0.2)$^T$ and $\mathbf{p}^2_{EXT_{1,1}}$ = (0.9, 0.1)$^T$.

At event $S_{1,2}$, the following information is available: in the case of small void ($s_{1,2,0}$), the probability of wide cracks ($s_{1,2,1}$) is less than twice of the probability of small cracks ($s_{1,2,2}$); twice of the probability of wide cracks ($s_{1,2,1}$) is more than the probability of no cracks ($s_{1,2,3}$); a small crack ($s_{1,2,2}$) is less probable than no cracks ($s_{1,2,3}$). These information could be expressed in inequalities: $P(s_{1,2,1}|s_{1,2,0}) \le 2P(s_{1,2,2}|s_{1,2,0})$; $2P(s_{1,2,1}|s_{1,2,0}) \ge P(s_{1,2,3}|s_{1,2,0})$; $P(s_{1,2,2}|s_{1,2,0}) \le P(s_{1,2,3}|s_{1,2,0})$ has three extreme points: $\mathbf{p}^1_{EXT_{1,2}}$= (0.29, 0.14, 0.57)$^T$, $\mathbf{p}^2_{EXT_{1,2}}$= (0.5, 0.25, 0.25)$^T$, and $\mathbf{p}^3_{EXT_{1,2}}$= (0.2, 0.4, 0.4)$^T$.

At event $S_{1,3}$, probability of collapse conditional to intermediate voids ($s_{1,3,0}$) is evaluated as: $0.5 \le P(s_{1,3,1}|s_{1,3,0}) \le 0.6$, and thus $\Psi_{1,3}$ has two vertices: $\mathbf{p}^1_{EXT_{1,3}}$ = (0.5, 0.5)$^T$ and $\mathbf{p}^2_{EXT_{1,3}}$ = (0.6, 0.4)$^T$.

To determine the extreme values of the failure probabilities, we need to find the maximum and minimum value of function $\sum_{i=1}^{3}\sum_{j=1}^{n_i} a_{1,i,j}(p_{1,i,j})(p_{1,i,0})$, which is a non-linear and non-convex function of probabilities $p_{1,i,j}$. Besides being computationally intensive (Luenberger 1984), non-linear and non-convex problems may yield local minima and maxima. Also, the computational effort will increase dramatically with the dimensions of the problem.

Here we are going to show how the problem can be efficiently solved: the idea is to solve the problem step by step, i.e., by breaking down the entire tree into sub-trees. In each sub-tree, linear optimization problems are solved, which are much easier to solve these non-linear and non-convex problems.

We first consider the sub-trees for $S_{1,1}$, $S_{1,2}$, and $S_{1,3}$, respectively. In set $\Psi_{1,1}$, the extreme values of function $a_{1,1,1}p_{1,1,1} + a_{1,1,2}p_{1,1,2}$ are achieved by solving the linear programming problem (1), where $a_{1,1,1}$ = 1 and $a_{1,1,2}$ = 0:

$$\textit{Maximize (minimize)}\ a_{1,1,1}p_{1,1,1} + a_{1,1,2}p_{1,1,2} \qquad (2)$$

*Subject to*

$$\begin{pmatrix} p_{1,1,1} \\ p_{1,1,2} \end{pmatrix} = c_1 \mathbf{p}^1_{EXT_{1,1}} + c_2 \mathbf{p}^2_{EXT_{1,1}};\ c_i \geq 0; \sum_{i=1}^{2} c_i = 1.$$

Its maximum value 0.9 is achieved at $\mathbf{p}^2_{EXT_{1,1}}$ and the minimum value 0.8 at $\mathbf{p}^1_{EXT_{1,1}}$.

For the sub-tree at $S_{1,2}$, the extreme values are equal to 0.5 and 0.2, achieved at $\mathbf{p}^2_{EXT_{1,2}}$ and $\mathbf{p}^3_{EXT_{1,2}}$, respectively. Likewise for $S_{1,3}$, the maximum value for $a_{1,3,1}p_{1,3,1} + a_{1,3,2}p_{1,3,2}$ ($a_{1,3,1} = 1$ and $a_{1,3,2} = 0$) is 0.6 at $\mathbf{p}^2_{EXT_{1,3}}$ and minimum value 0.5 at $\mathbf{p}^1_{EXT_{1,3}}$.

Next, we carry out the analysis for the sub-tree at $S_{1,0}$ based on the results from solutions for sub-trees at $S_{1,1}$, $S_{1,2}$and $S_{1,3}$. The optimization problems are

*Maximize:* $0.9p_{1,1,0} + 0.5p_{1,2,0} + 0.6p_{1,3,0}$

*Minimize:* $0.8p_{1,1,0} + 0.2p_{1,2,0} + 0.5p_{1,3,0}$

*Subject to*

$$\begin{pmatrix} p_{1,1,0} \\ p_{1,2,0} \\ p_{1,3,0} \end{pmatrix} = \sum_{i=1}^{4} c_i \mathbf{p}^i_{EXT_{1,0}};\ c_i \geq 0; \sum_{i=1}^{4} c_i = 1 \qquad (3)$$

Problem (3) achieves its maximal value (i.e., 0.58) at $\mathbf{p}^4_{EXT_{1,0}}$, and its minimum value 0.2 at $\mathbf{p}^2_{EXT_{1,0}}$. Therefore, the upper and lower failure probabilities are equal to 0.58 and 0.2, respectively.

## FTA WITH IMPRECISE PROBABILITIES

In Fault Tree Analysis, the failure event (major fault) is logically connected with the sub-events (alternative faults) by gates. Here we only consider two basic gates: OR- and AND-gates (See Fig. 2 and Fig. 3). Any event in the fault tree has only two possible states: occurrence or not occurrence. The occurrence probabilities for the failure events are assumed to be given imprecisely, i.e. as interval probabilities [$P_{\mathrm{LOW}}$, $P_{\mathrm{UPP}}$].

For the OR-gate in Fig. **2**, the occurrence probability for the failure event $E$ is

$$P(E) = 1 - P_{\underbrace{2,2,\ldots,2}_{n}} \qquad (4)$$

where $P_{2,2,\ldots,2}$ is the probability of that none of the $n$ events occurs, and thus 1- $P_{2,2,\ldots,2}$ is the probability that the complementary event (any of the $n$ events ) occurs.

For the AND-gate in Fig. 3, the occurrence probability for the event $E$ is

$$P(E) = P_{\underbrace{1,1,\ldots,1}_{n}} \qquad (5)$$

where $P_{1,1,\ldots,1}$ is the probability that all the $n$ events occur.

Within the methodology developed in this study, independence is not the only interaction assumed between sub-events. Various types of interaction can be considered, such as unknown interaction, different types of independence or irrelevance, correlation etc. More details regarding the interactions can be found from Tonon, You and Bernardini (2009).

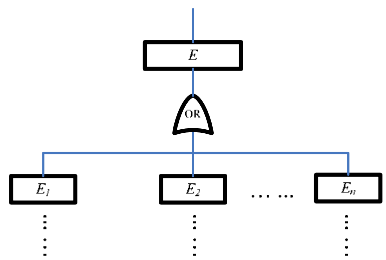


FIG. 2 Sub-tree with OR-gate.

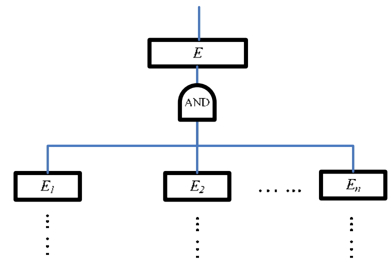


FIG. 3 Sub-tree with AND-gate.

The objective of FTA is to determine the upper and lower bounds of the failure probability of the top event. The FTA with imprecise probabilities proceeds in a bottom-to-top pattern:

1. Start the analysis from the bottom of the fault tree, where the basic failure events cannot be decomposed further.
2. Set up the constraints according to the defined interaction between sub-events and calculate $P_{1,1,\ldots,1}$ or $P_{2,2,\ldots,2}$.
3. Determine the upper and lower bounds of the upper level event.
4. Repeat Step 2 through Step 3 with all events in the same sub-tree till the top event is included.

## REVISIT CASE HISTORIES

***Cast History 1***: The event-tree analysis of Section 2 was applied to analyze the potential risks at the design stage of a 1.27 km long and 8.1-meter diameter TBM tunnel under crossing the Han River in South Korea. Because the tunnel started and ended in the downtown area, the major concerns were the potential risks to neighborhoods and local business, existing structures and facilities. A risk analysis was conducted to quantify the occurrence probability of accidents (Hong et al. 2009). In this section, ETA with imprecise probabilities is carried by the authors and compared to the results obtained by precise inputs and from Hong et al. (2009).

Three important initiating events: poor ground conditions, high water pressure, and heavy rainfall were identified after an extensive analysis of the available empirical data. Here we focuses on the analysis for poor ground conditions as the initiating event. Without any mitigation measures, the initiating event would lead to an accident and cause an impact on schedule and cost, even tunnel failure. To avoid or mitigate the impact, safety measures are proposed, and classified into five categories: A. investigation/design; B. Process planning; C. Machine type; D. Construction management; E. Reinforcement. Under each initiating event, the success probabilities of safety measures A through E are obtained by averaging the probability evaluations from four experts. Therefore, we could admit the imprecision in the available data by using imprecise probabilities. Table 1 lists both imprecise and precise success probabilities of safety measures adopted in the analysis.

The event tree with the initiating event ‘Poor ground conditions’ is depicted in Fig. 4. The occurrence of accidents and their consequences are identified at the end of each probability path. The consequences are evaluated at five levels: catastrophic, critical, serious, marginal, and negligible. Based on the consequence, accidents are classified into three risk levels: I, II, and II, where catastrophic and critical accidents are grouped in level I, serious and marginal accidents belong to level II, and negligible accidents are grouped in level III. For risk level I, significant mitigation measures are to be used to reduce the risk level or to remove the causes of risk reasons; for risk level II, proactive mitigation measures need to be considered; risks at level III should be taken care of in the construction management. The objective of the risk management is to ensure that the occurrence probability of risks at level I is less than 5%.

Results obtained from the both precise and imprecise probabilities are summarized in Table 2. Results in Table 2 show that the occurrence probability of risks at level I is equal to 0.25 if using precise probabilities, while with imprecise probabilities it can be larger than 0.29. To ensure that the occurrence probability of risk I is less than 5%, the upper probabilities of risk I must be less than 5%. It is a stricter requirement than that in precise probabilities, where the probability of risks at level I is represented by a single value. Therefore, by admitting the imprecision in probability evaluation, more attention should be paid to risk management to ensure that the upper probability be in the acceptable range.

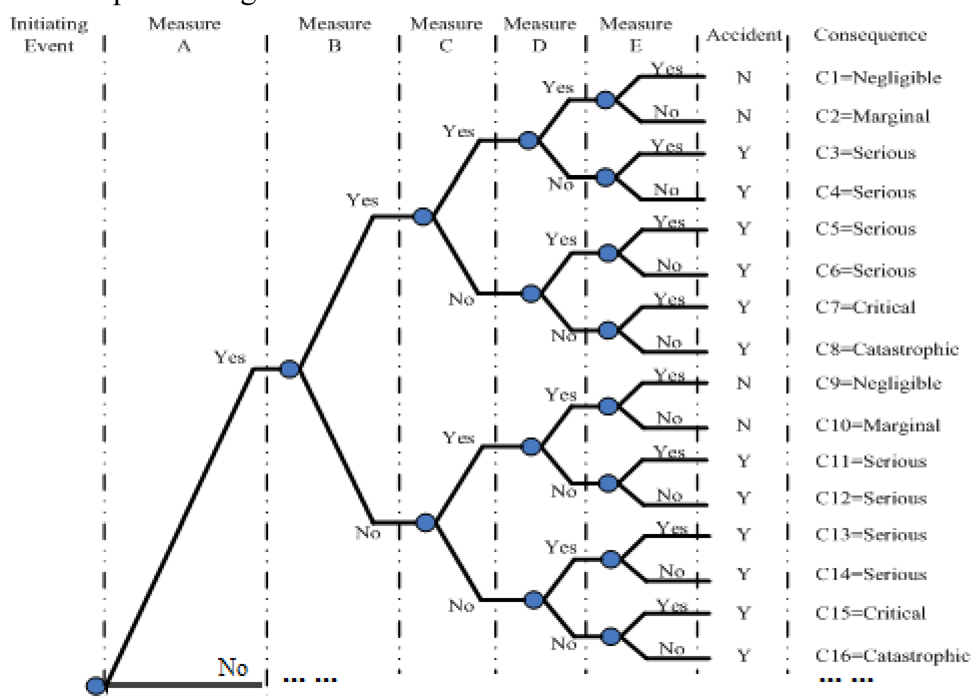


**FIG. 4 Event tree for initiating event of poor ground conditions (Hong et al. 2009)**

**Table 1. Success probabilities of safety measures**

| Safety measures | Imprecise | Precise |
|---|---|---|
| A. investigation/design | [0.00, 0.10] | 0.02 |
| B. Process planning | [0.10, 0.20] | 0.13 |
| C. Machine type | [0.60, 0.70] | 0.65 |
| D. Construction management | [0.60, 0.70] | 0.63 |
| E. Reinforcement | [0.30, 0.40] | 0.38 |

**Table 2. Probabilities of criticality and Probability of different risk levels**

| Consequence and Risk Level | Imprecise | Precise |
|---|---|---|
| Accident | [0.5100, 0.6400] | 0.59 |
| Risk Level I | [0.1807, 0.2944] | 0.25 |
| Risk Level II | [0.5208, 0.6819] | 0.59 |
| Risk Level III | [0.1080, 0.1960] | 0.16 |

***Case History 2***: The Stockholm Ring Road project is a vast underground construction project, and will provide a ring road around Stockholm to improve public transportation. The majority of the alignment is in hard rock, but several sections are in soft ground (Sturk et al. 1996). The project plan in 1992 based on "Dennis Agreement" was a political agreement on transit and highway improvements in and around Stockholm. However, the Stockholm Ring Road project has been opposed by green parties and local residents mainly because of environmental concerns since the permitting stage, which led to several project halts (Tollroads Newsletter, 1997). As of 2007, about half of the ring road was built. After a new environmental evaluation was completed, the project was resumed and is expected to be ready for opening in 2020 (Stockholm News, 2009).

Due to the high environmental concerns, in 1996 a 'Review Team' composed of experts in geotechnical engineering was set up at the beginning of the project to provide and ensure high quality technical solutions, where a risk analysis was conducted by using fault-trees to evaluate the environmental damage due to tunneling (Sturk et al. 1996). Fig. 5 shows the fault-trees, where the top event is 'the lime trees are damaged due to the tunneling activities'. It should be noted that all events in Sturk et al. (1996) are assumed to be independent to each other. Interaction noted in Fig. 5, such as 'unknown interaction' etc, is applied only when imprecise probabilities is considered later in this section. Finally, the occurrence probability for the top event is equal to 0.105, which Sturk et al. (1996) thought acceptable. However, the current status of the project tells us that it is not a good estimation. The probability might be higher than 0.105 and thus it is not acceptable.

As stated by Sturk et al. (1996), "the probabilities were assessed subjectively, based on expert knowledge and experience", which is a major reason to use imprecise probability instead of precise probabilities. As shown in Fig. 5, the interaction between events is assumed to be 'unknown interaction', 'independence', or 'uncertain correlation' with the correlation coefficient $\rho \in [0.5, 0.8]$. The lower and the upper probabilities for the top event are equal to 0.0189 and 0.3116, respectively.

Compare the two types of input: precise and imprecise. The only differences are (1) that the former is precise and the latter is given in terms of intervals, and (2) relaxing the constraint of independence and assuming different types of interaction. Finally, we find that the probability of the top event (i.e., the lime trees are damaged by tunneling activities) can be as high as 0.3116, which is much higher than the original estimation (0.105) and might not be acceptable anymore. As a result, further proactive and effective solutions should be considered to deal with the environmental concerns.

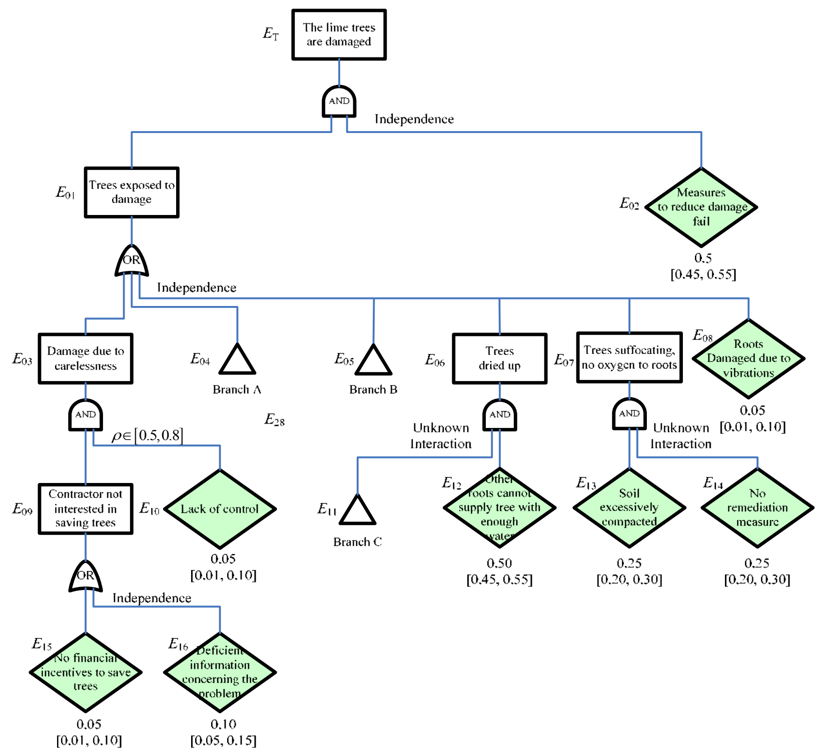


**FIG. 5. Fault tree for damage to lime trees, adapted from Sturk et al. (1996)**

## CONCLUSIONS

This paper proposed a novel method for dealing with risk analysis under imprecise probabilities. The ETA with Imprecise Probabilities starts the analysis from the sub-trees at the bottom, determines the upper and lower probabilities of the sub-trees, then continues to the upper part of the tree till the initiating event, and finally achieve the lower and upper bounds of the failure probability. In FTA with imprecise probabilities, the major fault is logically connected with the sub-events by OR- and AND-gates. The occurrence probabilities for the failure events are not assumed to be determined but are given imprecisely. Different types of interaction between sub-events can be taken into account, including unknown interaction, independence, and uncertain correlation. Two case histories of tunneling projects were revised. ETA and FTA were performed by using imprecise probabilities and precise probabilities, respectively. By comparing the results obtained from imprecise and precise inputs, we can conclude that by admitting the imprecision in probability evaluation, the upper and lower bounds on the failure probability or expected consequence convey the initial imprecision on the input values.

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