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An Integrated Quantitative Risk Assessment Method for Urban Underground Utility Tunnels

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A R T I C L E I N F O

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A B S T R A C T

With the rapid urbanization, urban underground utility tunnels have seen fast growth in China in the past few years. Urban utility tunnels can house various kinds of city 'lifelines' such as natural gas pipeline, heat pipeline, water supply system, sewer pipeline, electricity and telecommunication cables, which are of great significance to guarantee essential flows of energy, information and logistics for urban life. If a utility tunnel accident occurs, the consequences could be catastrophic. Risk assessment has been an important tool to examine the safety performance of industrial facilities and the effectiveness of safety measures. In this study, an integrated model based on dynamic hazard scenario identification (DHSI), Bayesian network (BN) modeling and risk analysis is proposed for risk assessment of urban utility tunnels. The worst-case scenario of urban utility tunnel accidents is identified by DHSI and modelled by BN. Meanwhile, risk analysis is conducted based on the results of BN considering casualties and economic losses. Finally, the integrated method is applied to evaluate the risk level of a real-world utility tunnel. The results indicate that the integrated quantitative risk assessment framework is an alternative and effective tool for safety assessment and land-use planning of urban utility tunnels.

1. Introduction

Urban utility tunnels (UUTs) are widely-used underground facilities in European countries and Japan for many years [1]. In the past few years, the rapid urbanization in China has greatly promoted the construction of UUTs, and the total length of which has increased remarkably since being encouraged by the Chinese government in 2015 [2]. Compared with the UUTs in Europe or Japan, those in China are more complex which contain most of city 'lifelines' such as gas pipelines, heat pipelines, water supply systems, sewer systems, electricity, and telecommunication cables. An allowable design of a utility tunnel prototype based on 'Chinese Technical Code for Urban Utility Tunnel Engineering' is illustrated in **Fig. 1** [3].

UUTs integrate various city lifelines in the underground space, with extra operation space for workers to install, inspect and maintain [4]. As a result, there is no need to frequently excavate roads, which may cause inconvenience of city life. However, as the UUTs contain several high-risk pipelines (particularly the gas pipeline) in an adjacent and small compartment, it is likely to cause serious coupling accidents, which could result in catastrophic casualties, economic losses and social impacts. Over the past few years, several serious lifeline accidents (gas pipeline, sewer pipeline, and heat pipeline) happened in China [5]. In Qingdao City, 2013, an explosion of gas pipeline resulted in 62 deaths; in Taiwan, 2014, a gas pipeline leakage caused a serious successive explosion resulting in more than 300 casualties and 3 roads hardly damaged; recently, in Guizhou province, a serious landslide led to the natural gas pipeline ruptured and then arose a serious explosion which resulted in 45 casualties. In the UUTs, the high-risk pipelines are possible to initiate a serious accident, and they may easily make coupling accidents because of the escalated impact of the domino effects [6]. Therefore, it is essential to put forward a comprehensive risk assessment model to analyze the risk of UUTs and provide appropriate technical supports to make risk-based emergency management.

The UUTs are newly emerging urban facility, and there are currently just a few research achievements on utility tunnel. The research work has mainly focused on utility tunnel operation management (regular operation, maintenance and inspection) and optimal structure framework design. How to conduct land-use planning for utility tunnel on

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multiple criteria (finance, safety, environment, convenience) is analyzed [7-9]. Several researchers have reviewed the development of utility tunnels from different countries [10]. More recently, Building Information Modeling (BIM) has been used to support the maintenance and operation of UUTs [11]. For the safety assessment and management of utility tunnels, some research has been done to identify the UUT hazards and the potential accidents [12-16], to simulate the gas leakage in UUTs [17-19], and to examine the influence of crustal movement (earthquake) on their structure stability [20,21]. However, comprehensive and quantitative studies for risk assessment of utility tunnel are still scarce, especially for the newly emerging complex underground utility tunnels in China.

In the past few years, although the studies of the comprehensive risk analysis of underground utility tunnels are rare, there has been much research on risk assessment of oil and gas pipeline, water supply pipeline, sewer system, or electricity lines [22-32]. These researches on pipeline risks could also provide technical supports for the risk analysis of utility tunnel accident. However, the conventional risk analysis methods such as fault tree are static with only binary states, which are often insufficient to make a comprehensive accident description and risk analysis. Furthermore, most UUT accident scenarios are dynamic with randomness and vagueness, and may involve secondary disasters due to domino effects. Compared with traditional risk analysis methods, Bayesian network (BN) is a promising technique that can incorporate uncertainties during the accident evolvement, perform probability updating given evidence, and handle multi-state variables [33,34]. Moreover, it can well demonstrate and assess accidents with secondary and derivative disasters due to domino effects [35-39].

In this study, an integrated risk assessment method based on Dynamic Hazard Scenarios Identification (DHSI), Bayesian network (BN) and risk analysis is proposed to evaluate and manage the safety of underground utility tunnel. DHSI is used to identify the worst-case scenario of utility tunnel accident, which may be initiated by gas leakage, sewer pipeline damage, heat pipeline failure or fire of wires and cables. Bayesian network is built based on the identified worst-case accident scenario. Risk analysis is calculated according to BN results. The proposed framework for risk assessment of UUTs could be helpful for the prevention and mitigation of utility tunnel accident and city land-use planning.

2. Methodology

The proposed framework for the integrated quantitative risk assessment of UUTs was illustrated in **Fig. 2**.

2.1. Dynamic hazard scenarios identification

The main capability of dynamic hazard scenario identification (DHSI) is aiming to identify the worst-case scenario of utility tunnel accidents, which is the foundation for risk assessment [40]. The origin of DHSI is from the work of Paltrinieri et al. who building the Dynamic Procedure for Atypical Scenarios Identification (DyPASI) [41]. The DyPASI method is focusing on identifying the high impact low probability (HILP) accident in the chemical plants. Due to the strong correlation between various pipelines inside UUTs, the hazards of UUTs are complicated and the HILP accidents are hard to identify. In addition, the operational conditions including the types of substance transported in the pipeline, the physical-chemical properties of the transported substances, the environmental factors, and the safety facilities should also be taken into account in the process of hazard identification. Furthermore, the defect of pipelines in the utility tunnel would have some coupling effects that may cause some new accident scenarios.

In this study, we present a DHSI method which can consider more parameters (the operational conditions of different pipelines, the physical-chemical properties of the transported substances, the environmental factors, and the safety facilities) during the accident evolution. The steps of the DHSI are presented as follows: 1) Identify the possible initiating events of a pipeline accident according to accident reports, database, research literature; 2) Build event chains for single pipeline accidents (check whether there are missing events; if some events are missing, revise the corresponding event chain) and try to figure out the connections between them; 3) According to the connections of previous event chains, establish different accident scenarios; 4) Determine the worst-case accident scenario taking advantage of occurrence threshold and expert experiences.

2.2. Bayesian network

Bayesian network (BN) is a widely used probabilistic method, which is a kind of directed acyclic graph (DAG). The BN nodes represent the target variables, and the arcs stand for the cause-effect relationships among BN node variables [42]. The BN nodes are divided into parent nodes and child nodes, a parent node is the cause of its child node in most condition. Every BN node is attributed with a conditional probability table (CPT), which reflects the probabilistic relationship between the target node and its parent nodes.

One advantage of the Bayesian network is that the joint probability distribution of its nodes can be easily calculated. If set $P_a(V_i)$ as the parent node of V_i, the joint probability distributions $P(V) = (V_1, V_2, V_3,$

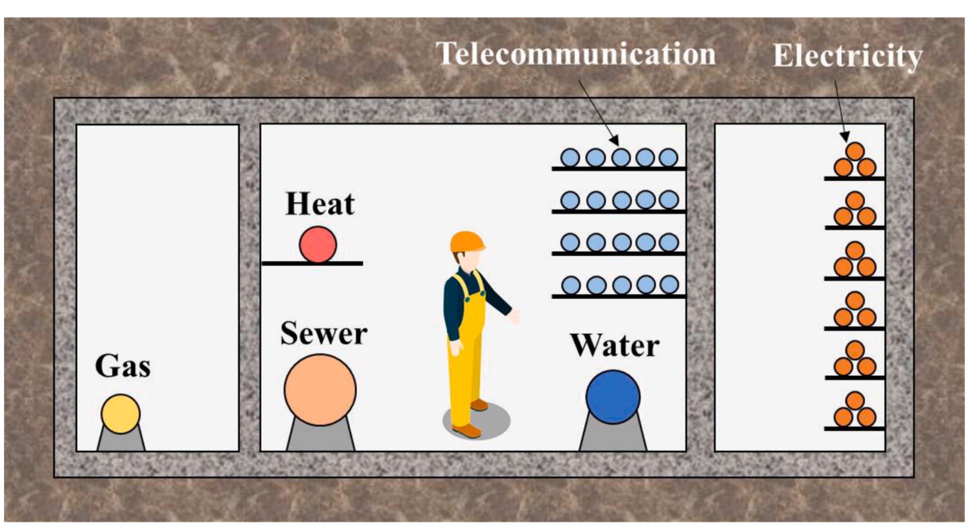

Fig. 1. The internal structure of a Chinese UUTs.

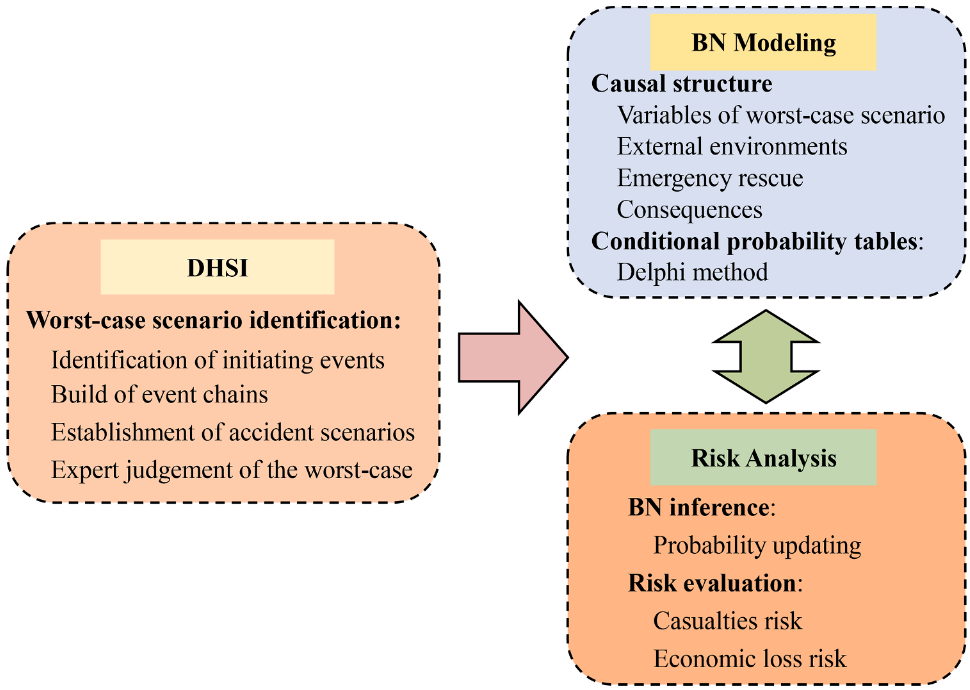

Fig. 2. The framework of the integrated quantitative risk assessment method.

…, V_k) can be calculated as follows:

$$P(V_1, V_2, \cdots, V_k) = \prod_{i=1}^{k} P(V_i|P_a(V_i)) \tag{1}$$

The other advantage of the Bayesian network is the attractive ability to update probability dynamically when new evidence becomes available. If set the prior probability of the variable V to $P(V) = (V_1, V_2, V_3, \ldots, V_k)$, the new evidence is Y, and the posterior probability $P(V/Y)$ can be obtained use Eq. (2):

$$P(V|Y) = \frac{P(V)P(Y|V)}{\sum_{i=1}^{k} P(Y|V_i)} \tag{2}$$

2.3. Risk analysis

The risk analysis for the UUTs accident should consider each potential accident. In a typical UUTs accident, a serious pipeline accident may lead to another secondary accident. For instance, a gas pipeline explosion in the gas compartment may destroy the concrete wall and made the other pipeline breakdown. Thus, all the risk of every potential pipeline accident should be considered when calculating the risk of UUTs accident.

Generally, the risk R is defined as the product of the occurrence probability P of a specific event and its severity S, as shown in Eq. (3):

$$R = P \times S \tag{3}$$

While in a UUT accident, the initiating event may cause various secondary accidents. In order to clarify the risk of each accident and be easy to calculate, the secondary events are assumed to be independent in this paper. It should be noted that the probability of each secondary event can directly obtain from BN as it has already considered the interaction between initiating events and secondary events. Thus, the expected risk value of all the potential accident of a utility tunnel accident (R_u) can therefore be determined by Eq. (4):

$$R_u = \sum_{i\in\{\text{All the events}\}} P_i \times S_i \tag{4}$$

Where P_i represents the occurrence probability of the accident events and S_i is the consequences of the event. In this study, the consequences of a utility tunnel accident are expressed by "Casualties" and "Economic loss", and the values of these two factors are intended to be estimated by BN inference results. The BN is established considering that an initiating event leads to dynamic hazard scenarios of utility tunnel accidents. Therefore, the initiating event is a key conditional point. Herein, P_{init} is the occurrence probability of the initiating event (e.g. a gas pipeline leakage), S_{fj} is the specific accident consequence factor f ($f\in$\{casualties, economic loss\}) of a cascading event j ($j\in$intermediate events) given the initiating event, P_{Sfj} is the occurrence probability of the corresponding cascading event (j) given the initiating event, R_{Sf} as the risk of the specific kind of accident consequence factor. In this case, the associated calculation of risk R_{Sf} can be specified by Eq. (5):

$$R_{Sf} = \left(\sum_{j\in\{\text{secondary events}\}} P_{Sfj} \times S_{fj}\right) \cdot P_{init} \tag{5}$$

Since the state classifications of BN nodes (Casualties or Economic loss) are set as discrete values (we use the range of number to represent the state of BN nodes), thus we implement the average interval ($\overline{Sij}$) as the representative value for the calculation in Eq. (6). Besides, for the state with infinite value, such as the serious state (More than 30 death) of "Casualties" node, we used '30′ in the calculation of risk.

$$R_{Si} = \left(\sum_{j} P_{Sij} \times \overline{S_{ij}}\right) \cdot P_{init} \tag{6}$$

3. Application

In this section, the proposed methodology is applied to analyze a real UUT accident which includes several accident scenarios involving domino effects. Based on the BN-based model, the impact of emergency rescue and safety measures are evaluated, and the risk of accident consequences are also estimated.

3.1. An allowable designed prototype of chinese UUTs

According to the Chinese Technical Code for Urban Utility Tunnel Engineering, the structure of UUTs can follow various patterns [3]. In this study, an allowable designed prototype of UUTs is presented as shown in Fig. 3. This UUTs is constructed under the greenbelt of a four-lane road with a hospital, a stadium, four residences and a business center nearby. The vertical distances of these buildings from the utility tunnel are 150 m, 80 m, 120 m, and 100 m respectively. The size of this hypothetical UUT is two hundred meters long, ten meters wide and four meters high. The UUT contains three compartments: the gas compartment with a gas pipeline only, the utility compartment contains a sewer pipeline, a water supply pipeline, a heat pipeline, several telecommunication lines and low-voltage electricity lines, and the high-voltage compartment with some extremely high-voltage electricity lines inside. The detailed information of three compartments and the pipelines is listed in Table 1.

3.2. Identification of the worst-case accident scenario

The complicated and fast-developing UUT is a kind of newborn facility in China, with little operational data or accident records. At this stage, DHSI is suitable for identifying the worst-case accident scenario of UUTs as follows.

First, based on accident reports, database, research literature of directly buried pipelines and considering expert experiences of the characteristics of utility tunnels, single-pipeline accidents (event chains) in the UUT were determined. There are six kinds of pipelines in this case: gas, sewer, heat, water, electricity and telecommunication. The gas and sewer pipelines contain flammable gas and may catch on fire and/or explode. The electric shock is a common accident for traditional electricity cables, but the cables in the utility tunnels are arranged in a relatively controlled space. However, the covering layer of electricity cables and telecommunication wires can be ignited easily. The rupture of heat pipelines can seriously burn personnel and harm facilities. Although the rupture of water pipelines can lead to drowning, it is relatively easy to control, with limited influence on other pipelines. So, four initiating events were identified: a leakage of gas, a leakage of sewer, a rupture of heat and fire of wires/cables.

Second, four typical single-pipeline accidents (event chains) of high-risk in the UUTs were determined: a gas leakage and fires/explosions, a sewer leakage and explosion, a rupture of heat and scalding, a fire of wires/cables. The first accident is initiated by gas leakage. In the early stage of gas leakage, if there is enough ignition energy near the source of the leakage, a diffusion fire (jet flame, flash fire) may occur. If the leaked gas doesn't catch on fire early to form jet fire, the leaked gas will continuously disperse and accumulate and can explode with enough energy and proper concentration. The gas explosion of a 20-meter utility tunnel model with 9.5% methane can result in 0.6 MPa peak overpressure and cracks in the concrete wall [43], which indicates that the explosion in the real 200-meter gas compartment is likely to damage the concrete wall seriously. Meanwhile, the gas leakage can also cause poisoning and/or suffocation of the maintenance personnel. The second accident is triggered by leakage of sewer pipeline. The sewer pipelines transfer domestic wastewater, which can produce sulfide and methane due to anaerobic biological transformations [44]. When the leakaed flammable gas continuously accumulates in the compartment without sufficient ventilation for a long time, poisoning, fire, or even explosion would occur. In addition, the leaked pollutants would affect the internal environment of the UUT and harm nearby pipelines and internal

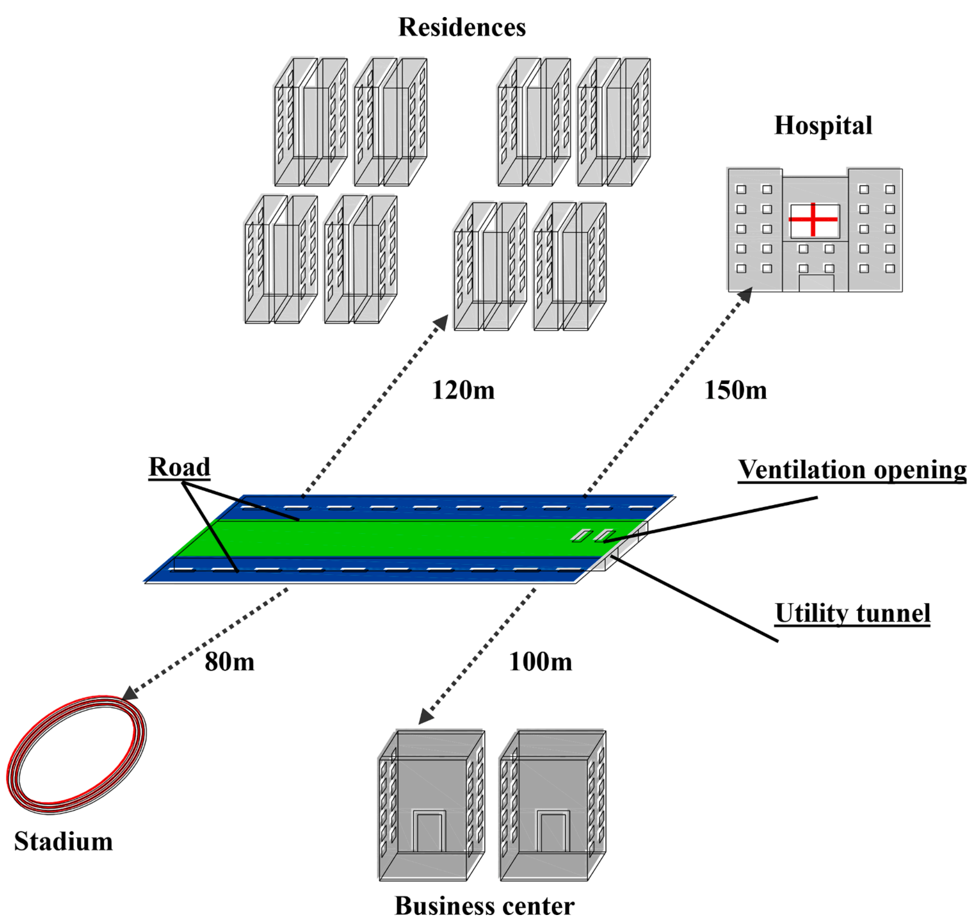

Fig. 3. The layout of an allowable designed prototype of Chinese urban utility tunnel.

Table 1
The detailed information of each compartment in the utility tunnel.

Compartment	Length (m)	Width (m)	Height (m)	Pipeline	Diameter (mm)	Pressure (Mpa)	Voltage (KV)
Gas	200	2.0	2.4	Gas	300	1.5	–
Utility	200	4.4	3.5	Heat	500	2.5	–
				Sewer	800	–	–
				Water	500	2.5	–
				Electricity	–	–	<10KV
				Telecommunication	–	–	–
High voltage	200	2.4	3.5	Electricity	800	–	>10KV

ancillary facilities. The third accident is caused by the heat pipeline leakage. The heat pipeline carries high-temperature and high-pressure (HTHP) medium, which can cause the maintenance personnel seriously injured. Besides, a large amount of HTHP substance could harm the nearby safety facilities in the same compartment and lead to other unexpected accidents. The fourth accident is a fire of wires/cables, which is triggered by short circuits, overloads, or smoking. The fire of wires/cables can easily propagate and ignite other nearby facilities.

Third, combining the four single-pipeline accidents (event chains), four accident scenarios were established as Fig. 4 shows. The explosion is the only kind of accident can damage the concrete wall of utility tunnels, so it can continuously damage other pipelines in the adjacent compartment. Hence, the explosion of gas pipelines and sewer pipelines can cause accidents of the other three pipelines. As for the rupture of heat pipelines and fire of wires/cables, they can only cause secondary accidents in the same compartment.

Finally, based on occurrence threshold and expert experiences, the worst-case accident scenario was determined. The scenario a and b are more catastrophic than others, since explosions of gas pipeline and sewer pipeline can cause damage to the concrete wall and secondary damage to other UUT pipelines, city road and nearby buildings. Both gas-triggered accident scenario and sewer-triggered accident scenario can cause accidents of other three pipelines. Liu tested methane concentration of sewer manhole 1320 times, 382 of which were 10% to 25% LEL (Lower Explosive Limit), 28 were 25% to 100%LEL, and 10 were higher than 100%LEL [45]. Although the methane concentration in sewer pipeline can reach the 100%LEL and explode with sufficient ignition, the probability of such condition is still rare. Hence, the worst-case accident scenario of UUTs is determined as gas-triggered accident scenario, as Fig. 4**a** shows.

3.3. Bayesian network modeling

3.3.1. BN nodes and the causal relationships

Based on the worst-case accident scenario, then considering the external environment of UUTs (surrounding building, occurrence time, population density), emergency rescue, and consequences (economic loss and casualty), a complete BN causal structure was established in Fig. 5. Meanwhile, the states and descriptions of all BN nodes were illustrated in Table 2 and the following passage respectively.

1) Defect of gas pipeline. The defect of a gas pipeline is the origin of gas leakage, fire/explosion and further secondary accidents. The two states represent the defect level of the pipeline structure caused by various influencing factors, such as erosion, incorrect manufacture, and unreasonable design. The “Puncture” state represents a hole smaller than 2 cm, while the “Rupture” represents a hole larger than 2 cm.
2) Ignition. Although fire is strictly prohibited in the utility tunnel, there are still some possible ways to cause fire or ignition, such as the electric spark, short circuit, illegal fire operation, and so on. Thus, this study gives an “Ignition” node with two states: “Yes” and “No”.
3) Ventilation. According to Chinese Technical Code for Urban Utility Tunnel Engineering, the air exchange frequency in the utility tunnel should not be less than two times per hour, and in the gas compartment, even more than six times per hour [3]. Furthermore, the frequency should be more than twelve times per hour, while accidents happen. The “Good” state represents the normal working situation of the ventilation instruments, while the “Poor” indicates the ventilation system is broken down.
4) Fire/Explosion-proofing measures. This node represents the condition of safety measures (such as automatic spraying system and fireproof door) in the UUTs.

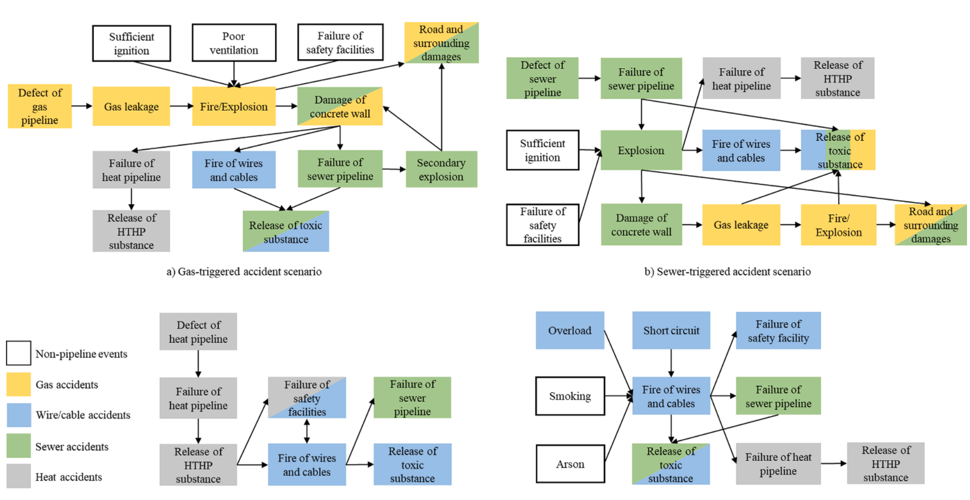

Fig. 4. The established accident scenarios of utility tunnel accidents.

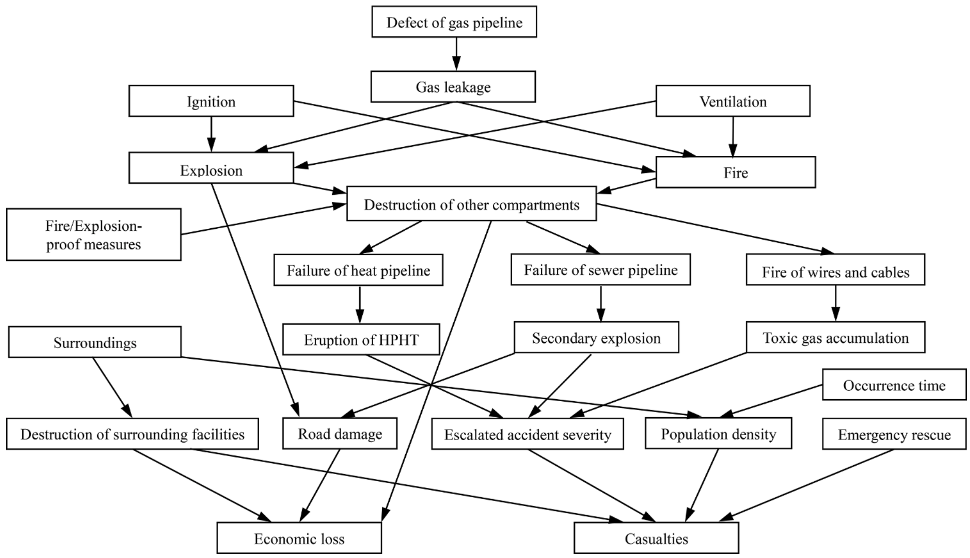

Fig. 5. The BN causal structure of a UUT accident scenario.

Table 2
The classified states of every BN node.

Node name	Classified states of every BN node
Defect of gas pipeline	(1) Puncture; (2) Rupture
Ignition	(1) Yes; (2) No
Ventilation	(1) Good; (2) Poor
Fire / Explosion-proof measures	(1) Good; (2) Poor
Surroundings	(1) Business center; (2) Hospital; (3) Residence; (4) Open area
Occurrence time	(1) Working time; (2) Rest time
Emergency rescue	(1) Good; (2) Poor
Gas leakage	(1) Slight; (2) Serious
Explosion	(1) None; (2) Slight; (3) Serious
Fire	(1) None; (2) Slight; (3) Serious
Destruction of other compartments	(1) None; (2) Slight; (3) Moderate; (4) Serious
Failure of heat pipeline	(1) None; (2) Slight; (3) Serious
Failure of sewer pipeline	(1) None; (2) Slight; (3) Serious
Fire of wires and cables	(1) None; (2) Slight; (3) Serious
Eruption of HPHT	(1) None; (2) Slight; (3) Serious
Secondary explosion	(1) None; (2) Slight; (3) Serious
Toxic gas accumulation	(1) Slight; (2) Moderate; (3) Serious
Destruction of surrounding facilities	(1) Slight; (2) Serious
Road damage	(1) Slight; (2) Serious
Escalated accident severity	(1) Slight; (2) Moderate; (3) Serious
Population density	(1) Less than 500/km^2; (2) 500 to 1000/km^2; (3) More than 1000/Km^2
Economic loss	(1) Less than 10 million; (2) 10million to 100 million; (3) More than 100 million
Casualties	(1) Slight; (2) Moderate; (3) Serious

5) Surroundings. The surroundings represent the type of buildings around the accident area. There are four kinds of states to represent the different level of finance importance and the population density: “Business building”, “Hospital”, “Residence” and “Open Area”.
6) Occurrence time. The occurrence time plays a critical role in a UUT accident. For instance, if the accident occurs at mid-night (rest time) near the business center, there wouldn’t be severe casualties, and if the accident time is ten o’clock in the morning, the accident consequences could be more severe.
7) Emergency rescue. The emergency rescue is essential when an accident occurs. A timely and effective rescue would reduce accident consequences dramatically. The states are set as “Good” and “Poor”, corresponding to the timely and delayed emergency rescue, respectively.
8) Gas leakage. “Slight” represents a small amount of gas leaking from the gas pipeline and accumulating in the gas compartment, while “Serious” stands for massive gas leakage and accumulating in the compartment.
9) Explosion. A gas explosion could cause overpressure. The “Slight” state means resulting in a slight crack of the compartment wall, “Serious” indicates that the energy of the explosion enables to badly destroy the concrete wall for separate compartments and destroy other pipelines in other compartments of the utility tunnel. The “None” state means no explosion.
10) Fire. The “Slight” state represents the energy is not able to destroy the concrete wall and cannot spread to another compartment. The “Serious” state means the fire can last several hours and make the fire-proof door or concrete wall fail. Thus, the pipelines in the other compartment could be influenced. The “None” state means no fire occurs.
11) Destruction of other compartments. This node means the damage caused by fire or explosion accident. “None” represents the compartments are not damaged. “Slight” state represents that the initial accident makes the pipelines slightly damaged in other compartments. “Moderate” represents the compartment wall is destroyed and the pipelines in other compartments are under damage. “Serious” means the UUT structure is seriously destroyed.
12) Failure of heat pipeline. This node means the damage level of the heat pipeline because of the initiating fire or explosion accident. If the concrete wall is slightly damaged, the failure probability of the heat pipeline is zero. However, if the wall is moderately damaged, the heat pipeline could be slightly impacted. The serious damage of the concrete wall could lead to heavy damage to the heat pipeline.
13) Failure of sewer pipeline. This node indicates the impact of fire or explosion on the sewer pipeline. The states of this node are classified as “None”, “Slight”, and “Serious”.
14) Fire of wires and cables. This node represents the fire of the wires and cable caused by the fire or explosion accident. The states of ‘Fire of Wires and Cables’ are classified as “None”, “Slight”, and “Serious”.
15) Eruption of HPHT. According to the regulation of China, if the heat pipeline transports water, the pressure should be less than 2.5 Mpa with the temperature less than 200°C, and if it transports

steam, the pressure is limited to 1.6 Mpa with temperature no more than 350℃ [46]. The "none" state means no water or steam burst out. The "Slight" state represents the pressure of HPHT is than 2 Mpa and the temperature is less than 100 ℃. The "Serious" state means the pressure is more than 2 Mpa and the temperature is bigger than 100 ℃.

16) Secondary explosion. The secondary explosion is normally caused by a failure of the sewer pipeline. The amount of flammable gas releasing from the sewer pipe determines the energy of the secondary explosion. The states are classified as "None", "Slight", and "Serious".
17) Toxic accumulation. The "Slight" state represents the concentration of released toxic gas only can make people uncomfortable; the "Moderate" state can suffocate people; the "Serious" state means the toxic gas enables to make people death [47].
18) Destruction of surrounding facilities. This node means the destruction of the original explosion and the secondary explosion. The "Slight" state represents the explosion overpressure wouldn't destroy the buildings, only the windows being broken. The "Serious" state indicates the explosion energy would make the entire building seriously damaged.
19) Road damage. Road damage represents the serious impact of the original explosion and secondary explosion.
20) Escalated accident Severity. This node represents the impact of coupling accidents. The conditions of the upper three nodes determine the states of this node. The "Slight" state means that the states of three upper parent nodes include no more than one "Moderate" state, while the "Serious" state represents the states of three upper parent nodes comprise at least one "Serious" state, and other state combination situations are given as "Moderate" state.
21) Population density. The population density has a great impact on accident consequences, especially for the casualties. In this study, the population density is classified into three states: "less than 500 persons/km2", "500 to 1000 persons/km2" and "more than 1000 persons/km2".
22) Economic loss. This node is to evaluate the consequences of utility tunnel accidents. According to the State Council Order No. 493 of China, the "Slight" state is less than RMB 50 million, the "Moderate" state is RMB 50 to 100 million, and the "Serious" is set as more than RMB 100 million [48].
23) Casualties. Casualty is a normal index for evaluating the consequences of an accident. According to the Production Safety Accident Report, Investigations and Handling Rules of China, this node is classified with three states. The "Slight" state represents "less than 10 deaths or less than 50 injuries"; the "Moderate" state means "11 to 30 deaths or 51 to 100 injuries", and the "Serious" state describes "more than 30 deaths or more than 100 injuries" [48].

3.3.2. Conditional probability tables

Generally, there are three approaches to determine conditional probability tables of the Bayesian network. First, if there is a large amount of statistical data, the parameter learning method could be a good choice. Second, if there is an absence of adequate historical data for the target cases, it has to employ an expert elicitation method. Third, it is taking advantage of both parameter learning and expert elicitation. Because of the lack of data on catastrophic events, the expert elicitation is normally used in BN derivation.

For the utility tunnel accidents, there have been few historical records or statistical data. In this study, we employ expert elicitation to derive BN probabilities (use the Delphi method to deal with experts' data to determine the CPTs of BN nodes), and furthermore refer to the data of direct-buried pipeline accidents or the referenced values in the previous studies. The Delphi method has been proven to be effective to construct BN in various applications [49]. In this study, the variation coefficient is applied to diagnose which expert's opinion varies from others, and the Cronbach's alpha is used to test whether the experts' data reach consistent [50]. Generally, when the Cronbach's alpha is greater than 0.8, it is believed that the experts are reaching a consistency. The corresponding calculation Equations are listed below:

$$Vj = \frac{\sigma j}{Xj} \tag{7}$$

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{k}\sigma^2 Y}{\sigma^2 X}\right) \tag{8}$$

where V_j is the variation coefficient of index j (the variation coefficient represents the variance of these experts' opinions on index j), σ_j is the averaged variances of the components, α is the Cronbach's alpha coefficient, K is the total number of target components, σ^2X is the variance of the obtained total scores, which are collected from the questionnaire distributed to the experts, σ^2Y is the variance of the specific components.

In this study, the prior probability of some root nodes is collected referring to some similar direct-buried pipeline accident records or literature, as shown in Table 3. The CPTs of other BN nodes are determined by the expert judgement that is treated by the Delphi method. The Cronbach's alpha is calculated through SPSS (IBM SPSS statistics 25.0).

Here is an example (node "Explosion") of determining the CPTs based on the Delphi method. The first three columns of Table 4 show all the possible combinations of the parent nodes' state. "E1 to E5" is the data collected from the five independent experts. After we collect all the data, the value of Cronbach's alpha can be calculated. In this example, the Cronbach's alpha is 0.981, higher than 0.8, which shows the five experts reach consistency. Thus the final CPTs of the corresponding state of "Explosion" can be calculated (the last column). If the value of Cronbach's Alpha can not reach the consistency criterion, the experts need to reconsider their decision until reach that criterion. After determining the CPTs to all the child nodes, the complete BN framework is established (see Fig. 6). In this study, the BN probability update and BN inference are achieved by using a widely used BN solver (Netica 4.16, Norsys Software Corp).

4. Results and discussion

UUT accidents are complicated and may result in various consequences. In this section, we mainly discuss three typical UUT accident scenarios to demonstrate the application of the proposed BN-based method. The setting states of the parent nodes of these three accident scenarios are listed in Table 5 (the * means this node will change to each state for comparison). The first accident scenario is aiming at estimating the expected risk of utility tunnel accidents among different surroundings. The second accident scenario shows the impact of the emergency rescue to the accident consequence. The third accident scenario focuses on examining the influence of fire/explosion-proof measures in the UUTs.

Table 3
The prior probability of some root nodes.

Node	State	Probability
Defect of gas pipeline	Puncture	0.76
	Rupture	0.24
Ventilation	Good	0.99
	Poor	0.01
Surroundings	Business center	0.2
	Hospital	0.1
	Residence	0.2
	Open area	0.5
Emergency rescue	Good	0.8
	Poor	0.2
Occurrence time	Working time	0.5
	Rest time	0.5

Table 4
Application sample of the Delphi method.

Parent BN nodes			Expert opinion on "None" state of "Explosion" node					Cronbach's alpha	Calculated results
Ignition	Gas leakage	Ventilation	E1	E2	E3	E4	E5		
(1) Yes	(1) Slight	(1) Good	95%	88%	60%	80%	85%	0.981	81.6%
(1) Yes	(2) Serious	(1) Good	50%	70%	50%	60%	65%		59%
(1) Yes	(1) Slight	(2) Poor	20%	70%	20%	30%	33%		34.6%
(1) Yes	(2) Serious	(2) Poor	0	5%	5%	5%	4%		3.8%
(2) No	(1) Slight	(1) Good	100%	100%	85%	90%	86%		92.2%
(2) No	(2) Serious	(1) Good	100%	98%	80%	90%	95%		92.6%
(2) No	(1) Slight	(2) Poor	100%	95%	70%	95%	96%		91.2%
(2) No	(2) Serious	(2) Poor	100%	75%	50%	80%	78%		76.6%

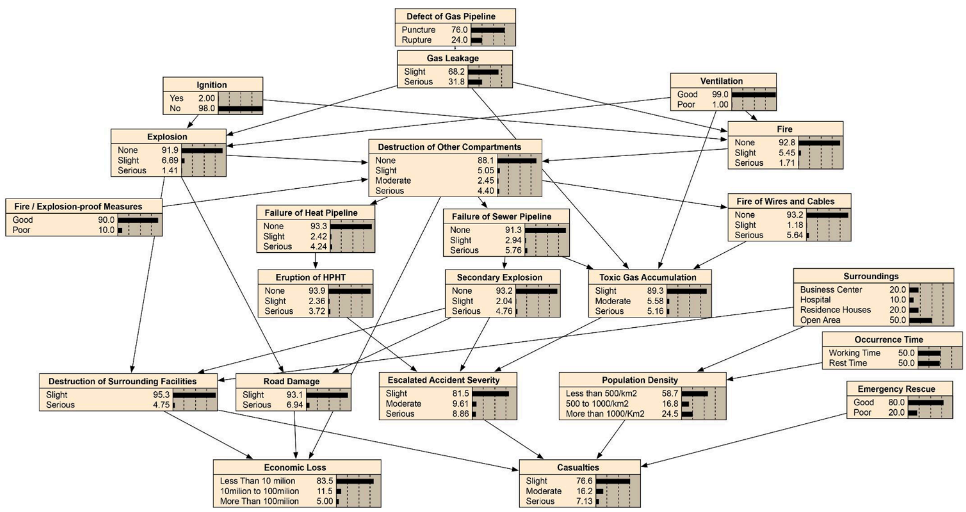

Fig. 6. Full Bayesian network of utility tunnel accident initiated by the defect of gas pipeline.

Table 5
The given evidence of some BN root nodes for three typical accident scenarios.

BN nodes	Setup of BN nodes		
	Scenario 1	Scenario 2	Scenario 3
Defect of gas pipeline	Rupture	Rupture	Rupture
Ignition	Yes	Yes	Yes
Ventilation	Poor	Poor	Poor
Fire / Explosion-proof measures	Good	Good	*
Surroundings	*	Business center	Business center
Occurrence time	Working time	Working time	Working time
Emergency rescue	Good	*	Good

4.1. Expected risk calculation via scenario 1

The estimated results of utility tunnel accident consequences (evaluated by Casualties and Economic loss) with different surroundings are presented in **Fig. 7**, which shows that a utility tunnel accident in open areas would cause less economic loss than that with other surroundings. However, the distribution of larger economic loss is still high. The main reason is the cost of rebuilding a utility tunnel is much more than other underground facilities. As for "Casualties", a utility tunnel accident that occurs in open areas is attributed to the lowest probability of serious accident consequences. However, when an accident occurs near "Business center" or "Hospital", the probability of the serious state increases dramatically with the value from 10.3% to 49.8% and 53.6%, respectively. However, the tendency of "Residence" is small compared to the other two surroundings. The main reason is that the population density in the hospital and business center at the working time is much higher than that in the residence.

The expected risk of a utility tunnel accident near different surroundings can be calculated according to Eq. (5) and (6). The statistical overall failure probability of gas pipeline from the European Gas Pipeline Incident Data Group is 5.75E-06/Km•year [51]. Referring to these statistics, in this study, we assume the initial failure probability of gas pipeline in the utility tunnel is 5.0E-08/Km•year. Taking a UUT accident that occurs in a business center as an example, the expected risk can be determined as follows:

a) For the expected "Economic Loss" risk:

$$R_{Economic} = \left(\sum_j P_{Sij} \times \overline{S_{ij}}\right) \cdot P_{init}$$
$$= \left(P_{S21} \times \overline{S_{21}} + P_{S22} \times \overline{S_{22}} + P_{S23} \times \overline{S_{23}}\right) \times Pinit$$
$$= (19.6\% \times 5 + 20.9\% \times 55 + 59.5\% \times 100) \times 5.0E - 08$$
$$= 3.60E - 06\ RMB\ million/Km{\cdot}year$$

b) For the expected "Casualties" risk:

$$RCasualities = \left(\sum_j P_{Sij} \times \overline{S_{ij}}\right) \cdot P_{init}$$
$$= \left(P_{S11} \times \overline{S_{11}} + P_{S12} \times \overline{S_{12}} + P_{S13} \times \overline{S_{13}}\right) \times Pinit$$
$$= (27.6\% \times 5 + 22.6\% \times 20 + 49.8\% \times 30) \times 5.0E - 08$$
$$= 1.04E - 06\ persons/Km{\cdot}year$$

In the same way, the expected "Economic loss" risk with other surroundings can be estimated as follows: "Hospital", 3.62E-06 *RMB*

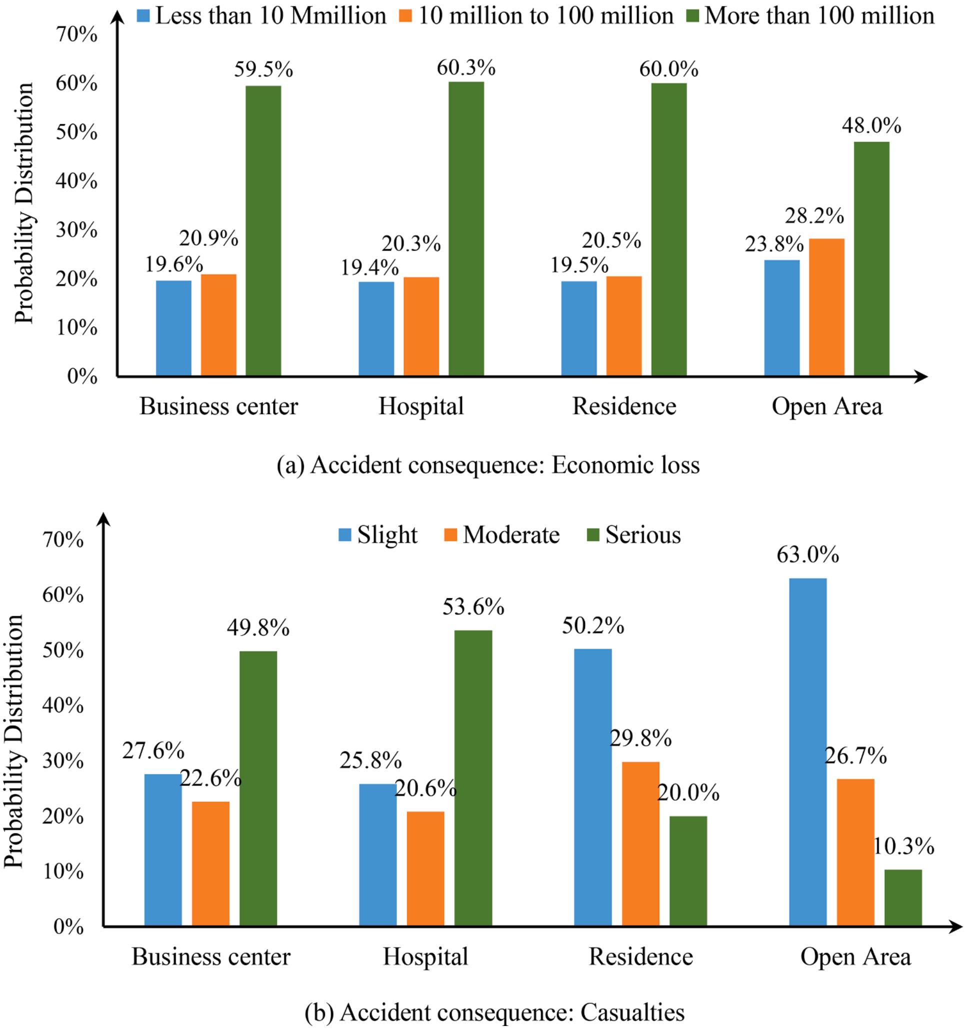

Fig. 7. The estimated probability distribution of accident consequences (Casualties and Economic Loss) with different ground surroundings.

million/Km·year; “Residence”, 3.61E-06 *RMB million/Km·year*; “Open area” 3.23E-06 *RMB million/Km·year*. The expected “Casualties” risk is 1.08E-06 *persons/Km·year*, 7.2 E-07 *persons/Km·year*, and 5.79 E-07 *persons/Km·year*.

4.2. Influence of emergency rescue via scenario 2

Normally, “Emergency rescue” could significantly influence the potential accident consequences, especially when there might be secondary accidents. When people face high-concentration toxic gas, the probability of casualty would increase. The estimated accident consequences (the probability distribution of “Slight”, “Moderate”, “Serious” consequence) under different “Emergency Rescue” are illustrated in Fig. 8. It can be observed that in the case of good “Emergency rescue”, the probability distribution of “Serious” casualties is only 49.8%, while the value significantly increases to 61.4% when the “Emergency rescue” is “Poor”. This demonstrates the significance of the effective emergency response for the control and mitigation of the utility tunnel accidents.

4.3. Impacts of fire/explosion-proof measures via scenario 3

Generally, fire/explosion-proof measures are significant to suppress initial-stage fire or mitigate explosions. The BN inference results of the probability distribution to examine the impacts of fire/explosion-proof measures are illustrated in Fig. 9 and Fig. 10. When the states of node “Fire/Explosion-proof measures” are set as “Good”, “Poor” respectively.

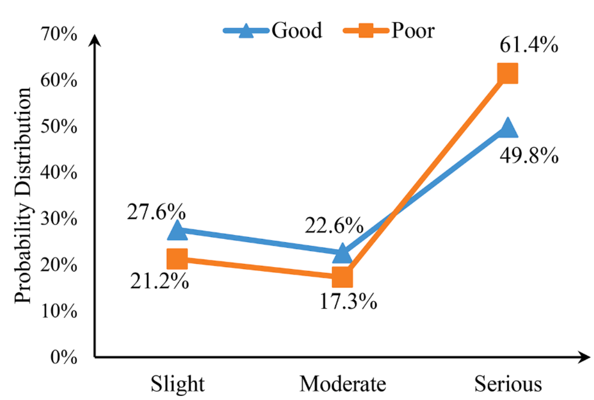

Fig. 8. The variance of “Casualties” with good and poor “Emergency Rescue”.

The variance of the estimated probability on “Serious” state of the accident consequences (“Casualties”, “Economic Loss”) are 3.2% (from 49.8% to 53.0%) and 6% (from 59.5% to 65.5%), respectively. It can be observed that whether the state of “Fire/Explosion-proof measures” is good or poor, the probability leading to “Serious” economic loss and casualties both stand for the largest probability proportion. As the state of node “Fire/Explosion-proof measures” is “Poor”, the “Slight” state and “Moderate” state of “Casualties” are distributed almost similar proportion: 18.8% and 16.5%, respectively. With regards to the node

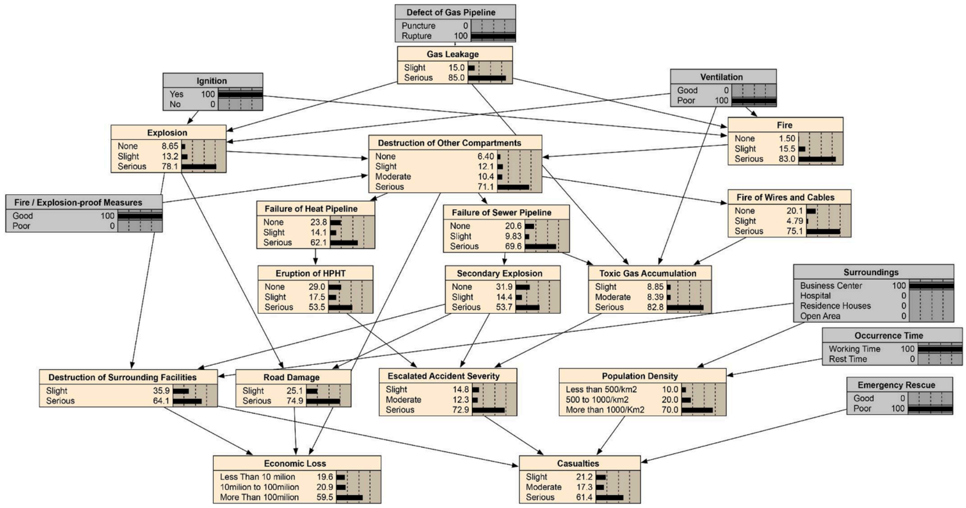

Fig. 9. "Fire/Explosion-proof Measures": Good.

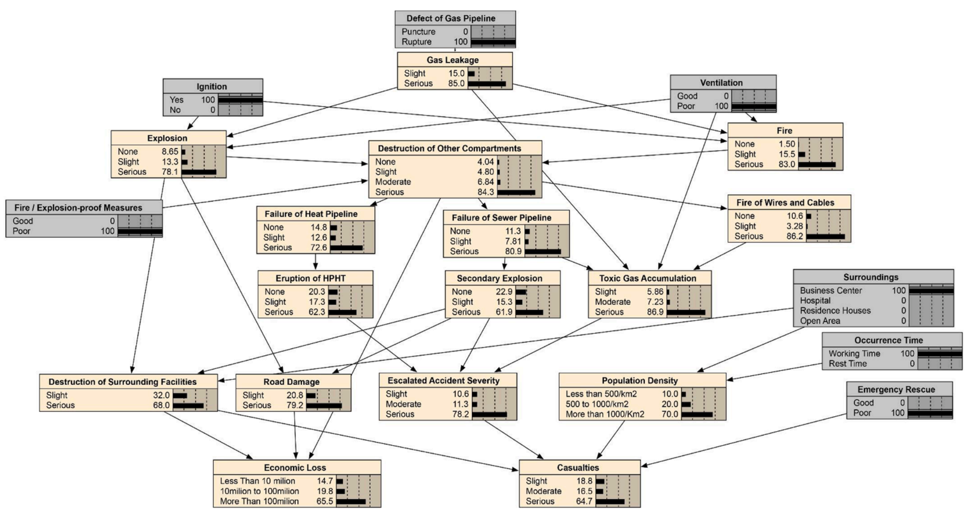

Fig. 10. "Fire/Explosion-proof Measures": Poor.

"Economic Loss", the probability proportion of state "10 million to 100 million" is 19.8%, higher than the probability of state "Less than 10 million" (14.7%). These results indicate that this catastrophic accident scenario has a high probability of severe economic loss and casualties even though the "Fire/Explosion-proof measures" are implemented.

5. Conclusion

In this paper, an integrated quantitative risk assessment method for urban underground utility tunnel was proposed based on the Bayesian network. The worst-case accident scenario was identified through dynamic hazard scenario identification (DHSI) and the escalated domino effects were taken into account during the establishment of the Bayesian network. The accident initiated by the gas pipeline leakage was identified as the worst-case accident scenario, and a 23-node Bayesian network of UUTs accident was established. For determining the CPTs of the proposed BN, the Delphi method was employed to obtain reliable expert judgements, and refer to the data of traditional direct-buried pipeline accidents.

From the scenario analysis of typical utility tunnel accidents, it can be seen that: a) the proposed integrated model can perform a reliable risk analysis of accident consequences with domino effects involved; b) The BN modeling can well present the impacts of fire/explosion-proof measures and emergency rescue on accident consequences; c) The BN-based graphical model can clearly and quantitatively present the evolution process of UUT accident from various causes to consequences, which cannot be achieved by traditional risk analysis methods.

Compared with a direct-buried pipeline accident, the UUT accident is so complicated that may involve various domino effects. To deal with the uncertainties and coupling effects in utility tunnel accidents, this paper employs a flexible Bayesian network to develop the risk assessment framework. However, at present, due to the scarcity of UUT accident data, the process of determining the CPTs of the proposed Bayesian network has to employ expert elicitation and refers to traditional directly buried pipeline accident data. Although the consistency of expertise is checked, the uncertainty may still exist. In the future, with the accumulation of UUT data, the proposed method could be more objective and exact. But indeed it is currently of great significance for quantitatively evaluating the overall risks to support safety management of utility tunnels and emergency decision-making for utility tunnel accidents.

CRediT authorship contribution statement

Jiansong Wu: Conceptualization, Methodology, Writing – original draft, Funding acquisition, Supervision. **Yiping Bai:** Visualization, Writing – original draft. **Weipeng Fang:** Software, Writing – original draft. **Rui Zhou:** Data curtion. **Genserik Reniers:** Formal analysis, Writing – review & editing. **Nima Khakzad:** Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declared no conflicts of interest with respect to the publication of this article.

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