Computer Communications 174 (2021) 190–204

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Ontology knowledge base combined with Bayesian networks for integrated corridor risk warning

Nan Hai, Daqing Gong *, Shifeng Liu

School of Economics and Management, Beijing Jiaotong University, Beijing, China

A R T I C L E I N F O

Keywords:
Integrated corridor
Risk warning
Ontology knowledge
Bayesian networks

A B S T R A C T

With the accelerated urbanization process, the emergence of urban underground integrated pipeline corridors is the trend for cities, especially large and medium-sized cities. However, due to the complexity of the internal system of the integrated corridor, there are various risks in the process of its construction and operation and maintenance, and the risk factors are complex and diverse. In this paper, we introduce ontology technology and knowledge base construction into the risk management of integrated pipeline corridor, build an ontology-based knowledge base of integrated pipeline corridor risk, and construct a Bayesian network based on the established risk knowledge base for risk evaluation of identified risk factors. The combination of ontology knowledge base construction and Bayesian network method of integrated pipeline corridor risk makes the risk identification system completer and more effective, and the method can effectively evaluate the disaster risk level of integrated pipeline corridor operation and maintenance, which can meet the practical needs of integrated pipeline corridor operation and maintenance risk management and disaster prevention and mitigation work.

1. Introduction

Urban underground pipeline corridor replaces the traditional practice of burying pipelines directly underground when they are laid, it is an important part of the modernization of urban infrastructure construction, it will be the urban infrastructure of the underground pipeline part of the centralized laying and management, and provides an effective solution to "urban diseases" such as "road zips" and "air cobwebs" brought about by the traditional pipeline laying process. In addition, it also effectively reduces the cost of repairing the road surface many times in the pipeline maintenance, maintains the integrity of the road surface, and facilitates the laying, maintenance, and management of various pipelines.

The location of the integrated pipe corridor construction is underground space, there are more risk factors, in the external complex environment, long-term different load role, there are different forms of structural cracks, uneven settlement, groundwater infiltration and other security risks, and its operation and maintenance process, all kinds of pipelines in the long-term role of the coupling relationship will appear fatigue, corrosion and other different forms and different degrees of damage, these injuries will become a weak link during the operation and maintenance of the corridor, and eventually evolve into safety incidents. After many years of operation and maintenance, the integrated pipeline corridor will experience varying degrees of aging and a complex disaster-causing environment may be formed within it. Once a disaster event occurs in a pipeline corridor, various types of disasters do not exist in isolation from each other, but are often interconnected in time, space and cause, forming a complex disaster chain system or disaster chain process. Therefore, the pipeline corridor risk management is an essential part of the integrated pipeline corridor operation and maintenance management process. Therefore, in order to effectively identify the possible risks of the integrated pipeline corridor, we use the WBS–RBS risk identification method to decompose the work into a WBS tree and the risk into a RBS tree, and then use the WBS–RBS matrix formed by the intersection of the work decomposition tree and the risk decomposition tree for risk identification, and then construct an ontology-based knowledge base of the integrated pipeline corridor risks, and combine it with Bayesian networks for multi-angle uncertainty inference to achieve a comprehensive analysis and assessment of the pipeline risk of the corridor, which can identify and analyze the integrated pipeline corridor risk in time, and take corresponding safety measures to prevent and reduce the occurrence of the integrated pipeline corridor risk events [1].

The paper is organized as follows. The paper is organized as follows. Section 2 presents the current state of research on the development of ontology modeling techniques and Bayesian networks used in this paper, in addition to the current state of research on the risks associated with integrated corridors. Section 3 provides a brief introduction to the methods used in this paper. Section 4 mainly applies the WBS–RBS decomposition method to decompose the risks of the integrated pipeline corridor, and obtains the final risk identification list. Section 5

* Corresponding author.
E-mail address: dqgong@bjtu.edu.cn (D. Gong).

https://doi.org/10.1016/j.comcom.2021.04.024
Received 29 December 2020; Received in revised form 4 April 2021; Accepted 22 April 2021
Available online 26 April 2021
0140-3664/

carried out the construction of the integrated pipeline corridor risk knowledge base [2]. Section 6 creates a Bayesian network model for the identified risks, and applies Bayesian network related algorithms to evaluate and warn risk factors. Section 7 is the conclusion of this article.

The contributions of the article are as follows.

At this stage, there are few studies on the construction of knowledge based for integrated pipeline corridors, and there is a lack of construction of risk ontology concepts in the risk management of integrated pipeline corridors and the design of risk knowledge bases for the construction and operation and maintenance of integrated pipeline corridors. This paper uses WBS–RBS decomposition to identify the risk factors in the construction and maintenance of the integrated pipeline corridor and constructs a corresponding knowledge base, while combining the Bayesian network method to carry out risk evaluation and risk warning.

(1) A integrated pipeline corridor risk identification and early warning system that combines WBS–RBS decomposition method, ontology knowledge base construction and Bayesian network method is proposed to make the risk identification system more complete and effective, while the wind factor assignment in Bayesian network is bound to change with the passage of time, bringing different risk factor weights into the assessment model, which is still applicable, making the risk assessment of urban underground integrated pipeline corridor initially reach the state of semi-dynamic risk assessment, which can meet the changes of inherent and accident risks in time and space.

(2) The risk incidents, risk categories and risk factors faced during the construction and operation and maintenance of the integrated pipeline corridor are analyzed. The WBS–RBS is applied to decompose them, and the WBS–RBS risk coupling matrix of the integrated pipeline corridor is constructed, and the safety risk identification list of the integrated pipeline corridor operation and maintenance is derived from the analysis results.

(3) On the basis of risk identification of integrated pipeline corridor construction and operation and maintenance, the method of Bayesian network is introduced to construct Bayesian network model for integrated pipeline corridor operation and maintenance safety risk assessment through Bayesian network structure learning and parameter learning, while the safety risk is assessed and analyzed with the powerful inference ability of Bayesian network, and the key risk factors affecting integrated pipeline corridor operation and maintenance safety risk are obtained, which provides the basis for risk control decision.

2. Related work

2.1. Ontological technology

The concept of ontology dates back to the 1980s, when Neches defined ontologies in the field of artificial intelligence: "An ontology is the basic terms and relations of a domain vocabulary, and the rules used to define terms and relations to define vocabulary extents. [3]" That is, an ontology is a set of concepts in a domain that covers defined semantic and conceptual relationships. The most widely used definition of ontology to date is Gruber's: "An ontology is a formal and displayed specification of a conceptual model in a domain. [4]" and on the basis of Gruber's ontology research, Guarino and Giaretta have refined and revised the concept of ontology: "An ontology is a set of logical theories that give a clear, partial account of the concepts of a domain. [5]" Later Borst also proposed that "ontologies are shared conceptualizations of formal normative accounts. [6]" Studer proposed that "ontologies are explicit formal specification of shared conceptualizations". He believes that ontology includes four aspects: shared, conceptualized, explicit, and formalized [7]. And Du summarized the development of ontology in foreign countries [8].

Although various experts and scholars have expressed the concept of ontology definition in different languages, fundamentally they understand ontological connotations as the linguistic basis for the mutual communication of subjects in the field, that is, the connection between definitions is expressed in terms with clear ontological definitions, so that users can reach a consensus among themselves.

2.2. BayesIan network

Regarding the concept of Bayesian, Pearl first proposed the Bayesian network model, which is the use of networked graphs based on probabilistic theoretical reasoning to deal with uncertainty in knowledge [9]. Bayesian network is a graphical model based on Bayesian probability theory, which has become an important research direction in artificial intelligence and has been applied to many other fields because of its good ability to deal with uncertainty problems. And Jensen defined Bayesian network as a probabilistic graphical model that can express probabilistic relationships among a set of random variables [10]. Stock concluded on the conclusion reached by Jensen that Bayesian networks model systems in the form of directed acyclic graphs, using nodes to represent the variables in the system, directed edges to represent the causal relationships between variables, and conditional probabilities to represent the degree of correlation between variables, which can express and analyze multi-source information and thus deal with uncertainty problems [11].

Regarding the combination of accident risk and Bayesian, Bensi proposed a Bayesian network-based approach for infrastructure earthquake risk assessment and post-earthquake emergency decision support [12]. Peng proposed a Bayesian network-based risk analysis and assessment model for flooding residents [13]. Ma constructed an urban earthquake secondary hazard evolution system based on Bayesian networks [14]. He constructed a storm flood risk analysis model based on Bayesian networks so as to provide corresponding disaster risk assessment and emergency decision reference [15]. Janjanam proposed a Bayesian network construction method for natural disaster risk analysis [16]. Regarding the combination of integrated pipeline corridors and Bayesian networks, Ayello created a pipeline risk assessment model using a Bayesian network probabilistic graphical model to calculate internal and external corrosion risk, manufacturing and construction risk, natural disaster risk, third-party damage risk, and maintenance error risk [17]. Chen analyzed the potential disaster risk factors during the operation and maintenance of integrated pipeline corridors, and then constructed a Bayesian network-based disaster risk assessment model [18].

In summary, Bayesian networks have been widely and successfully applied in various fields, especially in the areas of information fusion and causal analysis research, and are receiving increasing attention from scholars in different fields at home and abroad due to their various advantages.

2.3. Risk related to integrated pipeline corridor

The beginning of integrated pipeline corridors abroad can be traced back to 1833, when the first underground integrated pipeline corridor was built in Paris, France, to improve the problem of laying underground pipes in the city, and then London, Hamburg and other cities also started the construction of urban underground corridors.

With the development of the construction of integrated pipeline corridors, scholars have conducted a lot of research on the areas related to the risk of integrated pipeline corridors in recent years. Julian believed that there are many participants in the integrated pipeline corridor, the financing and ownership relationships are complex, and safety management is a key issue facing the management of integrated pipeline corridors, and proposed a method based on a combination of expert systems and color coding, using the hierarchical analysis method to analyze the potential key risk factors [19]. Jang studied gas explosions in integrated pipeline corridors due to gas leaks and unknown ignition. Wang analyzed the potential influencing factors of underground integrated pipeline corridor fire according to the three elements

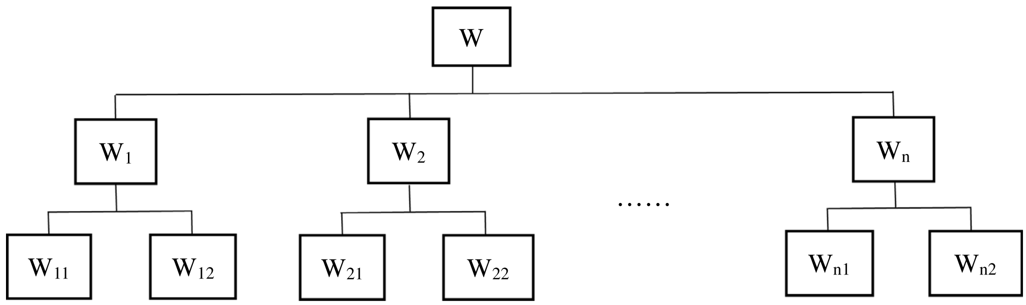

Fig. 1. WBS schematic.

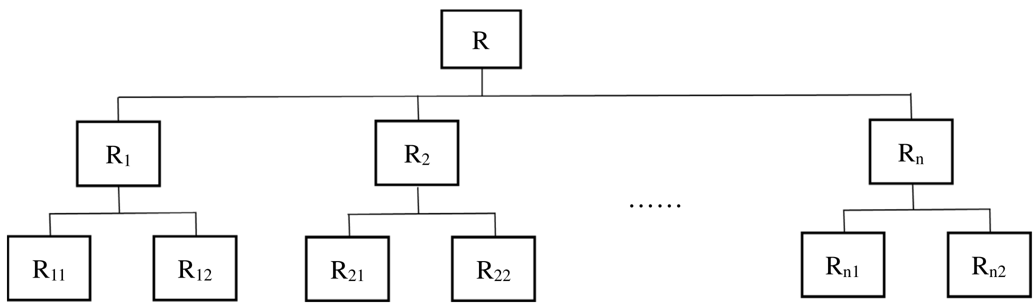

Fig. 2. RBS schematic.

of combustion, gave a range of fire warning setting for integrated pipeline corridor operation and maintenance [20]. Jin summarized twelve risk factors faced by the pipeline corridor project at macro, meso and micro levels, obtained the risk sharing scheme according to the risk sharing principles, process and stakeholder characteristics, and analyzed the risk pricing problem in the sharing process by using a three-stage bargaining game model to obtain the optimal proportion of risk sharing [21]. Wang applied the fuzzy mathematical method, established the coupling degree model, obtained the coupling relationship between multi-hazards, and finally proposed the risk evaluation method of multi-hazard coupled disaster-causing of integrated pipeline corridor [22]. Li used literature analysis, causal analysis and expert research, comprehensively analyzed the risk factors in the process of operation and maintenance management of integrated pipeline corridors in China, and applied the DEMATEL method to rank the degree of influence and importance of the 22 identified risk factors [23].Canto-Perello proposed an expert system combining color-coded, Delphi and hierarchical analysis methods to analyze the criticality and threat of integrated pipeline corridors, which was used to support the planning of urban underground facility safety policies [24]. Jang studied gas explosions in integrated pipeline corridors due to gas leakage and unknown ignition [25]. Jiang established a numerical model of the structure of the integrated pipeline corridor under land based on non-uniformly excited shaking table tests of the transverse jointed underground integrated pipeline corridor [26]. Zhao analyzed the temperature data of fire simulation tests within the integrated pipeline corridor model to derive the characteristics of the initial temperature field of fire in the electric compartment of the integrated pipeline corridor [27]. Zhu constructed an accident tree model and an evaluation system for the dimensional design safety and structural design safety of the integrated pipeline corridor based on the gray cluster analysis method [28]. Seo and Choi studied the impact of design on risk in the construction phase of underground projects and developed a risk assessment model [29].

In summary, scholars at home and abroad have conducted more in-depth research on risk identification, risk assessment, analysis and prediction, and risk sharing, and have made many research results. However, due to the lack of attention paid by scholars to the construction of the ontological knowledge base in respect of urban underground integrated pipeline corridors, research on the construction of the knowledge base for integrated pipeline corridors is scarce at this stage, and there is a lack of construction of the concept of risk ontology in the risk management of integrated pipeline corridors and the design of risk knowledge base for the construction and operation and maintenance process of integrated pipeline corridors. This paper combines ontology modeling techniques with Bayesian networks, not only was the risk knowledge base of the integrated corridor constructed, but Bayesian network was also used to derive the overall risk probability level and the key paths and key risk factors for the occurrence of risky accidents, and gives the corresponding early warning information. By analyzing the risk incidents in the pipeline corridor and proposing a reasonable risk assessment and analysis method, it helps managers to strengthen and improve the risk warning management and reduce the probability of disaster events in the pipeline corridor.

3. Research method

3.1. WBS– RBS decomposition structure

WBS (Work Breakdown Structure) refers to the decomposition of the studied project according to certain principles, so that the whole project is decomposed into smaller and more manageable independent units that can affect each other but are inseparable. [30] Fig. 1 show the decomposition process of WBS.

$$WBS = \left(W, W_n, W_{nm}\right) \tag{1}$$

where the specific meaning of each symbol is.
W: the corridor ontology in the WBS task node
W_n: the set of compartment types in the WBS corridor ontology
W_{nm}: the set of all types of pipelines in the WBS compartment type

RBS (Risk Breakdown Structure) refers to the classification and detailed decomposition of the risks of the project under study to find the root causes or risk factors. Fig. 2 show the decomposition process of RBS.

$$RBS = \left(R, R_n, R_{nm}\right) \tag{2}$$

where the specific meaning of each symbol is.

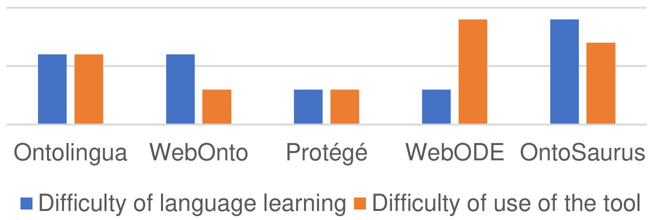

Fig. 3. Comparison of the ease of use of modeling tools.

R: risk of the corridor in the RBS task node
R_n: the set of risk types in the RBS compartment risk
R_{nm}: the set of risk factors in RBS corridor risk

3.2. Ontology modeling

Ontology is a philosophical concept that refers to the nature of things in themselves, and is used to describe the essence of things. In philosophy, ontology is "the systematic description of the objective existence of things in the world", i.e. "theory of existence", "theory of everything", etc. The concept of ontology first originated from the ancient Greek philosopher Aristotle's research on the nature of things. With the development and progress of society, people have introduced ontology into the research of computer science, artificial intelligence, information science and other fields, and have given their own research, definition, understanding and application [31].

3.2.1. Ontology description language and modeling tools

The representation language of ontology is also called ontology construction language. The most important point in the process of ontology construction is to use the computer language to represent the ontology, and only then it can be understood by the computer. It is characterized by its syntax, well-defined semantics, ease of representation, support for reasoning.

Nowadays, many ontology modeling tools have been developed to build, storage, searching and reasoning of ontologies, transforming the non-formal language we use in everyday life and making it easy for computers to understand. Commonly used ontology modeling tools can be broadly classified into two types: Based on a specific language (Ontolingua, OntoSaurus, WebOnto, etc.) and independent of a specific language (Protégé, WebODE, OntoEdit, OliED, etc.). Among them, Protégé is the most widely used. Tu compared several ontology modeling tools, Ontolingua, WebOnto, Protégé, WebODE, and OntoSaurus, and found that Protégé has a more prominent advantage in terms of language learning and ease of use, and Fig. 3 shows the comparison of the ease of use of several modeling tools.

The Protégé modeling tool is an ontology editing and knowledge acquisition software developed by Stanford University based on the Java environment, with the advantage of.

(1) Java-based environment, free source code, easy to learn and communicate.
(2) Internal extensions for ontology visualization, knowledge acquisition, etc.
(3) The ability to modify and edit ontologies in multiple languages.
(4) Internal examples and instructions, easy to use.

3.2.2. Basic components of the ontology knowledge base

The integrated pipeline corridor risk ontology knowledge base is based on artificial intelligence technology, using Protégé as a tool to establish the risk ontology of the urban integrated pipeline corridor, constructing risk events, cause classification, risk factors and other entities and inter-entity attributes, enabling staff to understand and grasp the risk events that may arise during the management of the urban integrated pipeline corridor in a timely manner, and to respond correctly to the risk events and take effective The risk factors and other attributes of entities and inter-entities enable the staff to understand and grasp the risk events that may occur in the process of urban integrated corridor management, and to react correctly to the risk events and take effective measures and solutions to reduce and mitigate the occurrence of risk events. Fig. 4 shows the basic composition of the risk ontology knowledge base of the integrated pipeline corridor.

3.3. BayesIan network model

Bayesian networks are a directed acyclic graph model that apply their learning and inference capabilities to reason about the properties of random variables$\{X_1,X_2,\ldots X_n\}$and their n sets of joint conditional probability distributions, and also to achieve tasks such as prediction, diagnosis, and classification. Bayesian networks are considered as an important theoretical approach to study uncertainty problems and one of the common theoretical approaches in risk management research. Fig. 5 shows a directed graph in a Bayesian network, calling D as the parent or root node of C; A,D,E as the neighbor nodes of C. The nodes in a Bayesian network represent random variables with probability distributions attached to them. The root node X is attached to the edge distribution $P(X)$, and the non-root node X is attached to the conditional probability distribution $P(X|\Pi(X))$. Let the node variables $X = [X_1,X_2,\ldots X_n]$, and multiply the probability distributions attached to each variable to obtain the joint probability distribution corresponding to them, that is.

$$P(X_1, X_2, \ldots, X_n) = \prod_{i=1}^{n} P\left(X_i|\Pi\left(X_i\right)\right) \tag{3}$$

3.3.1. BayesIan network probability theory principle

Bayesian network is a method based on the basic theory of probability theory, and its principal application process is mainly based on the following probability formulas and concepts as the basis [32].

(1) conditional probability

Let A, B are two sub-events of the basic event E, and $P(B) > 0$, then said

$$P(A|B) = \frac{P(A\cap B)}{P(B)} \tag{4}$$

for the conditional probability of the event A under the condition that the event B occurs. Similarly $P(A)>0$, then

$$P(B|A) = \frac{P(A\cap B)}{P(A)} \tag{5}$$

is said to be the conditional probability of event B under the condition that event A occurs.

(2) Full probability

Let S be the sample space of trial E. And B_1, B_2, …, B_n be a set of events of E. If

A. $B_i B_j \neq \varnothing, i \neq j, i, j = 1, 2, \ldots, n$
B. $B_1 \cup B_2 \cup \cdots \cup B_n = S$

Then we call B_1, B_2, …, Bn a division of the sample space S.

Let A be an event of E, $P(Bi)>0$, $(i = 1,2, \ldots,n)$, then

$$P(A) = \sum_{i=1}^{n} P(A|B_i)P(B_i) \tag{6}$$

is called the full probability formula.

(3) Bayesian formula

Let the sample space of trial E be S, A is an event of E, and B_1, B_2, …B_n is a set of events of E, and $P(A)>0$, $P(B_i)>0$, $(i = 1,2, \ldots,n)$, then the equation

$$P\left(B_i|A\right) = \frac{P\left(A|B_i\right)P\left(B_i\right)}{\sum_{j=1}^{n} P\left(A|B_j\right)P\left(B_j\right)} \tag{7}$$

is called Bayesian formula.

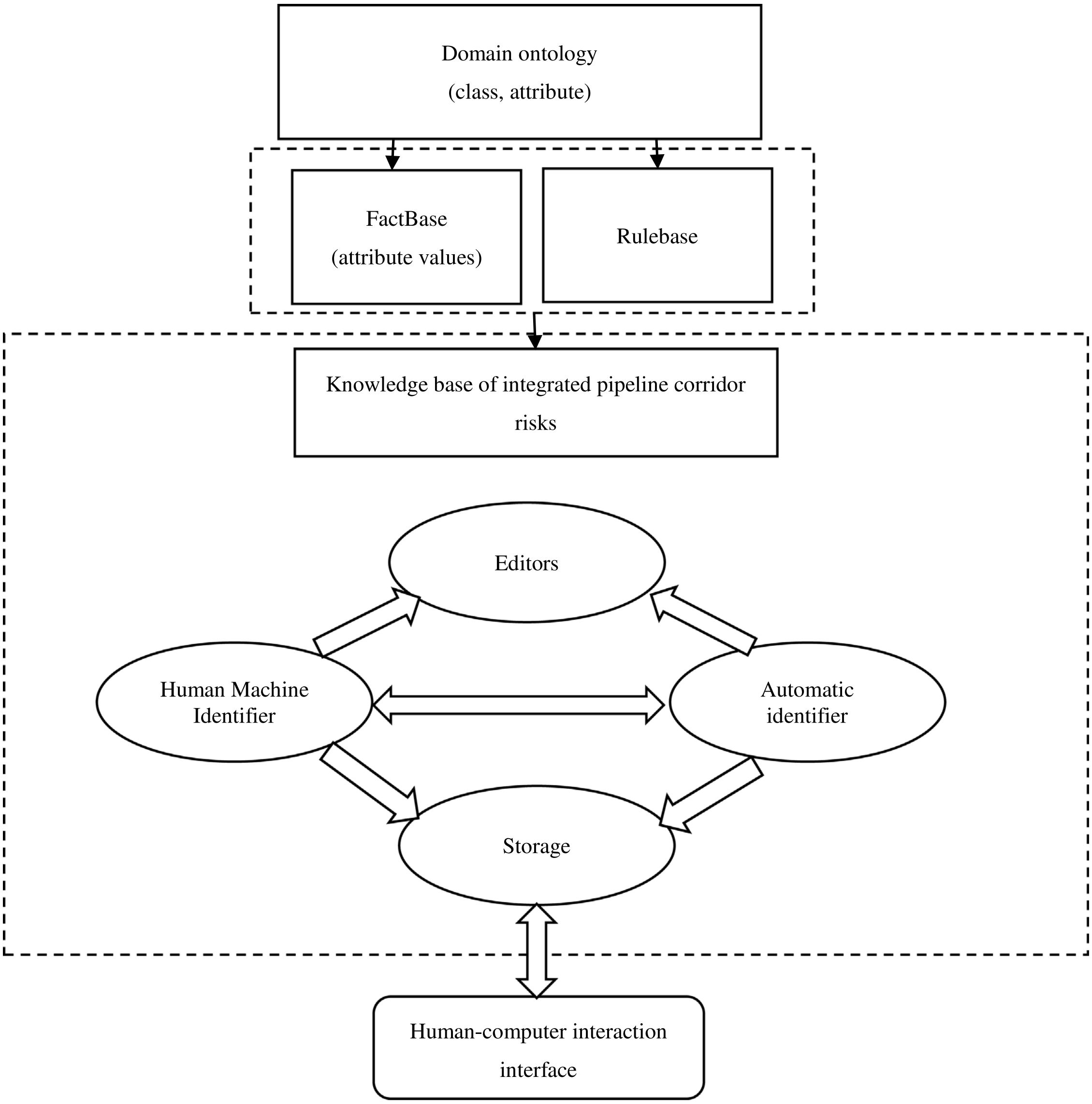

Fig. 4. Basic components of the risk ontology knowledge base for integrated pipeline corridors.

3.3.2. Probability of occurrence of each node

After determining the number of experts and expert weights, the probability distribution of the probability level of the disaster risk factors of the integrated pipeline corridor operation and maintenance can be obtained according to the following formula for calculating the results of the expert questionnaire research, which is the prior probability of the risk factors of the parent nodes in the Bayesian network model.

$$P\left(C_i = j\right) = \sum_{k=1}^{n} \omega_k P_{ijk} / \sum_{k=1}^{n} \omega_k \tag{8}$$

where $i = 1, 2, \ldots, 9$; $j = 1, 2, \ldots, 5$; $P(Ci = j)$ is the probability that risk factor Ci is at rank j; n is the number of questionnaires or experts; ω_k is the weight of the kth expert; P_{ijk} is the probability that the kth expert thinks risk factor *Ci* is at rank j; $P_{ijk} = 0$ *or* 1.

In determining the conditional probability of the child nodes, the chain principle that the parent nodes produce children of the same probability rank is followed, while assuming that the risk factors are independent of each other, i.e., if a parent node is at rank j and none of the other parent nodes is higher than rank j, then the child node is at rank j. Taking *P(B1| C1, C2, C3)* as an example, then

$P(B_1 = 1 | C_1 = 1, C_2 = 1, C_3 = 1) = 1$

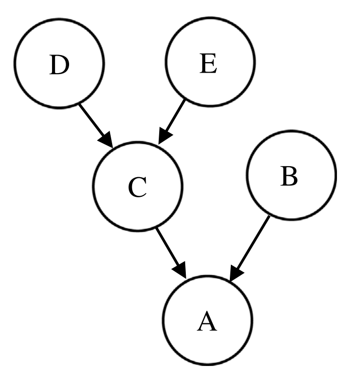

Fig. 5. Bayesian network diagram.

$P(B_1 = 2 | C_1 = 2, C_2 \leq 2, C_3 \leq 2) = 1$
$P(B_1 = 2 | C_1 \leq 2, C_2 = 2, C_3 \leq 2) = 1$
……
$P(B_1 = 5 | C_1 = 5, C_2 \leq 5, C_3 \leq 5) = 1$
$P(B_1 = 5 | C_1 \leq 5, C_2 \leq 5, C_3 = 5) = 1$

Table 1
Integrated pipeline corridor WBS decomposition.

WBS name	First-level decomposition	Second-level decomposition
Integrated pipeline corridor W	Cable compartment W_1	Power cable W_{11} Communication cable W_{12} Auxiliary facilities W_{13}
	Comprehensive compartment W_2	Heating pipeline W_{21} Water supply and reclaimed water pipeline W_{22} Auxiliary facilities W_{23}
	Gas tank W_3	Natural gas pipeline W_{31} Auxiliary facilities W_{32}
	Sewage tank W_4	Rainwater pipeline W_{41} Sewage pipeline W_{42} Auxiliary facilities W_{43}

$P(B_1 = 5| \ C_1 \neq 5, \ C_2 \neq 5, \ C_3 \neq 5) = 0$

In summary, this paper combines Ontology knowledge base construction with Bayesian network method, in which the seven-step method is chosen for ontology construction, which is the most widely used and can effectively identify the risks of integrated pipeline corridor construction and operation and maintenance, and followed by a risk evaluation of the identified risk factors with the help of a Bayesian network model to derive the overall risk probability level and the key The overall risk probability level and the key paths and key risk factors for the occurrence of disaster risk events are derived, and the corresponding early warning information is given. Fig. 6 shows the specific research process.

Firstly, by combining and analyzing the policy documents, professional literature and other materials on the risk of integrated pipeline corridor, the ontology is constructed with the help of the seven-step method proposed by Stanford University based on the protégé ontology construction tool, which includes ontology analysis, merging, concept addition and other ontology construction processes and is more mature, secondly, by analyzing the potential risk accidents in the process of integrated pipeline corridor operation and maintenance, applying the WBS–RBS method to decompose the safety risks of integrated pipeline corridor operation and maintenance, analyze the risk factors that lead to accidents, and list the risk factors identification list to provide the basis for risk assessment later. Then, a risk assessment model is constructed based on the theory related to Bayesian networks, which is used to evaluate and analyze the risk level during the construction and operation and maintenance of the integrated pipeline corridor and deal with the identified risk factors. Finally, the main risk elements were analyzed based on the calculation results.

In this paper, by combining WBS–RBS decomposition method, ontology knowledge base construction and Bayesian network method, a integrated pipeline corridor risk identification and early warning system is formed to make the risk identification system more complete and effective, while the risk factor assignment in Bayesian network is bound to change with time, bringing different risk factor weights into the assessment model is still applicable, so that the risk assessment of urban underground integrated pipeline corridor initially reaches the state of semi-dynamic risk assessment, which can meet the changes of inherent risk and accident risk over time and space.

4. Risk identification of integrated corridor based on WBS– RBS

4.1. WBS decomposition of integrated pipeline corridor

Based on the definition and characteristics of the integrated pipeline corridor, this paper will decompose the work structure of the integrated pipeline corridor according to its compartment type, and Table 1 shows the results of WBS decomposition.

For the WBS primary decomposition of urban integrated pipeline corridor, it can be classified according to the type of compartment inside the pipeline corridor class, which can be generally divided into four categories: cable compartment, integrated compartment, gas compartment and sewage compartment, but there may be other types of compartments due to the different regional construction needs and standards for the pipeline corridor. This paper classifies the compartments according to the types of pipelines arranged in the corridor and provides a secondary decomposition of the compartments. The decomposition results can help to accurately locate the risk incidents occurring inside the corridor and take targeted risk avoidance measures, which can make fuller use of resources and manpower. This paper summarizes and decomposes the internal compartments and their internal pipelines according to the types of pipelines usually laid out in integrated pipeline corridors, which should be appropriately supplemented and deleted according to the actual situation.

4.2. RBS decomposition of integrated pipeline corridor

Based on the characteristics of the integrated pipeline corridor at the same time summarized the accident occurred in the process of construction, according to the type of accident on the integrated pipeline corridor risk RBS decomposition [33], Table 2 for the RBS decomposition results.

For the RBS decomposition of the urban integrated pipeline corridor, the risk of the corridor is classified according to the type of accident, which can generally be divided into three categories: fire and explosion, flooding, and structural damage. Drawing on the idea of accident tree analysis, the risk accident is analyzed in terms of risk categories and the risk factors contained in each risk category, which are then broken down into risk incidents.

4.3. WBS– RBS risk coupling matrix

When the risk identification of the urban underground integrated pipeline corridor is carried out, the WBS–RBS risk coupling matrix of the integrated pipeline corridor can be established with the help of the decomposition results of WBS and RBS.

The matrix will be the WBS level decomposition of the chamber type as the horizontal coordinate, the RBS decomposition of the risk factors as the vertical coordinate, the establishment of integrated pipeline corridor WBS–RBS risk coupling matrix, the chamber type and each risk factor one by one correspondence, analyze whether the corresponding coupling event may occur, if it has occurred or may occur is recorded as 1; if it will not occur or extremely difficult to occur, it is recorded as 0, and then the integrated pipeline corridor risk identification coupling matrix, such as Table 3 for the WBS–RBS risk coupling matrix.

From Table 3, it is not difficult to find that the cable compartment, integrated compartment, gas compartment and sewage compartment inside the integrated corridor have coupling relationship with fire and explosion accident, that is to say, each compartment has fire and explosion risk; cable compartment, integrated compartment, gas compartment and sewage compartment have coupling relationship with flood accident, that is to say, each compartment has flood risk, but excluding natural factors (heavy rainfall and flooding), only integrated compartment and sewage compartment have coupling relationship with flood accident; cable compartment, integrated compartment, gas compartment and sewage compartment have coupling relationship with structural damage risk accident, that is to say, each compartment has structural damage risk.

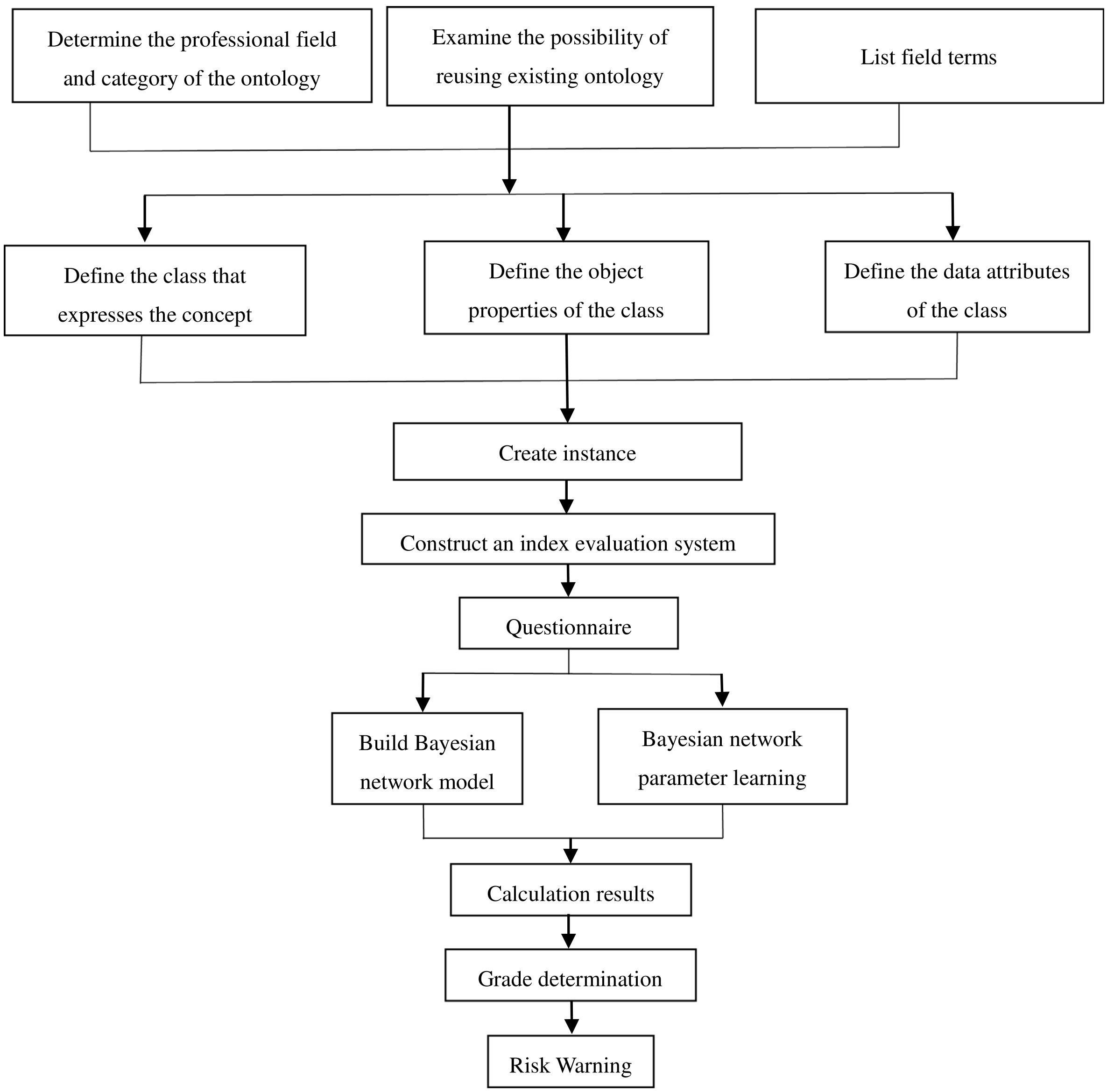

Fig. 6. Research flow.

4.4. Risk identification checklist

In order to accurately and comprehensively identify the potential risk factors in the process of integrated corridor operation and maintenance, this paper selects the WBS–RBS method to analyze the risk identification from both vertical and horizontal aspects (risk factors and compartments types). The WBS–RBS decomposition structure method can identify risks more comprehensively without adding extra workload to project management and is suitable for the risk identification of integrated corridor operation and maintenance.

After WBS–RBS decomposition of urban integrated pipeline corridor, we can get the risk identification list of three types of risk incidents, namely, fire and explosion, structural damage and flooding. The risk identification list can clearly and intuitively show the results of risk identification, i.e., the risks that may occur in the construction of urban underground integrated pipeline corridor, i.e., the operation and maintenance process, which is conducive to the risk evaluation of the identified risks and the corresponding avoidance measures, according to the RBS–WBS risk coupling matrix shown in Table 3, the corresponding risk identification list can be obtained, Table 4 shows the risk identification list.

5. Construction of ontology knowledge base

5.1. Modeling of the ontology

Based on the OWL syntax rules, the basic class Risks is modeled as shown in line 1 of Fig. 7 Similarly, we have created the basic classes Fire and explosion, Flooding, Structural Damage as shown in Fig. 7, lines 3,7,11. By using the "subclass" property, we define "Fire and explosion, Flooding, Structural Damage" as a subclass of "Risks".

5.2. Object attributes

The ontology framework expresses the concept of each class in the ontology construction and the links between each class. The ontology framework of urban underground integrated pipeline corridor risk contains risk incidents, risk categories and corresponding risk factors, as shown in Fig. 8, and their links in the ontology framework can be clearly seen through the OntoGraf plug-in in the protégé. The risk factors belong to a certain risk category, which in turn leads to a certain risk incident.

Table 2
RBS decomposition of integrated pipeline corridor.

RBS name	Risk accident	Risk category	Risk factors
Integrated pipeline corridor risk R	Fire and explosion R_1	Human operation risk R_{11}	Malicious arson R_{111} Irregular operation R_{112} Illegal fire R_{113}
		Equipment risk R_{12}	Ventilation and electrical equipment abnormal R_{121} Monitoring and alarm, fire protection system abnormal R_{122}
		Pipeline Direct risk R_{13}	Cable leakage R_{131} Cable overload R_{132} Wire short circuit R_{133} Cable contact resistance is too large or poor contact R_{134} Gas leakage R_{135} Sewage pipe combustible gas leakage R_{136} Heat pipe rupture R_{137}
		Management risk R_{14}	Daily maintenance and inspection of pipeline equipment is not timely R_{141} Fire protection Insufficient inspections R_{142} Insufficient daily training and drills R_{143}
	Floods R_2	Natural disaster risks R_{21}	Heavy rains and floods R_{211}
		Equipment risks R_{22}	Abnormal drainage facilities R_{221} Irrational drainage facilities setting R_{222} Abnormal drainage monitoring systemR_{223}
		Direct risk of pipelinesR_{23}	Leakage of water supply and reclaimed water pipelinesR_{231} Leakage of sewage pipelinesR_{232} Thermal pipeline leakageR_{233}
		Management riskR_{24}	Daily maintenance and inspection of pipeline equipment is not timelyR_{241} Insufficient daily training and drillsR_{242}
	Structural damageR_3	Natural disaster riskR_{31}	EarthquakeR_{311}
		Technical riskR_{32}	Early exploration is not in placeR_{321} Design is unscientific and unreasonableR_{322} Construction quality problemsR_{323}
		Structure DamageR_{33}	Uneven stiffness distributionR_{331} Road load is too largeR_{332} Structural waterproof layer breakageR_{333} Pipeline entrance and exit are not properly blockedR_{334} Uneven soil distributionR_{335} Improper foundation treatmentR_{336} Structural crack R_{337}
		Management riskR_{34}	Insufficient daily training and drillR_{341} Structural maintenance and repair are not timelyR_{342}

6. BayesIan network model construction for pipeline corridor risk

According to the WBS–RBS decomposition method to obtain the risk identification list (Table 4), the three types of relevant risk incidents within the list can be initially numbered, namely, fire and explosion A_1, flood A_2 and structural damage A_3, and Table 5 shows the specific risk factor division number.

The variable R is used to represent the disaster risk of integrated pipeline corridor operation and maintenance, and a Bayesian network is established. Firstly, the risk factors are used as the variables of Bayesian network model nodes, and the initial network structure is obtained by initially judging the causal relationship between the nodes. Fig. 9 shows the established Bayesian network diagram. In the Bayesian network directed acyclic graph, the nodes represent the random variables and the edges between the nodes represent the logical dependencies between the variables. Each node is attached with a probability distribution, and the parent node C is attached with its edge distribution P(C), and the children B, A, and R are attached with the conditional probability distributions P(B| C), P(B| C), and P(A| R). Bayesian network is a representation of the joint probability distribution, taking the chain $C_1, C_2, C_3 \rightarrow B_1 \rightarrow A_1 \rightarrow R$ as an example, the joint probability distribution function containing all nodes is.

$$P\left(C_2, C_3, B_1, A_1, R\right) = P\left(R|A_1\right) P\left(A_1|B_1\right) P\left(B_1|C_1, C_2, C_3\right) P\left(C_1\right) P\left(C_2\right) P\left(C_3\right) \tag{9}$$

7. Research results

7.1. Risk probability classification

Referring to the "Tunnel Risk Management Guide" issued by the International Tunneling Association (ITA), the probability of disaster events related to the risk of integrated pipeline corridors is divided into five levels, and Table 6 shows the criteria for the classification of risk probability levels [34].

When multiple experts evaluate the risk of the same disaster event, because each expert has different subjective awareness of the event, the evaluation results of multiple experts should be synthesized and analyzed to obtain a comprehensive result. By applying the weighting method of expert investigation, the evaluation value of experts is corrected by weighting coefficients according to their seniority, titles and influence, and the probability of occurrence of each disaster risk factor is finally determined. Because of the different experience of each

Table 3
RBS–WBS risk coupling matrix.

			Cable compartment	Comprehen-sive compartment	Gas tank	Sewage tank
Fire and explosion	Human operation risk	Malicious arson	1	1	1	1
		Irregular operation	1	1	1	1
		Illegal fire	1	1	1	1
	Equipment risk	Ventilation and electrical equipment abnormal	1	1	1	1
		Monitoring and alarm, fire protection system abnormal	1	1	1	1
	Pipeline Direct risk	Cable leakage	1	1	0	0
		Cable overload	1	1	0	0
		Wire short circuit	1	1	0	0
		Cable contact resistance is too large or poor contact	1	1	0	0
		Gas leakage	0	0	1	0
		Sewage pipe combustible gas leakage	0	0	1	1
		Heat pipe rupture	0	1	0	0
	Management risk	Daily maintenance and inspection of pipeline equipment is not timely	1	1	1	1
		Fire protection Insufficient inspections	1	1	1	1
		Insufficient daily training and drills	1	1	1	1
Floods	Natural disaster risks	Heavy rains and floods	1	1	1	1
	Equipment risks	Abnormal drainage facilities	0	1	0	1
		Irrational drainage facilities setting	0	1	0	1
		Abnormal drainage monitoring system	0	1	0	1
	Direct risk of pipelines	Leakage of water supply and reclaimed water pipelines	0	1	0	0
		Leakage of sewage pipelines	0	0	0	1
		Thermal pipeline leakage	0	1	0	0
	Management risk	Daily maintenance and inspection of pipeline equipment is not timely	0	1	0	1
		Insufficient daily training and drills	0	1	0	1
Structural damage	Natural disaster risk	Earthquake	1	1	1	1
	Technical risk	Early exploration is not in place	1	1	1	1
		Design is unscientific and unreasonable	1	1	1	1
		Construction quality problems	1	1	1	1
	Structure Damage	Uneven stiffness distribution	1	1	1	1
		Road load is too large	1	1	1	1
		Structural waterproof layer breakage	1	1	1	1
		Pipeline entrance and exit are not properly blocked	1	1	1	1
		Uneven soil distribution	1	1	1	1
		Improper foundation treatment	1	1	1	1
		Structural crack	1	1	1	1
	Management risk	Insufficient daily training and drill	1	1	1	1
		Structural maintenance and repair are not timely	1	1	1	1

expert, the research results must be subjective, and it is unrealistic to conduct detailed interviews and research on each expert, so it is necessary to take certain simplification means. Experts with age, seniority and experience, the judgment of things gradually tend to be robust and mature, and the reliability of their views will gradually increase, so the experts can be divided into four categories, expert weights of 1.0, 0.9, 0.8 and 0.7, respectively, as the basis for the investigation of disaster risk of integrated pipeline corridor operation and maintenance, Table 7 is the expert weight classification.

For risk factors that can be ignored, the probability of their occurrence and the adverse effects caused by them are very small, and the main focus can be placed on the daily management and operation, maintenance to ensure the orderly operation of the project; while for risk factors that need to be considered, attention to them should be strengthened, paying attention to the changes in risk factors; when risk factors are in an alert state, the changes in such risk factors should be closely monitored, especially some of the deteriorating conditions of Risk factors and risk factors that hinder the orderly operation of the pipeline corridor, and subsequently develop preventive measures

Table 4
Risk identification checklist.

Risk accident	Risk category	Risk factors
Fire and explosion	Human operation risk	Malicious arson Irregular operation Illegal fire
	Equipment risk	Ventilation and electrical equipment abnormal Monitoring and alarm, fire protection system abnormal
	Pipeline Direct risk	Cable leakage Cable overload Wire short circuit Cable contact resistance is too large or poor contact Gas leakage Sewage pipe combustible gas leakage Heat pipe rupture
	Management risk	Daily maintenance and inspection of pipeline equipment is not timely Fire protection Insufficient inspections Insufficient daily training and drills
Floods	Natural disaster risks	Heavy rains and floods
	Equipment risks	Abnormal drainage facilities Irrational drainage facilities setting Abnormal drainage monitoring system
	Direct risk of pipelines	Leakage of water supply and reclaimed water pipelines Leakage of sewage pipelines Thermal pipeline leakage
	Management risk	Daily maintenance and inspection of pipeline equipment is not timely Insufficient daily training and drills
	Natural disaster risk	Earthquake
	Technical risk	Early exploration is not in place Design is unscientific and unreasonable Construction quality problems
Structural damage	Structure Damage	Uneven stiffness distribution Road load is too large Structural waterproof layer breakage Pipeline entrance and exit are not properly blocked Uneven soil distribution Improper foundation treatment Structural crack
	Management risk	Insufficient daily training and drill Structural maintenance and repair are not timely

according to the specific situation; need to focus on the risk factors of the dangerous state, which induces a higher probability of disaster risk and must be effectively controlled, think about how to change the path of risk impact so as to change the nature of the consequences of risk, reduce the possibility of risk occurrence, reduce the size of the potential loss of risk, and develop a variety of countermeasures in advance. At present, the main countermeasures of risk control are risk avoidance, risk mitigation, risk transfer and risk sharing, etc. Generally, risk control should reasonably combine the above methods.

7.2. Probability of occurrence of risk at each node

The probability rank distribution of the parent nodes of the risk factors obtained from the calculation of the questionnaire results is brought into the Bayesian network model structure shown in Fig. 9, and the probability rank distribution of disaster risk for each other node can be calculated according to the chain transfer principle. In the probability distribution of disaster risk probability level, according to the principle of maximum affiliation, the disaster risk probability level corresponding to the maximum probability value is selected, and the maximum probability path and the key risk factors of the sub-node disaster events when they occur can be identified. Finally, the corresponding disaster prevention and mitigation measures are taken according to the key risk factors.

According to the a priori probability formula of the parent node risk factors for data analysis and processing of the questionnaire, Table 8 shows the probability level distribution of disaster risk factors for integrated pipeline corridor operation and maintenance obtained after processing.

With the help of Netica software, a Bayesian network implementation platform, the risk level distribution of the integrated pipeline corridor is systematically evaluated. The specific operation steps are as follows: First, based on the information security risk assessment index system of the smart city, all assessment indexes and interrelationships between indexes are used as network node inputs, node attributes are defined as discrete values, and node states are set as risk levels 1–5; second, the EM algorithm is used for parameter learning and combined with the probability calculation rule above to calculate the risk factor level of the parent nodes of the integrated corridor pipeline distribution a priori probability values and evaluate each type of risk factors; third, input the parent node risk factor level distribution a priori probability values obtained from the questionnaire into the Bayesian structural model to calculate the probability values of risk level distribution of the remaining nodes, and Fig. 10 shows the results of the software operation. Table 9 shows the final evaluation results.

From Table 9, it can be seen that among the structural damage risk accidents, natural disaster risk B_9 belongs to level 1 risk, which can be ignored, and the corresponding earthquake risk factor C_{23} can be monitored well on a daily basis; equipment risk B_2 and management risk B_4 in fire and explosion accidents, natural disaster risk B_5 and management risk B_8 in flood accidents and management risk B_{12} in structural damage accidents all belong to level 3 risk, and attention

```
<!-- http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Risks -->

<owl:Class rdf:about="http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Risks"/>


<!-- http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Structural_Damage -->

<owl:Class rdf:about="http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Structural_Damage">
    <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Risks"/>
</owl:Class>


<!-- http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Fire_and_explosion -->

<owl:Class rdf:about="http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Fire_and_explosion">
    <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Risks"/>
</owl:Class>


<!-- http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Flooding -->

<owl:Class rdf:about="http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Flooding">
    <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Risks"/>
</owl:Class>


<!-- http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Abnormal_drainage_facilities -->

<owl:Class rdf:about="http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Abnormal_drainage_facilities">
    <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/hainan/ontologies/2020/11/untitled-ontology-11#Equipment_risk"/>
```

Fig. 7. Modeling of Ontology Risks based on OWL.

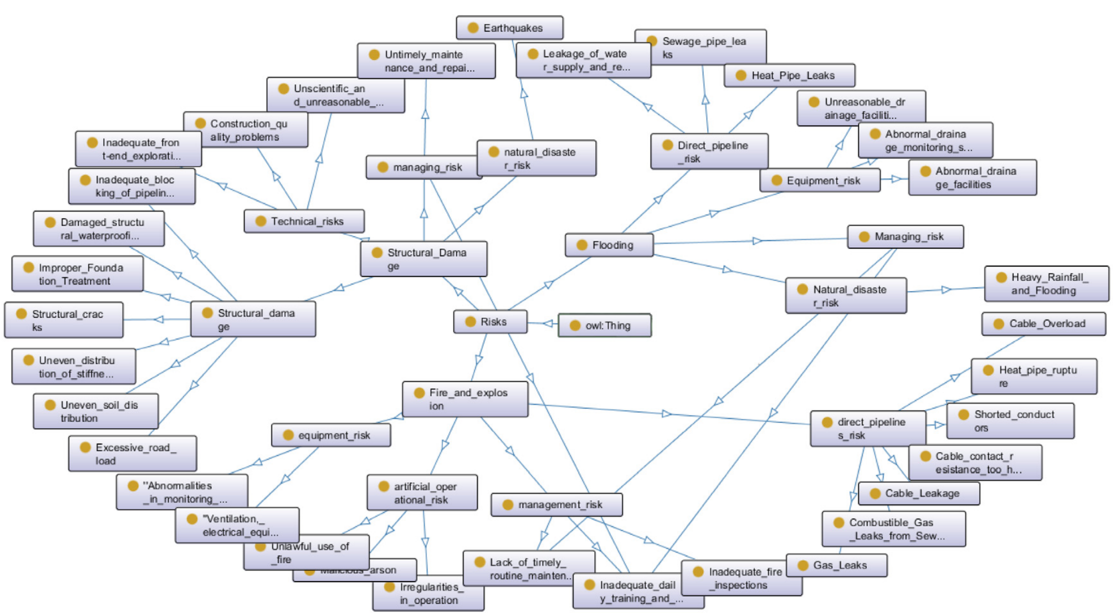

Fig. 8. Visualization of Knowledge Base.

should be paid to strengthen the corresponding management and inspection, pay attention to the transformation of risks; human operation risk B_1 in fire and explosion accidents, direct risk B_7 in flood accidents and technical risk B_{10} in structural damage accidents are level 4 risks, and the changes of such risk factors should be closely monitored and preventive measures should be formulated for specific situations; while direct risk B_3 in fire and explosion accidents, equipment risk B_6 in flood accidents and structural damage accidents Risk B_6 in fire and explosion accidents, equipment in flood accidents and structural damage B_{11} in structural damage accidents belong to risk level 5, which is a risk level and should be closely monitored and avoidance measures should be taken or methods to mitigate risk damage should be adopted and implemented. In addition, the overall risk probability level related to the integrated pipeline corridor pipeline is level 5, with a high risk probability, and the risk control during the operation and maintenance of the corridor should be strengthened.

Using the reverse inference ability of Bayesian network, four key paths leading to the occurrence of disaster events in the operation and

Table 5
Number of risk factors.

Risk accident	Risk category	Risk factors
Fire and explosion A_1	Human operation risk B_1	Malicious arson C_1 Irregular operation C_2 Illegal fire C_3
	Equipment risk B_2	Ventilation and electrical equipment abnormal C_4 Monitoring and alarm, fire protection system abnormal C_5
	Pipeline Direct risk B_3	Cable leakage C_6 Cable overload C_7 Wire short circuit C_8 Cable contact resistance is too large or poor contact C_9 Gas leakage C_{10} Sewage pipe combustible gas leakage C_{11} Heat pipe rupture C_{12}
	Management risk B_4	Daily maintenance and inspection of pipeline equipment is not timely C_{13} Fire protection Insufficient inspections C_{14} Insufficient daily training and drills C_{15}
Floods A_2	Natural disaster risks B_5	Heavy rains and floods C_{16}
	Equipment risks B_6	Abnormal drainage facilities C_{17} Irrational drainage facilities setting C_{18} Abnormal drainage monitoring system C_{19}
	Direct risk of pipelines B_7	Leakage of water supply and reclaimed water pipelines C_{20} Leakage of sewage pipelines C_{21} Thermal pipeline leakage C_{22}
	Management risk B_8	Daily maintenance and inspection of pipeline equipment is not timely C_{13} Insufficient daily training and drills C_{15}
Structural damage A_3	Natural disaster risk B_9	Earthquake C_{23}
	Technical risk B_{10}	Early exploration is not in place C_{24} Design is unscientific and unreasonable C_{25} Construction quality problems C_{26}
	Structure Damage B_{11}	Uneven stiffness distribution C_{27} Road load is too large C_{28} Structural waterproof layer breakage C_{29} Pipeline entrance and exit are not properly blocked C_{30} Uneven soil distribution C_{31} Improper foundation treatment C_{32} Structural crack C_{33}
	Management risk B_{12}	Insufficient daily training and drill C_{15} Structural maintenance and repair are not timely C_{34}

Table 6
Standards for the classification of risk probability.

levels	Probability description	Probability interval	Risk warning level	Remarks
Level 1	Rare	0–0.0003	negligible	Disaster events are extremely difficult to occur
Level 2	Infrequent	0.0003–0.003		Disaster events generally do not occur or rarely occur
Level 3	Occasionally	0.003–0.03	Need to be considered	Disaster events happen occasionally or rarely
Level 4	Possible	0.03–0.3	Warning	Disaster events may occur or multiple times
Level 5	Frequent	0.3–1	Dangerous	Disaster events frequently occur

maintenance of this integrated corridor pipeline can be found, which are $C_{12}\rightarrow B_3\rightarrow A_1\rightarrow R$, $C_{18}\rightarrow B_6\rightarrow A_2\rightarrow R$, $C_{32}\rightarrow B_{11}\rightarrow A_3\rightarrow R$, $C_{34}\rightarrow B_{12}\rightarrow A_3\rightarrow R$.that is, the key risk factors leading to the occurrence of disaster events in the operation and maintenance process of the integrated corridor pipeline are thermal Pipe rupture C_{12}, drainage facilities set unreasonable C_{18}, improper foundation treatment C_{32} and structure maintenance, maintenance is not timely C_{34}, pipeline construction as well as operation and maintenance process, according to the actual situation on site to control the probability of occurrence of various potential risk factors, and focus on controlling the above four risk factors, at the source to do a good job of disaster event risk control, to protect the safety of the corridor pipeline operation and maintenance, for the development of the city, operation Provide protection.

8. Conclusion

In this paper, we study the risk incidents that urban integrated pipeline corridors may face during construction and later operation and maintenance, decompose the corridor ontology and risk factors using the WBS–RBS decomposition method, and construct the WBS–RBS risk coupling matrix and the corresponding risk identification list. Based on the risk list obtained from the decomposition, the ontology modeling technique is used to build an ontology-based knowledge

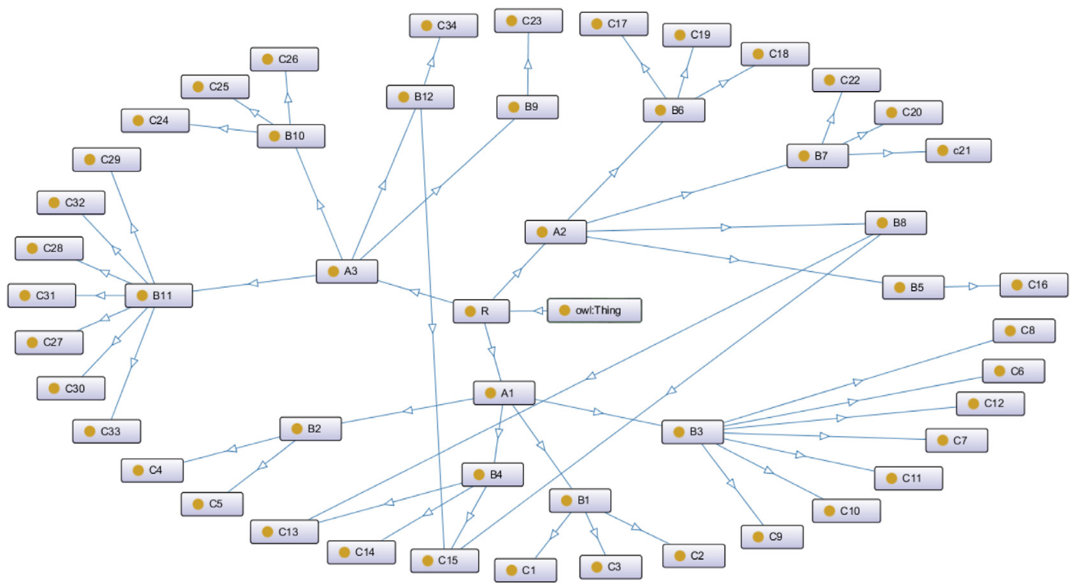

Fig. 9. Bayesian network diagram.

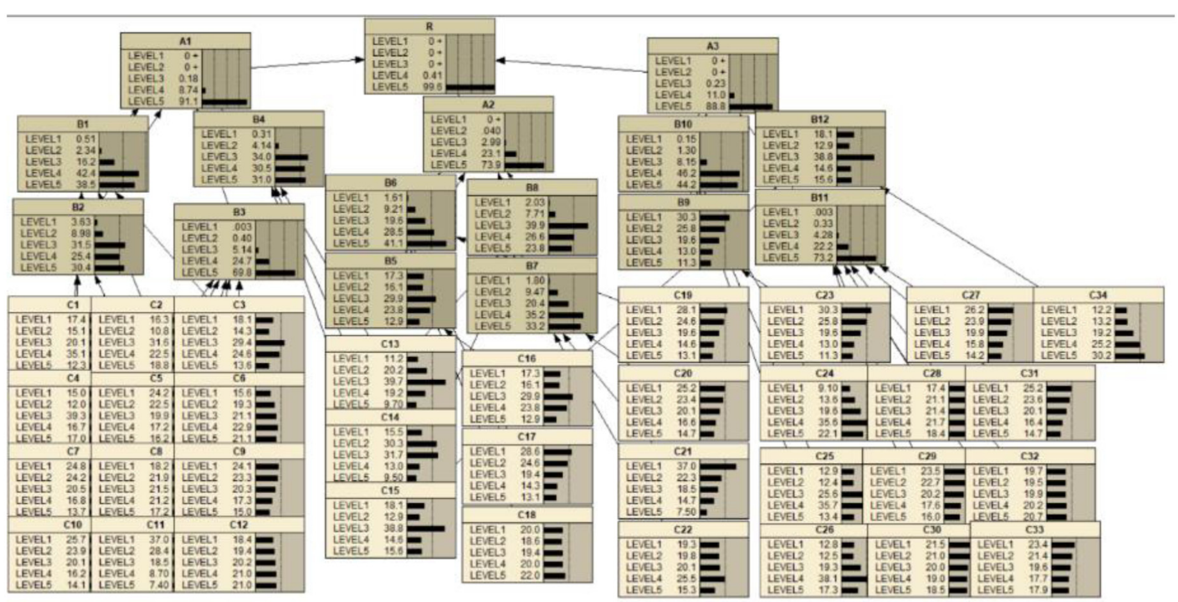

Fig. 10. Calculated probability of risk level distribution for each node of Bayesian structural model.

base of the integrated pipeline corridor risks. The Bayesian network method was introduced based on the established knowledge base, and the risk factors in the knowledge base were subjected to Bayesian network structure learning and parameter learning, and the risk factors were evaluated with the inference ability of the Bayesian model. The results show that the application of Bayesian network model can reflect the disaster risk level of integrated pipeline corridor operation and maintenance, which verifies the feasibility of the method and also provides a basis for the safe operation and maintenance of integrated pipeline corridor and disaster prevention and mitigation in the process of operation and maintenance.

There are still limitations in this study. Firstly, only three types of risk incidents, namely fire and explosion, flooding and structural damage, were analyzed, and risk incidents such as poisoning, electric shock and fall from height were not analyzed, the types of risk incidents studied in this paper are small and the risk factors identified are limited. Secondly, the Bayesian network model used for risk assessment is mainly constructed based on expert scoring, which is somewhat subjective.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by Beijing Social Science Foundation, China under Grant 19JDGLA002, 18JDGLA018, MOE (Ministry of Education in China) Project of Humanities and Social Sciences under Grant 19YJC630043, and was partially supported by Beijing Logistics Informatics Research Base, China. We appreciate their support very much.

Table 7
Expert weighting classification table.

Grade	Expert Grade Description	Weight
Class I	Senior experts in the field of integrated pipeline corridor Senior title of integrated pipeline corridor scientific research, design and engineering personnel	1.0
Class II	Senior title of integrated pipeline corridor scientific research, design and engineering personnel Integrated pipeline corridor management personnel with 10–20 years of service	0.9
Class III	Intermediate title of integrated pipeline corridor scientific research, design, engineering personnel Integrated pipeline corridor management personnel with 5–10 years of service	0.8
Class IV	Junior title of the integrated pipeline corridor scientific research, design, engineering personnel Integrated pipeline corridor managers with 1–5 years of service	0.7

Table 8
Probability distribution of accident risk factors in integrated pipeline corridor.

Risk level	level 1	level 2	level 3	level 4	level 5
C_1	0.174	0.151	0.201	0.351	0.123
C_2	0.163	0.108	0.316	0.225	0.188
C_3	0.181	0.143	0.294	0.246	0.136
C_4	0.150	0.120	0.393	0.167	0.170
C_5	0.242	0.225	0.199	0.172	0.162
C_6	0.156	0.193	0.211	0.229	0.211
C_7	0.248	0.242	0.205	0.168	0.137
C_8	0.182	0.219	0.215	0.212	0.172
C_9	0.241	0.233	0.203	0.173	0.150
C_{10}	0.257	0.239	0.201	0.162	0.141
C_{11}	0.370	0.284	0.185	0.087	0.074
C_{12}	0.184	0.194	0.202	0.210	0.210
C_{13}	0.112	0.202	0.397	0.192	0.097
C_{14}	0.155	0.303	0.317	0.130	0.095
C_{15}	0.181	0.129	0.388	0.146	0.156
C_{16}	0.173	0.161	0.299	0.238	0.129
C_{17}	0.286	0.246	0.194	0.143	0.131
C_{18}	0.200	0.186	0.194	0.200	0.220
C_{19}	0.281	0.246	0.196	0.146	0.131
C_{20}	0.252	0.234	0.201	0.166	0.147
C_{21}	0.370	0.223	0.185	0.147	0.075
C_{22}	0.193	0.198	0.201	0.255	0.153
C_{23}	0.303	0.258	0.196	0.130	0.113
C_{24}	0.091	0.136	0.196	0.356	0.221
C_{25}	0.129	0.124	0.256	0.357	0.134
C_{26}	0.128	0.125	0.193	0.381	0.173
C_{27}	0.262	0.239	0.199	0.158	0.142
C_{28}	0.174	0.211	0.214	0.217	0.184
C_{29}	0.235	0.227	0.202	0.176	0.160
C_{30}	0.215	0.210	0.200	0.190	0.185
C_{31}	0.252	0.236	0.201	0.164	0.147
C_{32}	0.197	0.195	0.199	0.202	0.207
C_{33}	0.234	0.214	0.196	0.177	0.179
C_{34}	0.122	0.132	0.192	0.252	0.302

Table 9
Integrated pipeline corridor risk accident probability distribution.

Risk level	level 1	level 2	level 3	level 4	level 5
B1	0.005	0.023	0.162	0.424	0.385
B2	0.036	0.090	0.315	0.254	0.304
B3	0	0.004	0.051	0.247	0.698
B4	0.003	0.041	0.340	0.305	0.310
B5	0.173	0.161	0.299	0.238	0.129
B6	0.016	0.092	0.196	0.285	0.411
B7	0.018	0.095	0.204	0.352	0.332
B8	0.020	0.077	0.399	0.266	0.238
B9	0.303	0.258	0.196	0.130	0.113
B10	0.002	0.013	0.082	0.462	0.442
B11	0	0.003	0.043	0.222	0.732
B12	0.181	0.129	0.388	0.146	0.156
A1	0	0	0.002	0.087	0911
A2	0	0	0.030	0.231	0.739
A3	0	0	0.002	0.110	0.888
R	0	0	0	0.004	0.996

References

[1] Y. Bilan, G. Mentel, D. Streimikiene, B. Szetela, Weather risk management in the weather-var approach. Assumptions of value-at-risk modeling, Econ. Comput. Econ. Cybern. Stud. Res. 54 (1) (2020) 31–48.

[2] M. Ibrahim, The integration of knowledge management into the lebanese graphic design business sector, J. Syst. Manage. Sci. 8 (1) (2018) 61–82.

[3] R. Neches, R.E. Fikes, T. Finin, et al., Enabling technology for knowledge sharing, AI Mag. 12 (3) (1991) 36–56.

[4] Thomas.R. Gruber, A translation approach to portable ontology specification, Knowl. Acquis. 5 (2) (1993) 199–220.

[5] N. Guarion, The Ontological Lvevl, R. Casati, B. Smith, G. White, Philosophy and the cognitive sciences, Psychol. Assess. 28 (7) (1994) 443–456.

[6] W. Borst, Construction of Engineering Ontologies, University of Twenty, Enschede, 1997.

[7] R. Studer, V.R. Benjamins, D. Fensel, Knowledge engineering: Principles and methods, Data Knowl. Eng. 25 (1–2) (1998) 161–197.

[8] Du Ping, Ontology-Based Research on the Identification and Extraction of Chinese Administrative Divisional Place Names, Lanzhou University, Lanzhou, 2011.

[9] Judea Pearl, Fusion propagation and structuring in belief networks, Artificial Intelligence 29 (3) (1986) 241–288.

[10] F. Jensen, T. Nielsen, Bayesian Networks and Decision Graphs, second ed., Springer Science Business Media, New York, 2007.

[11] J. Stolk, Complex systems simulation for risk assessment in flood incident management, in: 18th Biennial Conference on Modeling and Simulation, Australia, 2009.

[12] T. Bensi, D. Kiureghian, D. Straub, Bayesian Network Methodology for Infrastructure Seismic Risk Assessment and Decision Support, National Science Foundation, 2011, PEER 2011/02.

[13] M. Peng, L. Zhang, Analysis of human risks due to dam-break floods-parts 1: a mew model based on Bayesian networks, Nat. Hazards 64 (1) (2012) 903–933.

[14] Ma Zujun, Xie Zili, Analysis of the evolution mechanism of urban earthquake secondary hazards based on Bayesian networks, Disas. Sci. 27 (4) (2012) 1–5.

[15] S.C. He, L. Kang, X.M. Cheng, Y. Ding, Bayesian network-based flood risk analysis of the South-North Water Diversion Central Project, South-North Water Divers. Water Conserv. Sci. Technol. 10 (4) (2012) 10–13.

[16] D. Janjanam, S. Palivela, D. Nandyala, Building Bayesian networks for problems of risk attributable to natural hazards, Nat. Hazards Revi. 13 (4) (2012) 247–259.

[17] Francois Ayello, Tony Alfano, Davion Hill, et al., A Bayesian Network Based Pipeline Risk Management, NACE International, Salt Lake City, Utah, 2012.

[18] Chen Yongjun, L.I. Hongyuan, Wang Wenjuan, Xue Bo, L.I. Guanxun, Bayesian network-based disaster risk analysis of integrated pipe corridor operation and maintenance, J. Saf. Environ. 18 (06) (2018) 2109–2114.

[19] Julian Canto-Perello, Jorge Curiel-Esparza, Vicente Calvo, Criticality and threat analysis on utility tunnels for planning security policies of utilities in urban underground space, Expert Syst. Appl. 40 (11) (2013).

[20] Y. Jang, J.H. Kim, Quantitative risk assessment for gas-explosion at buried common utility tunnel, J. Korean Inst. Gas 20 (5) (2016) 89–95.

[21] Y.F. Jin, Research on Risk Sharing and Benefit Distribution of Underground Integrated Pipe Corridor PPP Project, Zhengzhou University, 2017.

[22] Wang Shuhong, Zhang Ze, Hou Wenshuai, Wang Feiasa, Multi-hazard coupled disaster-causing risk evaluation method for integrated pipeline corridor, J. Northeastern Univ. (Nat. Sci. Ed.) 39 (6) (2018) 902–906.

[23] Li Qian, Duan Wen, Xu Gaoqiang, Research on risk factors of integrated pipe corridor operation and maintenance management based on DEMATEL, Tunnel Constr.(in English and Chinese) 39 (1) (2019) 31–39.

[24] Julian Canto-Perello, Jorge Curiel-Esparza, Vicente Calvo, Criticality and threat analysis onutility tunnels for planning security policies of utilities in urban underground space, Expert Syst. Appl. 40 (11) (2013).

[25] Y. Jang, H. KimJ, Quantitative risk assessment for gas-explosion at buried common utility tunnel, J. Korean Inst. Gas 20 (5) (2016) 89–95.

[26] Jiang Luzhen, J. Li, Chen Jun, Numerical simulation of joint response of integrated pipe corridor under non-uniform seismic excitation, World Earthquake Eng. 31 (2) (2015) 101–107.

[27] Y.C. Zhao, G.Q. Zhu, Y.G. Gao, Research on the smoke te mperature field of urban underground integrated pipe corridor fire, Fire Sci. Technol. 36 (1) (2017) 37–40.

[28] Zhu Jia, Research on Safety Risk Identification and Evaluation System of Urban Integrated Pipeline Corridor, Chongqing Jiaotong University, 2017.

[29] H.H. Choi, H.N. Cho, J.W. Seo, Risk assessment methodology for underground construction projects, J. Constr. Eng. Manage. 130 (2) (2004) 258–272.

[30] Li Hongyuan, Research on Safety Risk Management of Urban Underground Integrated Pipeline Corridor Operation and Maintenance, Beijing University of Architecture, 2019.

[31] Jiao Haixia, Construction and Application of Ontology-Based Knowledge Base for Metro Construction Safety Risks, Southeast University, 2015.
[32] Y. Ari, A. Papadopoulos, Bayesian estimation of student-t Garch model using Lindley's approximation, Econ. Comput. Econ. Cybern. Stud. Res. 53 (1) (2019) 75–88.
[33] H. Shakil A. Ikramul, Investigation of the causes of accident in construction projects, J. Syst. Manage. Sci. 8 (3) (2018) 67–89.
[34] S.D. Eskesen, P. Tengborg, J. Kampmann, et al., ITA/AITES accredited material guidelines for tunnelling risk management: International Tunnelling Association, Working Group No. 2 q, Tunnell. Underground Space Technol. 19 (3) (2004) 217–237.