Research Article

Ontology-Based Risk Knowledge Construction for Integrated Pipeline Corridors

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In the construction process of different integrated pipe corridors, there exist a large number of similar and reusable risk analysis results. In order to improve the efficiency of risk analysis and the efficiency of dealing with accidents in the process of construction management of integrated pipeline corridors and systematize the fragmented risk analysis knowledge, this paper will build ontology-based knowledge for risk response in integrated pipeline corridors. This ontology knowledge base can not only standardize and informatize knowledge through the definition of knowledge attributes and classification of knowledge, which can help reuse risk management metaknowledge at different levels and greatly improve the efficiency of risk management, but also reason out the risk-causing mechanism and response strategy of new integrated pipeline corridor risk through the similarity between risks and the correlation between risk-causing factors, so as to realize the repeated application of risk knowledge.

1. Introduction

Nowadays, the construction of integrated urban underground pipe corridors is developing rapidly, and the integrated pipe corridor has become one of the best choices for the construction of urban municipal facilities with its superiority in terms of resource integration and convenient maintenance. In the process of construction of integrated pipe corridors, the frequency of risk accidents and the complexity of risk accident analysis have become one of the key issues. At present, the analysis of risk incidents and suggestions for countermeasures during the construction phase of integrated pipe corridors are often proposed by experts in the field, on the basis of which various types of risk analysis methods have been developed, such as the risk matrix method and the optimisation fuzzy comprehensive evaluation method. Although these risk analysis methods have improved the reliability and efficiency of risk analysis for integrated pipeline corridors to a large extent, the reusability of risk analysis results is still low and the knowledge is difficult to format and is not easily known or coded by others in practical applications. There are a large number of

similar and reusable risk analysis results in the construction process of different integrated corridors. Therefore, such knowledge can be standardized, coded, and stored in a standardized way for reuse, thus improving the efficiency of the analysis of risks and the handling of incidents in the construction of integrated pipeline corridors.

Ontologies have been widely used in areas such as natural language processing, knowledge management, medicine, Internet search, semantic Web, simulation, and modelling. In contrast, the use of knowledge ontology models is still a brand new topic in research in the field of construction engineering, especially in the study of risk management in integrated pipeline corridors. Building a knowledge base system based on ontologies is an effective way to improve the sharing, interoperability, maintainability, and reusability of knowledge. Therefore, in order to improve the efficiency of risk analysis and the efficiency of dealing with incidents during the construction management of integrated pipeline corridors and to systematize the fragmented risk analysis knowledge, this paper will build an ontology-based knowledge base for risk response in integrated pipeline corridors. The ontology knowledge base can

not only standardize and informatize knowledge through the definition of knowledge attributes and classification of knowledge, which can help reuse risk management meta-knowledge at different levels and greatly improve the efficiency of risk management, but also reason out the risk-causing mechanisms and response strategies of new integrated pipeline corridor risks through the similarity between risks and the correlation between risk-causing factors, so as to realize repeated application of risks knowledge.

The remainder of this paper is organized as follows. Section 2 reviews related works on the ontology and knowledge of risk management for integrated pipe corridor construction. Section 3 introduces the method and data of this paper. Section 4 provides the ontology-based risk management mode. Section 5 develops the results for risk management knowledge base construction, and Section 6 concludes the paper.

2. Related Work

2.1. Risk Management of Integrated Pipe Corridor Construction.

A comprehensive pipe corridor is a public works tunnel used for laying various engineering pipelines such as electricity, communication, gas, heating and water supply, and drainage under the city [1]. Its main purpose is to solve the long-standing problems of repeated excavation of urban roads, indiscriminate connection and erection of urban pipelines in the air, and waste of underground space resources to further optimize urban resources, beautify urban pipeline networks, and serve the construction of smart cities [2].

The academic and practical research on risk management in the construction phase of the integrated pipeline corridor includes three major aspects: risk identification, risk measurement, and risk response measures. Risk identification refers to the identification of the main risk events that occur during the construction, operation, and maintenance of the integrated pipeline corridor; risk measurement refers to the determination of the degree of impact of each risk event and the coupling correlation between risks; risk response measures refer to the timely proposal of the best response to possible risks and the targeted proposal of key technology implementation paths and safety assurance recommendations.

Accidents occurring in integrated pipeline corridors are often characterized by complexity, repetition, and multiplicity [3], especially in the construction phase where risk accidents are frequent, and the smoothness of the construction phase of integrated pipeline corridors plays a key role in the later construction and operation and maintenance. In order to address the heterogeneity of construction risk data and the complexity of spatiotemporal relationships, Hu et al. [4] developed a comprehensive pipeline corridor defect diagnosis system based on industrial base classes and semantic Web technology to provide support for decision-making regarding cause detection. Wang et al. [5] designed a comprehensive pipe corridor construction risk evaluation index system and then constructed a risk evaluation model using the optimal fuzzy comprehensive evaluation method.

Accurate and timely detection of integrated corridor construction risks and the development of effective maintenance strategies to maintain the safety and availability of the tunnels are essential. However, knowledge such as the analysis of risk incidents and recommendations for countermeasures during the construction phase of an integrated tunnel is often utilized on a one-off basis. This knowledge is difficult to format and is not easily accessible to others or encoded in practice [6]. In addition, the analysis of risk incidents and recommendations for countermeasures during the construction phase of a comprehensive pipeline corridor are often made by experts in the field, and once an experienced expert leaves the company, the safety management knowledge he possesses is lost, causing the company to lose a large amount of valuable knowledge assets. Nonexpert managers, on the other hand, need to devote more time and effort to sum up their experience in dealing with safety risk events due to their lack of experience, resulting in high management costs and low success rate of decision-making.

Therefore, for the integrated corridor field expert experience knowledge, it is necessary to mine and use effective knowledge representation methods to represent and save in the knowledge base, so as to solve the current integrated corridor in the construction phase of the risk problem, reduce the cost of risk management, and improve the level of risk management, which has important practical value to improve the efficiency of the integrated corridor risk response.

2.2. Ontology and Knowledge Method for Integrated Pipe Corridor Construction

2.2.1. Theoretical Study of Ontology and Knowledge Base.

Ontology is originally a philosophical concept: "a systematic description of what can be related to existence in the world, i.e. existentialism." As the understanding and study of ontology have evolved, the definition of ontology has also evolved, with several definitions of ontology being proposed by academics from different domain perspectives and focuses. In the field of Artificial Intelligence (AI), ontologies are often referred to as domain models or conceptual models, which are theories about various objects, object properties, and possible relationships between objects in a particular knowledge domain. In knowledge engineering, ontologies are used to represent knowledge structures that can be shared and reused [7].

For the understanding of a knowledge base, a narrowly defined knowledge base is a place where knowledge that has been structured according to a certain format is stored in the knowledge engineering technology of an AI discipline, while a broad understanding is a technical system that includes knowledge acquisition, organization, storage, forwarding, maintenance, and updating of all these functions. The establishment of a knowledge base allows for the representation, transfer, reasoning, and acquisition of knowledge to enable knowledge retrieval and meet user needs.

2.2.2. Applied Research on Ontology and Knowledge Bases. Currently, ontologies have been widely used in natural language processing, knowledge management, medicine, Internet search, semantic Web, simulation, and modelling. In contrast, the use of knowledge ontology models is still a brand new topic in the research in the field of construction engineering, especially in the research on risk management of integrated pipeline corridors. Xu and Raahemi [8] defined ontologies for the green construction domain according to the ontology creation process, as well as contextual ontology modelling on the two-layer structure. Liu [9] et al. proposed an ontology-based cost estimation representation model, which finally realized the cost estimation model of concept, work item ontology, and construction conditions, and solved the problem of knowledge representation, sharing, and utilization in the cost estimation process. Yang [10] used fuzzy ontology to improve the comprehensibility and sharing of risk evaluation, established a fuzzy ontology-based risk evaluation system for nonexcavation supply of municipal engineering, and discussed the specific implementation of the system, including the generation of fuzzy domain ontology, the establishment of fuzzy evaluation rule base, the establishment of fuzzy inference rules, and the update and improvement of the knowledge base.

Building a knowledge base system based on ontologies is an effective way to improve the sharing, interoperability, maintainability, and reusability of knowledge. At present, there are also a certain number of ontology knowledge base application cases at home and abroad, such as the high-performance knowledge base system of the US Department of Defense, the Cyc system researched by MCC in the US, and the TOVE system researched by the University of Toronto in Canada. Domestically, ontology knowledge bases have been successfully applied to the field of manufacturing process production [11], mobile Web service systems [12], traffic knowledge query systems [13], the field of emergency incident management [14], and so forth.

For the risk management of the construction phase of the integrated pipe corridor, the combination of knowledge reuse and semantic reasoning is proposed to achieve computer-understandable construction risk knowledge and semantic reasoning and the Protégé platform [15] to achieve the construction of a knowledge base.

2.3. Case-Based Study of Integrated Pipe Corridor Construction. Case-Based Reasoning (CBR) is a mode of reasoning in which solutions to current problems are obtained by accessing past solutions to similar problems in the case knowledge base, that is, using old examples or experiences to solve new problems, evaluate new problems, explain anomalies, or understand new situations. Pedro et al. [16] defined a standard reasoning process that consists of four parts: case retrieval, case reuse, case revision, and case learning parts, which become the 4R cycle, intuitively and highly abstractly reflecting the essential features of the CBR knowledge reasoning process. Among them, the most widely used methods for case retrieval are inductive indexing, nearest neighbor strategy, and knowledge-guided strategy.

Since the application of case reasoning needs to be supported by rich case experience, it is mainly applied to some fields with rich empirical knowledge going to lack of strong theoretical models, such as fault diagnosis [17], enterprise management [18], medical field [19], emergency response management [20], and other fields. In addition, the research on ontology-based case reasoning systems has likewise seen many achievements; for example, scholars at the University of Wollongong in Australia developed an ontology- and CBR-based student admissions audit system; the Computer Integration Technology and Open Laboratory at Shanghai Jiaotong University conducted in-depth research on an ontology-based reconfigurable knowledge management platform and reconfigurable paradigm storage technology; Beijing University of Aeronautics and Astronautics developed an ontology-based CBR system for automotive fault diagnosis.

Based on the literature review and research background in Section 1, in order to improve the efficiency of risk analysis in the process of integrated pipe corridor project management and systematize the fragmented risk analysis knowledge, this section will construct an ontology-based knowledge base for integrated pipe corridor construction risk management. The ontology knowledge base can not only standardize and informatize knowledge through the definition of knowledge attributes and classification of knowledge, which can help reuse risk management meta-knowledge at different levels and greatly improve the efficiency of risk management, but also reason out the risk-causing mechanisms and response strategies of new integrated corridor risks through the similarity between risks and the correlation between risk-causing factors, thus realizing the repeated application of risk analysis knowledge.

3. Method and Data

3.1. Method. In this study, from the characteristics of the knowledge base in the field of integrated pipe corridor construction risk management, a concept semantic similarity calculation method that integrates concept semantic distance, concept semantic hierarchy, and concept semantic overlap [21] is used based on a simple structure algorithm and comprehensive consideration of concept hierarchy depth, whereby the ontology knowledge base is used for reasoning about construction risk countermeasures in integrated pipe corridors.

3.1.1. Semantic Distance Similarity of Concepts. Assume that any 2 nodes in the knowledge ontology structure represent the target case and source case concept semantics, respectively, denoted as x_i and y_i; the conceptual-semantic distance $\text{Dist}(x_i, y_i)$ is the sum of the shortest path lengths from any node of the nearest common ancestor of the two concepts in the ontology structure graph to x_i and y_i. Let $\text{Sim}_1(x_i, y_i)$ denote the degree of conceptual-semantic similarity between nodes x_i and y_i, and the classical conceptual-semantic distance formula proposed by Palmer [22] et al. is used to calculate the conceptual-semantic similarity.

$$\text{Sim}_1\left(x_i, y_i\right) = \begin{cases} 1, & \text{if Dist}\left(x_i, y_i\right) = 0, \\[2mm] \dfrac{2 * N}{\text{Dist}\left(x_i, y_i\right) + 2 * N}, & \text{if Dist}\left(x_i, y_i\right) = I, \\[2mm] 0, & \text{if Dist}\left(x_i, y_i\right) = \infty. \end{cases} \tag{1}$$

3.1.2. Semantic Hierarchical Similarity of Concepts. Assume that the nodes in the ontology structures x_i and y_i are at levels $L(x_i)$ and $L(y_i)$ and the largest level of the nodes in the ontology structure is denoted as $L(z_i)$. Let $\text{Sim}_2(x_i, y_i)$ denote the conceptual-semantic hierarchical similarity between nodes x_i and y_i, using an improved application of the conceptual-semantic hierarchy calculation formula based on

$$\text{Sim}_2\left(x_i, y_i\right) = \begin{cases} 1, & \text{if } x_i = y_i, \\[2mm] \dfrac{L(x_i) + L(y_i)}{\left|L(x_i) - L(y_i)\right| + 2 * L(z_i)}, & \text{if } x_i \neq y_i. \end{cases} \tag{2}$$

3.1.3. Semantic Overlap of Concepts. The set of identical nodes in the process of reaching the root node from x_i and y_i, respectively, is denoted as $N(x_i) \cap N(y_i)$; the set of all nodes in the process of reaching the root node from x_i and y_i, respectively, is denoted as $N(x_i) \cup N(y_i)$. Let $\text{Sim}_3(x_i, y_i)$ denote the conceptual-semantic overlap between nodes x_i and y_i, using an improved application of the conceptual-semantic overlap calculation formula based on

$$\text{Sim}_3\left(x_i, y_i\right) = \left| \frac{\left(N(x_i) \cap N(y_i)\right)}{\left(N(x_i) \cup N(y_i)\right)} \right|. \tag{3}$$

Integrating the similarity calculation methods of conceptual-semantic distance (1), conceptual-semantic hierarchy (2), and conceptual-semantic overlap (3), this study proposes the conceptual-semantic similarity calculation method between the source case and the target case as shown in the following equation:

$$\text{Sim}^*(A, B) = \alpha * \text{Sim}_1\left(x_i, y_i\right) + \beta * \text{Sim}_2\left(x_i, y_i\right) + \gamma * \text{Sim}_3\left(x_i, y_i\right), \tag{4}$$

where α, β, and γ are all regulators and $\alpha + \beta + \gamma = 1$.

3.2. Data. This part collects, collates, and analyzes a large amount of relevant literature, summarizes the risk response measures for integrated pipe corridors in the construction process, and conducts a systematic and comprehensive study and analysis of existing research on ontology and case reasoning in order to identify the breakthrough point and provide theoretical support for this study. Web crawlers, topic modelling, and cluster analysis are used to collect first-hand cases of integrated corridor risk incident response and extract keywords and topic modelling, on the basis of which the knowledge base is constructed. These risks come from a variety of sources, such as pipeline rupture and leakage, flood, mudslide, landslide, poisoning and asphyxiation, fire, explosion, gas outage, equipment damage, drowning, electric shock, water outage, electrocution, fire, power outage, equipment damage, asphyxiation, scalding, thermal outage, fall, object strike, mechanical injury, poisoning and asphyxiation, and structural damage to the body of the corridor. The technical route is shown in Figure 1.

4. Ontology-Based Risk Management Mode

This section uses ontology knowledge base technology and case inference technology to optimize traditional safety risk management methods and construct an ontology-based safety risk management model for integrated pipe corridor construction, which is shown in Figure 2.

The application layer is a concrete application of the model's field operations and complements traditional safety risk management methods. There are three main application modules: the risk-causing factor identification module, the risk-causing factor analysis module, and the safety risk control module.

The business logic layer is responsible for sharing and reusing empirical knowledge, including two modules: rule reasoning and case reasoning; using the association rules of the rule reasoning module to reason and analyze the types of risk events and probability of occurrence corresponding to the newly emerged risk-causing factors; and using a combination of rule reasoning and case reasoning to push the security risk management proposal.

The data layer is mainly to complete the construction of the ontology knowledge base, case base, and rule base to realize the integration and structuring of historical accident cases, as well as the knowledge of experts in the field and relevant national and industry norms and standards, which is the basis for sharing and reusing knowledge in the field of comprehensive construction safety risks.

5. Risk Management Knowledge Base Construction

In this study, the maturity of ontology construction methods and the characteristics of domain ontology construction tools are examined in depth. On the basis of the characteristics of ontology construction tools Protégé, this study makes full reference to Stanford University's "seven-step approach" and combines knowledge inference and update. Four steps are as follows: define classes and class hierarchies, defining object-type attributes, defining numerical attributes, and example construction.

5.1. Define Classes and Class Hierarchies. Ontologies in the domain knowledge base use Classes to represent collections of individual concepts, and in Protégé Classes (concepts) are
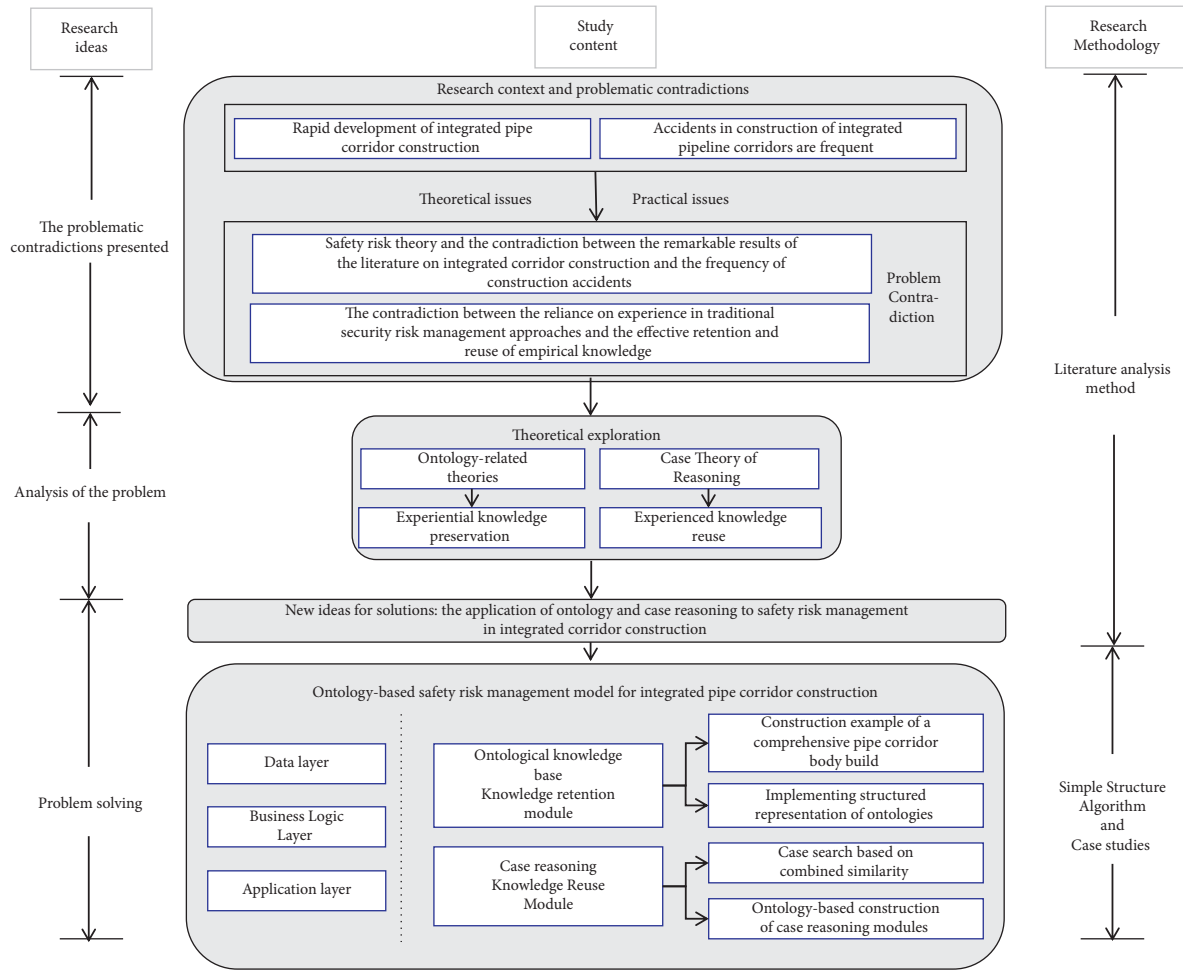
Figure 1: Technology roadmap.

expressed in software through a structure diagram consisting of Parent Class and Subclass.

Due to the complexity and refinement of the knowledge structure in the field of safety risks in integrated corridor construction, this chapter takes a top-down approach starting from the top of the concept and gradually refining it.

By identifying the risk-causing factors and using the nonlinear mapping relationship between risk-causing factors and construction accidents, we estimate the occurrence of risk events, the types of risk events, and the consequences of risk events, so as to strengthen risk management measures in a targeted manner to avoid the expansion of losses. The risk factors are then used to estimate the occurrence of risk events, the types of risk events, and the consequences of risk events, so that risk management measures can be targeted to avoid the expansion of losses. Therefore, this study expresses the ontological knowledge of the integrated corridor construction project, construction activities, risk-causing factors, risk events, risk event consequences, control measures, and the relationship between them, and the ontological framework of the integrated corridor construction safety risk domain is shown in Figure 3.

5.2. Defining Object-Type Attributes. In an ontology, it is not meaningful to define classes (concepts) alone; definitions of their properties are needed to describe general facts about class members and specific facts about individuals, as well as to illustrate common features of classes. Like the definition of classes, attributes can be arranged in a hierarchical manner. In the modelling primitives of ontologies, object-type properties (Datatype Property) refer to the relationship between two classes and are used to describe the non-quantifiable characteristic properties of a class, with their own Domains and Ranges. The definition domain is the upper class of the attribute relationship and the value domain is the lower class of the attribute relationship. Using the Protégé, the Object Properties tab of the software is used to describe the object-type properties between classes, as well as the definition domain and value range settings of the properties. The different object-type property settings for this study are shown in Table 1.

5.3. Defining Numerical Attributes. Data-based attributes are used to quantitatively describe the characteristic attributes of the class itself, such as project approval number and project
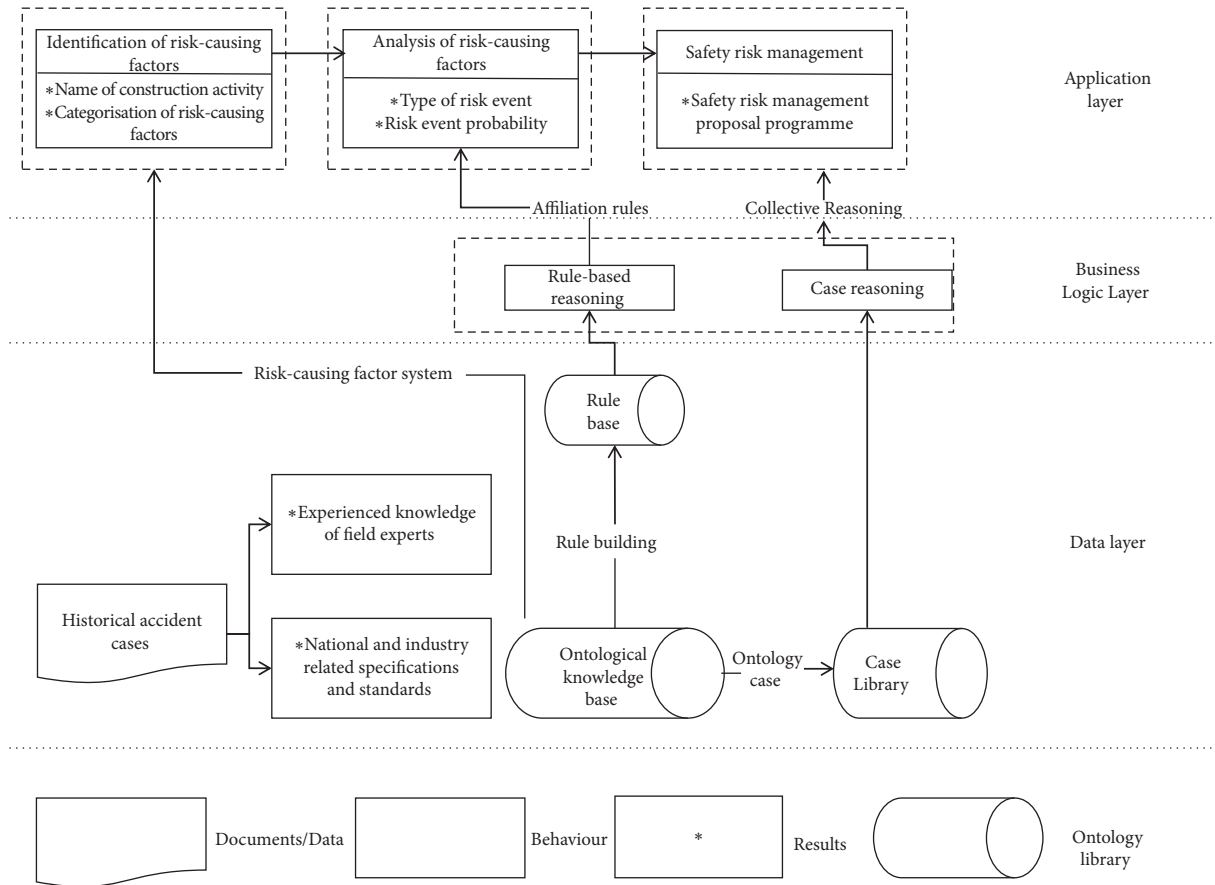
FIGURE 2: An ontology-based risk management model for integrated pipeline corridor construction.
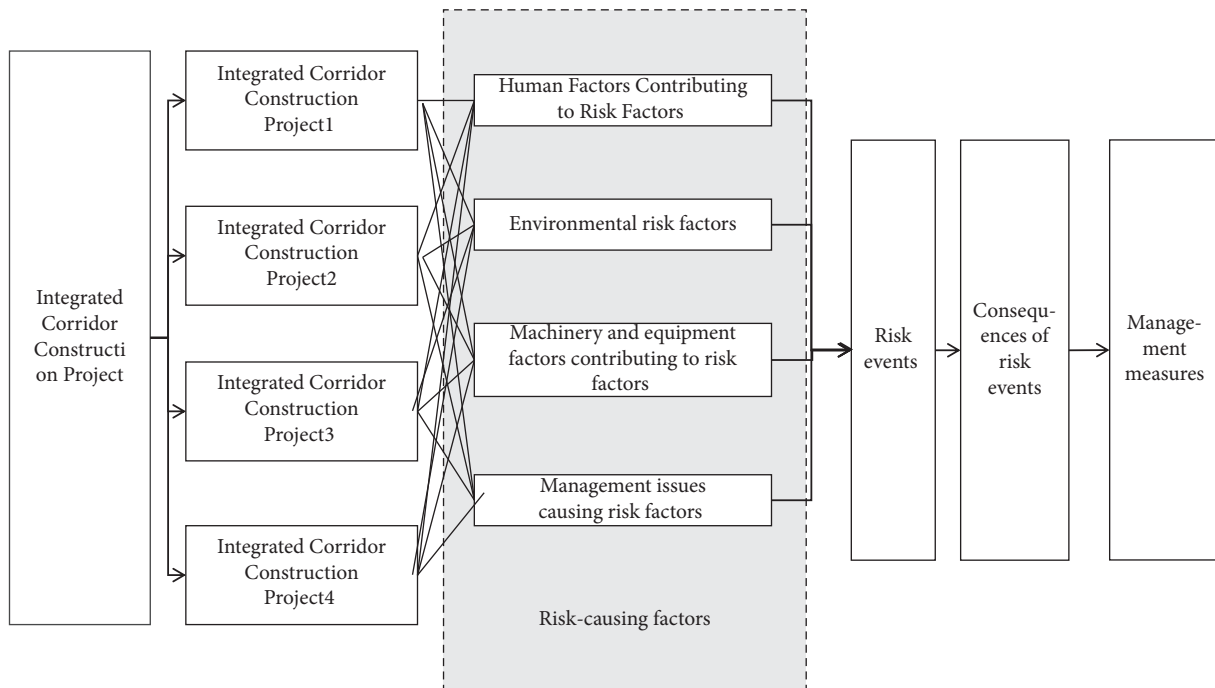

FIGURE 3: Ontological framework for safety risk areas in the construction of integrated pipeline corridors.

TABLE 1: Domain ontology object-type property settings.

Property name	Property meaning	Definition field	Value range
has_Construction	"Construction project" includes "construction activities"	Construction projects	Construction activities
cause_Risks Factors	"Risk-causing factors" arising from "construction activities"	Construction activities	Risk-causing factors
relate to_Risk Factors	The relationship between "risk-causing factors" and "risk factors"	Risk-causing factors	Risk-causing factors
cause_Risks	The correlation between "risk-causing factors" and "risk events nonlinear mapping relationship"	Risk-causing factors	Risk events
has_Risk Consequence	"Risk event" causing "consequences of risk event"	Risk events	Risk events consequences
has_Measures	"Control measures" taken in response to "consequences of risk events"	Risk events consequences	Control measures

TABLE 2: Domain ontology numeric attribute settings.

| Number	Data type	Type	Characteristics
1	Name of construction activity	String	Functional
2	Construction activity number	String	Functional
3	Item no.	String	Functional
4	Description of construction activities	String	Functional
5	Name of risk-causing factor	String	Functional
6	Risk factor number	String	Functional
7	Name of the consequence of the risk event	String	Functional
8	Description of affiliated risk events	String	Functional
9	Description of the measure	String	Functional
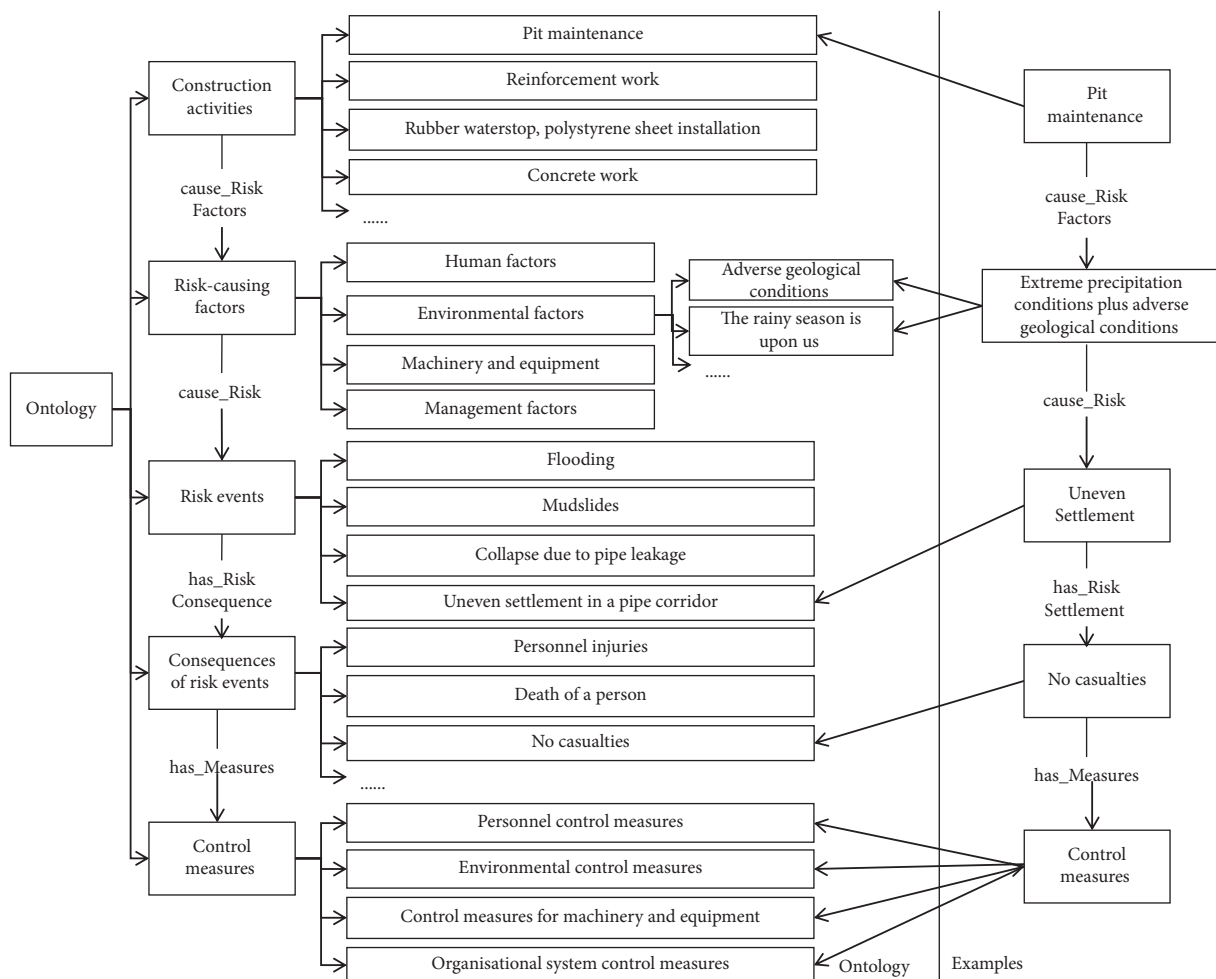
FIGURE 4: Framework for ontology examples in the field of safety risks in integrated pipeline corridors.
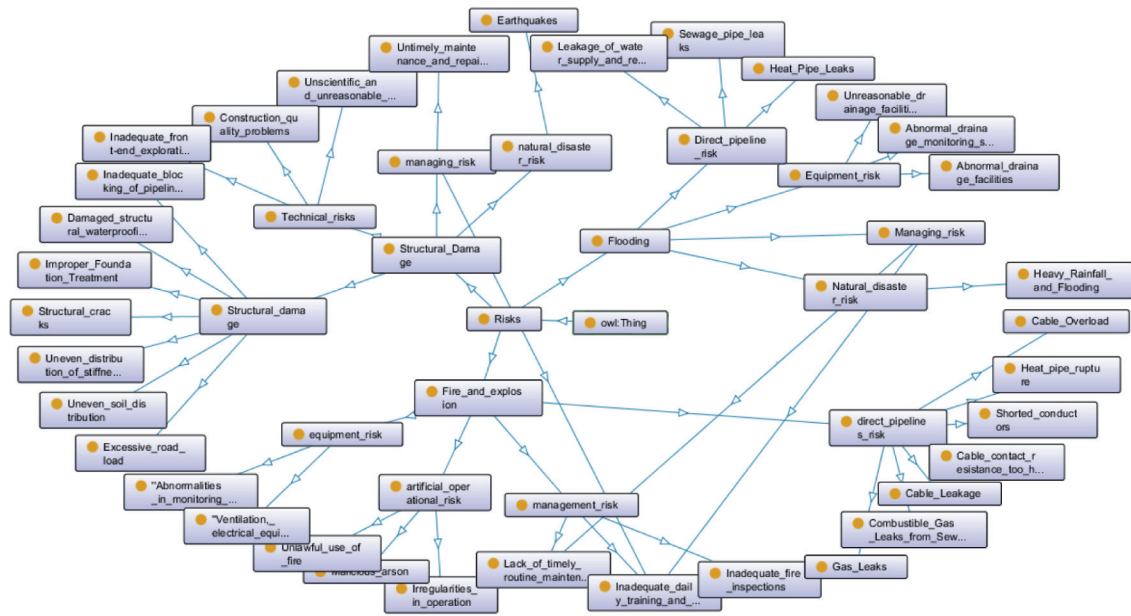
FIGURE 5: Ontological knowledge base of safety risk areas for integrated pipeline corridors.

name. Using the Protégé, the Data Properties tag in the software is used to describe the datatype properties of the class and to define the value type; for example, the value type of the project number is defined as "string." Some of the numeric property settings for this study are shown in Table 2.

5.4. Example Construction. In the definition of an ontology, an instance represents an object and a class (concept) is a collection of objects, so that an instance can be regarded as a special class (concept). However, it is often not very easy to distinguish whether a concept term is a class or an instance, mainly based on the minimum level of granularity of class (concept) expressions specified in the specific application domain and the starting division of instances. In this study, a concept with a larger scope is denoted as a class (concept), while for some of the most precise concepts subdivided below the class it is defined as an instance. In the construction of the ontological knowledge base of the integrated corridor construction risk domain, a specific integrated corridor construction project is an instance, the risk-causing factors generated by the specific construction process activities of the integrated corridor construction project are instances, and the risk events generated by the transfer of risk-causing factors are also instances.

According to the ontological framework of the safety risk domain of the integrated corridor in Figure 3, a complete safety risk management process should be a link between the created instances of construction activities, risk-causing factors, risk events, risk event consequences, and control measures, starting from the beginning of the link and adding each instance to another instance by adding their object-type attributes and selecting them to point to another instance. The creation of linking relationships allows for the effective preservation of expert knowledge and provides a basis for

the sharing and reuse of this knowledge. The framework of the ontology instance created in this study is shown in Figure 4.

Ultimately, the ontology-based knowledge base for integrated pipeline corridor risk schematic is constructed in Figure 5 (Hai et al. [23]). Based on the algorithm described, this part uses the concept semantic similarity calculation method that integrates concept semantic distance, concept semantic hierarchy, and concept semantic overlap, based on the simple structure algorithm and comprehensive consideration of concept hierarchy depth, according to which the ontology knowledge base is used to reason about the risk countermeasures in integrated pipe corridor construction. Case reasoning plays a leading reasoning role in the whole ontology-based integrated pipe corridor construction safety risk management model, completing case reasoning retrieval, case reuse, case correction, and case preservation, and realizing the sharing and reuse of empirical knowledge.

6. Conclusion

In the process of construction of integrated pipe corridors, the frequency of risk accidents and the complexity of risk accident analysis have become one of the key issues. A domain ontology knowledge base for safety risks in integrated pipeline corridor construction is constructed to achieve the preservation, sharing, and reuse of empirical knowledge.

In this paper, firstly, an ontology-based model for integrated pipeline corridor construction safety risk management is constructed, completing the hierarchical and modular design of the management model application layer, business logic layer, and data layer. Based on the existing modelling methods, the domain ontology modelling method and steps are proposed for the construction risk of the

integrated pipeline corridor and the Protégé. Based on the support of the data layer of the management model with the domain ontology knowledge base as the core, the business logic layer workflow of the case inference module is designed; based on the support of the data layer and the business logic layer, the application layer workflow of the comprehensive pipeline corridor construction risk response is designed to realize the sharing and reuse of experience knowledge. Based on the support of the data layer and the business logic layer, the application layer workflow of integrated pipe corridor construction risk response is designed to realize the sharing and reuse of experience knowledge in order to improve the level of integrated pipe corridor construction risk management.

Data Availability

The Oracle database data used to support the findings of this study are supplied by Beijing Jingtou Urban Utility Tunnel Investment Co., Ltd., under license and so cannot be made freely available. Requests for access to these data should be made to Beijing Jingtou Urban Utility Tunnel Investment Co., Ltd. (hbj93@hotmail.com).

Conflicts of Interest

The author declares that there are no conflicts of interest.

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