Ontology-Based Risk Assessment and Solution during Shield Tunnel Construction

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ABSTRACT: *The complexity and risk of tunnel construction always affect people, economy, and environment. But the management, sharing and reusing of risk knowledge of tunnel construction have always been inconvenient due to the weakness of traditional information management methods such as the relational database. However, currently, ontology has become an important method of knowledge representation, management, sharing and reusing, which enables efficient and semantic information retrieval and highly facilitates knowledge sharing and reusing, and it can be the solution for the above problems. At present, few studies focus on the use of ontology of tunnel construction, and the ontologies built by them still have some shortcomings. For example, the solutions for risk must be given by reasoning (e.g. SWRL), and the construction order and hierarchy cannot be expressed. In this paper, an ontology of shield tunnel construction is developed and then applied based on WBS and risk analysis of the shield tunnel construction, which eliminates the shortcomings mentioned above. Firstly, this paper makes WBS of shield tunnel construction. Secondly, the risk analysis of shield tunnel construction is developed after proposing the relationships between risk factors, risk precursor, and risk accidents and collecting relevant data of the above three risks. Then, the ontology of shield tunnel construction is developed by Protégé. Finally, the ontology is applied. This paper takes an actual shield tunnel subway construction project as an example, creates its related instances and uses SPARQL to query the risks and corresponding solutions in it. The results show that the risks and corresponding solutions can be correctly identified, which can provide a guidance for construction safety.*

KEYWORDS: *ontology; shield tunnel construction; risk management; risk precursor*

1. INTRODUCTION

The complexity and risk of tunnel construction always affect people, economy, and environment. Due to the differences and uniqueness of tunnel construction, the transfer, sharing and reusing of tunnel construction risk management knowledge have always been inconvenient. The weakness of the traditional risk management method lies in the management of information, i.e., the storage and retrieval of information. Traditional information management methods mostly store knowledge as text or in relational databases, and information retrieval methods are mainly based on keyword matching, which can only identify literally matched information, but not understand information at the semantic level. In addition, the knowledge stored by traditional methods faces enormous difficulties when they need to be reused, such as different or improper information expression, insufficient mining and utilization of information (Zhou *et al.*, 2019), and data fragmentation of different systems (Lin *et al.*, 2019). However, ontology can be the solution for the above problems.

In the field of artificial intelligence, (Neches *et al.*, 1991) first gave the definition of ontology, "An ontology defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary". The most used definition of ontology was from (Gruber, 1993), "Ontology is the specification of a conceptualization". Nowadays, ontology has evolved into an efficient and significant method for knowledge representation, management, sharing, and reusing.

At present, few studies focus on the use of ontology for risk management of tunnel construction. (Jiao, 2015) built a risk ontology for subway construction. (Zhong and Li, 2015) proposed an ontological and semantic approach for the construction risk inferring and application. However, the solutions for risks given by the above two researches relied on reasoning (e.g. Semantic Web Rule Language, SWRL), which should be used only if ontology cannot express and may cause redundancy in ontology after running multiple times. And these researches cannot express the order and hierarchy in the construction. (Hu and Huang, 2014) introduced a tunnel data organization method driven by ontology, which used some terminologies such as tunnel object, process, event, etc. like Industry Foundation Classes (IFC) to build a tunnel ontology. Nevertheless, this method cannot express risk well since it is similar to IFC, and need to combine expert knowledge to analysis problems manually. In this paper, an ontology of shield tunnel construction is developed and applied based on WBS and risk analysis of the shield tunnel construction. The shortcomings mentioned above are eliminated, so the solution can be represented in ontology instead of SWRL and the construction order and hierarchy can be expressed. It is worth noting that the method proposed by this paper is not final, but can be a foundation and provide ideas for future works.

This paper is structured as follows. Section 0 makes WBS of shield tunnel construction. Section 0 conducts risk assessment and solution with precursor analysis of shield tunnel construction. In section 4, the ontology of shield tunnel construction is developed. In section 5, the ontology is applied in an actual project. Finally, section 6 summarizes this paper and points out some future works.

2. WBS OF SHIELD TUNNEL CONSTRUCTION

A work breakdown structure (WBS) in project management and systems engineering, is a deliverable-oriented breakdown of a project into smaller components. According to some Chinese standards (GB50446-2017, STB/DQ-010001-2007) and related researches (Jiao, 2015; Liu, 2013), this paper firstly divides the shield tunnel construction into the following five categories: *Construction Preparation, Shaft Excavation, Shield Enter/Exit, Shield Excavation, Engineering Acceptance*.

Then, the WBS second level of the shield tunnel construction can be obtained by a consecutive decompose for each category above, as shown in Fig. .

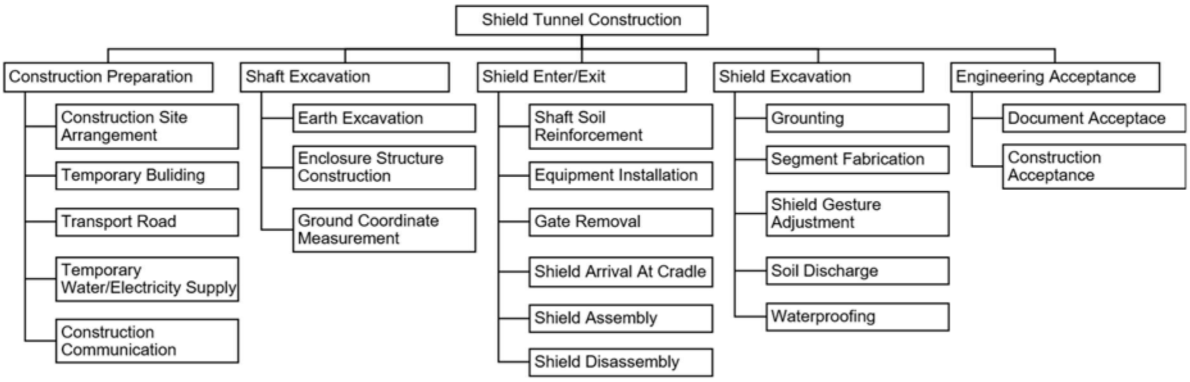


Fig. 1: WBS (1st and 2nd level) of the shield tunnel construction.

3. RISK ASSESSMENT AND SOLUTION WITH PRECURSOR ANALYSIS

Some researches about the application of risk precursor in the field of engineering have been made. (Weick and Sutcliffe, 2002) considered that the establishment of accident precursor information system can encourage effective and continuous communication between teams, and thus enhance their safety awareness. (Grabowski *et al.*, 2007) also believed that the identification of precursors before accidents' happening has great potential for improving the safety of the system.

However, the definition of some terms related to risk is still not clear and not unified. A now commonly used risk generation mechanism of tunnel engineering is, "Due to the existence of risk-pregnant environment and induction of risk factors, it may cause risk events and further damage to various risk-affected elements" (Cheng, 2004). Based on the above definitions and related researches, this paper proposes the concept of three risk elements, namely, *risk factor*, *risk accident*, and *risk precursor*. Their definitions are as follows, their relationships are shown in Fig. 1, and their details will be discussed in section 0-3.3.

- Risk factor. The direct cause or factor that can cause a risk accident.
- Risk accident. The event that deviates from the expected target or brings losses to the project.
- Risk precursor. A monitorable event that is generated by risk factors, which can predict risk accidents and has a higher frequency and less harm than the risk accident.

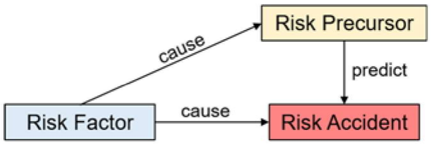


Fig. 2: the relationships between risk factor, risk accident, and risk precursor.

3.1. Risk factors and solutions

At present, researches on risk factors divide factors into some aspects: human, management, machinery, material, and environment. This paper combines some risk factors above, and will discuss them in three aspects, namely, human, mechanical, and environmental risk factors.

As for human risk factors, the "Swiss Chess Model" proposed by (Reason, 1990) described four levels of them, each of which affected the next level. Based on it, (Shappell and Wiegmann, 2000) proposed the Human Factors Analysis and Classification System (HFACS), which further subdivided the contents of its four levels and gave examples of possible instances in each level. Based on HFACS, (Wang *et al.*, 2010) established a construction accident analysis model HFACS-CI, which proposed a fifth level (external factors) above the fourth level of HFACS. By synthesizing the above researches, Table gives the human risk factors in shield tunnel construction.

As for mechanical risk factors, Construction Accident Cause (ConCA) model (Gibb *et al.*, 2006) divided the causes of equipment and materials into three categories: suitability, usability, and condition. This paper considers the combination of equipment and materials risk factors as mechanical risk factors, thus,

Table 2 gives the mechanical risk factors in shield tunnel construction.Finally, the environmental risk factors are divided into three categories, as shown in Table 3. This paper takes some instances in Table 1~Table 3 as examples and gives their solutions, as shown in Table 4.

Table 1: human risk factors in shield tunnel construction.

Level	Risk factors
Unsafe acts	Errors
	Violations
Preconditions for unsafe acts	Adverse mental states
	Adverse physiological states
	Physical/mental limitation
	Crew resource management
Unsafe supervision	Inadequate supervision
	Planned inappropriate operations
	Failed to correct problem
	Supervisory violations
Organizational influences	Resource/acquisition management
	Organizational climate
	Organizational process
External factors	Economy/social/political environment

Table 2: mechanical risk factors in shield tunnel construction.

Category	**Risk factors**
Equipment	Equipment performance
	Equipment suitability
	Equipment condition
Material	Material performance
	Material suitability
	Material condition

Table 3: environmental risk factors in shield tunnel construction.

Category	Risk factors
Natural environment	Whether condition
	Geological condition
	Hydrological condition
	Natural disaster
	Environmental damage
Surrounding environment	Surrounding underground pipeline
	Surrounding buildings
	Surrounding load
	Surrounding dangerous facilities
Working environment	Site arrangement
	Physical environment
	Sanitation

Table 4: solutions of some risk factor instances in shield tunnel construction.

Risk factor instances	Solutions
Shield tail sealing failure	Brush grease on seal frequently
(Mechanical)	Assemble segments centred
	Grouting the leaking part
Slurry low quality	Replace the slurry
(Mechanical)	Use a better performance slurry
Layer difference	Detecting information ahead
(Environmental)	Adjusting excavation parameters
	Adjusting shield gesture
Excavation obstacle	Ultrasonic obstacle detection
(Environmental)	Use stone crusher

3.2. Risk precursors and corresponding risk accidents

(Jiao, 2015) listed the monitorable information in subway construction according to the WBS of shield tunnel construction, which is similar to the risk precursors in this paper. Based on Jiao's research and related standards, Table gives the risk precursors in shield tunnel construction, and Table gives these risk precursors' limitation and corresponding risk accidents.

It is worth noting that the monitorable risk precursors listed in Table does not mean that they can only be monitored within their belonging constructions. For example, "ground settlement" in shaft excavation also can be monitored in shield excavation.

Table 5: risk precursors (monitorable) in shield tunnel construction.

Construction	Construction decomposition	Risk precursors (monitorable)
Construction preparation	Construction site arrangement	Site completeness
	Temporary building	Office security
	Transport road	Transport safety
	Temporary water/electricity supply	Water consumption
		Water supply pressure
		Power supply voltage
	Construction communication	Communication quality
Shaft excavation	Earth excavation	Shaft depth and size
		Distance from the nearest building
		Surrounding buildings deformation
		Surrounding pipeline settlement
	Enclosure structure construction	Enclosure wall maximum displacement
		Enclosure wall top displacement
		Ground settlement
		Soil deep settlement
	Ground coordinate measurement	Measurement accuracy
Shield enter/exit	Shaft soil reinforcement	Reinforcement area width and length
		Reinforcement soil compressive strength
	Equipment installation	Component installation deviation
		Component strength and stability
	Gate removal	Soil collapse amount

		Water leakage amount
	Shield arrival at cradle	Cradle deviation
		Segment vertical deviation
Shield excavation	Shield gesture adjustment	Shield axis deviance
		Jack position and thrust
		Excavation speed
	Segment fabrication	Segment quality
		Segment position deviation
		Segment joint opening
		Misalignment of adjacent segments
		Tunnel settlement
		Internal deformation
		Tunnel longitudinal deformation
		Tunnel segment steel bar stress
		Tunnel ring ovality
	Grouting	Grouting mix proportion
		Grouting amount
		Grouting pressure
		Slurry gelation time
		Slurry strength
	Soil discharge	Excavation face stability
		Pressure chamber pressure
		Shield rotation angle
		Blade wear
		Blade rotation speed and torque
		Soil discharge amount
	Waterproofing	Segment impermeability
		Crack maximum width
		Water leakage amount
		Drainage capacity

Table 6: limitations and corresponding accidents of risk precursors in shield tunnel construction.

Risk precursors (monitorable)	Limitations	Risk accidents
Enclosure wall top displacement (mm)	30	Collapse
Enclosure wall maximum displacement	50	
Ground settlement	30	
Reinforcement soil compressive strength	Design value	Collapse/Flood
Shield axis deviance	50	
tunnel ring ovality	±5‰D	
Segment position deviation	±50	
Excavation face stability factor	6	Collapse/Mechanical injury
Ground settlement above the pipeline	3	Collapse/Fire/Explosion/Poisoning
Ground cumulative settlement above the pipeline	10	

3.3. Risk accidents and solutions

Like risk precursors in section 0, this paper summarizes risk accidents and their solutions in shield tunnel construction based on related researches, as shown in Table .

It is worth noting that many researches considered some risk factors (e.g. shield mechanical failure) and some risk precursors (e.g. shield axis deviation) as risk accidents. But according to the classification criteria of three risk elements in this paper, they are not. So, the risk accidents given in this paper have filtered the unsatisfied elements.

Table 7: risk accidents and solutions in shield tunnel construction.

Construction	Risk accidents	Solutions
Shaft excavation	Foundation pit stability	Foundation pit precipitation
		Excavation support
		Enhance monitoring
Shield enter/exit	Shield forehead sink	Shield gesture adjustment
		Launch end elevation raising
Shield excavation	Excavation face stability	Control face support pressure
		Balance soil excavation and discharge
		Control excavation speed
		Enhance monitoring
	Ground collapse	Enhance waterproofing

		Balance soil excavation and discharge
		Increase grouting amount
		Change blade
		Enhance monitoring
	Tunnel floating	Shield gesture adjustment
		Increase grouting amount
		Enhance monitoring
	Explosion/Poisoning	Enhance ventilation

3.4. Example relationships between risk factors, precursors, and accidents

After collecting instances of risk factors, precursors, and accidents, Fig. 2 gives example relationships between them based on the relationships proposed in Fig. 2.

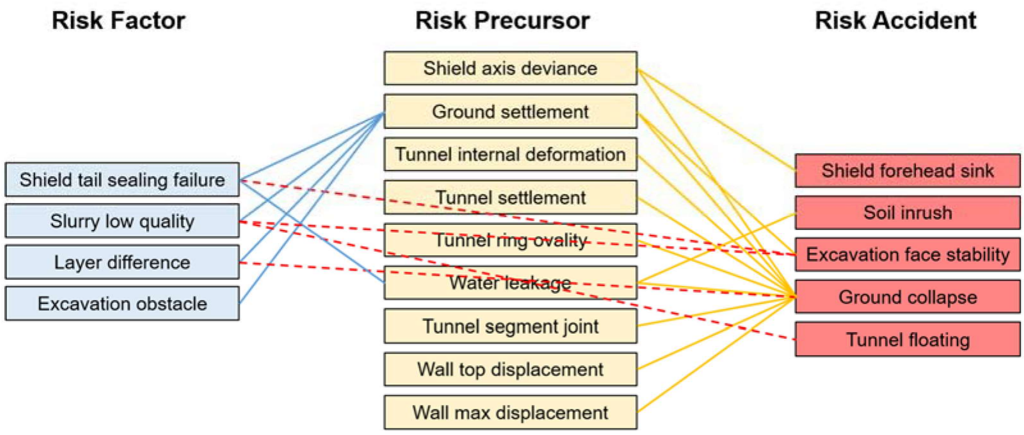


Fig. 2: example relationships between risk factors, precursors, and accidents.

4. ONTOLOGY DEVELOPMENT

As a recommended standard for W3C and a widely used ontology language, the Web Ontology Language (OWL) is designed to provide a common way to handle the content of Web information and be read by computer applications. However, the readability of OWL is not friendly to human, so a software is generally required for construction, storage, reasoning, and query of ontology. In this paper, we choose Protégé to develop the ontology of shield tunnel construction, which is an open source software developed by Stanford University (https://protege.stanford.edu/).

4.1. Definition of classes and properties

The core concepts in shield tunnel construction includes: Construction Method, Risk (Risk Factor, Risk Precursor, Risk Accident), and Solution. In order to make the ontology more suitable for engineering such as expressing the order and hierarchy of construction methods, this paper adds two concepts: Project and Task. In ontology, concepts are expressed by classes, so this paper builds 7 classes according to the above 7 concepts.

Relationships between classes are expressed by properties. Ontology divides property into object property and datatype property, while the former connects two objects and the latter connects object and built-in datatype. As for object properties, *hasPrecursor* links *ConstructionMethod* to *RiskPrecursor*, and *hasPrecursorAccident* links *RiskPrecursor* to *RiskAccident*. In addition, this paper defines datatype properties *hasPrecursorValue* and *hasPrecursorLimit* for *RiskPrecursor* class. These two properties denote the actual monitored value and upper limit of *RiskPrecursor* respectively, and once the monitored value exceeds the upper limit, the corresponding *RiskAccident* will be triggered.

Fig. 3 shows all classes and some of their properties in the ontology. In Fig. 3, rectangles represent classes, rounded rectangles represent built-in datatypes, blue/green lines means object/datatype properties.

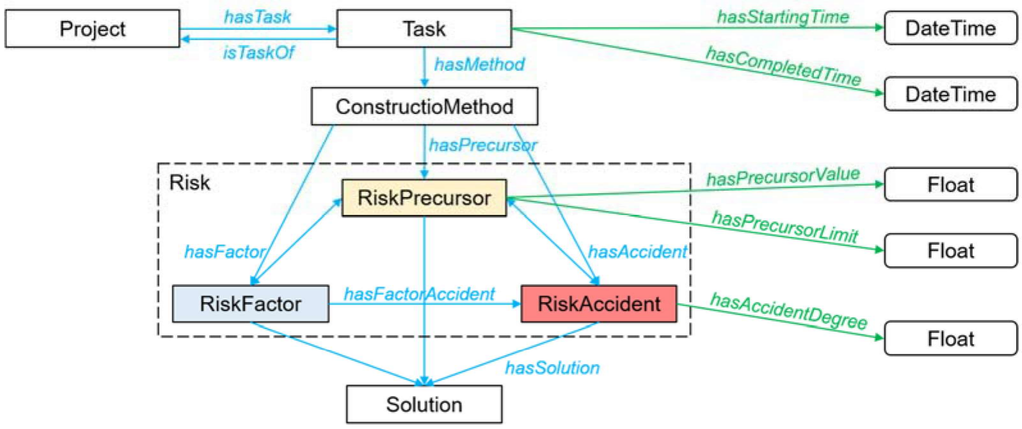


Fig. 3: classes and some of their properties in the ontology.

4.2. Developing ontology in Protégé

Fig. 4 shows the screenshots of classes and properties in Protégé. In Figure 5a, *ShaftExcavationMethod* is a sub-class of *ConstructionMethod*, and it is connected to three sub-classes of *RiskPrecursor* by the property *hasPrecursor*, such as *hasPrecursor some GroundSettlementPrecursor*. It does not intersect with any other sibling class, so there is a *Disjoint with* statement, and it has two instances.

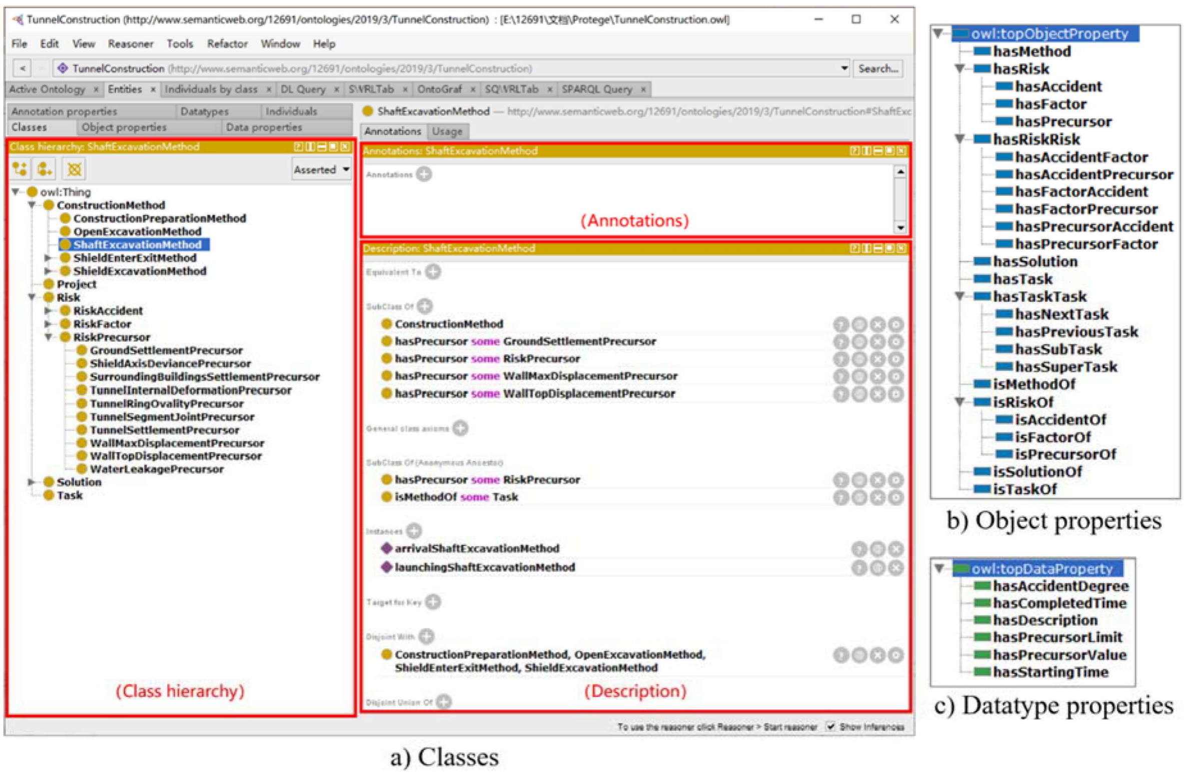


Fig. 4: screenshots of classes and properties in Protégé.

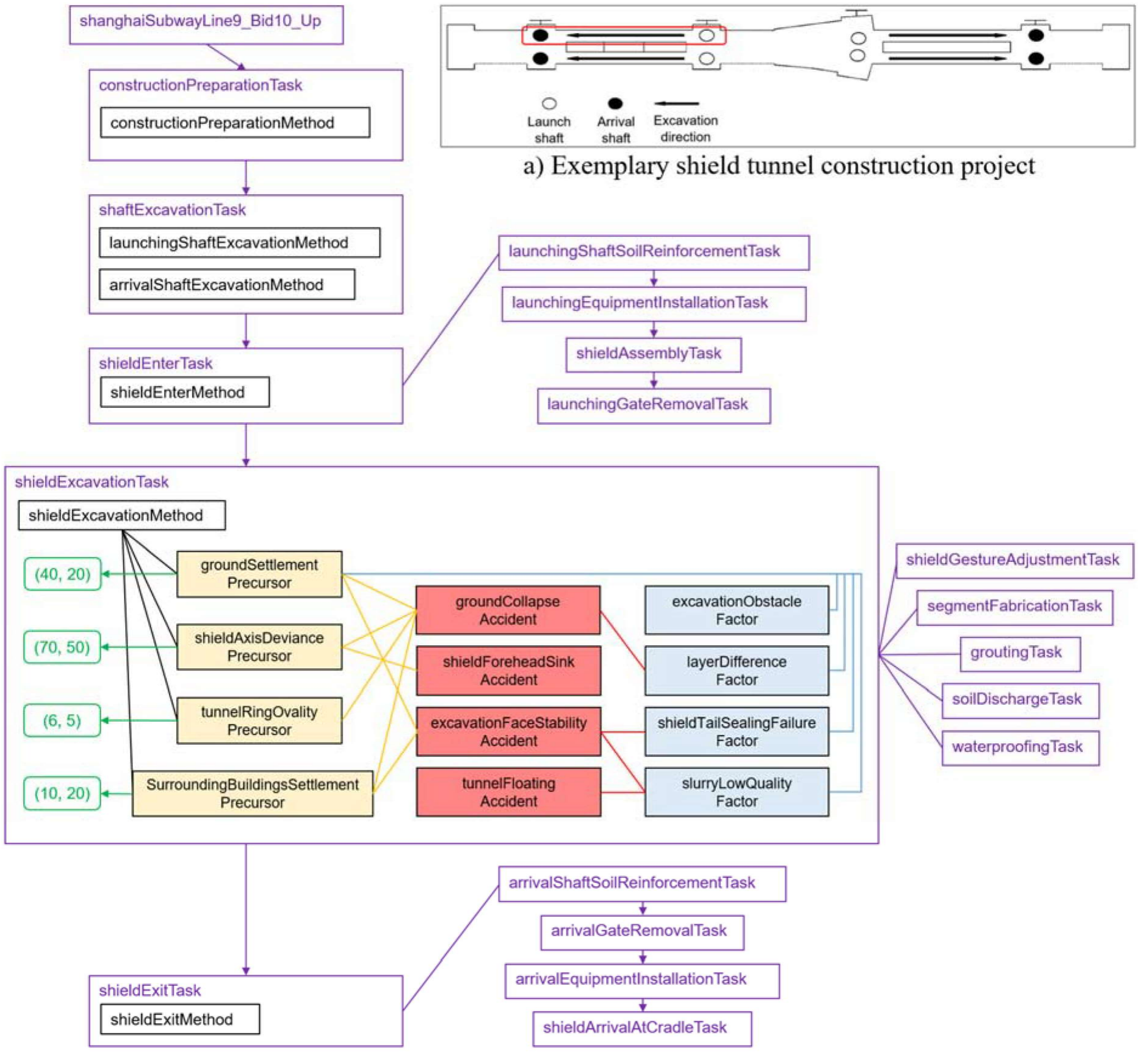
In Figure 5b, some properties are sub-properties of another property, such as *hasPrecursor* is a sub-property of *hasRisk*. In this condition, the sub-property's range is sub-class of the super-property's range, which can facilitate reasons and queries in the ontology. Besides, some properties are inverse of another property, such as *hasPrecusor* and *isPrecursorOf*, which means the domain (range) of *hasPrecursor* is range (domain) of *isPrecursorOf*.

5. DEMONSTRATION

5.1. Create instances

Classes stored in an ontology are conceptual and abstract, while actual projects are concrete. To use the ontology to express actual projects, we need to create instances of corresponding classes. In this paper, we create instances to express constructions and risks of a project, and identify risks through query in ontology. Fig. 5 a shows the exemplary shield tunnel construction project, which is a part of Shanghai subway Line 9 (the red box shows the selected construction section).

This paper selects the shield enter, shield exit, and shied excavation tasks in this project for further research in detail, and only represents risks in shield excavation task for simplicity. Fig. 5 b shows all created instances. In this figure, purple rectangles denote *Project* or *Task*, while black rectangles denote *ConstructionMethod*. In *ShieldExcavationTask*, *RiskFactor/Precursor/Accident* have colorful background, and green rounded rectangles means the (*hasPrecursorValue*, *hasPrecursorLimit*) of *RiskPrecursor*.



a) Exemplary shield tunnel construction project

b) Instances to represent the exemplary project

Fig. 5: the exemplary shield tunnel construction project and instances to represent it.

5.2. Semantic query in typical scenarios

This paper uses SPARQL Protocol and RDF Query Language (SPARQL) to query risks and their solutions in the exemplary project. SPARQL is a set of W3C Recommendations that provide language and protocols for querying and processing RDF content.

The contents to be query are: *RiskPrecursors* which satisfy *hasPrecursorValue >= hasPrecursorLimit*, and their corresponding *RiskAccidents* and *Solutions*. The query is implemented twice, the first for satisfied *RiskPrecursors* and *RiskAccidents*, while the last for the *Solutions*. The code of the first query is show in Fig. 6 (prefix part has been omitted). Note that the code of the last query only needs to change `SELECT DISTINCT ?m ?p ?pv ?pl ?a ?ad` to `SELECT DISTINCT ?a ?S.` The results of two queries are shown in Table and Table .

```
SELECT  DISTINCT  ?m ?p ?pv ?pl ?a ?ad
WHERE {
?M rdfs:subClassOf :ConstructionMethod.
?m a ?M.

?P rdfs:subClassOf :RiskPrecursor.
?p a ?P.
?p :isPrecursorOf ?m.
?p :hasPrecursorValue ?pv.
?p :hasPrecursorLimit ?pl.
?A rdfs:subClassOf :RiskAccident, ?rs.
?a a ?A.
?a :hasAccidentDegree ?ad.
?p :hasPrecursorAccident ?a.

?S rdfs:subClassOf :Solution.
?rs a owl:Restriction.
?rs owl:onProperty :hasSolution;
owl:someValuesFrom ?S.
FILTER (?pv >= ?pl) }
order by  (?p) desc (?ad)
```

Fig. 6: the code of query for satisfied *RiskPrecursors* and *RiskAccidents.*

Table 8: the first query result (*RiskPrecursors* and *RiskAccidents*)

m (ConstructionMethod)	*p (RiskPrecursor)*	*pv**	*pl**	*a (RiskAccident)*	*ad**
shieldExcavationMethod	*groundSettlementPrecursor*	40	20	*groundCollapseAccident*	1
				excavationFaceStabilityAccident	0.6
	shieldAxisDeviancePrecursor	70	50	*groundCollapseAccident*	1
				shieldForeheadSinkAccident	0.4
	tunnelRingOvalityPrecursor	6	5	*groundCollapseAccident*	1

* pv/pl means *hasPrecursorValue*/*hasPrecursorLimit* of corresponding *RiskPrecursors*; and ad means *hasAccidentDegree* of *RiskAccidents*

Table 9: the last query result (*Solutions*)

a (RiskAccident)	*S (Solution)*
groundCollapseAccident	*EnhanceWaterproofSolution*
	IncreaseGroutingAmountSolution
	ChangeCutterSolution
	ControlFaceSupportPressureSolution
	BalanceSoilExcavationAndDischargeSolution
	EnhanceMonitoringSolution
excavationFaceStabilityAccident	*ControlFaceSupportPressureSolution*
	ControlExcavationSpeedSolution
	EnhanceMonitoringSolution
	BalanceSoilExcavationAndDischargeSolution
shieldForeheadSinkAccident	*LaunchEndElevationRaisingSolution*
	ShieldGestureAdjustmentSolution

The query results show that all *RiskPrecursors* which satisfy the requirement are correctly queried and *Solutions* are given for each *RiskAccident*. For example, the *shieldAxisDeviancePrecursor* exceeds the limit (70 > 50); and the triggered *RiskAccidents* are: *groundCollapseAccident*, *shieldForeheadSinkAccident*; and the *Solutions* are: *IncreaseGroutingAmountSolution*, *ControlFaceSupportPressureSolution*, *ShieldGestureAdjustmentSolution*, etc.

6. CONCLUSION

This paper develops an ontology of shield tunnel construction according to the result of WBS and risk analysis and finally applies it. In the WBS of shield tunnel construction, this paper divides the construction into five categories: Construction Preparation, Shaft Excavation, Shield Enter/Exit, Shield Excavation, and Engineering Acceptance, and then decompose each of these categories to obtain the WBS second level of the shield tunnel construction. In the risk analysis, this paper proposes the concept and relationships of three risk elements, namely, risk factor, risk accident, and risk precursor, and gives detailed examples of each risk element and their relationships in shield construction. The ontology proposed by this paper eliminates some shortcomings in existing ontologies, which enables the solution can be represented in ontology instead of SWRL and the construction order and hierarchy can be expressed. The application results show that the ontology can help identify the risks in shield tunnel construction and give corresponding solutions, which can provide a guidance for construction safety.

The advantages of using ontology for risk assessment and solutions are that it makes knowledge to be: (1) stored and expressed in a more organized way; and (2) shared and reused with high convenience. The first advantage can enhance the efficiency and semantics of information retrieval compared to traditional knowledge management methods such as databases and literal records. In addition, ontology makes it possible to create a new knowledge base with existing knowledge bases, which facilitate the building of knowledge base to achieve higher level of detail and broader range of scope.

It is worth noting that, deficiencies still exit in the ontology developed in this paper. For example, *RiskAccidents* can only be triggered by single *RiskPrecursor* but not a combination of *RiskPrecursors*, and the same *RiskAccident* triggered by different *RiskPrecursors* may have different *Solutions* are also not considered, which can be further researched by future works.

7. ACKNOWLEDGEMENT

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