Sensors and Materials, Vol. 35, No. 2 (2023) 679–690
MYU Tokyo

S & M 3203

Construction of Monitoring Index System for Ancient Sites to Address Flood Disaster Risk

Xuping Zhang,[1,2*] Yungang Hu,[1,2**] and Yiran Wang[1,2]

[1]School of Geomatics and Urban Spatial Informatics, Beijing University of Civil Engineering and Architecture, Beijing, 100044, China
[2]Key Laboratory for Architectural Heritage Fine Reconstruction & Health Monitoring, Beijing, 100044, China

(Received January 10, 2023; accepted February 15, 2023)

Keywords: ancient sites, flood disaster, monitoring index, knowledge graph, semantic reasoning

In recent years, ancient sites in various locations have been frequently threatened by flood disaster, but there is no unified monitoring strategy; the monitoring methods using sensors, remote sensing, and other methods as well as the related monitoring data obtained are complicated and difficult to manage. Existing monitoring systems do not accurately reflect the relationship between the components of the system and the data. Knowledge graphs have attracted attention as semantic networks that can intuitively reflect the relationship between knowledge entities. In this study, a method of constructing a flood disaster risk knowledge graph for ancient sites was proposed and realized. First, the definition of a risk monitoring index system for ancient sites for flood disaster is proposed. Then, the knowledge graph structure of the monitoring index system is reorganized using semantic reasoning techniques, and the monitoring index bodies are extracted. The proposed method was used to monitor the Pujindu site in China. The results show that the knowledge graph has the advantages of visualization and a clear structure that can intuitively represent the relationship between entities, manage monitoring methods and data such as sensor and remote sensing data, and be effectively applied to the flood disaster risk monitoring of ancient sites.

1. Introduction

Ancient sites are important relics in different periods of development in the history of civilization and culture.(1) However, with the increasing impact of climate change, ancient sites are facing an increased risk of flood disasters, which has imposed severe challenges in the protection of ancient sites.(2,3) Many scholars have begun to carry out related research on the monitoring of ancient sites and cultural heritage,(4,5) and some scholars have explored the disaster monitoring of the Forbidden City, the Summer Palace, and other world cultural heritage sites.(6–8) In addition, the monitoring of ancient sites still has many problems such as the ambiguity of monitoring indexes and imperfect monitoring index systems.(9–11) In recent years, knowledge graphs have attracted attention as a new technology that can classify massive

*Corresponding author: e-mail: 915028935@qq.com
**Corresponding author: e-mail: huyungang@bucea.edu.cn
https://doi.org/10.18494/SAM4325

ISSN 0914-4935

amounts of data and establish mutual relationships,[12,13] and they have been widely used in medical, geographic information, and other fields.[14–16] Crack sensors, displacement sensors, temperature sensors, and humidity sensors are used to obtain critical disease and microenvironmental data during the monitoring of ancient sites. In the flood monitoring process, the water-monitoring data provided by remote sensing image data reflect the inundation of the monitored area, and the topographic maps obtained from the mapping also provide a reference for analyzing the environment surrounding the ancient site. Knowledge graphs provide a way to manage monitoring methods associated with sensors and remote sensing, as well as the monitoring data obtained, and to provide the required monitoring methods and monitoring data to monitor objects with various monitoring needs. Considering the problems and requirements in the field of ancient site monitoring, we propose a method of constructing knowledge graphs of monitoring indexes to enable a comprehensive study of ancient sites in response to flooding. We take the monitoring indexes of ancient sites as the research object to study the application of knowledge-graph-related technology in the concept and system of monitoring indexes.

2. Construction of Knowledge Graph

Figure 1 shows the general concept of analyzing a monitoring index system to evaluate the flooding risk of ancient sites by constructing a knowledge graph for ancient site monitoring. First, the content and structure of the monitoring indexes are defined, and the monitoring indexes are formally expressed. The method of using knowledge graphs to express monitoring indexes breaks through the limitations of the previous single description of monitoring indexes and allows the relevant content to be structured and organized. On this basis, knowledge graphs of monitoring indexes are studied. The method of expression is then described, a set of guidelines for monitoring index systems for ancient sites is complied, and the mechanism for monitoring the risk of flood disasters in ancient sites is also revealed.

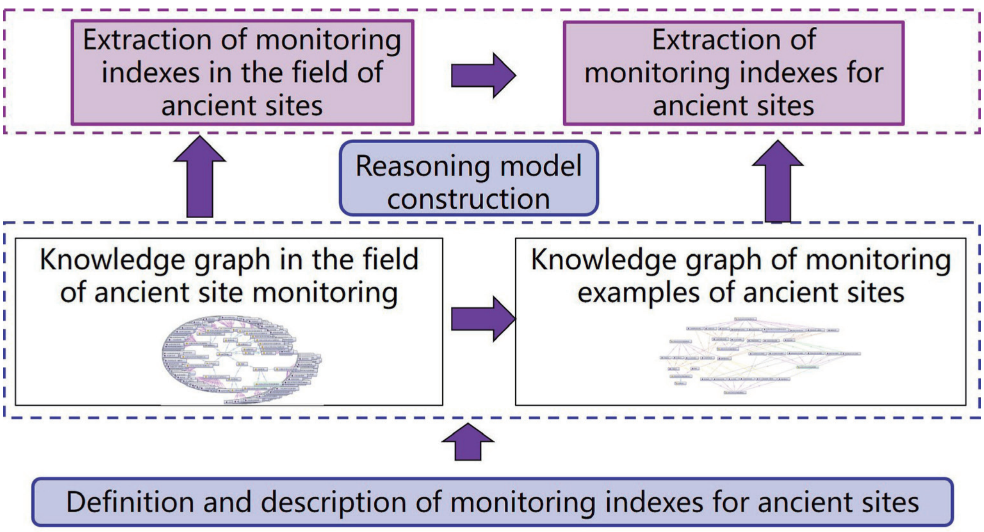

Fig. 1. (Color online) Construction process of the flood disaster risk monitoring index system for ancient sites.

3. Research Methods

3.1 Schema layer construction

Referring to the methods of constructing knowledge graphs for monitoring ancient buildings in the literature,[17] we designed a schema layer with six levels of monitoring object, monitoring content, monitoring method, monitoring project, principle, and data. We established a knowledge service database with entity-relationship-entity and entity-attribute-attribute value structures to form a conceptual layer of knowledge graphs for monitoring ancient sites, as shown in Fig. 2.

In accordance with the literature,[17] our knowledge graph construction method uses the ontology construction tool Protégé to build a knowledge graph ontology in the form of Web Ontology Language (OWL). Part of the content of the knowledge graph ontology in the form of OWL is as follows:

```
<!-- # Basic_data -->
<owl:Classrdf:about="# Basic_data">
<rdfs:subClassOfrdf:resource="# Data"/>
</owl:Class>
<!--# Monitoring_data -->
<owl:Classrdf:about="# Monitoring_data ">
<rdfs:subClassOfrdf:resource="# Data"/>
</owl:Class>
```

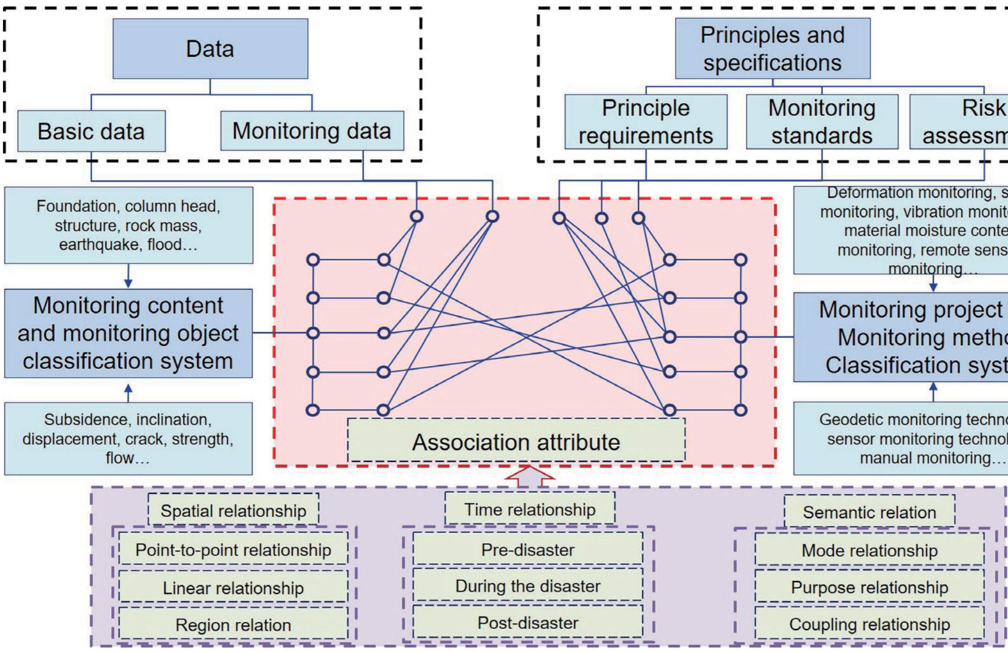

Fig. 2. (Color online) Conceptual layer of knowledge graph for monitoring ancient sites.

3.2 Data layer construction

The sources of data layers in this study are textual data and fieldwork data. The textual data include relevant reports of ancient site monitoring, flooding- and ancient-site-related monitoring standards, and historical meteorological and flooding-related information. The field data include topographic maps of relevant ancient sites, field monitoring data, and remote sensing images of relevant study areas.

There is a structural relationship between the monitoring content and the monitoring object, and the monitoring content is a collection of monitoring objects with the same characteristics. Owing to the presence of diseases in bodies in ancient sites, diseases and disease descriptions are added as entity attributes to the corresponding monitoring object entities; for some monitoring objects, an entity attribute status must be added to their real-time status.

There is also a structural relationship between monitoring projects and monitoring methods. A monitoring project is a collection of monitoring methods and attributes with the same purpose. Since it is necessary to consider whether a monitoring method is suitable for the monitoring object in actual operation, the following entity attributes are added to the monitoring method entity: monitoring frequency, monitoring point layout, and evaluation of suitability of the monitoring method.

Data are divided into two categories: monitoring data and basic data. Monitoring data include equipment monitoring data and remote sensing monitoring data, and basic data include environmental basic data and cultural relic ontology monitoring data.

In Protégé software, the top conceptual layer is constructed in the software, and the corresponding subschema layer is divided; the relevant knowledge and concepts are stored in the corresponding schema layer in the form of entities as the data layer. In accordance with the above structural relationship, existing entities and preliminary entity attribute information are used to build a knowledge graph for entities of ancient sites dealing with flood disaster risk (Fig. 3).

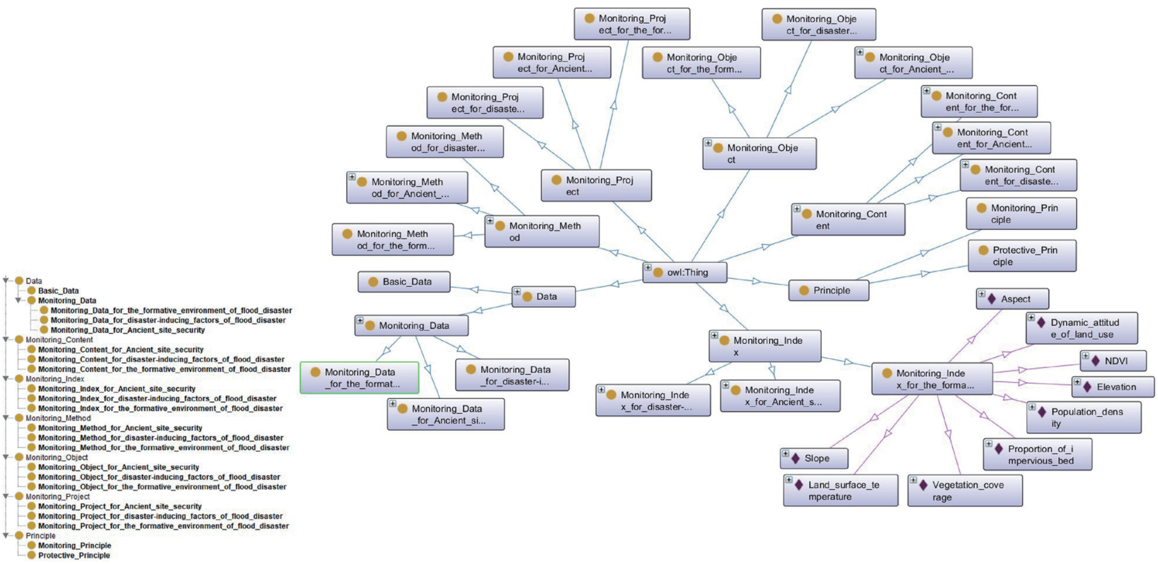

Fig. 3. (Color online) Knowledge graph of ancient sites dealing with flood disaster risk.

3.3 Construction of monitoring index body

The knowledge graph can realize the rational organization and management of concepts and data. As a result, the monitoring indexes constructed on the basis of the knowledge graph can correlate relevant information from various aspects. To distinguish the monitoring index body from monitoring indexes, in this section, we define the concept of a monitoring index body, which is mainly composed of two parts: the core attribute layer and the associated attribute layer (Fig. 4).

The associated attribute layer corresponds to the relevant content of the schema layer in the knowledge graph; in the core attribute layer, the monitoring index name originates from the monitoring content or monitoring object, and the index value originates from the monitoring data. The monitoring index reference value represents the reasonable range of the monitoring index value or alert thresholds for monitoring indexes. Each part of the monitoring index body forms a multilevel small knowledge graph structure. In addition, to facilitate the extraction of the monitoring index body, the following mathematical definitions are given for the monitoring index body:

An ancient site dealing with the flood disaster monitoring index body is denoted as $G_m = \{M_c, M_o, M_p, M_m, M_d, I_m\}$, where M_c represents the monitoring content, M_o represents the monitoring object, M_p represents the monitoring project, M_m represents the monitoring method, M_d represents the data, and Im represents the monitoring index and its core attributes.

3.4 Semantic reasoning based on knowledge graph ontology

3.4.1 Monitoring index body extraction based on semantic reasoning

The monitoring index body is an open, small structure composed of knowledge graph schema layers. The domain knowledge graph ontology initially constructed in Sect. 3.2 is a simple directed graph structure, and the relationship between entities is only a single relationship. Rule-

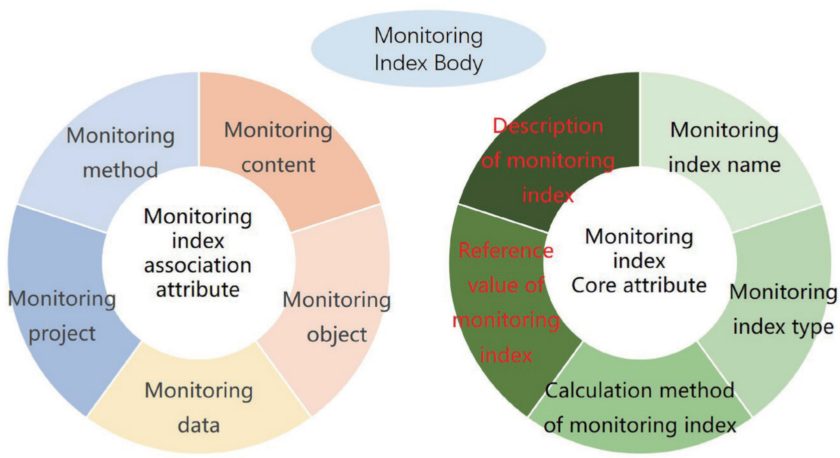

Fig. 4. (Color online) Schematic diagram of structure of monitoring index body.

based semantic reasoning techniques can be used to extract the hidden relationships and attributes between monitoring objects and monitoring indexes in the knowledge graph[18] and to recombine the original simpler knowledge graph structure to form the monitoring index body.[19] Thus, the purpose of providing a reference for actual monitoring work can be achieved (Fig. 5).

3.4.2 Reasoning rules

Reasoning rules are the basis of semantic reasoning. Logical language is used to describe the knowledge nodes and relationships in a knowledge graph, and then the reasoner interprets them to mine the hidden attributes or relationships between entities. Reasoning rules are usually written in Semantic Web Rule Language (SWRL).[20] The reasoning sentence (Imp) of SWRL is composed of two parts: the reasoning premise (Body) and the reasoning conclusion (Head). Both parts are composed of the Atom, Variable, and Building.[21] Entity variables are expressed in the form "?x". The general structure of a reasoning rule is as follows:

$$\text{Imp(Body) -> Imp(Head)} \tag{1}$$

After formulating the reasoning rules, they are input into the reasoner (HermiT) for reasoning, and the reasoning results are output. The implementation process is shown in Fig. 6.

First, the reasoning rules are written, then the Atom is constructed, and the reasoning premise and reasoning conclusion involved in the Atom are clarified. Finally, the reasoning rules are expressed in SWRL.[22] In this paper, targeting the risk monitoring of flood disasters in ancient sites, in accordance with the composition of the monitoring index body, we organize the associated attributes, core attributes, and related contents that make up the monitoring index body into the reasoning composition Atom, as shown in Table 1.

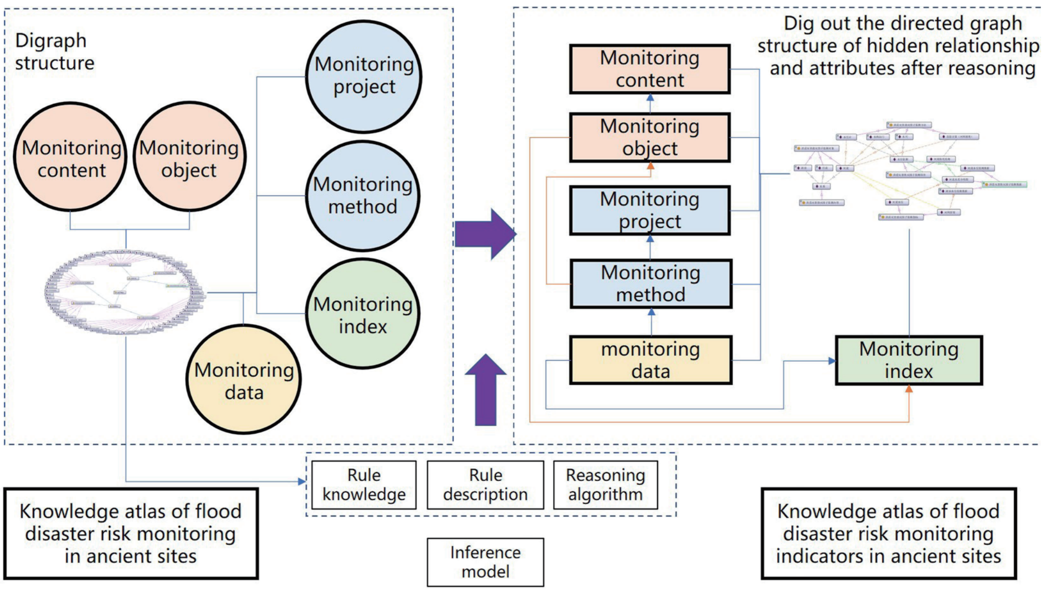

Fig. 5. (Color online) Extraction of monitoring index body.

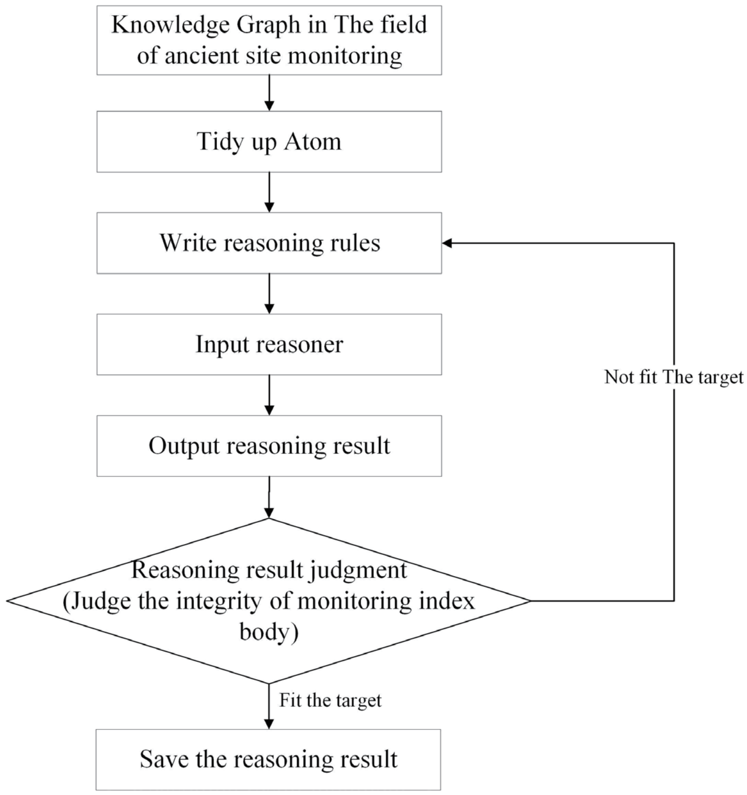

Fig. 6. Process of reasoning rule usage.

Table 1
Atom classes

Atom	Description
Monitoring_object (?o)	"o" represents entity data of monitoring object class.
Monitoring_method (?m)	"m" represents entity data of monitoring method class.
Monitoring_data (?d)	"d" represents entity data of monitoring data class.
Monitoring_index (?i)	"i" represents entity data of monitoring index class.
Monitoring_behavior (?m,?o)	Monitoring method m performs monitoring behavior on monitoring object o.
Monitoring_results (?d,?m)	Monitoring data d is monitoring result of monitoring method m.
Calculation_basis (?d,?i)	Monitoring data d is basis for calculation of monitoring index i.
Formulation_basis (?o,?i)	Monitoring object o is basis for formulation of monitoring index i.
Disease (?o,"x")	Monitoring object o has disease x.

The reasoning rules are formulated in accordance with their structure, as well as the existing relevant materials and standards, and combined with existing field inspection results and expert opinions. Some of the rules are in the following form:

Rule 1: If monitoring object x has disease z, then there is a monitoring behavior relationship between monitoring method y and monitoring object x. Taking the monitoring method of 3D laser scanning as an example, the SWRL format is expressed as follows:

Monitoring_object (?x)^Disease (?x,"collapse") -> Monitoring_behavior(Three-dimensional_laser_scanning,?x).

Rule 2: The monitoring behavior of monitoring method a is based on monitoring object b, monitoring data c is the result of monitoring method a, and monitoring data c is the calculation basis of monitoring index d. Then, monitoring object b is the basis for the formulation of monitoring index d. Taking the rate of collapse and the east wall of the monitoring object as an example, the SWRL format is expressed as follows:

Monitoring_object (?a)^Disease (?a, “collapse”)^Monitoring_behavior (Three-dimensional_laser_scanning, ?a)^Monitoring_results (Area_of_collapse, Three-dimensional_laser_scanning)^Calculation_basis (Area_of_collapse, Rate_of_collapse) -> Formulation_basis (?a, Rate_of_collapse).

Rule 3: This rule is used to verify that the monitoring indicator body obtained from the inference results of Rules 1 and 2 matches Fig. 4. Rule 3 is expressed in SWRL format as follows:

Monitoring_object (?a)^Monitoring_method (?b)^Monitoring_data (?c)^Monitoring_index (?d)^Monitoring_content (?e)^Monitoring_project (?f)^Monitoring_behavior (?a,?b)^Monitoring_results (?c,?a)^Calculation_basis (?c,?d)^Formulation_basis (?b,?d)^be_part_of (?a,?e)^ be_part_of (?b,?f)- > Validate the result (?a, “passed”).

Whether the reasoning result meets the expected goal depends on the monitoring object after reasoning from Rules 1 to 3. If the reasoning result is “passed”, the output reasoning result will be saved; otherwise, the reasoning result will not be saved, and the reasoning rule will be modified.

4. Case Analysis

4.1 Overview of study area

The Pujindu site is located in Yongji City, Shanxi Province, China. The site itself is subject to natural damage such as fracture and collapse, as well as man-made damage, and it also faces a serious threat from flooding. In addition, environmental changes around the site affect its safety. We select Xiwengcheng of the Pujindu site as a research example, construct a knowledge graph system, and extract the monitoring index body.

4.2 Construction and analysis of monitoring knowledge graph for Pujindu site

The monitoring knowledge graph for Xiwengcheng of the Pujindu site shown in Fig. 7 is constructed on the basis of the actual flood monitoring needs of Xiwengcheng and the corresponding contents of the domain knowledge graph ontology constructed above.

The east wall of the inner city walls of Xiwengcheng has two types of damage: collapse and fracture, and a complete monitoring index system including monitoring methods, monitoring data, and monitoring indexes is used for monitoring. For reference, some semantic reasoning rules written in accordance with the monitoring requirements are shown in Table 2.

The interface for implementing semantic reasoning based on the reasoning rules formulated in this study is shown in Fig. 8.

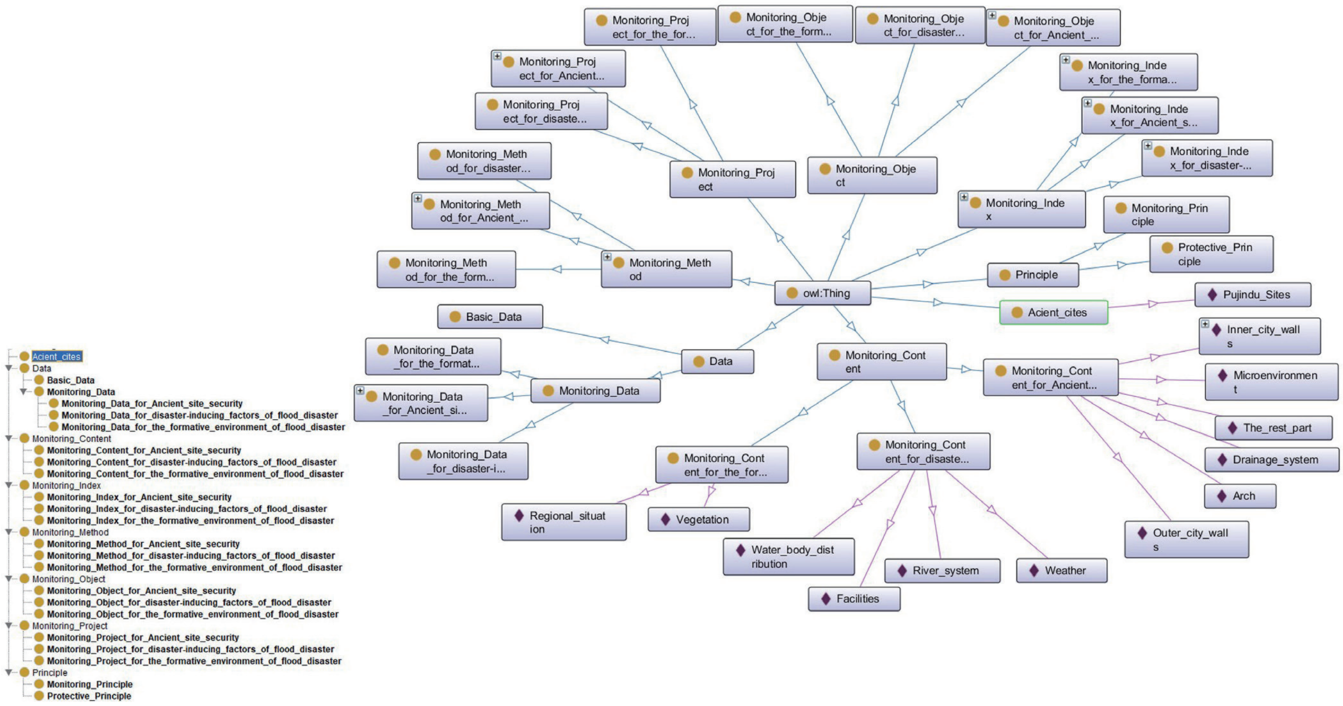

Fig. 7. (Color online) Monitoring knowledge graph of Xiwengcheng of Pujindu site.

Table 2
Partial list of reasoning rules in flood risk monitoring of ancient sites.

Reasoning rules in flood risk monitoring of ancient sites	Description
Monitoring_object (?x)^Disease (?x, “collapse”) -> Monitoring_behavior (Close-range_photogrammetry,?x)	If monitoring object x has disease “collapse”, then monitoring behavior relationship exists between monitoring method “Close-range photogrammetry” and monitoring object x.
Monitoring_object (?x)^Disease (?x, “fracture”) -> Monitoring_behavior (Crack_sensor,?x)	If monitoring object x has disease “fracture”, then monitoring behavior relationship exists between monitoring method “Crack sensor” and monitoring object x.
Monitoring_object (?a)^Disease (?a, “collapse”)^Monitoring_behavior (Close-range_ photogrammetry,?a)^Monitoring_results (Area_of_ collapse, Close-range_photogrammetry)^Calculation_ basis (Area_of_collapse, Rate_of_collapse) -> Formulation_basis (?a, Rate_of_collapse)	Monitoring method “Close-range photogrammetry” is used for monitoring object a, monitoring data “Area of collapse” is monitoring result of monitoring method “Close-range photogrammetry”, and monitoring data “Area of collapse” is calculation basis for monitoring index “Rate of collapse”. Then, monitoring object a is basis for formulation of the monitoring index “Rate of collapse”.
Monitoring_object (?a)^Disease (?a, “fracture”)^Monitoring_behavior (Routine_ inspection,?a)^Monitoring_results (Number_of_ fractures,Routine_inspection) ^Calculation_basis (Number_of_fractures, Degree_of_fracture’s_ development) -> Formulation_basis (?a, Degree_of_ fracture’s_development)	Monitoring method “Routine inspection” is used for monitoring object a, monitoring data “Number of fractures” is monitoring result of monitoring method “Routine inspection”, and monitoring data “Number of fractures” is calculation basis for monitoring index “Degree of fracture’s development”. Then, monitoring object a is basis for formulation of monitoring index “Degree of fracture’s development”.

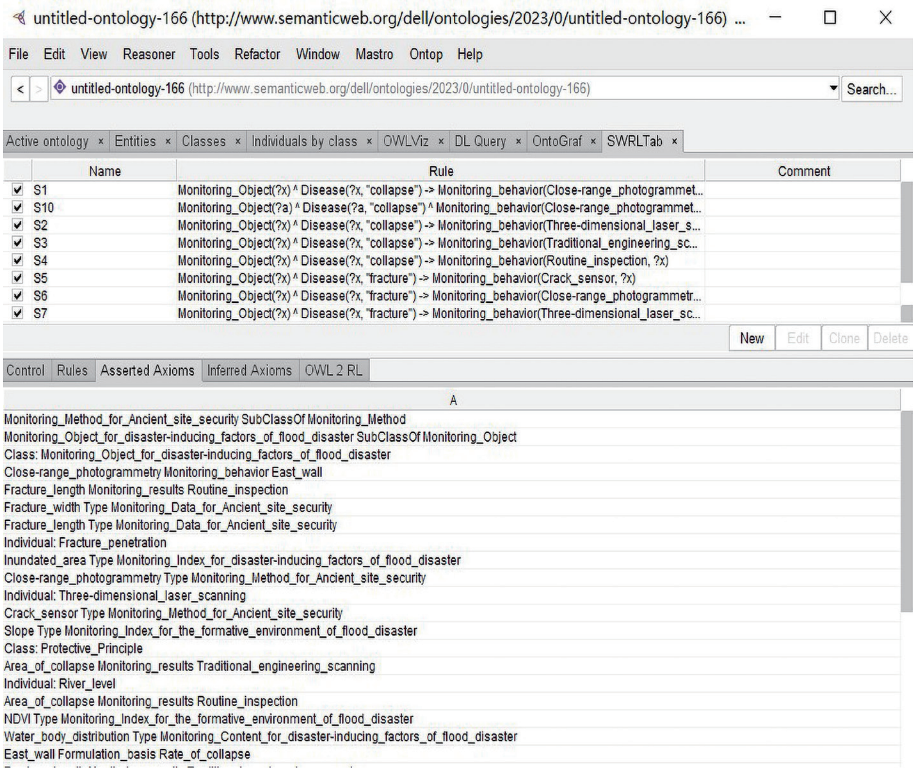

Fig. 8. Reasoning interface.

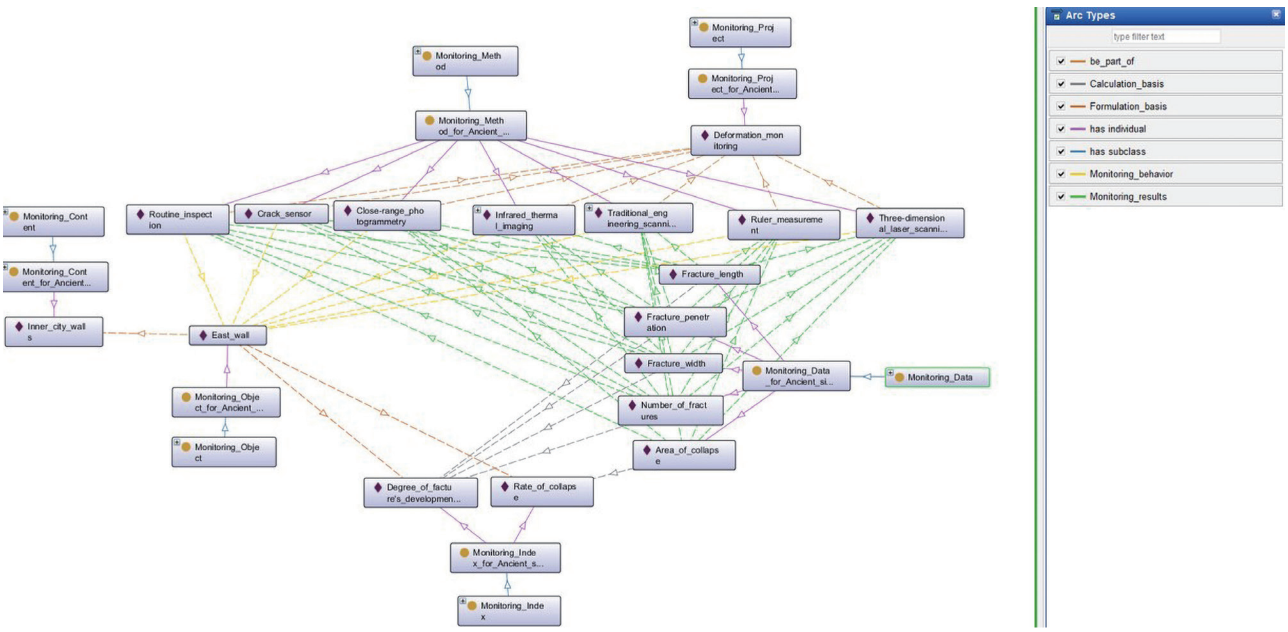

Fig. 9. (Color) Results of extracting monitoring index body of east wall.

Finally, the monitoring index body of the east wall extracted in accordance with the monitoring needs is shown in Fig. 9. The extracted monitoring index body can clearly represent the monitoring method, monitoring data, monitoring indexes, and other physical attributes required by the east wall during the monitoring process. The process provides a theoretical reference. The result of the monitoring index body meets the expected target, and the result is output and saved.

5. Conclusion

A knowledge graph provides a new approach to constructing semantic relationships for various natural disasters. In view of the lack of a unified and comprehensive semantic relationship framework in the current study of index systems for ancient sites threatened by flooding, we construct a knowledge graph of the monitoring index for ancient sites to address flood risks. This knowledge graph is based on the data related to the ancient site obtained from sensor monitoring, as well as data about floods and the surrounding environment obtained from remote sensing images and topographic maps, and historical information data. Knowledge-graph-related techniques are used in the process of knowledge graph construction. On this basis, we propose the definition and structure of a monitoring index body. On the basis of the theory of the monitoring index body, the knowledge graph of the flood risk of Xiwengcheng of the Pujindu site is initially constructed as an example. We use semantic reasoning techniques to initially recombine the existing knowledge graph structure and extract monitoring indexes. Finally, the results are visually presented. In the subsequent research, we will continue to expand the range of multi-source data and summarize and improve the new knowledge, so as to improve the completeness of the index system framework proposed in this paper.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2019YFC1520804) and the National Natural Science Foundation of China (NSFC) (No. 41930650).

References

1 Y. Yi and J. Chen: Southeast Culture **4** (2021) 191 (in Chinese).
2 Y. Sun: Chin. Cultural Heritage **4** (2021) 19 (in Chinese).
3 Y. Liu, Z. Chen, and L. Zhou: Chin. J. Rock Mech. Eng. S**2** (2009) 3795 (in Chinese).
4 X. Liu: Identification Appreciation Cultural Relics. **9** (2017) 84 (in Chinese).
5 Y. Zhang and T. Wu: Chin. Cultural Heritage **1** (2018) 51 (in Chinese).
6 C. Yang: Study of Indicator System and Adaptive Technology for Monitoring on Attributes of Domestic Ancient Architectural Heritage (Tianjin University, Tianjin, 2019) (in Chinese).
7 Z. Wang: Research on Natural Environmental Monitoring Indicator System and Monitoring Technology of Chinese Ancient Architectural Heritage—Take Case of The Summer Palace (Tianjin University, Tianjin, 2018) (in Chinese).
8 L. Liang: The Research of Summer Palace's Heritage Monitoring Index System (Tianjin University, Tianjin, 2016) (in Chinese).
9 Y. Di: Chin. Cultural Heritage **3** (2020) 43 (in Chinese).
10 X. Wang: Dunhuang Res. **1** (2015) 104 (in Chinese). https://doi.org/10.13584/j.cnki.issn1000-4106.2015.01.015
11 J. Tian and H. Yang: Wireless Internet Technol. **14** (2020) 1 (in Chinese).
12 G. Qi, H. Gao, and T. Wu: Technol. Intell. Eng. **1** (2017) 4 (in Chinese).

13 Q. Li, Y. Li, H. Duan, Y. Liu, and Z. Qin: J. Comput. Res. Dev. **3** (2016) 582 (in Chinese).
14 S. Wu, G. Li, M. Bu, Y. Liu, and Z. Qin: Comput. Eng. Appl. **22** (2021) 304 (in Chinese).
15 B. Jiang, X. You, K. Li, X. Zhou, and H. Wen: Geomatics Inf. Sci. Wuhan Univ. **6** (2020) 836 (in Chinese). https://doi.org/10.13203/j.whugis20200153
16 Z. Du, Y. Li, Y. Zhang, Y. Tan, and W Zhao: Geomatics Inf. Sci. Wuhan Univ. **9** (2020) 1344 (in Chinese). https://doi.org/10.13203/j.whugis20200047
17 Y. Hu, J. Lin, Y. Qiao, Y. Deng, and M. Hou: J. Beijing Univ. Civ. Eng. Archit. **38** (2022) 71 (in Chinese). https://doi.org/10.19740/j.2096-9872.2022.04.10S
18 Guan, X. Jin, Y. Jia, Y. Wang, and X. Cheng: J. Software **29** (2018) 2966 (in Chinese). https://doi.org/10.13328/j.cnki.jos.005551
19 J. Chen, W. Liu, H. Wu, Z. Li, Y. Zhao, and L. Zhang: Geomatics Inf. Sci. Wuhan Univ. **44** (2019) 38. https://doi.org/10.13203/j.whugis20180441
20 I. Horrocks, P. Patel-Schneider, H. Boley, S. Tabet, B. Grosof, and M.Dean: SWRL: A Semantic Web Rule Language Combining OWL and RuleML, http://www.daml.org/2003/11/swrl/rules-all.html (accessed November 2022).
21 L. Qian: The Design and Implementation of an Ontology and Rule Inference based Query System (Southeast University, Nanjing, 2006) (in Chinese).
22 R. Cao: The Application Research of Ontology Construction and Knowledge Discovery in the Field of Traditional Chinese Medicine (Beijing University of Posts and Telecommunications, Beijing, 2021) (in Chinese). https://doi.org/10.26969/d.cnki.gbydu.2021.001921

About the Authors

Xuping Zhang received her B.S. degree from Capital Normal University, China, in 2020. Since 2020, she has been a master's candidate at Beijing University of Civil Engineering and Architecture. Her research interest is in remote sensing. (915028935@qq.com)

Yungang Hu received his B.S. degree from Shandong University of Science and Technology, China, in 1997 and his M.S. and Ph.D. degrees from China University of Mining & Technology, Beijing, China, in 2003 and 2007, respectively. Since 2007, he has been an assistant professor at Beijing University of Civil Engineering and Architecture. His research interests are in surveying and mapping. (huyungang@bucea.edu.cn)

Yiran Wang received her B.S. degree from Hebei University of Technology, China, in 2021. Since 2021, she has been a master's candidate at Beijing University of Civil Engineering and Architecture. Her research interest is in remote sensing. (wangyiran9821@163.com)