A Knowledge Representation Method for Virtual Restoration of Ancient Chinese Stone Arch Bridges

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Abstract

As an important cultural heritage, ancient Chinese stone arch bridges have profound historical, artistic and technological values. However, affected by multiple factors such as natural disasters and human activities, their historical features are gradually disappearing. Virtual restoration has become a key means to reconstruct their original appearance. However, how to obtain information such as the geometric appearance and texture of ancient bridges at different historical points requires the integration of knowledge in many aspects such as structural form, material technology, historical documents, and archaeological surveys. Therefore, in the face of this interdisciplinary problem, it is urgent to integrate and accurately express relevant knowledge. This paper proposes a knowledge expression method for virtual restoration of ancient stone arch bridges based on CIDOC CRM, which integrates top-down and bottom-up construction strategies, constructs an ontology model from the two dimensions of entity and process, and constructs a knowledge graph based on the Neo4j graph database to achieve semantic integration and visual association of interdisciplinary knowledge. Taking the Wanning Bridge in Beijing as an example, the verification results show that this method can systematically organize complex knowledge such as structural characteristics, historical changes and restoration activities, effectively improve knowledge retrieval efficiency, and provide semantic support for restoration decisions. This study not only provides technical support for the digital protection of ancient bridges, but also contributes new ideas to the knowledge modeling method of cultural heritage.

1. Introduction

Ancient Chinese bridges have a long history, are built in large numbers, and are rich in variety and form. They are buildings closely related to human life. Like other architectural heritage, ancient bridges are also an important carrier of local cultural identity. They are not only material assets preserved in history, but also cultural resources needed for future development (Chang Qing et al., 2016). The construction history of Chinese stone arch bridges can be traced back to 1,400 years ago. They not only show the exquisite application of mechanical principles by ancient craftsmen, but also record the social outlook and aesthetic characteristics of different historical periods through artistic forms such as bridge carvings and inscriptions (Mao Yisheng, 1986). As the pinnacle of ancient Chinese bridge technology, stone arch bridges are the most numerous among the existing ancient bridges. Most of the stone arch bridges that are still in use today were built in the Ming and Qing dynasties (1368-1644 AD), and most of them are seriously damaged (Qing, C. et al., 2022). Today, some ancient bridges are not only used for transportation, but also have important cultural value. However, when they were built, they did not consider the environmental changes and traffic loads thousands of years later. With the acceleration of industrialization and the expansion of urbanization, they are now generally facing the problem of the disappearance of historical features due to multiple threats such as natural disasters, climate change and human activities. In this context, virtual restoration technology simulates the historical features of bridges through digital means, becoming a key tool for balancing heritage protection and sustainable use. This technology can effectively solve the common problems of excessive intervention and loss of historical information in physical restoration, and achieve precise protection under the principle of "minimum intervention". However, the effective implementation of this technology is highly dependent on systematic and semantic knowledge support.

In recent years, ontology and knowledge graph technology have attracted widespread attention due to their powerful semantic expression capabilities. The CIDOC Conceptual Reference Model (CRM) proposed by the International Documentation Committee is the core semantic framework in the field of cultural heritage. Through standardized entity relationship definitions, it realizes the semantic integration of cross-domain data (Doerr, M., 2003). Its extended model CRMba (architectural heritage ontology) further supports the description of architectural structure evolution (Ronzino, P. et al., 2016). CRMsci supports the semantic recording of scientific observation data such as material testing (Doerr. et al., 2011). The rise of knowledge graphs has opened up new paths for complex semantic modeling. As an emerging form of digital resource knowledge organization, knowledge graphs can accumulate and convey real-world knowledge, provide semantic, visual and intelligent display, and thus achieve efficient storage and application of knowledge (Peng, C. et al., 2023). In the field of cultural heritage, Yang S et al. (2023) proposed a knowledge graph representation method to provide explicit knowledge to participants at different stages of cave semantic three-dimensional modeling, solving the problem that the existing domain ontology and knowledge graph are insufficient in representing the knowledge of Chinese caves.

Zhao, Y. et al. (2024) established a complete ontology model (XJUBontology) of Xinjiang unearthed brocade in this study. The XJUBontology includes knowledge about brocade and its cultural derivatives. The implementation of XJUBontology in Protégé and SPARQL query verification not only centrally manages Xinjiang unearthed brocade and related knowledge, but also establishes important connections between these scattered information. Xu, L. et al. (2023) built an intelligent question-answering system for Nanjing brocade digital resources based on knowledge graph, using Neo4j graph database for efficient organization, storage and protection of Nanjing brocade knowledge, thereby revealing its profound cultural connotation. Fan, T. et al. (2023) proposed a method for constructing a multimodal knowledge graph (CICHMKG) based on text and image entities from multiple data sources, and provided a practical construction framework to help the public gain a deeper understanding of intangible cultural heritage. Hiebel, G. et al. (2021) took the three-dimensional reconstruction of tombs as an example to demonstrate how to use knowledge graphs related to digital resources to obtain available information that is crucial for virtual reconstruction in specific tasks. They also demonstrated a modeling method for representing the interpretations that support the reconstruction and associating them with the materials used, thereby providing transparency for the model and the provenance data. Ronzino, P. et al. (2022) applied the CRMba model to the documentary records of Roman architecture (especially the Roman amphitheater), demonstrating how the semantic model encodes information about the building structure and its evolution over time and space, emphasizing the concepts of "empty space" and "functional space" defined by form, and focusing on the relationship between form and function. Knowledge representation methods are of central significance for organizing, integrating and reusing complex heterogeneous information from multiple disciplines such as archaeology, architecture, history and digital humanities. In summary, the current research on knowledge expression in the field of cultural heritage has initially formed a diversified development pattern, covering multiple aspects from semantic modeling, domain ontology construction to knowledge organization and application based on graph databases. These studies have shown strong pertinence and practical value in different heritage types such as cave art, unearthed cultural relics, traditional crafts, intangible cultural heritage and architectural remains, and have effectively improved the expression ability and accessibility of cultural heritage knowledge. However, the current research on ancient Chinese stone arch bridges mainly includes damage detection (Chen, B. et al., 2021), structural safety assessment (Ma, Y. et al., 2024) (Qing, C. et al., 2022), etc., and there are few studies on the knowledge expression methods of ancient stone arch bridges. The information of ancient Chinese stone arch bridges is scattered, inconsistent and incomplete, and the storage tools are unorganized and inefficient, which makes the knowledge of ancient Chinese stone arch bridges unsystematic. At present, there are still significant knowledge management defects in the field of ancient Chinese stone arch bridges, and it is necessary to propose a knowledge expression method with sufficient information.

The relevant data of ancient Chinese stone arch bridges in the real world has the characteristics of large data volume, wide sources and complex structure, which puts higher requirements and new challenges on its information integration, processing and analysis capabilities. This paper proposes a knowledge expression method for virtual restoration of ancient Chinese stone arch bridges. This method uses CIDOC CRM as the core framework, integrates the knowledge of ancient Chinese stone arch bridges using ontology technology, builds an ontology model, and uses Beijing Wanning Bridge as a case to complete the development of the database, verifying the effectiveness of the model in restoration plan simulation and cultural value interpretation. This study not only provides technical tools for the protection of ancient Chinese stone arch bridges, but also contributes new methods to the theoretical system of knowledge modeling of other ancient bridges.

2. Methodology

This section introduces in detail the knowledge expression method of ancient Chinese stone arch bridges, which combines the "top-down" and "bottom-up" strategies. The method includes two stages: model layer construction and data layer construction. The construction process is shown in Figure 1. The model layer is the construction of the ontology of ancient Chinese bridges. First, the concepts and terms are obtained by using highly professional literature resources, and their conceptual system and relationships are sorted out. The ontology is constructed from top to bottom. The constructed ancient bridge ontology library can provide a conceptual model and logical basis for the knowledge graph; the data layer is based on the processing of the ancient Chinese stone arch bridge data source, and the entities and relationships in the field of ancient Chinese stone arch bridges are extracted for different ancient Chinese stone arch bridge data sources. After the knowledge is integrated according to the constructed ontology framework, a unified structure of the ancient Chinese stone arch bridge knowledge graph is formed. The ontology is improved from bottom to top, and the construction of the ancient Chinese stone arch bridge knowledge graph is completed, and finally the visual presentation and application are realized.

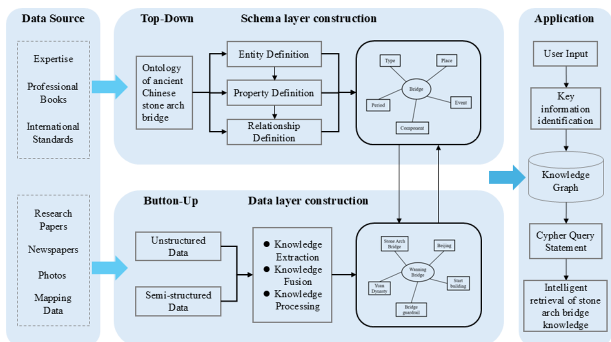

Figure 1. The framework of knowledge graph construction

2.1 Model layer construction

This paper uses ontology to construct the model layer of the knowledge graph of ancient Chinese stone arch bridges. It refers to the seven-step method (Noy NF,2001) and combines the task-driven approach to construct the ontology of ancient Chinese stone arch bridges. The ontology is equivalent to the mold of the knowledge graph and determines the quality of the knowledge graph construction. The main steps of constructing the knowledge ontology of ancient Chinese stone arch bridges are as follows:

2.1.1 Clarify the scope and purpose of the ontology: The ontology constructed in this study is based on ancient Chinese bridges, integrating multi-dimensional knowledge of bridges, focusing on structural composition, construction materials, historical evolution, damage status, historical events, etc. The goal of this ontology is to provide knowledge support for the virtual restoration of stone arch bridges, meeting the needs of domain experts for structural analysis, historical restoration, and damage restoration, while also providing some interesting knowledge to the public.

2.1.2 Refer to existing ontologies: Referencing existing ontologies related to the target domain can reduce the difficulty of work and improve completeness to a certain extent. During the construction process, CIDOC CRM Version 7.1.3 was mainly referenced, which provides a general framework for the semantic expression of cultural heritage knowledge. These existing ontologies provide a standardized theoretical basis for the semantic modeling of stone arch bridges. Table 1 provides a list of the main classes reused in CIDOC CRM and their source descriptions.

Class Name	Describe
E55_Type	Used to characterize the type of bridge
E57_Material	The type of material that makes up the bridge structure or decoration, reflecting the physical composition of the bridge entity
E4_Period	The historical period to which the bridge belongs or when it was built
E53_Place	Detailed description of the bridge's geospatial location
E3_Condition_State	The current state of the bridge or the state of its preservation at a certain time
E5_Event	Important events in the history of bridges
E25_Human-Made_Feature	Structural decorative or constructional features formed by artificial processing
E26_Physical_Feature	Physical features of a bridge surface or structure that occur naturally or over time
E34_Inscription	Text information engraved on the surface of bridge components
E39_Actor	Human individuals or organizations related to bridge construction, design, repair, etc.
E41_Appellation	The name or title of the bridge
E54_Dimension	Geometric property measurements of bridges to describe their spatial characteristics
E58_Measurement_Unit	Standard units for expressing bridge measurements
E60_Number	Numerical information related to bridge eigenvalues

Table 1. List of main classes reused in CIDOC CRM and their descriptions

2.1.3 List domain concept terms and their structural hierarchy: In the process of constructing the model layer of the knowledge graph of ancient Chinese stone arch bridges, it is necessary to systematically sort out the core concepts and their structural relationships in this field. Based on the analysis of historical documents, professional books and industry standards, this study extracts and organizes key terms covering dimensions such as bridge classification, structural materials, historical periods, and structural components. These terms can fully reflect the knowledge characteristics and entity relationships in the field of ancient Chinese stone arch bridges. In order to avoid concept confusion and hierarchical ambiguity, in the process of term organization, this paper adopts the concept framework method to construct the term system of the ontology based on the classification logic of "from abstract to concrete", and combines the modeling strategy of "top-down" and "bottom-up": that is, on the one hand, abstract the superordinate concepts from the existing theoretical system, and on the other hand, extract the specific reality entities based on the actual data, and gradually refine and optimize the concept hierarchy. According to the extraction results, a term structure system covering four core dimensions was initially constructed. Table 2 provides some related concept terms and their hierarchical structures in the field of ancient Chinese stone arch bridges.

Class	Concept
Type	Single arch bridge, multi-arch bridge
Material	Granite, bluestone, limestone, sandstone, white marble
Period	Qin, Han, Three Kingdoms, Wei, Jin, Southern and Northern Dynasties, Sui, Tang, Five Dynasties and Ten Kingdoms, Song, Yuan, Ming, Qing, Modern and Contemporary
Component	Arch, abutment, bridge deck, baluster, balustrade, drum stone, side wall, ground cover, sky-raising stone, vertical connecting stone

Table 2. Examples of main terms in the field of ancient Chinese stone arch bridges (partial)

2.1.4 Defining concept properties: The conceptual attributes of ancient Chinese stone arch bridges include object attributes and data attributes. Object attributes refer to the relationship between concepts or instances; data attributes are used to define the attribute relationship within an instance. The basic relationship between ontology concepts mainly refers to CIDOC CRM, as shown in Table 3.

Properties	Domain	Range
P1_is_identified_by	E1_CRM_Entity	E41_Appellation
P2_has_type(is_type_of)	E1_CRM_Entity	E55_Type
P4_has_time-span	E2_Temporal_Entity	E52_Time-Span
P7_took_place_at	E4_Period	E53_Place
P14_carried_out_by	E7 Activity	E39 Actor
P43_has_dimension	E70_Thing	E54_Dimension
P44_has_condition	E18_Physical_Thing	E3_Condition_State
P45_consists_of	E18_Physical_Thing	E57_Material

P46_is_composed_of	E18_Physical_Thing	E18_Physical_Thing
P56_bears_feature	E19_Physical_Object	E26_Physical_Feature
P90_has_value	E54_Dimension	E60_Number
P91_has_unit	E54_Dimension	E58_Measurement_Unit
P128_carries	E24_Physical_Human-Made_Thing	E33_Linguistic_Object

Table 3. Refer to the basic relationships between CIDOC CRM ontology concepts

2.1.5 The main model of ancient Chinese stone arch bridge: Figure 2 shows the ontology structure model of the knowledge graph of ancient Chinese stone arch bridges. The model takes "Ancient Chinese stone arch bridge" as the core class and constructs a multi-dimensional semantic expression system around the structural composition, material technology, spatial location, historical events, preservation status and size information of the bridge. The model is extended on the basis of the CIDOC CRM framework, reusing common classes such as E41_Appellation, E55_Type, E57_Material, E53_Place, E4_Period, and E5_Event, and refines the structural hierarchy through the custom class "component". Semantic associations are established between the various classes through attributes such as P1, P2, P4, P43, P45, and P46, forming a top-down, multi-layer nested ontology structure. The model supports the semantic description of information such as materials, dimensions, inscriptions, decorative features, and damage status of bridge components. It has good structural integrity and expansion capabilities, and provides a unified semantic basis for knowledge organization and visual query in the virtual restoration scenario of stone arch bridges.

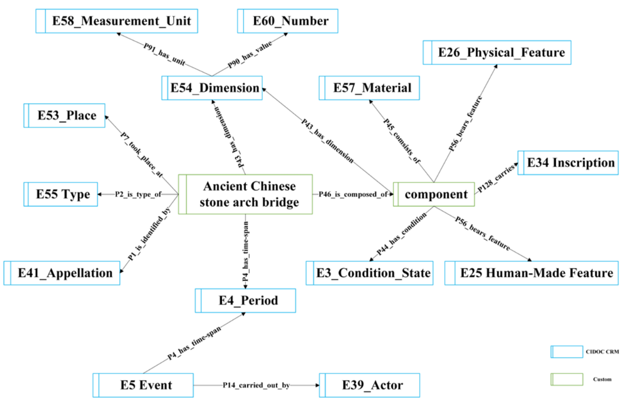

Figure 2. The main model of ancient Chinese stone arch bridge

2.2 Data layer construction

The construction of the knowledge graph of ancient Chinese stone arch bridges requires a large number of entities and attribute relationships between entities as support. This paper automatically extracts ancient bridge knowledge based on relevant books, research papers, newspapers, archaeological reports and other texts and encyclopedia website data, stores the extracted conceptual knowledge into the model layer, and constructs the data layer from the bottom up, mainly including knowledge acquisition, knowledge fusion and knowledge application.

2.2.1 Knowledge Acquisition: Knowledge acquisition is the basic link in building a knowledge expression model, which is responsible for extracting domain-related structured information from multi-source data. In the field of virtual restoration of ancient Chinese stone arch bridges, knowledge acquisition covers important contents such as the historical background, structural composition, damage status and restoration activities of the bridge. This paper achieves high-quality knowledge acquisition through multi-source data integration and technical method optimization. In terms of knowledge extraction, a combination of manual extraction and automatic extraction is adopted to improve the efficiency and accuracy of entity, relationship and attribute extraction. Entity extraction identifies key concepts such as the bridge as a whole, arch, pier, and restoration activities; relationship extraction captures the relationship between the bridge and time, space and activities, such as "Wanning Bridge was built in the Yuan Dynasty"; attribute extraction extracts the span, height, material and other features of the bridge from text and surveying data. This process lays a solid foundation for the organization of the data layer.

2.2.2 Knowledge Fusion: Knowledge fusion plays an important role in the integration of multi-source heterogeneous data, solving problems such as entity redundancy, relationship conflict and attribute inconsistency, and ensuring the consistency and integrity of the knowledge system. In the process of entity alignment and disambiguation, the multiple naming forms of the same bridge from different sources are unified through contextual semantic analysis and standard term mapping. For example, "Wanning Bridge" and "Houmen Bridge" are clearly defined as the same entity and merged in the knowledge system. In addition, for ambiguous descriptions, semantic confusion is eliminated by associating context information, providing higher accuracy for entity representation. Relationship and attribute information are semantically unified and logically optimized in the fusion process. For example, "Wanning Bridge was built in the Yuan Dynasty" and "Zhaozhou Bridge was built in 1285" are normalized into consistent descriptions through time reasoning; the span attribute of the bridge arch is preferentially based on high-precision surveying and mapping data, and the inconsistency in the text description is eliminated. In addition, logical verification technology is used to check the consistency of the timeline in the knowledge system, such as verifying whether the repair activity occurs later than the damage event.

2.2.3 Knowledge graph expression: Based on the above-mentioned ancient Chinese stone arch bridge ontology library and structured ancient Chinese stone arch bridge data, Neo4j graph database is used to store and visualize the knowledge graph. Neo4j is one of the most commonly used graph databases. It can process relational data more efficiently and accurately in terms of scale, performance and ease of use, and meet the visualization needs of massive data in different fields today. The specific method is to import the ontology built in protégé into the Neo4j graph database, and combine the python language to import the processed ancient Chinese stone arch bridge data in the format of a CSV document to realize the storage of ancient Chinese stone arch bridge resource entities, attributes, and relationships.

3. Experiment and analysis

Our case study is an ancient bridge in China called Wanning Bridge, which is located in Beijing and is located on the central axis of Beijing City. Its geographical location is shown in Figure 3. Wanning Bridge was built in the 22nd year of the

Yuan Dynasty (1285). The Yuan Dynasty also built Chengqing Gate (Chengqing Upper Gate) on the west side of Wanning Bridge. Today, only the ruins of the gate remain. This place has a long history and value. It is a typical ancient Chinese stone arch bridge. In 2014, the Grand Canal of China, including Wanning Bridge, was announced as a World Cultural Heritage by the United Nations Educational, Scientific and Cultural Organization. In 2024, Wanning Bridge was selected as a World Heritage as part of the "Beijing Central Axis - A Masterpiece of China's Ideal Capital Order".

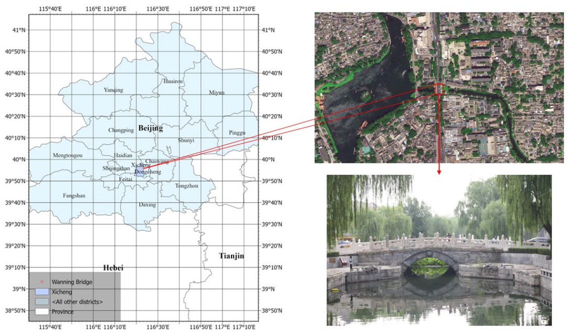

Figure 3. Wanning Bridge Location

3.1 Experimental data and processing

The virtual restoration process of ancient Chinese stone arch bridges, represented by Wanning Bridge, is highly dependent on the integration and analysis of multi-source heterogeneous data. In order to construct a knowledge graph with complete structure and unified semantics, this paper constructs a multimodal knowledge acquisition framework that integrates text, images, surveying and mapping drawings, and expert knowledge, as shown in Figure 4, which provides a solid data support for subsequent ontology modeling and graph construction. Text data is the core source of historical construction, cultural connotation, and restoration process modeling of bridges. This paper systematically organizes ancient books and documents (such as "Xijin Zhi Jiyi" and "Qingguanshi Bridge Practice"), research papers, local chronicles, newspapers, and encyclopedia resources, covering key contents such as the construction background, structural characteristics, historical evolution, and repair records of bridges. Among them, professional books and archival materials provide systematic historical information, research papers deeply explore the structural performance and disease types of bridges, and news media and online encyclopedias supplement modern protection and public cognition information. These texts provide a corpus basis for the semantic modeling of bridge events, temporal status, and cultural value. Image data provides an intuitive basis for visual status modeling and historical comparison of bridges. It includes high-definition photos taken on site and historical old photos. The former is used to record the current overall shape of the bridge and the status of detailed components, which helps to identify the damaged location and component characteristics; the latter reflects the changes in the morphology of the bridge in different periods and is an important reference for historical restoration reasoning. The surveying and mapping data mainly comes from CAD drawings in bridge engineering archives and professional survey results, covering two-dimensional engineering drawings such as plan views, elevations and sections. CAD data provides the structural dimensions, spatial layout and connection relationships of key components such as arches, piers and parapets. Through the structural analysis of the drawings, this paper extracts geometric parameters such as length, width, height and span, and establishes topological structure mapping between components. Compared with three-dimensional scanning data, CAD drawings have the advantages of strong drawing standardization and clear structural expression. They are suitable for component-level structural modeling and geometric attribute extraction, and can be directly mapped to E54_Dimension, E60_Number and E58_Measurement_Unit in the ontology. As a high-value practical knowledge source, expert oral materials provide an important supplement to the understanding of bridge damage mechanisms, repair strategies and cultural significance. Through interviews with bridge historians, architectural restoration engineers, and cultural relics protection experts, this paper collected information on component restoration standards, construction process selection, and material judgment basis, filling the gaps in textual materials in terms of process details and judgment standards, and providing empirical support for the semantic modeling of restoration activities. According to comprehensive statistics, the experiment collected 312 pieces of structural entity data related to Wanning Bridge, 145 sets of semi-structured surveying and mapping drawing data, and about 1,500 pieces of unstructured text information, covering key elements such as bridge components, historical events, geometric attributes, material types, spatial locations, and restoration records, forming a multi-source semantic data foundation to support the construction of knowledge graphs.

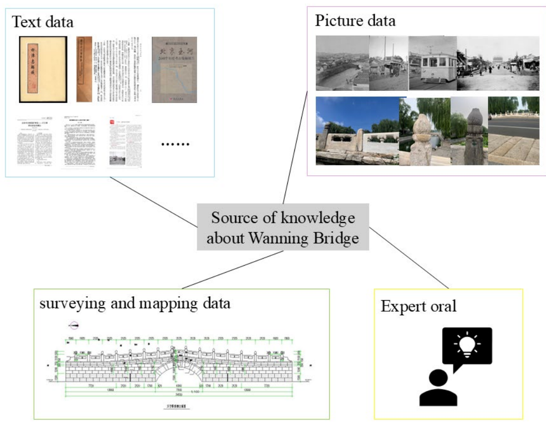

Figure 4. The source of Wanning Bridge knowledge

This paper designs a unified knowledge extraction and fusion process for multiple data types such as structured, semi-structured and unstructured data to achieve semantic integration and consistent expression of cross-source heterogeneous knowledge. For structured and semi-structured data, such as CAD surveying and mapping drawings and standardized field data, the format conversion and semantic mapping methods are used to convert the original data into triple representations that meet the requirements of the ontology model. In this process, field standardization, unit unification and semantic type alignment are completed to ensure that the data can be embedded in a unified knowledge framework. For unstructured text data, including historical documents, research papers, news reports and encyclopedia materials, a strategy combining manual annotation and automatic extraction is adopted to identify key knowledge elements such as bridge entities, component names, geometric attributes, construction and repair activities, and convert them into triple forms. In the extraction process, template matching, entity recognition and syntactic analysis techniques are combined to improve the efficiency and accuracy of structured expression of unstructured corpus. For some abstract knowledge that is difficult to automatically obtain through text, such as the cultural value and functional cognition of bridges, it is supplemented and constructed through the participation of domain experts and manual modeling to ensure the integrity and semantic depth of the knowledge system. In the knowledge fusion stage, entity alignment, attribute standardization and spatiotemporal logical association were achieved based on the constructed ontology model of ancient Chinese stone arch bridges. The semantic alignment method was used to merge the different names of the same bridge from different sources into a unified entity, and a temporal chain between the bridge state and historical restoration activities was established. The priority strategy based on credibility and data accuracy was used to resolve conflicts for attribute values that differed between data sources. The fused knowledge was stored in the Neo4j graph database in the form of triples, and a stone arch bridge knowledge graph with Wanning Bridge as the core was constructed. The graph uses nodes to represent the bridge as a whole, component units and historical events, and edges to represent semantic relationships, achieving a unified expression of structure, process and state, and providing a reliable foundation for semantic-oriented query, reasoning and restoration decision support.

3.2 Wanning Bridge Knowledge Graph

As an important representative of ancient Chinese stone arch bridges, Wanning Bridge has a complex structure and a long history. It is an ideal demonstration object for the construction of knowledge graphs of bridge cultural heritage. Relying on the Neo4j graph database, a knowledge graph with Wanning Bridge as the core is constructed. Through the semantic association between nodes and edges, multi-dimensional knowledge expression of bridge components, material information, damage status and repair activities is presented. The graph uses a graph structure to model entities and their relationships. Nodes represent entity objects, and edges represent semantic relationships. It supports visual query and graphical exploration of structured knowledge.

Figure 5 shows the visualization effect of the "Wanning Bridge" knowledge graph in the Neo4j environment. The central node is "Wanning Bridge", and multiple component nodes such as bridge arches, balusters, and abutments are developed around it, as well as knowledge elements such as repair events, material types, and damage causes. The highlighted part on the right side of the figure shows the detailed attribute information of a specific component node in the graph. The component is "vertical connecting stone", and its attributes include component name, component material, size parameters, quantity, damage cause, and current damage status. All attribute information is presented in a structured form as the internal attributes of the component node, reflecting the advantages of the graph in fine-grained entity expression.

Through Neo4j's Cypher query language, users can initiate semantic query operations on any node to dynamically track the structural composition, component attributes, historical repair activities, and other contents of the Wanning Bridge. Logical relationships are established between nodes in the graph through semantic edges, such as "composed of...", "repaired", "made of", "damaged", etc., to build a complete bridge semantic network. The graph not only improves the visualization ability of complex structural knowledge, but also provides intuitive decision support for historical restoration, damage analysis, and repair design of bridges.

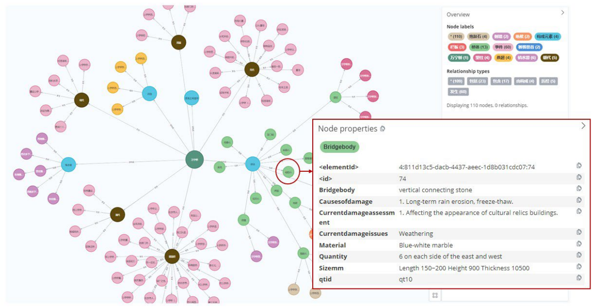

Figure 5. Wanning Bridge Knowledge Graph

3.3 Discuss

The knowledge expression method proposed in this study can provide systematic knowledge support for the virtual restoration of Wanning Bridge by integrating multi-source data and semantic modeling technology. The experimental results show that the knowledge framework built based on the CIDOC CRM extension can effectively express the complex relationship between bridge structural characteristics, historical events and restoration activities; at the same time, the efficient query function implemented by the Neo4j graph database significantly improves the efficiency of knowledge retrieval and analysis. Nevertheless, there are still some issues that need to be explored in depth in the practical application of the model, which need to be further improved and optimized in subsequent research.

4. Conclusion and future perspectives

This paper proposes a knowledge expression method for the virtual restoration of ancient Chinese stone arch bridges, and systematically analyzes and verifies the Wanning Bridge as a case. Based on the knowledge expression framework constructed by CIDOC CRM, the semantic expression and efficient retrieval of bridge structural characteristics, historical evolution, damage status and restoration activities are realized by integrating multi-source heterogeneous data such as text materials, image data, surveying and mapping information and expert oral statements of Wanning Bridge. The research results show that the model can not only systematically express the professional knowledge in the field of bridges, but also provide accurate semantic support and scientific decision-making basis for virtual restoration, and promote the innovative development of knowledge modeling in the field of cultural heritage protection.

Despite the remarkable results, there is still room for improvement in this method. First, in the process of multi-source heterogeneous data fusion, the model's expression and reasoning ability of complex semantic relationships needs to be further improved; second, the degree of automation of knowledge extraction and fusion needs to be strengthened to meet the processing needs of larger-scale bridge and cultural heritage data; in addition, the current model application is mainly concentrated on a single case, and it is urgently needed to expand to the comprehensive modeling and analysis of multi-scenario and multi-type cultural heritage in the future.

Future work will focus on the following three aspects: first, optimizing the semantic logic rules in the knowledge expression model to enhance its reasoning ability and scope of application;

second, exploring knowledge extraction and fusion methods based on artificial intelligence technology to improve data processing efficiency and model expansion capabilities; third, combining virtual reality and physical simulation technology to apply the knowledge expression model to the simulation and evaluation of virtual bridge restoration plans, as well as the digital display and educational dissemination of cultural heritage. Through continuous optimization and innovation, it is expected that the model will play a wider role in the field of cultural heritage protection and provide more comprehensive technical support for scientific restoration and cultural inheritance.

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