Dynamic Health Assessment of Shield Tunnel Structures Based on Knowledge Graph

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Abstract. The safety and performance of shield tunnel structures are essential for metro operations. Therefore, a scientific assessment of the health of the tunnel structure is required during its service life. Although the performance of tunnel structures is affected by complex factors, these factors change over time, and so does the health of the tunnel structure. This study introduced a data-driven method based on the Knowledge Graph (KG) to fully assess the structure of a shield tunnel based on the evolution characteristics of the structure and its historical data. First, the method adopted Neo4j as the storage system, thus establishing a KG containing the data of a shield tunnel from its construction to the present. Then, based on the KG, the shield tunnel will be divided dynamically into sections based on their defects characteristics. Finally, the areas with defects will be assessed automatically through an improved tunnel serviceability index. Through KG, more information related to the tunnel structure can be constructed. Simultaneously, the dynamic evolution tendency of the tunnel structure health can be recorded by considering the time effect. Based on the KG, the main factors affecting tunnel structural health can be used to optimize tunnel operation and maintenance decisions. In this study, a framework for structural health assessment of metro shield tunnels based on KG is constructed and applied in Shanghai Metro Line1.

Keywords: shield tunnel, Knowledge Graph, dynamic, health assessment
1. Introduction
Shanghai metro tunnel has a history of more than 30 years. Various problems inevitably occurred with the gradual extension of its service life [1], according to inspection results and expert experience on the 130 km soft soil tunnels in Eastern China. Shi and Li found that the major issues associated with shield tunnels in soft soil areas are dislocation, material deterioration, damage of connecting bolts, leakage, crack, spalling, and deformation [2]. These faults interactively worsened the performance of the tunnel and caused serious accidents, resulting in substantial economic and property losses. Furthermore, tunnel construction is quite expensive. For example, a 5-meter-diameter tunnel is about $6 million in South Africa, and the cost of the same diameter tunnel in the United States or Europe is two to three times higher [3-4]. Therefore, it is uneconomical and impossible to rebuild or replace existing tunnels.

Galehouse et al. pointed out that specific tunnel maintenance at the right time can significantly help improve the overall performance of the structure with a lower cost [5]. An accurate health assessment can guide tunnel maintenance. In Japan, tunnels are classified into four safety classes A, B, C, and D; corresponding criteria for malpractice in cracks, water leakage, and spalling. The U.S. classifies tunnel performance into ten grades of 0–9. Chinese scholars have also conducted relevant research in this area. Zhang et al. combined different data from multiple sensors to identify tunnel health states using fuzzy analytic hierarchy process (AHP) synthetic evaluation models [6]. Wu et al. analyzed the influence of cracks on segment durability using a fuzzy comprehensive evaluation method [7]. However, most of these methods can only qualitatively evaluate tunnel performance and are very subjective.

Compared with other methods, The tunnel serviceability index (TSI) is considered the feasible and effective method for tunnel evaluation because of the advantage of quantifying the impact of faults on tunnel structure health [8]. However, the tunnel is divided into 200 equal length sections to form basic evaluation units when using the TSI method. Thus, the evaluation results cover up the existing local bad faults or health conditions.

The incomplete and unstructured data obtained also restricts the assessment of tunnel performance. For example, the data of the Shanghai metro tunnel collected in the past 20 years by engineers working in Shanghai Shentong Metro Group, is stored in different systems and formats, so the data can not be used directly. To solve the problem, Chen et al. proposed a Bayesian ordered probability model to find useful information from the collected data and predict the tunnel performance [9]. In the developed TDDS system based on a Semantic Web developed by Hu et al., the meta standard was introduced to deal with multi-source heterogeneous data [10]. However, all the researchers only focus on data mining, ignored data structure.

Knowledge Graph (KG) is an essential part of artificial intelligence technology (KG), is excellent at structured organization and management data, and has been widely used in many fields [11-12]. Wang et al. analyzed the metro engineering accident using KG [13]. Fang et al. combined KG with the computer vision method and constructed the construction site risk automatic monitoring system [14]. Finally, Wang et al. applied the KG to building fire control [15].

This study proposed a KG-based dynamic approach to assess the health state of shield tunnel structures to solve the existing tunnel health assessment challenges mentioned above. Some typical faults in Shanghai shield tunnel and the tunnel health assessment method based on the dynamic
segmentation are introduced in Section 2. Section 3 describes the KG’s model development. A case study is provided in Section 4. Discussions are presented in Section 5, and finally, conclusions in Section 6.

2. The structure health assessment method of shield tunnel

Shield tunnel is a common structure in the Shanghai metro. The shield machine assembles the prefabricated segments into the lining structure of the tunnel, as shown in Figure 1. The lining ring of the Shanghai metro is mainly composed of one top block (F), two adjacent blocks (L), two standard blocks (B), and one arch bottom block (D), connected by bolts. Each prefabricated segment has a standard width of 1200 mm, a standard outer diameter of 6200 mm, and a standard thickness of 350 mm.

2.1 Selection of evaluation indicators

The assessment method's effectiveness depends on the selection rationality of the evaluation indexes [8]. According to the principles of scientificness, practicability, independence, and measurability, this study adopted an average lateral diameter change \( c_{ave} \), average relative settlement \( s_{ave} \), mean differential settlement \( s_{diff ave} \), total water leakage area \( d_t \), total crack length \( d_c \) and total flaking area \( d_f \) as indices for assessment.

Average lateral diameter change \( c_{ave} \) reflects the change of tunnel transverse diameter, which be described as Equation (1):

\[
c_{ave} = \frac{\sum_{i=1}^{n} |d_i - D|}{Dn} \times 1000
\]

where \( n \) is the number of transverse convergence monitoring points; \( d_i \) is the measured outer diameter of the \( i \) monitoring point; \( D \) is the outer design diameter.

As depicted in Equations (2)–(4), the relative settlement \( s_{ave} \) is the difference between the minimum and maximum settlement values. The difference settlement \( s_{diff ave} \) indicates the difference between the settlement of two neighboring pipe rings.

\[
s_{diff i} = \frac{|s_{ri} - s_{(i-1)}|}{l_i}
\]

\[
s_{ave} = \frac{\sum_{i=1}^{m} s_{ri}}{m}
\]

\[
s_{diff ave} = \frac{\sum_{i=2}^{m} s_{diff i}}{m-1}
\]

where \( m \) is the number of the settlement monitoring point; \( s_{ri} \) is the settlement amount of point \( i \); \( s_{diff i} \) is the differential settlement at the \( i \) point; \( l_i \) is the distance between the two neighboring monitoring points.

2.2 Assessment method

Expert evaluation is still the most widely used method in assessing the tunnel health state due to the complexity and uncertainty of shield tunnel states. Thus, based on expert evaluation, this study proposed a multi-index comprehensive evaluation method through dynamic segmentation. Figure 2 shows the flowchart of KG and health assessment.
2.2.1 Dynamic segmentation.

In the conventional methods, the entire channel is divided into several basic evaluation units with equal length, and the performance of each unit is evaluated by experts, fuzzy mathematics, AHP, and cloud models. However, when the basic unit is quite long, the evaluation results are the average value of an extended unit. This shows a better condition than the real one and helps to eliminate the partial bad condition of tunnel shields. Moreover, when the basic unit is relatively shorter, the results can be too discrete to effectively guide the maintenance work [16]. Therefore, the evaluation method based on static and constant segmentation may not meet the engineering requirements.

![Figure 1. Typical segment lining.](image1)

![Figure 2. Flow chart of evaluation method.](image2)

Studies have shown that deformation is a crucial index to assess tunnel performance [17-19]. Hence, this study proposes a dynamic segmentation method with deformation as a linear element. This method mainly contains three steps: (1) obtain the deformation data required to evaluate the tunnel state, (2) take the change of transverse diameter and curvature radius of longitudinal deformation as the key elements to divide the shield tunnel into each unit by single element division unit based on the classification standard shown in Table 1, and (3) the multi-element integrated dynamic element division is carried out for shield tunnel by combining the above two single-element division units.

**Table 1. The standard of Dynamic segmentation.**

| Grade                        | I   | II  |
|------------------------------|-----|-----|
| The change of transverse diameter /‰ |     |     |
| Curvature radius of longitudinal deformation /m | >10000 | ≤10000 |

2.2.2 TSI method combined with dynamic segmentation.

The TSI method proposed by Li et al. in 2017 is widely used by the Shanghai Shentong Metro Group [20]. The details of the TSI were presented in [8]. This study adjusted the original TSI formula based on dynamic segmentation, and the improved TSI formula is described by Equation (5):

\[
TSI = 5.23 - 0.09C_{ave} - 0.16\sqrt{S_{ave}} - 0.01S_{diff ave} - 0.16d_l - 0.1d_c - d_s
\]  

(5)
3. Construction of KG for shield tunnel

Data heterogeneity and semantic gap are the main problems restricting the continuous accumulation and reuse of tunnel data. KG can describe concepts, entities, and their relationships in the real world through nodes and edges as a new method of representing information. Establishing shield tunnel KG has the following advantages:

1. integrating the multi-source heterogeneous information generated during the whole life cycle of a shield tunnel;
2. realizing the reuse and continuous accumulation of shield tunnel knowledge;
3. providing data support for tunnel health assessment;
4. providing a basis for intelligent application and visual display of shield tunnel knowledge.

3.1 Knowledge modeling

Knowledge system modeling aims to establish an ontology to formally express the concepts, entities, and relationships about the shield tunnel. An ontology defines the domain scope described by the KG and provides a template for structured knowledge storage. This study uses Ontology Development 101 to construct the domain ontology.

Based on the existing research and expert experience, the terminologies involved in the shield tunnel were extracted and divided into nine core concepts: Element – the physical structure including the tunnel; organization – a list of all project participants; Accident – the collection of tunnel construction, and operation and maintenance related accidents; Defects – a record of current and historical tunnel faults, the maintenance activities of the tunnel, and the root causes of the tunnel faults; Construction – consists of the design criteria, basic information, structural form; Time – contains the time information; and Hydrogeology – represents geological information. In addition to the relationships between the different concepts listed in the diagram, The ontology includes relationships such as Inheritance, Subclass_of, and Side-by-side. The concepts, entities and their relationships are shown in Figure 3. Figure 4 shows the shield tunnel ontology constructed with Protege.

3.2 Knowledge extraction and storage

3.2.1 Knowledge extraction.

The key knowledge elements involved in the KG of shield tunnels mainly refer to the concepts, entities, and relationships shown in Figure 3. Knowledge extraction aims to extract these knowledge elements from the collected data. For structured, semi-structured, and unstructured data, graph mapping, wrapper, and information extraction can be used to extract knowledge elements. The methods include the rule-based approach, deep learning, and statistics-based methods [13, 21].

Building Information Modeling (BIM) contains a large amount of structured data, one of the essential data sources. This study takes the IFC data format as an example to introduce its extraction process. As an open data format, IFC is widely used in the field of BIM. Therefore, it can be used to describe all elements in BIM. The framework for extracting IFC file formats is shown in Figure 5.
3.2.2 Knowledge storage.

The knowledge elements extracted from knowledge extraction need to be stored by a specific physical structure. Neo4j is a kind of open-source graph database implemented by Java, using an attribute graph model to store graph structure data with node and relation as objects, thus having a powerful data relation processing function. The “LOAD CSV” command in Cypher query language was used to import the data extracted in the previous section into the Neo4j in batches, after which Cypher can achieve efficient retrieval of Neo4j. “MATCH” command can quickly match entities and relationships. 

\[
\text{MATCH } X = (a: \text{Line} \{\text{name}: \text{"Line 10"}\} ) - [\text{Is Related}] - (b: \text{Organization}) - [\text{IsRelated}] - (c: \text{Line} \{\text{name}: \text{"Line 1"}\}) \text{RETURN } (X),
\]

Units participating in both Line 1 and Line 10 projects can be queried and the results are shown in Figure 6.
Based on the py2neo toolkit, Python can be linked to Neo4j. Python was employed to realize dynamic segmentation for the neo4j graph database based on deformation data. Figure 7 is an example after automatic segmentation.

4. Application
Shanghai Metro Line 1 was put into service in 1995, and in December 2010, the maximum cumulative settlement reached about 294.9 mm. The Shanghai Metro Line 1 data was collected from the Huang Pi South Road Station to the People's Square Station uplink in 2014, containing 244 sets of tunnel cross-section convergence data, 76 sets of settlement data, 22 sets of water leakage data, 34 sets of crack data, and 19 sets of spalling data. The convergence data was measured every five rings, and the settlement data was measured every 20 rings.

Finally, 599 entities and 325 relationships were extracted by knowledge extraction from the collected data, where storage results are shown in Figure 8. Based on the knowledge of Neo4j, dynamic segmentation and health state assessment can accomplished using Python. Figure 9 shows the dynamic segmentation of the tunnel section based on the convergence and settlement data. Due to the long service time and large tunnel deformation, the tunnel section has been divided into 14 basic evaluation units, beneficial to the efficient use of the data. The evaluation results of each unit are shown in Figure 10, indicating that the performance of the uplink from Huangpi South Road Station to
the People's Square Road Station is good, and most of the sectional TSIs are above 4.0. For example, the TSI of section K10+100-K10+370 and section K10+625-K10+700 are 3.3 and 3.5, respectively. The former has a large uneven settlement (K10+100 settlement = 90.7 mm and K10+370 settlement = 202.9 mm), while the latter is located in the bypass (K10+661) and convergence deformation, but maintained safe operation after steel ring reinforcement.

5. Conclusions

To enhance the tunnel maintenance efficiency and reduce operation risk, a method for comprehensive performance evaluation of shield tunnels in soft soil areas based on the KG and dynamic segmentation is proposed. The method consists of two parts: (1) the KG is used to integrate tunnel life cycle information, and (2) the TSI method based on dynamic segmentation. This method is applied to Shanghai Metro Line 1, and its performance is evaluated, proving the method's effectiveness.

Compared with the previous studies on health assessment methods, the shield tunnel was segmented according to the severity of the convergence and settlement in this study. At the same time, the KG was used for tunnel health assessment. It establishes the semantic relationship between data to facilitate the management and use of the data. Although this method is proposed based on the Shanghai metro; the conclusions are mainly applicable to soft soil tunnels with the same structure.

The application of KG in tunnel health assessment is still in its infant stages and much work needs to be done in the future. Our future work will focus on: (1) using a more efficient approach to build a large, comprehensive KG of shield tunnel, and (2) consider the application of this method to non-soft soil tunnels.

Figure 8. KG of Shanghai Metro Line 1.
Figure 9. Dynamic segmentation of Line 1.

Figure 10. The evaluation results of Line 1.

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