INTEGRATION OF HBIM/GIS TO PRESERVE INFRASTRUCTURE HERITAGE ALONG THE CHINESE EASTERN RAILWAY

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ABSTRACT:

The infrastructure heritage is the symbol of the highest standard of the technical construction and design methodologies of the Chinese Eastern Railway (CER). As an important component of the cultural heritage of the CER, their conservation hasn’t attracted more attention than the architectural heritage part. However, some heritage infrastructure components have been already demolished while others were threatened by urban expansion and natural degradation during the past hundred years. In this study, we have analysed structural features based on the original drawings and fieldwork for the reconstruction of the vanished and invisible parts of CER. HBIM will be used to support the conservation of the surviving elements. In addition, we collected geographical coordinates of the heritages using on-site GNSS records and Google Earth\(^6\). We propose a method to facilitate the preservation of this historical infrastructure by building a database that integrates HBIM and GIS, including information about historical data and the status quo. In this way, this database will not only be useful for planning purposes by the government and the conservation agencies, but also it will benefit the entire society and the public through its online display and information collection.

1. INTRODUCTION

According to the suggested justifications and criteria of the four well-known heritage railways on the World Heritage List (WHL) selected by UNESCO (see Table 1), they have two common features: culture communication and excellent infrastructure engineering construction. These railways always spread through isolated regions with ancient civilizations and serve as a link between them and contemporary culture. Because of physical boundaries that made it impossible for mature civilizations and cultures to expand during a period when transportation was mostly powered by human and animal power, these areas are known as cultural peripheries. With the emergence of rail technology, the introduction of modern civilization into these isolated areas became a reality. This is due in large part to the development of infrastructure construction such as bridges, tunnels, and spiral lines.

<table>
<thead>
<tr>
<th>Railway heritage</th>
<th>Opening time</th>
<th>Region</th>
<th>Date of inscription</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Semmering Railway</td>
<td>1854</td>
<td>Austria</td>
<td>1998</td>
</tr>
<tr>
<td>Rhätische Railway in the Albula/</td>
<td>1888/1904</td>
<td>Switzerland</td>
<td>2008</td>
</tr>
<tr>
<td>Bernina Landscapes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mountain Railways of India</td>
<td>1908</td>
<td>India</td>
<td>1999</td>
</tr>
<tr>
<td>Trans-Iranian Railway</td>
<td>1938</td>
<td>Iran</td>
<td>2021</td>
</tr>
</tbody>
</table>

Table 1. The Selected Railway Heritage on the World Heritage List (WHL)

These cultural and technical characteristics can be also found in the Chinese Eastern Railway (CER), which connects Russia with the northeastern region of China that is far from the cultural centre of China. As the easternmost part of the Great Siberian Railway (GSR), originally the CER was designed by the Russians to connect the two important harbours of Dalniy and Vladivostok, and the far-east part. Dalniy, now called Dalian, is the southwest harbour in northeast China with a relatively short freezing period during winter. The main line of CER starts from Manchuria and extends via Harbin, the only first-classed station and railway hub on the line, to the east border station (today called Sui Fenhe). From there, the south branch line reaches Dalniy. Between 1897 and 1903, diverse and numerous classifications of infrastructure elements such as bridges, culverts, tunnels, and spiral/loop lines were designed and built to overcome the terrain obstacles, including rivers, gorges, ravines, and the complex and varied topographical conditions along the line (Chinese Eastern Railway, 1900; Liu and Wang, 2018; Liu et al., 2020). After Russia lost the Russian-Japanese War in 1904, the southern section from Kuanchengzi to Dalniy along the south branch line was controlled by the Japanese-coined South Manchuria Railway Co. (SMR), which eventually took over the left sections of CER from the Soviet Union in the 1930s. Kuanchengzi, now known as Changchun, was the capital city of Manchukuo and now is the capital city of Jilin Province, China. Meanwhile, double lines were built in some sections to increase shipment capacity and operation efficiency. To achieve this objective, SMR adds a number of new infrastructure elements, which enriched the diversity of the heritage classifications (see Fig. 1) (The Lvshun Museum, 2007).

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According to the Nizhny Tagil Charter (TICCIH, 2003), infrastructure heritage is an important component of a historical railway line that is representative of the highest technical achievements. However, compared to the architectural heritage located in the cities and towns along the railway, the conservation of infrastructure heritage has rarely attracted attention from the public, researchers, and the administration in China.

This study is based on the original design drawings and on new fieldwork aimed at the analysis of structural features for the reconstruction of the lost parts of CER and the documentation of the remained elements. In addition, we collected geographical coordinates of the heritage items using on-site GNSS (Global Navigation Satellite System) records and Google Earth®. We propose a method to facilitate the preservation of this historical infrastructure by building a database that integrates HBIM (Heritage Building Information Modelling) and GIS (Geographic Information System), including information about the history and current photos, materials, structure, and so on. In this way, this database will not only be useful for government planning and conservation agencies but also would benefit the entire society and the public through its display online and information collection.

2. STRUCTURAL FEATURES AND DESIGN METHODOLOGIES

Except for the King’an Tunnel, the construction of the entire infrastructure was completed in six years due to the advanced methodologies of standardized design and modular construction. Moreover, the design methodology adopted a combination of universal design for small and medium-sized infrastructures and individual design for large infrastructures, which decreased the construction and preparation time. Furthermore, the fact that most infrastructure elements have been used for more than a hundred years demonstrates the reliability of the infrastructure’s structure with little conservation measures (Xu, 2022).

2.1 Standardized structure design

Piers and abutments all adopt a standardized design. There are three general span units with a length of 10.7 m, 21.3 m and 32.0 m, which were designed to cross small-scale rivers, ravines and valleys. All the abutments were designed to be U-shaped with 17 formats and most of them have an arch on both sides, which is decorated with different formats of arches to decrease masonry volume. Only the abutments of large-scale stone arch bridges have different amounts and tiers of arches for terrains, masonry construction, and flood discharge (see Table 2).

### Table 2. The abutment of bridges with different supports has diverse arches (Chinese Eastern Railway, 1900).

<table>
<thead>
<tr>
<th>Type of Abutment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spandrel wall with a sharp arch</td>
<td></td>
</tr>
<tr>
<td>Spandrel wall with an ellipse arch</td>
<td></td>
</tr>
<tr>
<td>Spandrel wall with a semi-circle arch</td>
<td></td>
</tr>
<tr>
<td>Spandrel wall with a multi-type arch</td>
<td></td>
</tr>
</tbody>
</table>

Compared to the abutment design, the influencing factors of the pier’s design not only consist of topographic factors (e.g., the depth of the river and the valley) but also include hydrographic factors. Therefore, the upper formats of piers have the same shape (Fig. 3) and the lower part styles were decided by the flux, speed and direction of the river flow, the flood, and the span length. The melted ice flows at the start of spring and continuous heavy rainfalls in summer always arouse the format changes in the lower part design. The basic type of the cutwater’s plan is a rectangle, and the style of its front and back ends can be interchanged with a semi-circle or sharp angle (Fig. 4).

For the multi-span bridge, the design of their total length and the span-unit length all adopts the modular design methodology. Both temporary bridges and diverse permanent bridges were designed in this way. The temporary bridge was built entirely of wood with three types: the beam bridge, the strut-framed bridge, and the truss bridge (see Table 3). They were only used during the construction time. The bridge’s total length has two combination methods. The first one accumulates with the same...
Another type of bridge is structured on span units featuring different lengths. This combination method was applied for the most individually designed bridges. The specific manifestations are truss bridges crossing rivers combined with two or three span-unit of the same or different truss types. For example, the Nuoni River Bridge has six 74.7 m curved chord trusses and six 32 m and two 21.3 m two types of deck trusses. The combination method of the First Songhua River Bridge is eight 74.7 m curved chord trusses and eleven 32 m deck trusses. For other examples along the line of the combination types see Table 4. Except for the former three units, 10.7 m, 21.3 m and 32.0 m, every type of bridge has its modular span units (see Table 5).
Table 4. The combination types of bridges with diverse span units (river and bridge are in short with R. and B.).

<table>
<thead>
<tr>
<th>Span Unit (m)</th>
<th>Longitudinal Elevation and Structure Details</th>
<th>Cross-section Structure</th>
<th>Cutwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.4</td>
<td><img src="image1.png" alt="Longitudinal Elevation and Structure Details" /></td>
<td><img src="image2.png" alt="Cross-section Structure" /></td>
<td><img src="image3.png" alt="Cutwater" /></td>
</tr>
<tr>
<td>10.3</td>
<td><img src="image4.png" alt="Longitudinal Elevation and Structure Details" /></td>
<td><img src="image5.png" alt="Cross-section Structure" /></td>
<td><img src="image6.png" alt="Cutwater" /></td>
</tr>
<tr>
<td>12.8</td>
<td><img src="image7.png" alt="Longitudinal Elevation and Structure Details" /></td>
<td><img src="image8.png" alt="Cross-section Structure" /></td>
<td><img src="image9.png" alt="Cutwater" /></td>
</tr>
<tr>
<td>Universal Plan</td>
<td><img src="image10.png" alt="Longitudinal Elevation and Structure Details" /></td>
<td><img src="image11.png" alt="Cross-section Structure" /></td>
<td><img src="image12.png" alt="Cutwater" /></td>
</tr>
</tbody>
</table>

Table 5. The span-unit of all classifications of bridges.

Table 6. The universal design of a small-scale two-span stone arch bridge (Chinese Eastern Railway, 1900)

Figure 4. The universal design drawings in the 1900s (Chinese Eastern Railway, 1900) and the current real view of tunnels.

Figure 5. The classification of culverts along the CER.
2.2 Design methodologies of the large-scale bridges

Bridges are the largest size infrastructure type along the CER and may be also considered as the most representative high-tech symbol. Russians and Japanese had already carried out the design and construction of many large-scale railway bridges in their countries and accumulated excellent experience. To shorten the construction time and complete the construction works as soon as possible, as well as to minimize the threat of river flow damage to the bridge safety, CER and SMR applied more advanced and mature bridge structure design methodologies in the medium/large-scale bridge and added abutment and pier protection measures. As part of the individual design’s objects, selecting truss forms for these bridges is the key point. We can find three principal truss forms: (1) the Howe Truss; (2) the Pratt Truss; and (3) the Warren Truss. Russians adjust some details for those truss forms to improve their mechanical property to make them suitable for multiple terrains. Firstly, the Howe Truss was only applied in the temporary timber truss bridge because of the long winter and harsh weather conditions in northeast China (Tongji University et al., 1961). This truss was widely used in the construction of the Nikolaev Railway (from St. Petersburg to Moscow in Russia) in 1847 with 64 bridges among all 187 bridges (St., 2020). However, their reliability was affected by the shrinkage of the timber components just a few years after the opening of the line operation. In view of this, the Howe trusses were not applied in the permanent bridges of CER crossing through the regions with a similar climate to the GSR.

Secondly, in a different way from the general forms, the Pratt Truss in the CER is unique with two subtypes. For the parallel chord one, to improve the stability of the bottom chord and prevent it from deformation, the designer has double webbed the diagonal webs in the middle part to improve the compression resistance of the bridge. This type is always designed in a half-through truss. The second one is the curved chord truss with a 75 m span length, which is the longest one among all trusses and was designed to cross the main shipping lane of the wide river such as the Nuoni River, the Songhua River and the Second Songhua River. This truss not only reduces the impact on the navigable area of the river but also reserves sufficient river clearance to meet the needs of large ships passing through. An example is the First Songhua River Bridge built in 1901, which is a nearly 1,000 m (949.63 m) long and consists of 8 spans of 75 m curved chord truss and 11 spans of 32 m deck truss (Fig. 8).

The third widely used truss along the CER is the Warren Truss. This truss consisted of several equilateral triangle chord component units and was connected only by the top and the bottom crossbeams along the longitudinal direction. Owing it can be assembled on-site with the same size chord components, it is very suitable for prefabricated modular deck truss bridges to overcome two types of rivers. One type is the small-scale river with a narrow width and shallow water. Another type is some large-scale rivers, like Taizi River and the Mudan River, which have a large width, but the water depth is not adequate for large vessels. The Warren Truss applied in CER has two forms. The first one has two parallel chords at the upper and lower part. The second one has diagonal bars between the first and last three sections of the lower chords. Furthermore, for increasing the tensile strength of this truss, the engineers added small diagonal webs to the upper part of the former to improve its mechanical properties and to add uprights to the latter for support (Fig. 9).

Figure 7. Bridges were designed with the Warren Truss

Except for the technical features of the truss bridge, we can review the construction and design level of the Russian part by analysing the structural characteristic of the stone arch bridge. Two factors, the total length and the maximum single span length, reflect the design standard and technical strength of the Russian side of the CER. As mentioned before, most multi-span arch stone bridge consists of many standard modular span units. For example, the Muling River Bridge keeps the record to be the longest stone arch bridge (128 m length) along the CER, consisting of six elliptical arches with a single span of 21.3 m. The triple-centred pointed arches and flat arches were widely applied, while single-centred flat arch can be rarely seen. The triple-centred pointed one is only designed for the main arch with a 4.2 m span. The flat one has numerous examples, ranging from 6.3 m to 21.3 m, which can be seen among small-scale rivers, deep valleys, and gullies. Compared with the first two, the single-centred pointed flat arch is rare, being found only in single-span stone arches of 12.8 m (see Table 7).

By analysing the design of the substructure, we can see that the Russian engineers have done a lot of localised design and consideration into the design of the infrastructure. The regions passing the CER have a long winter with freeze and frequent rainfalls and snowfalls. Under the influence of long time soaking and washing of the meltwater and the effect of freezing and thawing, the structural safety of the bridge could be severely affected. Therefore, the medium/large-scale stone arch bridges are equipped with drainage pipes at different locations to keep the safety of infrastructures (see Table 8). Though the Russians surveyed and mapped the hydrological data along the CER before the design and construction, they did not know well about the historic data. Thus, protective dikes on the waterfront side of bridge abutments were built at river bends, whose function is the same as the cutwater to piers (Fig. 10).
3. INTEGRATION HBIM/GIS

In addition to the individual architectural heritage, the conservation of that infrastructure heritage along the CER has its own characteristics and differences. The distribution of infrastructure heritages is wide, isolated, and linear except for those heritage groups consisting of infrastructures and buildings such as heritage groups of the Khing'an Spiral Line and the Daguan Ridge Spiral Line. From the perspective of data collection, the work of surveying and mapping them is harder than in other cases to the problems to reach those mountain places. Moreover, the difficulties of reusing them are also much harder and more low-profitable than architectural heritages having physical space and distributing concentration, because most of them were built among remote towns and untraversed places like forests and mountains. Furthermore, as a series of heritage sites designed during a specific time and constructed by multiple companies, the conservation work should also be based on deep knowledge and on interdisciplinary cooperation. Therefore, the mentioned reasons also cause the current protection dilemma of that infrastructure heritage.

Since BIM (Building Information Modelling) technology has been introduced into the field of cultural heritage conservation, it is regarded as an innovative methodology for accurate recording, flexible collecting of data and saving protection costs (Logothetis et al., 2015). In terms of the research objects of this study, the advantages of BIM are useful and helpful to solve those dilemmas. On the one hand, BIM can reappear that concealed technical heritage and reconstruct the vanished heritage. Take caissons as an instance, this method was applied to build the basement of the large-scale truss bridges’ piers, which locate in the centre of the river with wide channels and larger depths such as the Nuoni River, the Songhua River, and the Taizi River. Based on the original design drawings published by CER (Chinese Eastern Railway, 1900) and historical document of the bridge built in Russia at that time (Красковский et al., 1994), we reconstructed the model of caissons (see Fig. 11). The reconstruction of the heritage, which has lost all its structure, can be also obtained with the assistance of BIM.
On the other hand, BIM/HBIM (Heritage BIM) is not only useful for the documentation of the remaining structure, including the integrated heritage and the remaining structures, but also contributes to congregating all the historic data such as design drawings, historic photos, and current research outcomes (Cursi et al., 2022). Especially for those bridges and tunnels which were built by SMR, the implementation of HBIM will change the forepassed conservation situation, which lacks first-hand data. Based on some recent research which focuses on important infrastructure monuments, for instance, Lizbor Bridge (1860) in Spain (León-Robles et al., 2019), and Azzone Visconte in Lecco, Italy (Barazzetti et al., 2016), applying HBIM to record stone arch bridges along the CER seems to be a feasible plan in the following study based on current the research of the NURBS-based modelling (Barazzetti et al., 2015). Besides, since there is only little relevant research focused on the HBIM for 20th-century steel structures (Morganti et al., 2019), the research on the reconstruction and scanning of steel bridges such as truss bridges and plate girder bridges is also an important part of the following study.

HBIM has an aptitude for 3D modelling for the individual monument through parametric elements selected from the common libraries. However, for linear heritage or heritage groups, it still has two problems, querying the reconstruction of complex spatial and integrating the modelling in its surroundings. GIS (Geographic Information System) mainly focus on three items: (1) analysing spatial data, objects attribute, and the relationship between different elements, (2) managing, and (3) querying. Meanwhile, it’s not only a management and analysis tool but also a modelling tool that has been widely used to procedurally model large-scale heritage scenes (Schwarz et al., 2015). GIS can be used to establish databases for monuments at regional and national levels (Von Schwerin et al., 2013). Based on the mentioned reasons, the importance of the integration HBIM/GIS has been demonstrated by several works in architectural heritage conservation (Isikdag et al., 2008; Yaagoubi et al., 2015).

In the conservation and management of infrastructure heritage, integrating HBIM/GIS is an effective and appropriate method. Indeed, the HBIM approach allows the reconstruction and modelling of individual elements, while GIS allows considering the geospatial extension of the historical railway line (Garramone et al., 2020; 2022). Especially for the infrastructure heritage along the CER with numerous and diverse types of elements, introducing this new method to preserve the heritage will build a solid and cooperative background for both conservation sectors and stakeholders from two sides. The reasons are as follows. Firstly, based on the urgency and necessity of this heritage sustainable conservation, during the past three-year fieldwork, we collected geographical coordinates of the heritages located in places that are easy to reach using on-site GNSS records. For the reasons of management and terrains: (1) infrastructures locate in the Border Management Area, (2) infrastructures are operated by the Administration of Railway, (3) infrastructures locate in remote areas inaccessible, we collected the data of them with Google Earth®. Then we created a basic profile for every remaining heritage using ArcGIS® 10.2 and add historic information (Cursi et al., 2022) based on the systematic collection and collation (Fig. 12). This profile consists of the following items of every infrastructure: identification code, region, geographic coordinates, type, structure form, status quo, protection level, current function, status description, technical achievements, design drawings, and historical photos. Meanwhile, facing such a massive volume of data and the compatibility of different software packages, it is worth exploring problems like efficient processing data storage and integration of data cross-platform.

4. CONCLUSIONS AND FUTURE WORK

The paper illustrates the structural features and design methodologies of the infrastructure heritage along the CER (Chinese Eastern Railway) and proposes an integration HBIM (Heritage Building Information Modelling)/GIS (Geographic Information System) way to preserve and valorise this cultural heritage and its historic data in a sustainable way. Rarely received attention, the infrastructure heritage along the CER is vanishing and being threatened by both human and natural factors. The reconstruction of these remained, vanished, and concealed heritage with BIM (Building Information Modelling)/HBIM required support from the clear illustration of structural characteristics. Meanwhile, geographical data collection and the creation of a preliminary database of the heritage in this stage provide a solid basement for heritage management using GIS. Moreover, introducing the integration of HBIM/GIS will become a shared and sustainable platform for conserving the heritage, which is an effective and profound way to integrate all types of historic data.

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