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HBIM-GIS Integration of Infrastructure Heritage with Complex Documentation and Conservation States: Methodology and Application to the Historic Bridges along Chinese Eastern Railway Main Line

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Abstract

Cultural heritage assets are frequently subjected to both natural and human-induced transformations over time, often resulting in the physical deterioration or disappearance of structures, as well as the enrichment or loss of historical records. Infrastructure heritage presents significant conservation challenges due to its large spatial scale, complex site conditions, and diverse intervention histories. This study proposes an innovative HBIM–GIS integration workflow tailored to infrastructure heritage sites affected by both complex physical conditions and varied levels of archival preservation. Unlike conventional HBIM or GIS-only approaches, the proposed workflow is designed to adapt to three different scenarios: (1) well-preserved but lacking archival records, (2) extensively documented but physically lost, and (3) structurally altered with layered historical interventions. The goal is to produce accurate, georeferenced, and semantically enriched digital records while enhancing interactivity and visualization quality through 3D representation. Integrated outcomes are made accessible via remote access and online publication using the ArcGIS® platform. The methodology is validated through three representative historic bridges along the Chinese Eastern Railway (CER) main line: the Huli River Bridge III, the dismantled Mayan River Bridge, and the Muling River Bridge. The results demonstrate the workflow's adaptability and contribution to both scholarly research and public engagement in infrastructure heritage conservation.

1. Introduction

Cultural heritage assets face significant challenges and uncertainties due to the combined effects of natural processes and human activities throughout their long and complex histories (Sesana et al., 2021). Continuous environmental weathering, hydrological erosion, and climate-related hazards, together with human actions such as reconstruction, expansion, restoration, and even demolition, all leave tangible impacts on the material fabric of heritage sites. These natural and anthropogenic factors often generate large volumes of scattered historical records; however, war, administrative negligence, and inadequate heritage awareness can also result in severe losses of documentation (Seila et al., 2025). Consequently, modern conservation efforts encounter two major difficulties: the reliable identification and systematic management of heritage records, and the accurate documentation and assessment of current heritage conditions (Garramone et al., 2023).

HBIM–GIS integration is increasingly recognized as an efficient, accurate, and traceable approach to cultural heritage conservation, particularly for assets characterized by extensive spatial distribution, complex site conditions, rich historical documentation, and the need for remote accessibility (Garramone et al., 2022). HBIM enables detailed digital representation of heritage elements, including their geometry, materials, and associated attributes (García-Valldecabres et al., 2023). Geographic Information Systems (GIS) excel at capturing broader environmental contexts, facilitating spatial analysis and large-scale 3D scene visualization (Barrile and Genovese, 2024). The combination of these two systems supports the generation of comprehensive documentation and clear visual outputs, thereby enhancing both the accessibility and usability of heritage-related data (Dionizio and López-Chao, 2025).

The Chinese Eastern Railway (CER) spans four provinces in Northeast China and is recognized as a nationally significant industrial heritage and historical railway system (The State Council of the People's Republic of China., 2013). Since 1897, Russian and Japanese engineers constructed numerous bridges, tunnels, and spiral lines to overcome geographic barriers along the route (The Lvshun Museum, 2007; д, 190AD). These efforts created a distinctive heritage landscape and generated a substantial body of historical documentation. However, the conservation of these assets now faces serious challenges. On the one hand, limited heritage awareness, railway decommissioning, and long-term natural degradation have led to insufficient maintenance. Many structures are poorly repaired, left unattended, or even demolished after damage. Surrounding heritage landscapes have also suffered from uncontrolled development. On the other hand, the associated archival materials are at risk of loss, fragmentation, or mismanagement. These problems hinder the accurate identification of heritage status and the development of a systematic archival framework.

This study aims to explore an HBIM–GIS integration methodology tailored to infrastructure heritage sites with complex physical conditions and varying levels of historical archives. The primary objective is to generate accurate, comprehensive, georeferenced, and accessible digital records, thereby enhancing data interactivity and visualization quality. Additionally, the study implements remote access and online publication of integrated outputs through the ArcGIS® Online (ESRI, 2024). The proposed workflow is empirically validated through three representative bridge heritage sites along the Chinese Eastern Railway main line: the Huli River Bridge III, the Mayan River Bridge, and the Muling River Bridge. The outcomes contribute to advancing the digital preservation and information sharing of infrastructure heritage, while promoting a more systematic, scientific, and sustainable approach to heritage management.

2. Introduction to the Infrastructure Heritage Sites

This study focuses on three infrastructure heritage sites along the eastern section of the CER main line in Heilongjiang Province, China. The Huli River Bridge, which was designed by Japanese engineers on the double-track of Taipingling spiral line in the 1940s. Mayan River Bridge, a bridge dismantled in 2023 after a flood struck, was designed and constructed by Russian engineers at the beginning of the 20th century. The third is the Muling River Bridge, which is China's first stone railway arch bridge (The Compilation Committee of the Historical Records of Chinese Railway Bridges, 1987). This bridge has undergone multiple phases of human intervention. These cases show different preservation conditions and varying levels of archival documentation. They offer important insights into the adaptability of HBIM and GIS integration workflows in different heritage scenarios.

2.1 Huli River Bridge III: Well-preserved but Lacking Archival Data

The Huli River Bridge III (BHLR-III) [(1)] is located along the uphill spiral section near Taipingling, which comprises two parallel lines: the original alignment designed and constructed by Russian engineers between 1897 and 1903, and a double-track extension added by Japanese engineers in the 1940s to increase transportation capacity (Figure 1). As the Huli River is a major watercourse intersecting this section multiple times, both engineering teams constructed several bridges in the area to facilitate the crossing.

Since 2019, the research team has made continuous efforts to locate archival materials related to the construction period, design drawings, and historical photographs of the bridge. However, no such documentation has been found to date. A field investigation conducted in 2020 confirmed that the bridge is constructed of concrete, comprises two spans, and remains structurally intact overall, although partial surface damage and material detachment were observed.

2.2 Mayan River Bridge: Extensively Documented but Physically Lost

The Mayan (or Mayi) River Bridge (BMYR) is located east of Yimianpo Town in Heilongjiang Province. The bridge has a total length of 119.55 meters and features a four-span, three-cantered stone arch structure. With a maximum single-span length of 21.34 meters, it held the record for the longest span among all multi-span full-stone arch bridges along the Chinese Eastern Railway. Both abutments measure 12.29 meters in length, and the bridge deck rises 12.43 meters above the riverbed. The abutments and pier foundations were constructed using cofferdam methods, with a foundation depth of 5.34 meters (Figure 2).

The main arches and abutment arches are made of concrete and clad in dressed ashlar masonry for decorative purposes. Both the upstream and downstream faces of the piers are fitted with semicircular cutwaters. Six drainage openings are distributed across the masonry walls above the piers, with three positioned on each side of the bridge.

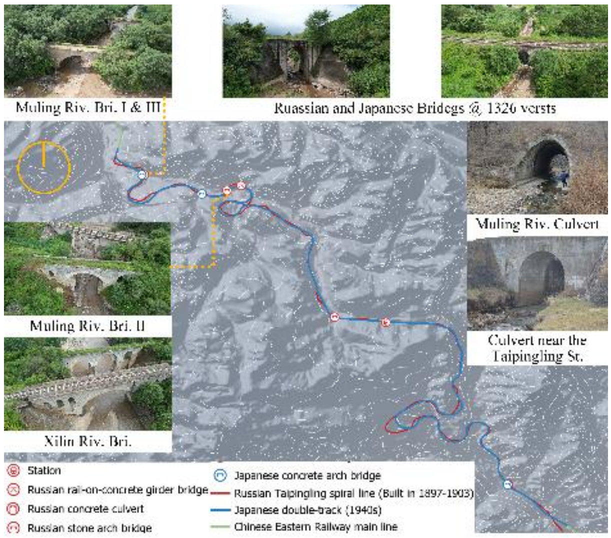


Figure 1. Location of BHLR-III along the Taipingling Spiral Line.

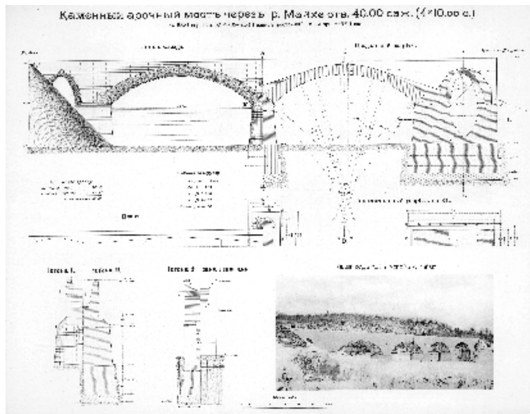


Figure 2. Original design drawings of the BMYR (190AD).

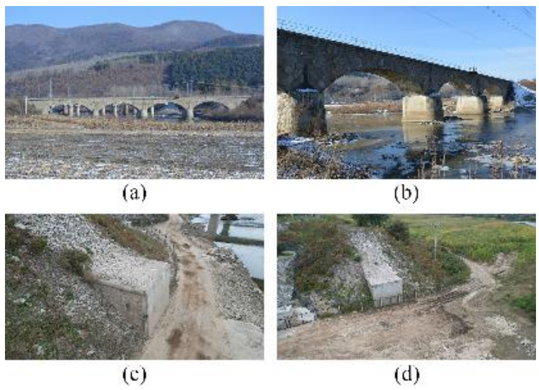


Figure 3. The BMYR's situation in 2020 and 2024: (a) upstream-side elevation in 2020, (b) downstream-side elevation in 2020, (c) remaining abutment segments on the Harbin-facing side in 2024 and (d) remaining abutment segments on the opposite side in 2024

(1) In this study, the two single-span stone arch bridges across the Huli River, which were both designed and constructed by Russian engineers between 1897 and 1903 along the Taipingling Spiral Line, are referred to as Huli River Bridge I and Huli River Bridge II, based on their relative proximity to Harbin. A third bridge, constructed at a later period by the Japanese as part of a double-track expansion, is correspondingly designated as Huli River Bridge III.

The research team conducted an initial field survey of the bridge in 2020, documenting the physical structure in detail Figure 3 (a) and (b). In the summer of 2023, a flood event struck the Mayan River, resulting in the collapse of the bridge's central spans. Subsequently, the managing authorities dismantled the entire structure, including what had been the longest-span arch bridge along the Chinese Eastern Railway. Figure 3 (c) and (d) presents the site condition as observed in the summer of 2024, with the remnants of the abutments still clearly visible.

2.3 Muling River Bridge: Structurally Altered but Rich in Historical Records

The Muling River Bridge (BMLR), designed and constructed by Russian engineers between 1897 and 1901, holds the distinction of being the first stone arch railway bridge built in China. According to the original design, the bridge measured a total length of 174.34 meters and consisted of ten arches, each spanning 12.80 meters. The bridge deck was initially constructed without any longitudinal slope and provided a vertical clearance of 9.67 meters from the deck to the riverbed. The foundations for the abutments and piers were set at a height of 3.20 meters. At both ends of the bridge, each abutment supported an additional arch with a span of 4.26 meters (Figure 4).

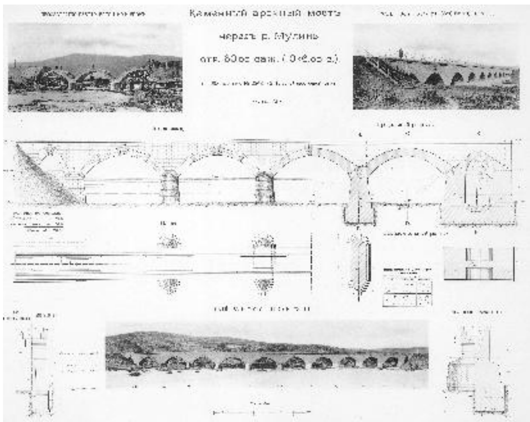


Figure 4. Original design drawings of the BMLR (190AD)

Over its century-long history, the BMLR has undergone multiple episodes of damage, repair, and functional transformation, resulting in a structurally complex condition characterized by layered historical interventions. During World War II, Arches 2 [(2)] and 3 were severely damaged by explosions (The Compilation Committee of the Mudanjiang Railway Admission, 1999). The subsequent restoration in 1945 was relatively refined, with simulated masonry joints meticulously incised into the concrete surface to replicate the bridge's original appearance. In 1965, the external masonry layers of Arches 6 through 9 were eroded by flooding. The repairs that followed were comparatively rudimentary, relying primarily on concrete reinforcement with minimal consideration for the original materials and architectural detailing-joint lines were carved only on the arches, while the remaining surfaces were left smooth and undecorated (Figure 5). In 1989, the bridge was repurposed for road traffic use.

Figure 5. Upstream and downstream elevations of BMLR.

3. Methodology

The CER has undergone a complex historical trajectory, and the infrastructure heritage along its route often presents a range of challenging characteristics. These challenges include the absence or ambiguity of historical archives, or in some cases, an overabundance of fragmented documentation. They also involve damage caused by natural deterioration, destruction related to war, intentional removal due to limited heritage awareness, and inappropriate repairs that prioritize functionality while neglecting heritage value. As a result, the HBIM/GIS integration process for such infrastructure heritage differs significantly from that applied to landmark cultural heritage sites with well-preserved and clearly documented histories.

The workflow illustrated in Figure 6 consists of the following eight steps: (1) Construction of a Historical Archive Database (Database 1), (2) Development of a GIS Database (Database 2), (3) Field Survey and Droned-Based Photogrammetric Documentation, (4) Assessment and Classification of Heritage Conditions, (5) Point Cloud Generation and Processing, (6) HBIM Implementation, (7) HBIM/GIS Integration, and (8) Remote Access to Integrated Results.

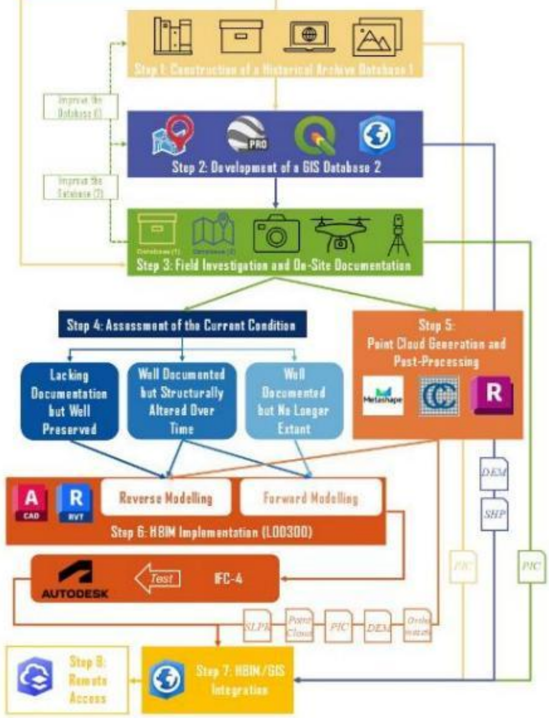


Figure 6. HBIM/GIS Integration workflow for infrastructure heritage sites with complex preservation conditions in this study.

(2) In this study, the numbering of the bridge's structural elements begins from the Harbin-facing side. The arches located on the abutments at both ends are designated as Arches 1 and 12, while the main arches are numbered consecutively from 2 to 11. The piers are numbered from 1 to 9.

3.1 Development of the Historical Archive and GIS Databases (Databases 1 and 2)

Based on the collection and analysis of historical materials, a structured archival database was developed for infrastructure heritage sites with existing documentation, such as the last two cases. This database comprises engineering drawings, historical photographs, and textual records, including metadata such as code, location, bridge length, structural type, height, gradient, and opening/closure dates. However, in cases such as BHLR-III, which is located in a remote and sparsely populated area and lacks detailed historical documentation, the archival information was supplemented by analysing satellite imagery and conducting on-site field verification.

Building upon Database 1, the research team assigned geographic coordinates to the three previously documented infrastructure heritage sites using Google Earth® Pro (Google, 2025). In addition, historical imagery of the heritage site's surrounding environment was also collected (Figure 7). The archival data were then imported into QGIS ("QGIS (Version 3.30.2)," 2023), where the OpenTopography DEM Downloader ("OpenTopography DEM Downloader (Version 3.0)," 2024) plugin was utilized to obtain and visualize surrounding Copernicus Global DSM 30m data. Subsequently, shapefile representations of the railway lines were created. For the Taipingling Spiral Line, the original alignment was reconstructed through georeferencing and redrawing based on historical maps.

Figure 7. Historical imagery of the BMYR site surroundings (2009–2022).

In addition to commercial solutions, such as ArcGIS® Pro (ESRI, 2024) platform, part of the workflow was implemented with open-source tools such as QGIS plugins, ensuring wider reproducibility and lowering dependency on proprietary platforms. All historical archival materials were stored in image format and geotagged using GEOSETTER ("GEOSETTR (Version 3.5.3)," 2019). Figure 8 presents the GIS database entries for the two case-study bridges recorded in archives. Future extensions will explore Arches ("Arches (Version 8.0.3)," 2025) for spatial data management and 3D modeling and visualization.

3.2 Field Survey and Droned-Based Photogrammetric Documentation

This step was carried out based on the outputs of two databases, and the results further enriched the content of both datasets. Following the initial field investigation in 2020, a preliminary record for Case 1 was established. During the data acquisition campaign in 2024, which coincided with the local flood season, geometric data were collected using drone-based photogrammetry with a DJI AIR 2S drone equipped with an FC3411 8.38 mm lens. Images were captured at a resolution of 5472 × 3078 pixels, resulting in a ground sampling distance (GSD) of approximately 2.63 μm per pixel.

For the Case 3, aerial photography included both nadir (overhead) and oblique (side) perspectives, acquired from an average altitude of 42.2 meters above the bridge deck. A total of 98 nadir and 106 oblique images were collected. For Case 1, the same method was applied, with 78 images captured from approximately 30 meters above the deck (Figure 9). All images were georeferenced using the WGS 84 coordinate system.

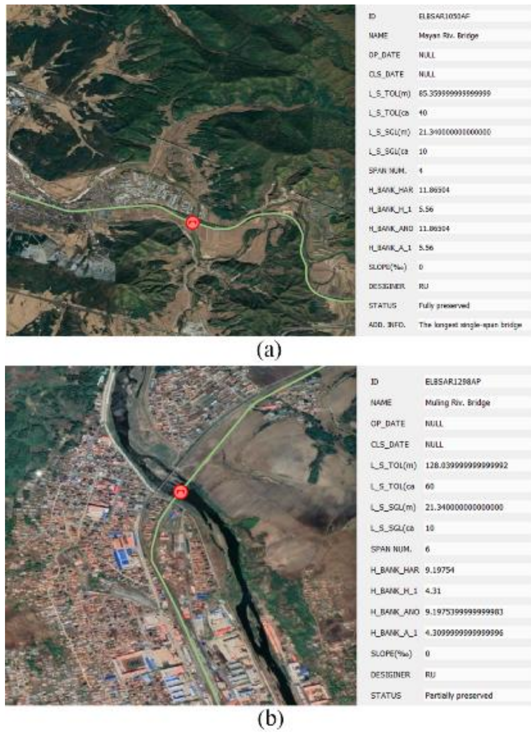


Figure 8. GIS database entries for the historically documented BMYR (a) and BMLR (b).

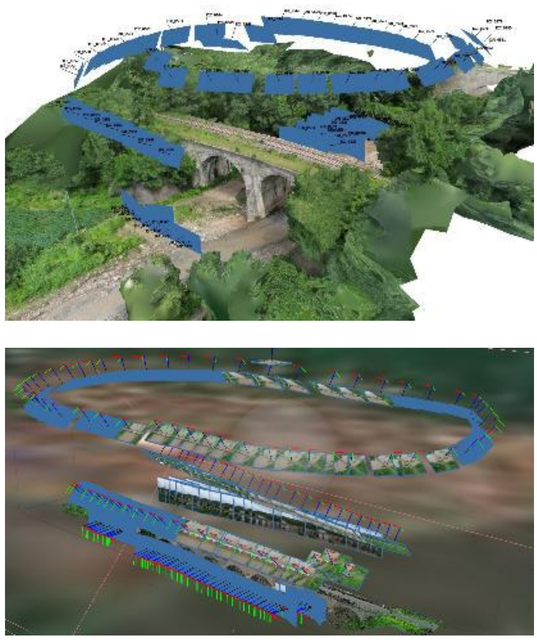


Figure 9. Drone flight paths applied for the photogrammetry: BHLR-III and BMLR.

During the 2024 field investigation, the research team observed that due to the limited heritage awareness of local authorities and management agencies, cases of anthropogenic damage to heritage sites and the broader railway landscape continue to occur. The cultural landscape associated with the Taipingling Spiral Line has been severely compromised by newly constructed road infrastructure. Meanwhile, the BMYR was dismantled after its central two spans were damaged in the 2023 flood, with the responsible authorities opting for immediate demolition rather than restoration (Figure 10). This discouraging outcome prompted the research team to update the contents of both archival and GIS databases.

Figure 10. Landscape destruction at BHLR-III due to road construction and dismantling of BMYR (Photographed in summer 2024).

3.3 Assessment and Classification of Heritage Conditions

Based on the availability and type of historical documentation, as well as the current preservation status of each infrastructure heritage site, three categories were established: (1) Well-preserved but lacking archival documentation; (2) Extensively documented but physically lost; and (3) Structurally altered but rich in historical records.

Accurate categorization plays a critical role across multiple stages of the workflow. It informs the enrichment of both the archival database (Database 1) and the GIS database (Database 2), while also shaping the modelling strategy and execution during Step 6: HBIM implementation.

For Category (1) sites, archival information must be developed based on field survey data, including the acquisition of spatial and geometric attributes. In Category (2), although historical documentation is available, the layered history of structural interventions introduces significant complexity to the HBIM process, both in terms of information richness and modelling difficulty. For Category (3), HBIM models are constructed entirely from archival sources and serve primarily as digital reconstructions for interpretation and communication.

3.4 Point Cloud Generation and Processing

The generation of point cloud data followed a Structure-from-Motion (SfM) and Multi-View Stereo (MVS) photogrammetric workflow (Granshaw, 2018), processed using Agisoft Metashape® (Version 2.2.0) (Agisoft LLC., 2024). The resulting dataset was exported in LAS format and subsequently refined in CloudCompare (Version 2.14.alpha) (CloudCompare, 2025), which included slicing, denoising, filtering, and elevation-based colour rendering (Figure 11).

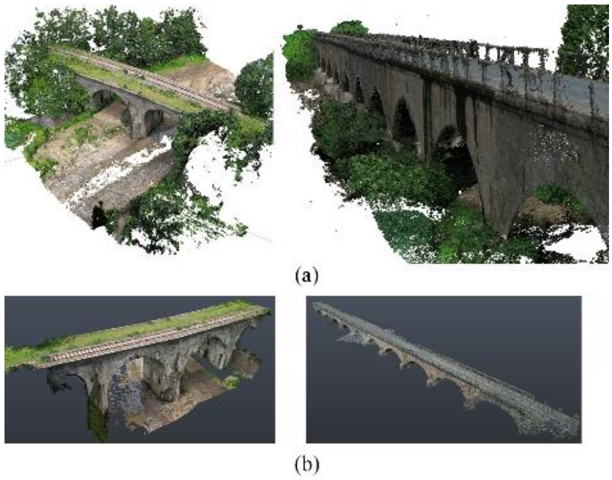


Figure 11. Raw point clouds (a) and processed point clouds for HBIM modelling (b) of the BHLR-III and BMLR.

To facilitate HBIM development, the refined point cloud was converted into a Revit®-compatible format using Autodesk® Recap® (Version 25.1.0.307) (Autodesk, Inc., 2024). In parallel, tiled 3D models were generated in Scene Layer Package (SLPK) format to enable efficient visualization and integration within ArcGIS® Pro (ESRI, 2024).

3.5 HBIM Implementation

Based on the LOD 300 standard (Autodesk, Inc., 2025), the HBIM modelling process in this phase employed two complementary approaches tailored to the specific conditions of the heritage cases studied: (1) Forward modelling was developed from historical documentation and applied to the construction phase of Category 2 heritage, which refers to sites that have been dismantled but are rich in historical records. It was also used for all phases of Category 3 heritage, which includes structurally complex sites with extensive documentation. (2) Reverse modelling was based on point cloud data and implemented for Category 1 heritage, which is well-preserved but lacks archival data, as well as for the current condition of Category 2.

Both modelling approaches were primarily conducted using Autodesk® Revit® (Autodesk, Inc., 2025b). The model was structured according to three main categories of bridge elements: superstructure, substructure, and abutments. Table 1 summarizes the subcategories and family types within each of these classifications. Phases were created to correspond with key historical periods experienced by each structure. Two standard phases were applied across all models: construction and existing (Table 2). For the structurally complex and well-preserved BMLR, two additional phases were included to document successive episodes of damage and repair based on historical records. In contrast, the minimally documented BHLR-III was modelled only in its existing condition, while the demolished BMYR was represented solely in its construction phase.

Category	Superstructure	Substructure	Abutment
Sub-category	Arch	Pier	Abutment Wall
	Deck	Cutwater	Arch on Abutment
	Handrail	Foundation	Foundation
	Spandrel Wall	Timber Cofferdam	Timber Cofferdam
	Capstone		
	Track		
	Track Bed		

Table 1. Families created according to bridge structural components.

BHLR-III	1	2024_Drone Surveying and Mapping
BMYR	1	1897-1903_Initial Construction Structures
BMLR	1	1897.03-1901.01_Initial Construction Structures
	2	1945_1st Damage & Repair Structures
	3	1965-1968.12.31_2nd Damage & Repair Structures
	4	1989_Additional Structures Following Functional Transformation
	5	2024_Drone Surveying and Mapping

Table 2. Defined phases for HBIM development of the three case studies.

The forward modelling process followed the original design drawings, with the two arch bridges modelled by creating families corresponding to the structural categories listed in Table 1. Different families were developed for each component, including both generic families applicable to Russian-engineered bridges and custom families tailored to the specific characteristics of each case (Figure 12). The bridges were then assembled according to the original plans to complete the historical reconstruction. Each element was assigned a corresponding *IFC4* classification and linked to its designated construction phase (Figure 13).

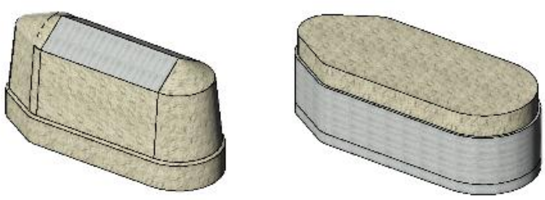
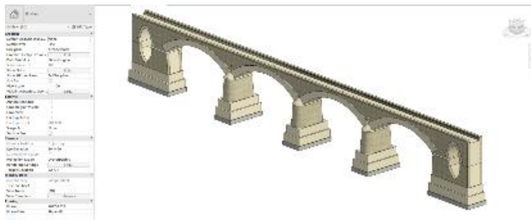
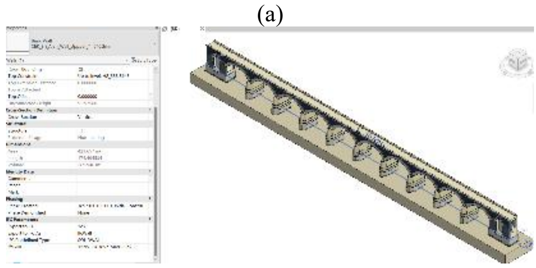


Figure 12. Pier and pier foundation with cutwaters developed for the BMLR.



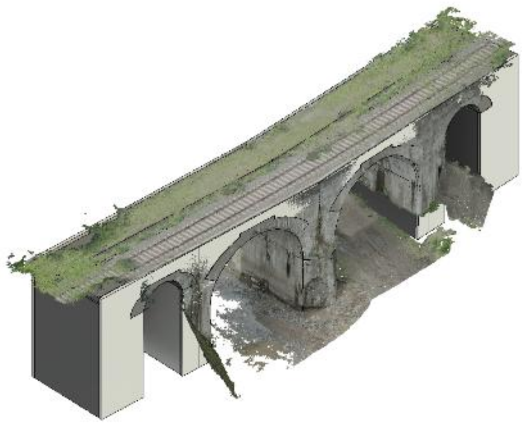
(a)



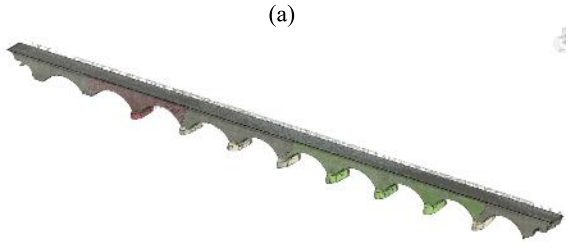
(b)

Figure 13. HBIM models of the two bridges: (a) BMYR and (b) BMLR.

In the reverse modelling process based on point cloud data, Autodesk® AutoCAD® was primarily employed to extract structural boundaries of heritage components corresponding to different historical periods. These extracted outlines, together with the RGB-enhanced point cloud (Figure 14), served as the foundational references for the HBIM reconstruction.



(a)

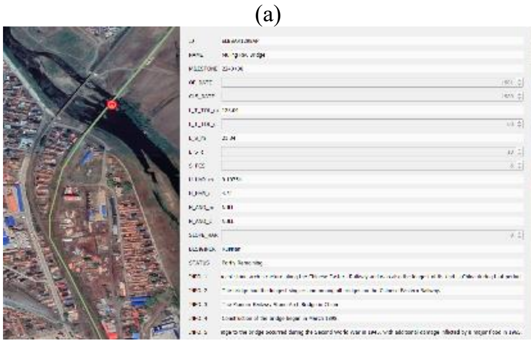


(b)

Figure 14. HBIM models representing the current condition of the heritage asset based on point cloud data: (a) BHLR-III and (b) BMLR.

Through the implementation of HBIM, key structural characteristics and changes in the heritage fabric were effectively identified and documented. For instance, BHLR-III exhibits an arc-shaped alignment in plan, with a calculated curvature radius of approximately 113.48 meters. The bridge deck presents a cross-sectional slope and measures approximately 8.5 meters in width. Vertically, the height from the riverbed to the upstream edge of the deck is 11.50 meters, while the downstream edge reaches 12.04 meters. The overall length of the bridge is approximately 48.06 meters on the upstream side and 48.72 meters on the downstream side. Similarly, a detailed comparison of the BMLR's original design drawings with field data collected in 2024 revealed a significant alteration: the deck now exhibits a longitudinal slope, descending approximately 2.02 meters from the Harbin-facing side to the opposite end. This corresponds to a gradient of approximately 1.16%, indicating deformation likely caused by long-term structural stress or environmental impacts. This contributed to the enhancement and refinement of the contents in both Database 1 and Database 2 (Figure 15).

(a)



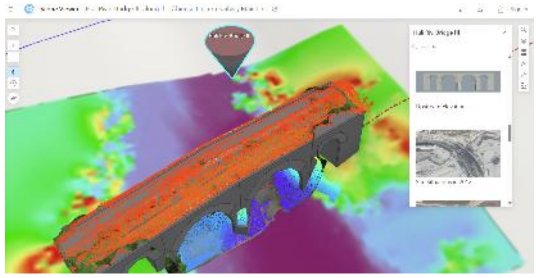
(b)

Figure 15. (a) BHLR-III and (b) BMLR with completed records in the GIS database.

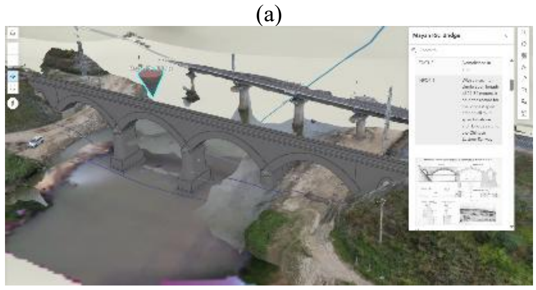
3.6 HBIM/GIS Integration and Remote Access

In ArcGIS® Pro, a global 3D scene was created for each case study, incorporating the corresponding GIS database, which included shapefiles of railways and bridges, as well as large-scale DSM (30 m resolution) data. Additional datasets generated in Step 5, including the digital elevation model (DEM), orthophoto, elevation-mode visualized point cloud data, and a Scene Layer Package (SLPK) model, were sequentially imported. The HBIM models, representing different historical phases and formatted in *IfcBuildingElement* schema, were then integrated into the scene.

The comprehensive scene was published online via the Web Scene functionality. In ArcGIS® Online, further refinement of the visualization was carried out through layer adjustments. Historical documents and site images stored in image format within the archival database were added using the Top-Up feature. Finally, by modifying access permissions for layers and associated files, a shareable short link was generated to facilitate public remote access and online viewing of the integrated results (Figure 16): https://arcg.is/qLGHC0 (BHLR-III), https://arcg.is/rv5T2 (BMYR), and https://arcg.is/1189jG0 (BMLR).



(a)



(b)

(c)

Figure 16. Integrated results accessible via remote access, arranged: (a) BHLR-III, (b) BMYR, and (c) BMLR.

The duration of accessibility to the HBIM/GIS integrated outcomes of the three bridges is determined by two primary factors. On the one hand, the data holders retain the autonomy to define the specific period for which the integrated outcomes remain accessible. On the other hand, the availability of these outcomes is constrained by the validity period of the software licenses procured by the researchers affiliated institutions.

The integrated outcomes are disseminated through a web-based platform, which can be accessed directly via standard web browsers. Within the platform interface, users may click the orange triangular markers located above each bridge (highlighted in blue in Figure 16) to retrieve key information, including design drawings, historical photographs, and satellite imagery. In addition, the layer manager positioned on the right-hand side enables the selection and visualization of multiple datasets, including HBIM models, SPLK , point cloud data, site DEM/DSM models, and orthophotos.

This mode of multi-source data integration and visualization not only provides the public with an intuitive and interactive means of exploring the bridges but also facilitates a multi-perspective understanding of their design evolution and historical transformations. Ultimately, such an approach contributes to strengthening public awareness of cultural heritage preservation and infrastructure management.

4. Conclusion and Future Work

This study proposed a structured HBIM–GIS integration workflow tailored to infrastructure heritage sites influenced by both their current physical conditions and the varying availability of historical documentation. The approach was validated through three case studies along the Chinese Eastern Railway main line. The workflow consists of three core components. First, archival-oriented databases for heritage and GIS were established to guide field surveys and documentation. These surveys, in turn, dynamically enriched the databases by capturing unrecorded information. Second, heritage sites were categorized based on their physical condition and archival completeness, which determined the most appropriate digital documentation strategies. These included HBIM models, point cloud datasets, Scene Layer Package (SLPK), DEMs, and orthophotos, all equipped with geospatial and semantic information. Third, the heritage archives, GIS databases, and digital records were integrated and published via the ArcGIS® platform to enable remote access and online interaction.

The main contributions of this research are twofold. On the one hand, the workflow introduces a systematic method that is adaptable to archival absence, physical loss, and complex structural transformations, thus extending the application of HBIM–GIS beyond traditional landmark heritage cases. On the other hand, through enabling remote access, interactive visualization, and multi-source integration, the study enhances public awareness of cultural heritage and provides a reproducible model for large-scale infrastructure heritage management.

Nevertheless, this research has certain limitations. The 3D visualization and web publication rely on commercial software platforms. Future work will focus on developing open-source alternatives based on QGIS and Arches to enhance accessibility.

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