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Value-based conservation of Zhaozhou Bridge: Inspiration from World Heritage Bridges

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Abstract: The Zhaozhou Bridge, built during the Sui dynasty (581–600) by Li Chun, is a masterpiece of world bridge engineering for its 37.02 m span, remarkably low rise-to-span ratio of 0.195, and two spandrel arches on each side. Although the bridge was included in the list of “potential World Heritage Bridges” in the ICOMOS 1997 document, its heritage values have not yet been systematically examined within the World Heritage framework. Against this background, this paper aims to improve the conservation of the Zhaozhou Bridge based on a value-based approach, which is widely used for the nomination, protection and management of World Heritage Sites. The paper analyses the heritage values of the Zhaozhou Bridge, identifying the value attributes and their expressed elements based on an understanding of the principal concepts in the World Heritage framework, and examines the bridge’s current conservation practices. Then, the paper proposes value-based conservation strategies, including establishing a long-term protection and management mechanism, digitally interpreting the bridge’s original structure, recovering its historical settings, and recognizing and protecting the Chinese open-spandrel stone arch bridges. These strategies could enhance the authenticity and integrity of the Zhaozhou Bridge’s value expression and promote a more comprehensive and sustainable approach to its conservation.

Keywords: historic bridge; Zhaozhou Bridge; World Heritage; heritage values; long-term protection and management; digitally interpreting

1 Introduction

Bridges are infrastructure constructed to facilitate communication and overcome physical obstacles. Beyond their practical function, bridges represent humanity’s continuous efforts to connect and communicate physically and symbolically. Owing to their outstanding historical, artistic, scientific, and intangible values, many historic bridges are recognized as having significant potential to be regarded as cultural heritage.

Zhaozhou Bridge (also known as Anji Bridge) is located on the Xiao River to the south of Zhao County, Hebei Province, China. Built during the Sui dynasty (581–600) by the bridge master Li Chun, the bridge is striking for its single span as long as 37.02 m, a remarkably low rise-to-span ratio of 0.195, and two spandrel arches on each side. Owing to these features, it was designated as the national Cultural Relics Protected Unit (CRPU) by the State Council of PRC in 1961, and was listed as one of the International Historic Civil Engineering Landmarks by the American Society of Civil Engineers in 1989, as the only Chinese constructions on the list. It was also included in the list of “potential World Heritage Bridges” in the 1997 ICOMOS document Context for World Heritage Bridges (WHB) [1]. Taken together, the Zhaozhou Bridge is a cultural property of outstanding universal significance with World Heritage potential, although it has not yet been listed.

Studies on the Zhaozhou Bridge have been carried out since

1930s, ranging from early field surveys [2–3] and historical textual research [4] to more recent interdisciplinary studies, including mechanical analysis [5], protection technology discussion [6–7]. However, little attention has been paid to a comprehensive analysis of the bridge’s heritage values and its condition of authenticity and integrity based on the World Heritage framework. Its heritage values have yet to be systematically examined, and its conservation needs have not been fully addressed at the World Heritage level.

Against this background, this paper aims to improve the conservation of the Zhaozhou Bridge based on a value-based approach. Such an approach is widely used in the World Heritage framework for the nomination, protection and management of World Heritage Sites [8–9]. Unlike material-based or structure-based approaches, which put emphasis on the protection of a cultural property’s physical fabric and structural form, the value-based approach begins with the analysis and identification of the property’s heritage value and its relevant attributes, and it aims to develop conservation strategies that protect the property’s values and strengthen the authenticity and integrity of their expression.

The paper examines the principal concepts of the World Heritage framework, including the notion of Outstanding Universal Value (OUV) and the requirements of authenticity and integrity. It discusses how these concepts should be understood and applied in the context of bridge heritage. On this basis, the paper analyses the

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historical, artistic, and scientific values of the Zhaozhou Bridge, identifies the attributes of these values and their expressed elements, and evaluates the impacts of the bridge's current conservation practices. Then, it develops appropriate conservation strategies for the Zhaozhou Bridge, aiming to improve the overall understanding of its heritage value, and enhance the authenticity and integrity expression, thereby promoting a more comprehensive and sustainable approach to its conservation.

2 Conservation of Zhaozhou Bridge: A Chinese bridge with World Heritage potential

2.1 Zhaozhou Bridge and its technical achievement

Zhaozhou Bridge is a single-span stone arch bridge, with a clear span of 37.02 m and a width of about 6.25 m. The arch has a clear

rise of 7.23 m, accounting a rise-to-span ratio of 0.195. There are four spandrel arches, with two on each side. The spandrel arch close to the arch springing has a span of 4 m, while the other one spans 2.72 m. The elevation of the bridge and a photo are shown in Fig. 1.

The arches of the Zhaozhou Bridge were formed with a series of separate but adjoining arch rings. Viewed from below (Fig. 2), the bridge consists of 28 parallel arch rings running longitudinally, each made up of 43 voussoirs. This arrangement allowed individual rings to be erected or repaired without disturbing the others. However, the lateral connections between adjacent rings are relatively weak. To improve the transverse integrity of the structure, the Zhaozhou Bridge employs iron hoops linking the rings together (Fig. 3) [2, 7].

The Zhaozhou Bridge, built in the seventh century, is a masterpiece of human creative genius for the following reasons:

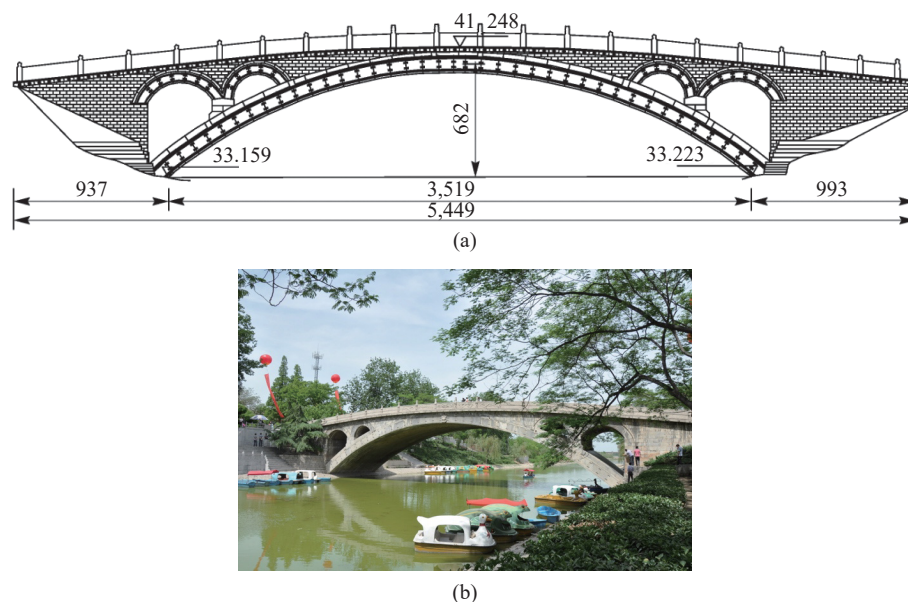


Fig. 1 Zhaozhou Bridge. (a) Elevation (Unit: cm) [10]; (b) Photo.

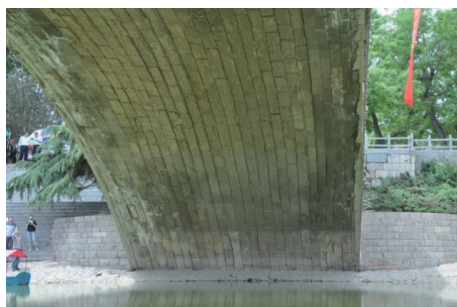


Fig. 2 Parallel stone arch rings of the Zhaozhou Bridge.

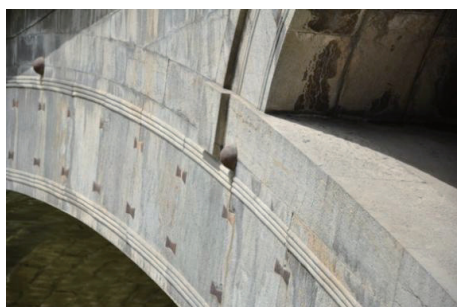


Fig. 3 Hoops of the Zhaozhou Bridge's arch.

(1) By employing a segmental arch, i.e., a shallow circular arc rather than a complete semicircle, the bridge broke with the traditional assumption that only semicircular arches could effectively transfer loads downward to the pier springings. This innovation resulted in a rise-to-span ratio of only 0.195 and an arch height of 7 m, producing a much gentler bridge deck slope. Such a design appeared earlier than comparable structures in the West by about 700 years, such as the Ponte Vecchio in Florence (c. 1339–1345), and demonstrated notable technical advantages over them [11]. Therefore, the Zhaozhou Bridge has been regarded as one of China's great scientific and technological inventions that exerted an influence on the Western world [12].

(2) The introduction of two pairs of spandrel arches not only reduces the self-weight of the superstructure (lightened 15.3%, about 500 t) but also facilitates flood discharge by permitting water to flow through the openings. This design did not appear in Western bridges until the 19th century [11].

(3) The bridge has a span of 37.4 m, which was the longest stone arch span in the world at that time. The span remained the longest span of arch bridges in China until the middle of the 20th century.

Zhao County, where the bridge located, is characterized by a warm-temperate semi-humid continental monsoon climate, with a mean annual temperature of 12.5 °C and annual precipitation of about 464 mm, much of it concentrated in summer, while local records indicate that the bridge withstood severe floods in 1963 and

1996. This context helps explain the significance of its low-rise arch and open-spandrel design in coping with hydrological pressures.

Inspired by the Zhaozhou Bridge, many similar bridges were constructed in subsequent centuries, most of them in northern China. Its construction technology may also have spread to other regions through cultural exchanges via merchants, travelers, and other approaches. As a masterpiece of early bridge engineering, the Zhaozhou Bridge occupies a significant position in the history of bridge development worldwide.

2.2 Historical restoration of the Zhaozhou Bridge

Throughout its history, the Zhaozhou Bridge underwent ten major repairs, mainly as targeted responses to specific structural problems such as the tilting of the spandrel arches and the detachment of arch stones [13]. The last restoration project carried out between 1952 to 1958 had the most significant impact on the bridge's present structure and appearance.

Before the Restoration Project (1952–1958), the Zhaozhou Bridge was severely deteriorated and at imminent risk of collapse [14]. As a result of long-term poor maintenance, wartime damage, and sustained use for vehicular traffic, the arch exhibited significant displacement, devious weathering and salt-induced deterioration.

According to field investigation, among the 28 arch rings (Fig. 2), the eastern three had long since collapsed, and the two adjacent ribs were cracked and outwardly inclined by over 20 cm, teetering on the verge of failure. The remaining 25 rings were slightly distorted, likely due to lateral shifts in opposite directions, and the four spandrel arches were severely weathered. The deck was uneven, and the parapet slabs were all non-original. The abutments on both banks were basically intact, and the foundations remained sound [15].

Moreover, the Guandi Temple at the southern end of the bridge was destroyed by warfare. Under the bridge, the Jiao River, which was a small tributary used for drainage and flood discharge, was dry at the time of the survey, exposing the silty riverbed, where many fallen bridge stones were found embedded in the mud.

Based on careful investigation and aimed to ensure the bridge's survival while preserving its ingenious design, the restoration focuses the straightening and replenishing of the arch rings. Thanks to the bridge's parallel arch-ring construction (Fig. 2), this intervention was confined to the affected rings and did not disturb the surviving Sui-dynasty fabric. In the restoration of the arch rings, the original stone materials were reused as much as possible, and the supplemented ones were come from the bluish-white limestone quarried with consistent as original materials.

Following common international practices at the time [16], which tended to prioritize visual integrity and structural safety, modern engineering materials and techniques were introduced in

the restoration project. High-strength cement mortar injection was used to reinforce deformed main arch rings. In addition, reinforced concrete slab was cast over the crowns of both the main arch to enhance transverse connections and improve overall structural stability [17]. To increase tensile resistance, this slab was connected to the original spandrel stones through a toothed interlocking system, in which each recess was filled with concrete containing embedded steel bars extending into the adjacent masonry. Moreover, a layer of linen fabric and asphalt waterproofing was also added to prevent rainwater infiltration.

To restore the lost and damaged balustrades, carved stone fragments were excavated from the mud in the riverbed and studied to reconstruct the original decorative patterns. On this basis, replacement balustrades were carved in accordance with the original designs, while the surviving fragments were preserved and are now exhibited in the local museum.

2.3 Environmental improvement and current condition

Since the establishment of China in 1949, the Zhaozhou Bridge has undergone continuous conservation. In 1955, a temporary wooden beam bridge and an approach road were built downstream beside the bridge. From then on, motor vehicle traffic was diverted away from the historic bridge, which has reserved for pedestrian use only. In 1986, the wooden beam bridge was replaced by a concrete arch bridge.

In 1984, a 2.47-ha park was set up around the Zhaozhou bridge. To protect the bridge from seasonal flooding, a new canal was constructed to divert the watercourse that originally flowed beneath it (Fig. 4).

In 1993, the park was further expanded to about 8.70 ha, extending to cover the space between the original river and the later canal. New elements, including a small exhibition hall for ancient bridges, a collection of inscription steles of the bridge, and modern sculptures representing the folk legends of the Zhaozhou Bridge, were added.

The collapsed Guandi Temple at the southern end of the bridge was later rebuilt in a different architectural style. In the southeastern part of the site, a pedestrian stone-beam covered bridge was built to provide visitors with a viewpoint to appreciate the Zhaozhou Bridge, and souvenir shops were set up nearby (Fig. 5).

In 2012, a sewage diversion project was undertaken in the water system to address the park environment. An underground sewage system was installed to carry wastewater, while a water-retention system and aquatic plants such as reeds, cattails, and lotus were introduced above it. As the result, the water system in the park maintains stable volume and beautiful waterscape during the whole year. Visitors can now also view the bridge's arch structure from boats, further enhancing its touristic presentation.

As a National 4A Tourist Attraction, the Zhaozhou Bridge park has long functioned as one of the main tourist attractions in the



Fig. 4 Spatial relationship among the Zhao County, Zhaozhou Bridge and the bridge park.



Fig. 5 A pedestrian stone-beam covered bridge as a viewpoint for the Zhaozhou Bridge.

Zhao County. It remained a ticketed scenic area until 2023, then it was opened to the public free of charge through a reservation system. Its main visitors are tourists.

3 Zhaozhou Bridge under the World Heritage Framework

3.1 World Heritage Framework and its key concepts

Though the Zhaozhou Bridge was included in the list of “potential World Heritage Bridges” in the International Council on Monuments and Sites (ICOMOS) 1997 document Context for World Heritage Bridges, it is not yet been listed as a World Heritage Site. To examine Zhaozhou Bridge within the World Heritage framework, it is first necessary to clarify the key concepts on which this framework is based.

The World Heritage system was established by United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1972 to protect cultural and natural heritage considered to be of outstanding significance to all humanity, and to ensure its transmission to future generations. Within this framework, three concepts are especially fundamental: Outstanding Universal Value (OUV), authenticity, and integrity.

OUV is the fundamental condition for inscription on the World Heritage List. It means that a World Heritage site should have priceless and irreplaceable value for humanity as a whole [18]. For cultural heritage, OUV is commonly understood from the aspects of historical, artistic or scientific significance. In recent years, these values are also recognized as being embodied in intangible dimensions, such as symbolic meanings, social functions, collective memory, and associated cultural practices [19].

According to the Operational Guidelines for the Implementation of the World Heritage Convention (OG in short), a property’s OUV should be assessed by the following six criteria:

- (i) Represent a masterpiece of human creative genius.
- (ii) Exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design.
- (iii) Bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared.
- (iv) Be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history.
- (v) Be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change.
- (vi) Be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance (this criterion should preferably be used in conjunction with other criteria).

Unlike the three types of significance, which describe the intrinsic value of a cultural property, the OUV criteria assess its relative value, that is, the extent to which it is rare or representative in comparison with other properties of the same type, period, region or cultural context.

Besides the assessment of OUV, a World Heritage property also need to meet the conditions of authenticity and integrity. Authenticity concerns the truthfulness and credibility of the attributes through which OUV is expressed. The text of authenticity is not the same in every case; rather, it should be determined according to cultural context and heritage type the property belongs to. This makes authenticity a complex issue.

Integrity, on the other hand, addresses the wholeness and completeness of the property and its ability to sustain the full range of attributes that express OUV. It therefore requires the inclusive protection of both the property itself and its immediate and wider setting, including its physical, visual, social, and spiritual dimensions.

As one could notice here, the concept of attribute is vital to understanding authenticity and integrity. According to the Resource Manual Preparing World Heritage Nominations [20], it means “aspects of a property which are associated with or express the OUV”. In the case of cultural heritage, attributes may include form and design, materials and substance, use and function, traditions, techniques and management systems, location and setting, language and other forms of intangible heritage, as well as spirit and feeling (Fig. 6). They are embodied in different tangible and intangible elements in accordance to the type of the cultural property and its cultural context. In conservation practice, it is these elements constituting the direct objects of conservation management and protection planning.

3.2 World Heritage Bridges and their OUV

In this paper, bridges inscribed on the UNESCO World Heritage List as the sole or dominant elements of their respective cultural properties are called World Heritage Bridges (WHB). At present, there are eight WHB as listed in Table 1.

Among the eight bridges, criteria (i), (ii), and (iv) are the most frequently applied. This pattern reflects the fact that bridges are commonly recognized for their structural and technical innovation, as well as for their role in the interchange of human values. By contrast, criteria (iii) and (v) are less often applicable to bridges as individual structures, while criterion (vi) is used only in specific cases where a bridge carries broader symbolic or historical significance.

It is noteworthy that, although the engineering and technological achievements of bridges as “masterpieces of human creative genius” are strongly emphasized in some authoritative documents [1], the analysis of the inscribed WHB demonstrates that their OUV is actually a composite value system. Except for the highly specific case of the Old Bridge of Mostar [21], the remaining seven bridges each satisfy at least two OUV criteria, with some cases meeting up to four criteria. In this composite system, engineering and technological achievements are intertwined with historical testimony, symbolic and social meanings, landscape integrity, and, in many cases, continued functional use. Therefore, the conservation practices of WHB must be conducted based on the understanding of the full view of the value structure.

Like other types of World Heritage properties, WHB must meet the conditions of authenticity and integrity. However, the attributes for understanding these two concepts should be determined based on the consideration of the characteristics of bridge heritage. Firstly, the attributes of “form and design” should not only mean the original form and design of historical bridges, but also its structural stability. Because the latter ensures the physical survival of the bridge, which is the fundamental condition for its OUV. Accordingly, in the conservation and management of many WHB, the use of modern materials and technologies may be allowed with two

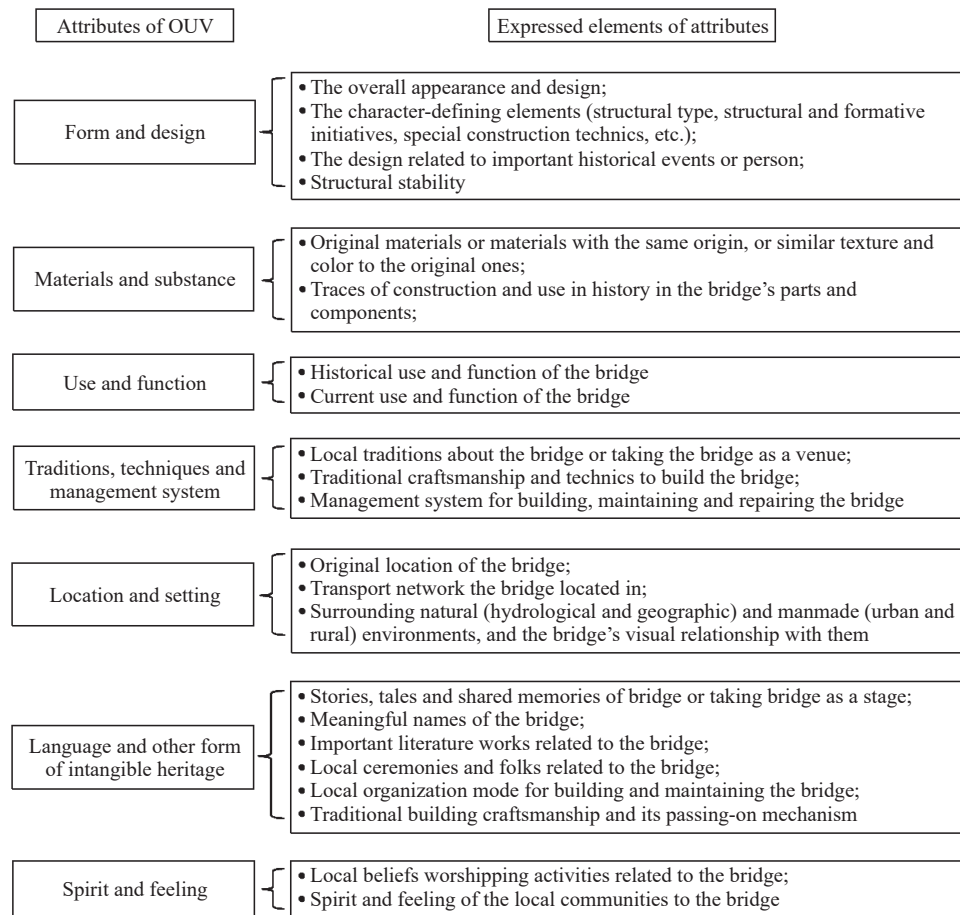


Fig. 6 Bridge Heritage's attributes of OUV and its expressed elements.

Table 1 List of the eight WHB.

Name of the Property and the Bridge	Country	Criteria of OUV for the inscription	Interpretation methods
Pont du Gard (Roman Aqueduct)	France	(i) A master piece of Roman technique and an outstanding artistic achievement; (iii) Unique witness to the Roman civilization; (iv) One of the most representative works of the construction processes of the Roman imperial era.	Structural conservation and restoration; landscape protection; fire/flood risk management; daily maintenance; landscape monitoring; visitor management
Vizcaya Bridge	Spain	(i) A surprising work combines beauty, aesthetics and functionality; (ii) The innovative nature from the technological point of view and its condition of pioneer in this kind of constructions.	Continuous structural maintenance in use; periodic engineering renewal faithful to authenticity; long-term operational management
Mehmed Pasa Sokolovic	Bosnia and Herzegovina	(ii) Located in a position of geostrategic importance, bears witness to important cultural exchanges between different regimes, religious groups and cultures; (iv) A remarkable architectural testimony to the apogee of the classical age of the Ottoman Empire.	Structural conservation and foundation repair; water-level and dam-impact monitoring; environmental management; tourism management
Pontcysyllte Aqueduct and Canal	UK	(i) A highly innovative monumental civil engineering structure, bears witness to the production capacities of the British ironmaking industry; (ii) Bears witness to technical interchanges and decisive progress in the design and construction of artificial waterways; (iv) Bears witness to a crucial stage in the development of heavy cargo transport.	Management-plan-based conservation; infrastructure maintenance; monitoring programme; visitor and setting management
Aqueduct of Padre Tembleque Hydraulic System	Mexico	(i) An architectural masterpiece; (ii) Exhibits an important interchange of European tradition, Arab-Andalusian know-how and Mesoamerican culture; (iv) An outstanding example of hydraulic water architecture at the time of Mesoamerican-European encounters.	Regular maintenance; annual monitoring; inter-institutional coordination; community-based management; risk and visitor management
The Forth Bridge	UK	(i) A masterpiece of creative genius for its distinctive industrial aesthetic; (iv) An extraordinary and impressive milestone in the evolution of bridge design and construction during the period when railways dominate long-distance land travel.	Statutory protection; property management plan; condition and maintenance indicators; stakeholder coordination; tourism/interpretation management
Ironbridge Gorge (Iron Bridge)	UK	(i) The first known metal bridge in the world, a masterpiece of man's creative genius; (ii) Exerted great influence on the development of techniques and architecture; (iv) Provides a fascinating example of the development of an industrial region in modern times.	Management-plan-based protection; planning control; regular review; stakeholder coordination; condition and archaeological surveys
Old Bridge Area of the Old City of Mostar (Stari Most)	Bosnia and Herzegovina	(vi) The "renaissance" of the Old Bridge and its surroundings provides a symbol of coexistence of communities from diverse cultural, ethnic and religious backgrounds.	Reconstruction using authentic materials and techniques; integrative rehabilitation of the historic core; management-plan-based protection; sustainable-use management

essential premises: first, the impact of their use on the bridge's key value elements (usually its genius form, design and structure) should be minimized and the material's compatibility and reversibility should be guaranteed. Secondly, the introduction of their use should markedly prolong the bridge's service life and enhances its structural reliability.

Two representative examples are the Mehmed Paša Sokolović Bridge and the Vizcaya Bridge. In the former case, a series of modern materials and technologies, including hydraulic mortar injection, laser scanning, and digital structural analysis, have been introduced and have contributed significantly to the bridge's long-term conservation [22]. In the latter case, the renewal of protective coatings in different colors is permitted for they can improve durability and extend service life to a considerable extent [23].

Moreover, given that bridges are typically situated in dynamic environmental settings, which usually means complex riverine and estuarine hydrological regimes, as well as moisture and pollutant-related atmospheric conditions, it is necessary to safeguard structural stability through long-term monitoring and continuous management of the bridge's structure and its components.

The attribute "use and function" involves the selection of the bridge's traffic mode. Unlike buildings, a bridge's original function is limited to pedestrian passage, vehicular traffic, aqueducts, and rail transport. In the context of bridge heritage, decisions regarding its adaptive use in modern times are generally made by assessing of the current traffic demand of the transport network to which the bridge belongs and the bridge's load-bearing capacity.

Based on this evaluation, a historic bridge may either continue to perform its original function or be functionally downgraded, such as conversion from vehicular use to pedestrian use. In the case of railway bridges or other linear-infrastructure bridges, where the continuity of the entire transport line must be ensured, historic bridges may need to be structurally strengthened using modern materials and technologies to meet operational requirements, or relocated to maintain the functionality of the route while safeguarding the heritage structure.

To conclude, structural stability, the management of surrounding environments, and the choice of traffic mode should be given special consideration in the conservation of bridge heritage.

3.3 Assessment of Zhaozhou Bridge in the World Heritage Framework

Based on the understanding of the World Heritage framework and the characteristics of WHB, the heritage values of Zhaozhou Bridge and its conditions of authenticity and integrity are assessed here.

In terms of heritage significance, Zhaozhou Bridge possesses important historical, artistic and scientific values:

- **Historical value:** Since ancient times, Zhao County has occupied a strategically important location, and the route crossing the Xiao River via the Zhaozhou Bridge long served as an official north–south thoroughfare. By connecting the routes on both sides of the river, the bridge facilitated regional economic exchange and political integration, which made it an important material testimony to regional development and governance. Moreover, the inscriptions and carved motifs on parts of the bridge stones record the bridge's construction and restoration activities in different period, which are not only valuable historical information for understanding socio-economic condition of ancient societies of different periods, but also offer evidence to important historical events such as wars, floods, and earthquakes [24].

- **Artistic value:** the segmental arch and the two pairs of spandrel arches with different spans create a dynamic arch form, resulting a sense of beauty arising naturally from the bridge's structural rationality. Moreover, the stone carvings on the handrails, columns, and other decorative elements are vivid in form and in composition, demonstrating the advanced skills and refined aesthetic sensibilities of Sui Dynasty stone carving.

- **Scientific value:** the segmental arch of Zhaozhou Bridge reduces the amount of masonry used and lowers the elevation of the approach road; the open-spandrel structure decreases the bridge self-weight while increasing its flood discharge capacity; the long span of the bridge made it possible to cross wide river with a single span, which facilitate shipping. Together, these features demonstrate the bridge's outstanding scientific value as an exceptional achievement in bridge engineering. Its structural innovations reflect an advanced understanding of mechanics, material efficiency, hydraulic adaptation, and construction techniques of ancient Chinese engineers, and mark a milestone in the history of bridge design and construction on a global scale.

Besides these intrinsic values, the Zhaozhou Bridge is also significant for its associative intangible heritage. Since 1961, the essay "Zhaozhou Bridge" written by the famous bridge expert Yisheng Mao has been incorporated into primary school textbooks, making the bridge a nationally familiar symbol of the creativity of the Chinese nation. Moreover, the Folk Narrative of the Zhaozhou Bridge, which is derived from relative legends widely known and shared in Zhao County in Hebei Province since the Tang Dynasty [25], was designated and protected as the Hebei Province's Intangible Cultural Heritage since 2013.

According to the classification of the attributes of value, the expressed heritage elements of the Zhaozhou Bridge is listed in Table 2, providing an operational basis for assessing its authenticity and integrity. It should be noted that not all value attributes carry equal weight in a particular heritage property. For the Zhaozhou bridge, a bridge heritage distinguished primarily by its technical achievement and by its great antiquity, the attributes of "form and design", "materials and substance", and "use and function" are of particular significance.

Generally speaking, the current condition of the Zhaozhou Bridge still demonstrates a considerable degree of authenticity in several key aspects. The Restoration Project (1952–1957) has effectively prevented further deterioration and possible collapse of the bridge, thereby ensuring its continued survival. The bridge's form and design have been particularly well preserved: its innovative structural form, overall proportions, and distinctive visual character remain clearly legible. In addition, efforts of improvement on its environment, safeguard and interpret traditional legends and related cultural associations have further reinforced the Zhaozhou Bridge's heritage value in the intangible aspects.

However, the authenticity of Zhaozhou Bridge is not fully satisfactory, and its integrity has likewise been affected by the cumulative loss of some value-expressed elements in the surrounding areas.

Firstly, the introduction of reinforced concrete and high-strength cement mortar altered the original structural system, in which parallel arch rings coexisted and were flexibly connected by iron dovetails. As a result, the original load transfer mechanism, which constitutes a key element of the bridge's historical and scientific value, was fundamentally modified. Consequently, the traditional building techniques associated with the bridge's intangible value have lost their material embodiment. The toothed interlocking system used to connect the reinforced concrete slab to the original stones harmed the latter's historical fabric and made the intervention irreversible. In addition, material incompatibility between the stone and cement mortar has led to persistent efflorescence, indicating long-term conservation challenges. Taken together, these factors directly affect the authenticity of the bridge's technological and structural attributes.

Moreover, beyond the structural interventions, the transformation of the surrounding hydrological and infrastructural environment, including the diversion of the original river channel and the conversion of the bridge into a park setting, has fundamentally altered its historical context and role in the transportation system. As a result, the authenticity and integrity of its historical value have been significantly reduced.

Table 2 Zhaozhou Bridge's value attributes, expressed elements and the condition of authenticity.

Attributes of values	Expressed elements of the attributes	Condition of authenticity
Form and design	The innovative structural form of segmental arch rings and spandrel arches, which save arch materials, decrease the elevation of the approach road, reduce the dead load, and improve the hydraulic performance.	Maintained
	The span of 37.4 m was the longest stone arch bridge in the world at that time, and the longest span arch bridges in China until the middle of the 20th century.	Maintained
	The remarkably coordinated compositional and proportional relationship among the different components is manifested both in its extraordinary dimensions and in its harmonious visual effect.	Maintained
	The original connection approach and load-bearing mechanism of the parallel stone arch rings	Mainly lost
Materials and substance	Reliefs and other decorative elements on the bridge	Partially lost
	Original stone and iron materials	Partially lost
	Original arch rings built in the Sui dynasty	Mainly maintained
	Traces of construction and workmanship and traces related to historical events or persons (donkey hoofprints, cart ruts, etc.)	Partially lost
Use and function	Transport function as a bridge	Maintained
Traditions, techniques and management systems	Original role as an important node in regional transport networks	Lost
	The bridge's delicate building techniques and management mode reflect the technical capacity and organizational capability of state-controlled handicraft production in Sui Dynasty.	Insufficient evidence
	Original site	Maintained
Location and setting	The bridge spanned the Xiao River and functioned as a crucial node on the principal route leading out of Zhao County, linking the major north–south transportation corridor.	Lost
	Surrounding natural settings, including hydrological features and geographic features (hills and vegetation);	Mainly lost
	The ancient Guandi Temple on the south end of the bridge.	Lost
Language and other forms of intangible heritage	Association with the folk narrative of the Zhaozhou Bridge, which is a provincial ICH in China	Maintained
	Reflection of the folk belief of “dragon” in traditional Chinese societies	Maintained
Spirit and feeling	A symbol of the creativity of Chinese nation.	Improved

In conclusion, although the Zhaozhou Bridge still retains outstanding heritage value and a considerable degree of authenticity in several important respects, the authenticity and integrity of some key value-expressed elements, particularly those related to its historical and scientific significance, have been substantially affected by the 1950s Restoration Project and the environmental transformations since the 1980s. These changes have weakened the material and contextual basis through which the bridge's outstanding values are expressed, and therefore pose challenges to its evaluation and potential nomination as an individual World Heritage property.

3.4 Bridges followed Zhaozhou Bridges and their current conditions

After Zhaozhou Bridges, many stone arch bridges with the segmental arches and spandrel arches have been constructed in China. These bridges are called as Zhaozhou-Bridge-Like (ZBL) bridge in this paper. Thirteen of them have been found in the historic literatures [13, 26], eleven in northern China and two in southern China (Fig. 7).

In addition, the Xiaoshang Bridge in Henan Province, dated to about eleven years earlier than the Zhaozhou Bridge, is a stone arch bridge with a segmental arch and two approach arches partially entering into the main arch, and is generally regarded as an early ex-

ploratory example of a similar stone arch bridge. From this perspective, the Xiaoshang Bridge, the Zhaozhou Bridge, and the other thirteen ZBL bridges together testify to a developmental trajectory, from early exploration to maturity, dissemination, and subsequent evolution. The basic information for all fifteen bridges is listed in Table 3.

Of the fifteen bridges, eight were constructed before the Ponte Vecchio (c. 1339–1345) and two others date to roughly the same period. This chronology demonstrates that the open-spandrel stone arch bridges had already reached a remarkably early and mature development in China, long before comparable examples appeared in the West.

With the Zhaozhou Bridge as the central reference, one bridge is located in the same county, three lie within approximately 100 km, and the rest are distributed mainly in northern China, with one additional example in southern China. The spatio-temporal distribution of these ZBL bridges further underscores the far-reaching influence of the Zhaozhou Bridge.

Meanwhile, the bridges' construction dates range from the 6th to the 19th century. Although most of these bridges were smaller in scale than Zhaozhou Bridge, they collectively testify to the far-reaching, long-lasting dissemination of its technology and regional

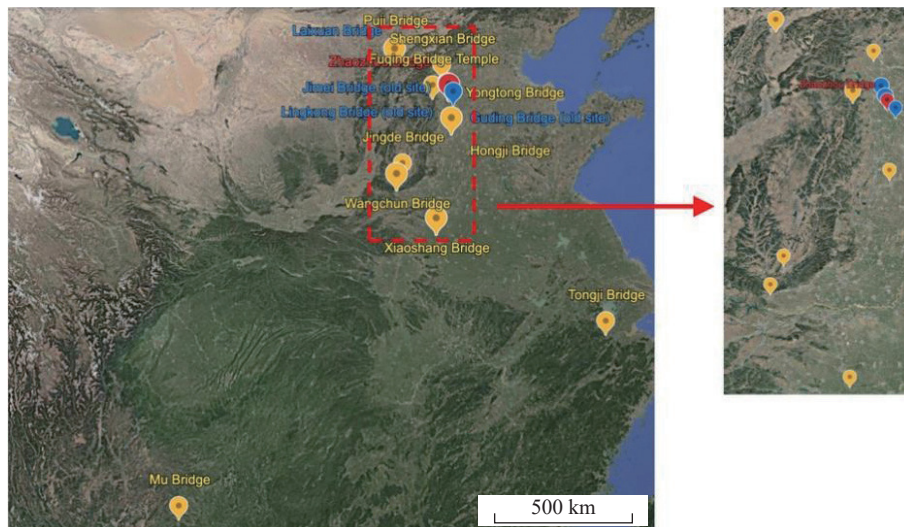


Fig. 7 A map of the fifteen Chinese open-spandrel bridges (Red: Zhaozhou Bridge; Yellow: existing bridges; Blue: disappeared bridges).

Table 3 List of fifteen similar bridges.

No.	Name	Location	Construction year	Current condition
1	Zhaozhou Bridge	Zhao County, Hebei Province	595-605	Preserved
2	Yongtong Bridge	Zhao County, Hebei Province	765	Preserved
3	Jimei Bridge (old site)	Zhao County, Hebei Province	1 549	Destroyed
4	Hongji Bridge	Handan City, Hebei Province	N/A (rebuilt in 1 582)	Preserved
5	Jingde Bridge	Jincheng City, Shanxi Province	1 189	Preserved
6	Puji Bridge	Yuanping City, Shanxi Province	1 203	Preserved
7	Lingkong Bridge (old site)	Luancheng City, Hebei Province	1 205	Destroyed
8	Guding Bridge (old site)	Ningjing County, Hebei Province	1 360	Buried
9	Shengxian Bridge	Xingtang County, Hebei Province	742	Buried
10	Fuqing Bridge Temple	Jingxing County, Hebei Province	N/A	Preserved
11	Wangchun Bridge	Jiyuan City, Henan Province	N/A	Preserved
12	Xiaoshang Bridge	Leihe City, Henan Province	584	Preserved
13	Laixuan Bridge	Chunyang County, Shanxi Province	1 203	Destroyed, rebuilt in a different style
14	Tongji Bridge	Hangzhou City, Zhejiang Province	1 368	Preserved
15	Mu Bridge	Xingyi County, Guizhou Province	1853	Preserved

influence across China.

Most of these bridges were built across rivers to connect important historic transport and trade routes. The open-spandrel design responded effectively to practical challenges posed by seasonally rapid currents and soft alluvial riverbeds, while also reducing the quantity of stone required. Meanwhile, the parallel arch-ring masonry method made it possible for construction to be interrupted and resumed during frequent flood seasons without harm the integrity of the entire bridge. Together, these features demonstrate a profound understanding of the natural environment and an exceptional human capacity to respond to complex engineering problems with ingenuity and efficiency. For this reason, the Zhaozhou Bridge and the broader group of Chinese open-spandrel bridges can be understood not merely as regional technical achievements, but as an outstanding testimony to a significant stage in the global history of civil engineering.

3.5 Case studies of three ZBL bridges

In all the fifteen bridges, three have disappeared, twelve still survive, with two buried under modern roads. The case studies of three existing bridges, based on a preliminary survey, are presented here to better understand the general state of their heritage value, their connections to the Zhaozhou Bridge, and their current preservation conditions.

3.5.1 Xiaoshang Bridge

Xiaoshang Bridge over the Xiaoshang River is located in Linying County, Henan Province (Fig. 8). According to existing studies, it was originally built in 584 during the Sui dynasty, approximately eleven years earlier than the Zhaozhou Bridge.



Fig. 8 Xiaoshang Bridge.

The bridge has a total length of 21.3 m and a width of 6.45 m. Its main arch is a segmental arch with a clear span of 12.14 m and a rise of 3.06 m, resulting in a rise-to-span ratio of 1:4. At each end of the main arch, there is two small arches: one with a span of 2.85 m and a rise of 0.78 m, and the other with a span of 2.78 m and a rise of 0.87 m [27]. As shown in Fig. 9, one springing of each small arch

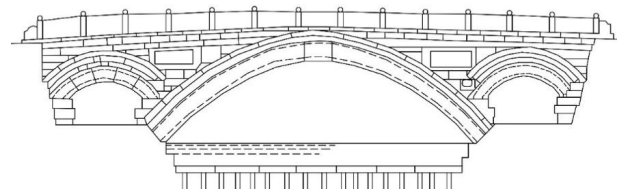


Fig. 9 Schematic elevation of Xiaoshang Bridge.

is supported on the main arch. Both the main arch and the small arches are constructed from 20 parallel arch rings connected by iron hoops.

Xiaoshang Bridge has undergone multiple restoration throughout history. The original structure is mainly remained, while the bridge deck and the carvings on the bridge largely date from repairs carried out in different dynasties. The bridge witnesses the growth of transportation and the economy in the Central Plains in China during the sixth to tenth centuries, which gives it important historical significance. More importantly, it reflects an early phase in the emergence of the open-spandrel bridge in China and constitutes an indispensable part in the evolutionary sequence of this bridge type.

In 1982, Xiaoshang Bridge was rediscovered by bridge specialists and identified as a structure dating to the Sui dynasty. In 1986, it was designated as a provincial CRPU and then a national one in 2001. In 1992, a scenic area was established around the bridge. A major restoration project was conducted in 1994, which preserved the main historic features of the bridge, including its structural design, the red quartz sandstone used in its construction, and the inscriptions on the balustrades recording donations for bridge repairs in different historical periods [28].

3.5.2 Yongtong Bridge

Yongtong Bridge is located in the northern part of Zhao County, crossing the Jiao River approximately 2.5 km upstream of the Zhaozhou Bridge (Fig. 10). It is a typical ZBL, originally built in the Tang dynasty (around 765), approximately 160 years later than Zhaozhou Bridge.

The bridge has a clear span of 23.48 m and a clear rise of 4.64 m, with its main arch constructed from 20 parallel arch rings. Because its span is much smaller than that of the Zhaozhou Bridge, it is known as the “Small Stone Bridge”, in contrast to Zhaozhou Bridge, which is also known as the “Big Stone Bridge”. Together, these two bridges served as key nodes in the historic transportation network of the area.

Compared with the Zhaozhou Bridge, the Yongtong Bridge has a larger open-area ratio in its spandrel, owing to the relatively greater spans of its spandrel arches: 3.08 m and 2.78 m for the larger ones at the east and west ends, respectively, and 1.77 m and 1.71 m for the smaller ones. Meanwhile, its deck slope is gentler, at approximately 3 %, making it better suited to ox- or horse-drawn carts. This was achieved by setting the crown of the spandrel



Fig. 10 Yongtong Bridge.

arches at nearly the same elevation as that of the main arch [15].

The bridge was designated as the national CRPU in 1961. In 1986, a restoration project was carried out to improve its poor condition. This intervention adopted an approach similar to that used for Zhaozhou Bridge but almost reconstructed: the original bridge was wholly dismantled firstly; all stones were checked and the severe deteriorated ones were replaced with new; then, the structure was reassembled. In the restoration, original stone materials were reused in the visible parts of the bridge, and the stone carvings on the bridge were retained in order to preserve its historic appearance. Some modern materials and techniques were introduced, including the use of cement mortar, reinforced concrete beams, and the rubber waterproof layer.

In 2009, a park was developed centering the Yongtong Bridge, and barriers were installed to prohibit motor vehicle traffic. It is a free park for both local communities and tourists. However, because the river course has not yet been effectively treated, the environmental setting remains unsatisfactory.

3.5.3 Shengxian Bridge

Shengxian Bridge is located in Xingtang County, Hebei Province, about 80 km from the Zhaozhou Bridge. It was originally built in 742 during the Tang dynasty, about 200 years later than the latter. As a ZBL bridge, it demonstrates the strong and longlasting influence of the Zhaozhou Bridge in ancient China.

Shengxian Bridge was repaired in 1090 during the Song dynasty, and was structurally reinforced in 1955. In 1984, when the moat was filled in and transformed into Shengxian Bridge Road as part of urban planning works, both ends of the bridge were buried, the openings on the arch spandrel were covered over, and the balustrades on the north side were damaged during the construction of the road revetment. Today, the bridge is largely buried beneath the road surface, with only parts of the structure still visible (Fig. 11).

Since being buried, Shengxian Bridge has continued to deteriorate under the combined effects of vehicular traffic pressure from above, underground sewage infiltration and natural weathering. Its masonry has gradually decayed and flaked away, placing the bridge in an increasingly dangerous condition. Although designated as a provincial CRPU in 1993, it did not receive corresponding restoration and protection.

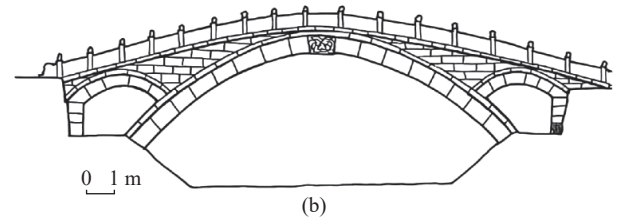
Taken together, the investigation of these bridges demonstrates the outstanding heritage value of Chinese ZBL bridges as a cohesive ensemble and the possibility to protect them as a whole. At the same time, it also reveals their vulnerable state of preservation and the need for a more systematic and comprehensive approach to their protection and management.

4 Value-based conservation strategies for the Zhaozhou Bridge

Based on the above analysis, four strategies are proposed for the value-based conservation of Zhaozhou Bridge.



(a)



(b)

Fig. 11 Shengxian Bridge under modern roads;

(a) Photo; (b) Imaged elevation [29].

4.1 Establishing a long-term protection and management mechanism for the Zhaozhou Bridge

Although the Zhaozhou Bridge does not currently face an urgent safety threat, its structural reliability has decreased. Field investigations indicate varying degrees of stone weathering and cracking across different parts of the bridge. In addition, corrosion has been observed in some of the iron dovetails, and large-scale efflorescence has developed at the crown of the main arch. These conditions remain a long-term concern. Therefore, a comprehensive risk management system is essential for its sustainable preservation. Such a system should prioritize maintaining the bridge's overall form, structural safety and durability through continuous monitoring and targeted mitigation of material deterioration.

It should also incorporate a climate change-adaptive perspective, taking into account the potential intensification of hydrological and environmental risks, including flood events, riverbed scour, and the possible acceleration of stone decay due to changes in moisture and atmospheric chemistry under extreme weather conditions [30].

Modern technologies adopted in the conservation of many WHB [31–32], including Structural Health Monitoring (SHM) measures, Bridge Maintenance Design and HBIM Implementation Plan, as well as the advanced non-invasive sensor and digital tools, should be integrated into the long-term management strategy of the Zhaozhou Bridge. These technologies can support continuous structural assessment, deterioration diagnosis, and comprehensive condition evaluation within a preventive conservation framework. In particular, the long-term SHM framework should include early-warning indicators for riverbed scour and for environmental changes, such as fluctuations in atmospheric acidity and moisture, that may accelerate stone deterioration.

4.2 Digital reconstruction and interpretation of original structure and construction technologies

Although many original fabrics and construction details of the Zhaozhou Bridge were altered during the 1950s restoration, both the original structural system and restoration details in the subsequent periods can be digitally constructed and represented through contemporary technologies. This would provide more credible information sources for understanding the bridge and help strengthen the authenticity of its value expression. For example, high-precision 3D laser scanning, structural modeling, and simulation may be employed to reconstruct the bridge's original load-transfer mechanism and to demonstrate the structural efficiency

and ingenuity of the open-spandrel segmental arch system.

Virtual Reality/Augmented Reality (VR/AR)-based interpretation and digital exhibitions can further enhance public understanding of the bridge's traditional construction knowledge and engineering logic. In this way, they strengthen the informational foundation for assessing the bridge's authenticity.

Moreover, digital technologies can be used to present the overall picture of ZBL bridges, enhancing public recognition of this bridge type as a coherent heritage group and of all cultural properties it involved.

4.3 Recovering the historical settings of the Zhaozhou bridge

Today, the Zhaozhou bridge is largely managed within a scenic-site framework, which tends to emphasize visual appreciation and tourism functions. However, as a major historic bridge, Zhaozhou Bridge should be understood and managed primarily as a publicly accessible heritage place.

From this perspective, conservation should extend beyond the bridge itself to the wider spatial and environmental context through which its values are expressed. Around the bridge, pedestrian pathways and related circulation spaces could be introduced or reorganized to recover its historical role as a traffic node for pedestrian.

In addition, a museum could be established near the bridge, exhibiting the outcomes of digital reconstruction and interpretation as mentioned in Section 4.2. In this way, the bridge's surroundings would no longer be treated merely as part of a tourist setting, but as an important part of interpreting its heritage values.

4.4 Extending the conservation for the single Zhaozhou Bridge to group ZBL bridges

As discussed in Section 3.4, the heritage significance of Zhaozhou Bridge lies not only in the monument itself, but also in its role as a technological prototype for ZBL bridges featuring open-spandrels and segmental arches in China and, more broadly, in the history of bridge engineering worldwide.

The thirteen Chinese ZBL bridges, together with Xiaoshang Bridge, present a relatively complete trajectory of the development of Chinese open-spandrel stone arch bridges and testify to the far-reaching and long-lasting influence of the Zhaozhou Bridge. In this sense, the Zhaozhou Bridge, the Xiaoshang Bridge and the related ZBL bridges together constitute an outstanding achievement of human creative genius, significantly extending the known history of the stone arch in world bridge construction.

Therefore, the research and conversation of the Zhaozhou Bridge should be extended to all the existing ZBL bridges. All these bridges with similar heritage values should be considered as a group. At present, only preliminary research has done on these bridges. Further investigation is required to identify more related examples and to gain a deepened understanding of their history, spatial distribution, structural characteristics, and current state of conservation. This would make it possible to develop more clearly trajectory of open-spandrel arches and their construction technologies in China, thereby providing a solid background for the interpretation of the Zhaozhou Bridge. Furthermore, the comprehensive interpretation and protection of the Zhaozhou Bridge and the bridges influenced by its structural model in the name of "Chinese open-spandrel bridges" will strengthen its historical and scientific significance within a broader technological and regional framework, and enhance the recognition of the outstanding values of this bridge type at a universal level.

The involvement of both government-based and/or non-governmental organizations (NGOs), together with all relevant stakeholders of the fifteen bridges mentioned above, is recommended. Further researches should be undertaken, and conversation strategies should be studied based on the common heritage values of the group and the specific situations of each bridge.

5 Conclusions

This paper analyzed the Zhaozhou Bridge's heritage value, its attributes and the expressed elements based on the World Heritage framework. It evaluated the authenticity and integrity condition of the Zhaozhou Bridge and identified the imbalance between the outstanding significance of the heritage value and the dissatisfied condition of authenticity and integrity. Such a condition was mainly due to the loss of some expressed elements of the attributes of its heritage values in the 1952-1958 restoration project and later transformations of its surrounding environments. Relatively, the Zhaozhou Bridge's artistic and intangible value are better maintained through continued representation and interpretation.

To strengthen the overall expression of the bridge's heritage values and improve its conservation conditions, the paper proposed several strategies according to the value-based conservation approach. These strategies include: the establishment of a long-term risk management mechanism based on routine monitoring and preventive maintenance; employment of digital reconstruction and interpretation to represent the bridge's original structure and building technologies; and the recovery of the bridge's historical settings; and the extension of recognition and protection of the Zhaozhou Bridge to the broader group of "Chinese open-spandrel bridges".

Taken together, the study of the Zhaozhou Bridge in this paper suggests that the conservation of historic bridges should not focus only on the survival of the structure itself, but also on the continued expression of the multiple values that make such bridges heritage. It may serve as a practical reference for the conservation and management of other bridge heritage sites.

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Author contribution statement

Shujie Chen: Conceptualization of the study, acquisition of funding, provision of resources, drafting of the original manuscript, development of the research methodology, data collection and organization. Valentina Pintus: Participation in manuscript preparation, data organization and analysis, and assistance with the research process, English language editing of the manuscript. Cong Li: Participation in manuscript preparation, data organization and analysis, and assistance with the research process.

Data availability statement

Data will be made available on request.

Use of AI statement

During the preparation of this manuscript, the authors used Grammarly to enhance the grammar and readability of the text. The authors carefully reviewed and edited the content afterward and assume full responsibility for the final manuscript.

References

- [1] DeLony E. Context for World Heritage Bridges. Paris: ICOMOS & TICCIH, 1997.
- [2] Liang SC. Open spandrel bridges of ancient China-I: The An-chi Ch'iao at Chao Chou, Hopei. *Pencil Points*, 1938, 19: 25–32.
- [3] Hu DH, Xia SL. An investigation report on the abutment foundation and subgrade of the Anji Bridge. *Municipal Engineering Technology*, 1997(3): 11–16.
- [4] Li ST. Textual research on the construction date of Zhaozhou Bridge. *Journal of Hebei Normal University (Philosophy and Social Sciences Edition)*, 2002(1): 87.
- [5] Qian LX. Analysis of Load-Bearing capacity of Zhaozhou Bridge. *China Civil Engineering Journal*, 1987(4): 39–48.
- [6] Wang B, Wang J. Analysis on the Diseases of the Status of Zhaozhou Bridge. *Journal of Beijing University of Civil Engineering and Architecture*, 2015, 31(4): 40–44.
- [7] Jiao CY, Yang LQ, Li LN. Review of domestic and foreign research on Zhaozhou Bridge. *Studies on Ancient Chinese Bridge* 2024 (7).
- [8] Jokilehto J. What is OUV? Defining the outstanding universal value of cultural world heritage properties. *Monuments and Sites XVI*. Berlin: ICOMOS, 2008.
- [9] Avrami E, Macdonald S, Mason R, et al. (Eds.) *Values in heritage management: Emerging approaches and research directions*. Los Angeles: Getty Conservation Institute, 2019.
- [10] Weng W. Analysis of bridge construction technology and characteristics based on the results of Zhaozhou bridge investigations. Beijing: Beijing University of Civil Engineering and Architecture, 2016.
- [11] Knapp RG. *Chinese Bridges: living architecture from China's past*. Rutland: Tuttle Publishing, 2008.
- [12] Needham J, Ling W, Robinson KG. *Science and civilisation in China, Vol. 4: Physics and the physical technology, Part 1: Physics*. Cambridge: Cambridge University Press, 1962: 33.
- [13] Mao YS. Bridges among the national cultural relics protected units: Luding Bridge, Lugou Bridge, Anping Bridge, Anji Bridge and Yongtong Bridge. *Cultural Relics*, 1963(9): 33–47, 69–70.
- [14] Gao XN. Zhaozhou Bridge restoration project (1952-1957)-I. *Yanzhao Life*, 2020(8): 27–29.
- [15] Mao YS. *Technique history of ancient bridges in China*. Beijing: Beijing Press, 1986.
- [16] Genovese RA. The Congress of Athens of 1931: methodological and technical contributions for the conservation of architectural and environmental heritage. *Protection of Cultural Heritage*, 2021(12): 113–121.
- [17] Gao XN. Zhaozhou Bridge restoration project (1952-1957)-II. *Yanzhao Life*, 2020(9): 22–25.
- [18] UNESCO. *Operational guidelines for the implementation of the World Heritage Convention*. Paris: UNESCO, 2025.
- [19] Munjeri D. Tangible and intangible heritage: From difference to convergence. *Museum International*, 2004, 56(1-2): 12–20.
- [20] UNESCO, ICCROM, ICOMOS, IUCN. *Preparing World Heritage Nominations*, 2nd ed. Paris: UNESCO, 2011.
- [21] Chen SJ, Candeias A, Chen BC, et al. Conservation measures of Min-Zhe wooden arch bridges based on authenticity principle of World Heritage Bridges. *World Bridges*, 2025, 53(1): 108–115.
- [22] Vujović V. Case study-The Mehmed Pasha Sokolovic Bridge. *Procedia Structural Integrity*, 2018(13): 489–495.
- [23] UNESCO World Heritage Center. *Periodic Report-Section II-Vizcaya Bridge*. Paris: UNESCO, 2014.
- [24] Wu JB. My Views on the stele inscription Zhaozhou Dashiqiao Ming. *Wenwu Chunqiu*, 2006(1): 55–56, 58.
- [25] Qu SN. A brief analysis of the folkloric and cultural connotations of the legends of Zhaozhou Bridge. *Qinghai Social Sciences*, 2012(3): 190–194.
- [26] Tang HC. *Chinese ancient bridges*. Beijing: Cultural Relics Publishing, 1957: 44–55.
- [27] Niu N, Wang GQ. An investigation report on Xiaoshang bridge in Linying, Henan. *Wenwu*, 1997(1): 65–72.
- [28] Guo F, Ma QW, Pei SY. Analysis of the current situation of ancient bridges in Henan and study on conservation strategies. *Proceedings of the 2025 International Ancient Bridge Symposium and the 11th Annual Meeting of the Ancient Bridge Research and Protection Committee*. Quanzhou, 2025: 173–183.
- [29] Tang HC, Tang H. *History of Chinese Bridge Technology, Vol. 1: Ancient Times*. Beijing: Beijing Jiaotong University Press, 2017.
- [30] ICOMOS Climate change and cultural heritage working group. *The future of our pasts: engaging cultural heritage in climate action*. Paris: ICOMOS, 2019.
- [31] Zhang F, Deng JC, Zhang KQ, et al. Research progress in the planning and conservation of bridge cultural heritage in 2020. *Journal of Civil and Environmental Engineering*, 2021, 43(S1): 252–260.
- [32] Cruz A, Coffey V, Chan TH, et al. Engineering in heritage conservation. *Journal of Cultural Heritage Management and Sustainable Development*, 2022, 12(4): 426–443.