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Engineering Archives and Preventive Conservation of a Leaning Masonry Pagoda: Evidence from the Yunyan Temple Pagoda in Suzhou, China

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Abstract

Engineering archives generated during heritage conservation projects contain valuable evidence on deterioration, intervention processes, and subsequent maintenance needs, yet such records are often retained as fragmented project documentation rather than organized for long-term preventive conservation. This study investigates the long-term leaning Yunyan Temple Pagoda in Suzhou, China, using completion reports, as-built drawings, construction records, site photographs, digital documentation, and available monitoring information. Archival evidence was systematically extracted, coded, and cross-validated to reconstruct three major conservation campaigns, classify five interacting deterioration categories, and map the 2015 interventions to corresponding conservation objectives and follow-up indicators. The results show that moisture-related conditions were closely associated with surface weathering, freeze–thaw-related deterioration, biological colonisation, and corrosion of earlier steel reinforcement. Previous stabilization components were also found to become part of the later deterioration system, demonstrating the need for lifecycle reassessment of conservation interventions. Based on these findings, a closed-loop diagnosis–intervention–monitoring framework was developed to connect historical records, intervention locations, material information, and subsequent verification needs. The proposed approach provides a structured and traceable basis for using engineering archives to support preventive maintenance and conservation decision-making in historic masonry structures with repeated intervention histories.

Keywords: architectural heritage; masonry pagoda; engineering archives; deterioration diagnosis; preventive conservation

1. Introduction

Historic masonry pagodas present distinctive conservation challenges because their considerable height, complex masonry configuration, prolonged environmental exposure, and accumulated deformation can generate interacting structural and material risks[1,2]. Their long-term management therefore extends beyond isolated repair and may involve global inclination, foundation behaviour, local masonry deterioration, moisture ingress, biological colonisation, ageing of previous reinforcement, and difficult high-altitude access. Effective conservation consequently requires continuity among diagnosis, intervention, documentation, monitoring, and subsequent maintenance rather than a sequence of disconnected repair events[3,4].

The Yunyan Temple Pagoda in Suzhou, commonly known as the Tiger Hill Pagoda, provides a representative case of a long-term leaning masonry heritage structure that has undergone repeated conservation interventions. Constructed between the late Five Dynasties period and the early Northern Song Dynasty, the seven-storey octagonal pagoda has experienced prolonged weathering, historical fire-related loss, differential deformation, and several major conservation campaigns. Its documented condition combines global inclination with local masonry weathering, water ingress, freeze-thaw-related deterioration, deformation of arched openings, biological growth, and corrosion of earlier steel reinforcement[5]. At the same time, the pagoda preserves a multi-stage intervention history extending from emergency stabilization and foundation treatment to localized maintenance and preventive monitoring.

Built-heritage conservation has increasingly shifted from emergency repair and one-time restoration toward condition-based and preventive approaches. Terrestrial laser scanning, photogrammetry, three-dimensional modelling, heritage information systems, and sensor-based monitoring can provide geometric baselines, spatially referenced condition records, and repeated observations over time[6,7]. When combined with field diagnosis and intervention records, these technologies can support the localization of deterioration, documentation of repairs, comparison of subsequent changes, and long-term maintenance planning. In practice, however, digital models, construction archives, and monitoring information are often generated at different stages of a conservation project and remain only partially connected[8,9].

A related limitation concerns the treatment of engineering archives themselves. Completion reports, as-built drawings, construction photographs, intervention records, and maintenance documentation are commonly retained as evidence of completed work, yet they also contain information on deterioration conditions, intervention locations, materials, construction procedures, and requirements for later verification[10,11].

73 Previous research has extensively addressed structural assessment, material deterioration,
74 individual repair techniques, digital documentation, and monitoring of historic structures,
75 but less attention has been given to reorganizing heterogeneous project records into a
76 traceable evidence chain linking diagnosed deterioration, intervention decisions, and
77 subsequent monitoring priorities[12,13] .

78 This problem becomes particularly important in heritage structures that have undergone
79 repeated conservation campaigns. Their present condition reflects not only the ageing of
80 the original fabric but also the long-term performance of materials and reinforcement
81 introduced during earlier interventions[14,15] . Previous conservation measures may
82 remain structurally important while simultaneously developing new deterioration
83 risks[16,17] . In the Yunyan Temple Pagoda, corrosion of earlier steel reinforcement, for
84 example, became associated with cracking and separation of adjacent masonry,
85 demonstrating that previous interventions can themselves become part of the later
86 deterioration system. Conservation assessment must therefore consider the temporal
87 relationship among original fabric, previous intervention, present condition, and future
88 monitoring.

89 This study therefore asks whether heterogeneous engineering records generated across
90 successive conservation campaigns can be systematically reorganized into a traceable
91 evidence chain linking deterioration mechanisms, intervention decisions, and subsequent
92 monitoring priorities. The Yunyan Temple Pagoda is used as a case study to address this
93 question through completion reports, as-built drawings, construction records, site
94 photographs, digital documentation, and available monitoring information. The study
95 aims to: (1) reconstruct the changing objectives of the major conservation campaigns; (2)
96 classify the principal pre-maintenance deterioration mechanisms documented in the
97 archival record; (3) map the 2015 interventions to their corresponding deterioration
98 conditions and conservation objectives; and (4) derive intervention-specific priorities for
99 subsequent condition verification.

100 The contribution of this study lies in establishing a traceable diagnosis–intervention–
101 monitoring framework that treats engineering archives as reusable technical evidence
102 rather than as passive project records. The framework links deterioration type and
103 location with intervention measures, materials, procedures, and follow-up indicators,
104 while distinguishing documented observations from proposed monitoring variables.
105 Rather than quantitatively evaluating the mechanical effectiveness of individual repairs,
106 the study focuses on how fragmented engineering, conservation, and monitoring records
107 can be structured to support lifecycle assessment of previous interventions and iterative
108 preventive maintenance. The proposed approach is intended for historic masonry towers
109 and related heritage structures that have experienced multiple intervention campaigns

but retain incomplete or fragmented long-term datasets.

2. Methods

2.1 Study case and documentary scope

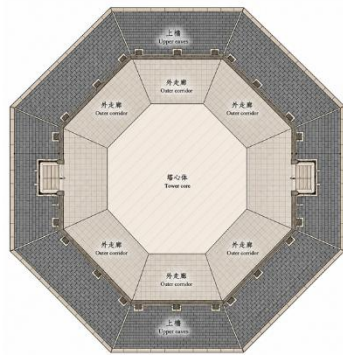
The Yunyan Temple Pagoda, commonly known as the Tiger Hill Pagoda, is located on Tiger Hill in Suzhou, Jiangsu Province, China. The existing structure is a seven-storey octagonal masonry pagoda constructed between the late Five Dynasties period and the early Northern Song Dynasty. Over more than one thousand years, the pagoda has experienced environmental weathering, structural deformation, fire-related damage, and repeated conservation interventions while remaining preserved in a distinctly leaning condition at its original site.

The pagoda has a base diameter of approximately 13.78 m in the north–south direction, decreasing to approximately 8.16 m at the seventh level. Its remaining height from ground level to the surviving finial is approximately 46.99 m. Structurally, it comprises an outer wall, a circumambulatory corridor, an inner wall, and a central core chamber. Historical records indicate a north-eastward inclination of approximately 2.34 m over a structural height of approximately 47.7 m, corresponding to an inclination angle of approximately 2°49'. The original timber eaves and upper finial components have been lost as a result of historical fire events and long-term deterioration[18] .

The case was selected because it combines three characteristics relevant to the present analysis: long-term structural inclination, multiple documented conservation campaigns, and the coexistence of original masonry fabric with reinforcement and repair measures introduced during earlier interventions. These characteristics allow the present condition of the pagoda to be examined not only as a consequence of material ageing and environmental exposure, but also in relation to the long-term performance of previous conservation measures.

Fig. 1 summarizes the architectural configuration and documented condition of the pagoda, including the redrawn plan, south elevation, vertical section, pre-maintenance exterior condition, temporary scaffolding, and present leaning appearance.

(a)



(b)



(c)



(d)



Fig. 1. Overview and architectural configuration of the Yunyan Temple Pagoda.

(a) redrawn plan, south elevation and vertical section of the octagonal masonry pagoda; (b) exterior view before maintenance; (c) temporary scaffolding erected for high-altitude maintenance work; and (d) present leaning appearance of the pagoda.

2.2 Archival and digital evidence

The study used existing engineering and conservation records associated with the Yunyan Temple Pagoda, with particular emphasis on documentation from the 2015 maintenance campaign. The documentary corpus comprised conservation completion reports, as-built drawings, construction records, deterioration and repair records, site photographs, available three-dimensional laser-scanning data, digital models, and documentation describing the subsequent structural monitoring system. These documentary forms served complementary roles in reconstructing the conservation process and examining relationships among deterioration diagnosis, intervention measures, and subsequent monitoring.

Completion reports were used to identify the recorded condition of the pagoda, project objectives, major deterioration problems, and intervention strategies. As-built drawings were used to locate interventions and interpret their spatial configuration, including lightning-protection layouts, local structural details, and repair extents. Construction records and site photographs were used to reconstruct intervention procedures and verify the treatment of individual components. Available digital documentation was used to characterize the spatial and information-management context of the conservation work, including three-dimensional scanning, digital models, and documentation of the monitoring system.

The present study did not undertake new structural testing, numerical simulation, material characterization, or experimental performance testing. It also did not analyse a complete long-term sensor time-series dataset. The monitoring system was therefore considered through its documented configuration and available monitoring information rather than as a source for quantitative before-and-after performance assessment. The analysis was designed to examine how existing documentary evidence could be reorganized into a traceable structure linking deterioration, intervention, and subsequent verification needs.

An inventory of the documentary sources and their analytical roles is provided in Supplementary Table S1. Selected evidence from the 2015 maintenance archive is provided in the Supplementary Information.

2.3 Evidence extraction and coding

Documentary evidence was extracted and coded using a common set of analytical fields: source type, document date, component or spatial location, deterioration condition, interpreted deterioration mechanism, intervention measure, conservation objective, and proposed follow-up indicator[19,20] . This coding structure was used to establish correspondence among observations recorded before maintenance, interventions implemented during the 2015 campaign, and variables relevant to subsequent condition verification. The analysis distinguished documented observations from interpretive classifications: visible conditions, intervention procedures, material applications, and locations were retained as documentary observations, whereas broader deterioration categories were assigned during analysis to organize related evidence consistently.

2.4 Cross-document validation

Cross-document validation was undertaken by comparing information across distinct documentary forms, including completion reports, construction records, as-built drawings, and site photographs. A condition or intervention supported by more than one documentary form was treated as corroborated within the archival corpus. Information appearing in only one documentary form was retained as documented evidence but was

not treated as independently corroborated. Where differences occurred among records, including discrepancies in dates, terminology, or intervention descriptions, the inconsistency was retained and considered during interpretation rather than being silently harmonized. This procedure was intended to reduce reliance on any single retrospective source and to preserve the distinction between explicitly documented evidence and subsequent analytical interpretation.

2.5 Deterioration–intervention mapping

The documented conservation history was first reconstructed to identify changes in the dominant conservation objective across successive campaigns. Pre-maintenance deterioration records were then grouped into five analytical categories: moisture-related deterioration, freeze–thaw and surface weathering, corrosion-induced deterioration of metal components, biological deterioration, and local masonry deformation. The 2015 conservation measures were subsequently mapped to the deterioration conditions they were intended to address. For each intervention, the analysis linked the documented manifestation, treatment location, procedure, conservation objective, and potential follow-up indicator. This step produced the deterioration–intervention matrix used to compare treatment logic across different deterioration mechanisms.

2.6 Framework synthesis

Archival records, intervention documentation, digital assets, and available monitoring information were integrated into a diagnosis–intervention–monitoring framework. Three relationships were used to structure the synthesis: spatial relationships linking deterioration locations, intervention areas, and monitoring points; temporal relationships linking recorded condition, treatment, and subsequent change; and logical relationships linking deterioration mechanisms, selected interventions, and indicators relevant to later verification. The resulting framework is an archival evidence structure rather than a quantitative model of structural or material performance, and it is intended to support repeated diagnosis, intervention review, monitoring, and subsequent maintenance of historic masonry structures.

3. Results

3.1 Conservation trajectory from emergency stabilization to preventive management

Archival reconstruction identified three major conservation campaigns in 1957, 1986, and 2015, followed by the establishment of a preventive monitoring system in 2020. Rather than representing isolated repair events, these interventions show a progressive change in conservation objectives from immediate structural stabilization to foundation control,

225 localized maintenance, and continuous condition management.

226 The 1957 campaign responded to severe structural deterioration, including large internal
227 voids, vertical cracking, and extensive vegetation growth. Circumferential steel hoops
228 were installed at each level to improve global confinement and reduce collapse risk. The
229 dominant conservation objective was therefore emergency stabilization.

230 The second major phase addressed a different risk profile. By the 1970s, cracking and
231 crushing of the stylobate masonry, foundation settlement, and pronounced inclination
232 had become major concerns. The intervention completed in 1986 used surrounding piles
233 and pressure grouting to strengthen the foundation and control differential settlement.
234 The conservation focus consequently shifted from superstructure stabilization to
235 foundation-level control of long-term deformation.

236 By 2015, the dominant problems documented in the project archive had changed again.
237 Surface weathering, water leakage, local cracking, corrosion of earlier steel reinforcement,
238 and deterioration of exposed masonry components became central maintenance
239 concerns. The campaign therefore emphasized localized repair, moisture control,
240 treatment of previous reinforcement, lightning-protection renewal, and surface
241 conservation rather than another whole-structure stabilization programme. The
242 preventive-conservation system introduced in 2020 extended this trajectory toward
243 continuous monitoring and risk warning.

244 Table 1 summarizes the staged characteristics of the three major conservation campaigns.
245 Together with the later monitoring stage shown in Fig. 2, the records indicate a transition
246 from structural survival, through control of global deformation, to management of
247 distributed deterioration and continuous condition information.

248 Table 1. Staged characteristics of major conservation campaigns of the Yunyan Temple Pagoda

Conservation phase	Main issues	Main interventions	Conservation significance
1957 – First campaign	Severe structural cracking, large internal voids, vertical fissures, and vegetation growth, leading to a critical risk of collapse	Installation of three circumferential steel hoops at each level to enhance global confinement and control further leaning	Emergency stabilization aimed at reducing collapse risk and ensuring overall structural safety
1986 –	Cracking and	Foundation	Shift from

Second campaign	crushing of stylobate masonry, foundation settlement, and pronounced structural inclination	strengthening using surrounding piles and pressure grouting techniques	superstructure emergency repair to foundation-level stabilization, effectively controlling settlement and inclination
2015 – Third campaign	Increased surface weathering, expanding cracks, water leakage, and corrosion of earlier steel reinforcement components	Structural maintenance, protective enclosure, lightning protection system renewal, masonry repair, and roof-level conservation	Transition from emergency repair to routine maintenance and preventive conservation, emphasizing localized deterioration control, environmental improvement, and continuous care

Cross-period comparison shows that each conservation phase responded to a different combination of risk and management need. The sequence should therefore be understood as a continuous conservation trajectory rather than as a series of isolated repair projects.

Fig. 2 summarizes this temporal transition and provides the historical basis for linking intervention records with current monitoring and future maintenance planning.

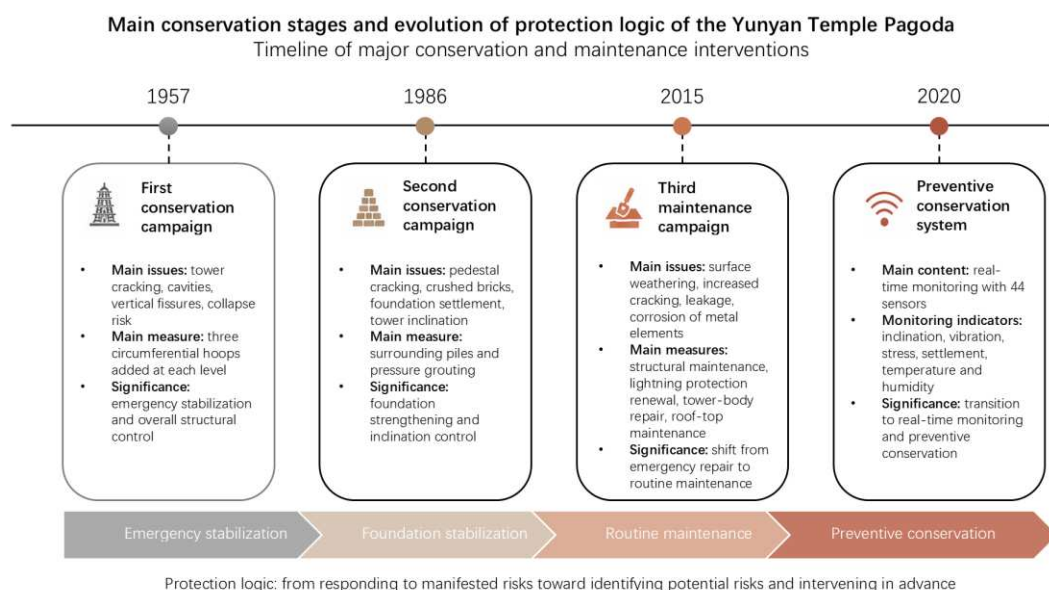


Fig. 2. Main conservation stages and evolution of protection logic of the Yunyan Temple Pagoda, showing the transition from emergency stabilization to foundation stabilization, routine maintenance, and preventive conservation.

3.2 Interacting deterioration mechanisms documented before the 2015 campaign

Pre-maintenance records indicate that deterioration of the Yunyan Temple Pagoda was not associated with a single mechanism. Instead, the archival evidence documented interacting forms of moisture-related deterioration, surface weathering and freeze–thaw-related damage, corrosion of earlier metal reinforcement, biological colonisation, and local masonry deformation . The recorded condition therefore reflects the cumulative interaction of environmental exposure, structural deformation, and earlier conservation materials.

Representative manifestations are shown in Fig. 3, including biological growth, leakage and detachment at the pagoda top, corrosion of embedded steel plates, open masonry joints, and deformation of arched openings. These observations provide the basis for the analytical classification used below and for linking diagnostic results with subsequent interventions and monitoring priorities.

A detailed evidence-based inventory of the pre-maintenance deterioration conditions is provided in Supplementary Table S2.



Fig. 3. Main deterioration types and representative pre-maintenance manifestations of the Yunyan Temple Pagoda:

(a) biological deterioration; (b) detachment and leakage at the pagoda top; (c) corrosion of steel plate; (d) open masonry joints; and (e) deformation of the arched opening.

Moisture ingress was among the most recurrent deterioration conditions documented before the 2015 maintenance campaign. Engineering records describe limited water resistance of weathered masonry surfaces, open joints, and local cracks. Leakage at the pagoda top was associated with plaster detachment, brick weathering, and corrosion of embedded metal components, while insufficient drainage around the base increased long-term damp exposure in lower masonry zones.

The archival evidence therefore indicates that moisture functioned not only as an isolated surface problem but also as a connecting factor among several deterioration processes. Open joints and cracks provided pathways for further water ingress, while prolonged damp exposure was associated with corrosion, biological growth, and freeze–thaw-related surface degradation. This relationship later informed masonry repointing, roof-top repair, water-repellent treatment, and drainage improvement.

Surface deterioration documented before maintenance included brick powdering, plaster detachment, weathered masonry surfaces, and local loss of eave bricks. Project records attributed part of this damage to repeated freeze–thaw action under long-term environmental exposure. At exposed eave and offset zones, material loss had progressed beyond surface weathering to component detachment, creating an additional falling-debris risk.

Earlier conservation campaigns introduced steel hoops and corner steel plates to improve global stability and control deformation. Later archival photographs and construction records documented corrosion and expansion of some of these components together with cracking and separation of adjacent masonry. The evidence therefore associates ageing reinforcement with a later maintenance problem rather than treating the earlier intervention as a permanently stable addition.

This relationship is particularly important because it shows that previous conservation measures had become part of the later deterioration condition of the pagoda. Earlier reinforcement remained functionally relevant, but ageing and corrosion created new maintenance requirements. The 2015 campaign therefore treated previous reinforcement as a lifecycle-management issue rather than simply retaining or removing all earlier components.

Archival photographs documented weeds, small trees, and root growth within masonry joints and cracks. Biological colonisation was concentrated in areas where moisture retention, open joints, and limited drainage provided favourable conditions. Root penetration was associated with local joint disturbance and widening of existing openings.

Local deformation was documented at arched openings, masonry joints, exposed eaves, and cracked sections of the pagoda body. These manifestations occurred within the broader context of long-term structural inclination, local material loss, moisture ingress, and deterioration of earlier reinforcement. The records therefore support interpretation of local deformation as the product of interacting structural and environmental factors rather than as an isolated defect.

Open joints and cracks also created pathways for water, roots, and environmental agents to enter the masonry body. Severe brick loss at eaves indicates that some areas had progressed from surface weathering to partial component failure, with implications for structural and public safety. Local deformation and cracking therefore represent integrated outcomes of multiple interacting processes.

Table 2 summarizes the five analytical categories and their corresponding manifestations, drivers, conservation risks, and intervention implications.

Table 2. Classification of pre-maintenance deterioration patterns of the Yunyan Temple Pagoda and associated conservation implications.

Deterioration type	Representative manifestations	Main deterioration drivers	Potential conservation risks	Intervention implications
Moisture-related deterioration [21,22]	Poor waterproofing capacity of masonry, leakage at the pagoda top, rainwater ingress into interior spaces, and inadequate drainage around the tower base	Wind-driven rain, open masonry joints, crack development, and insufficient drainage organization	Long-term dampness of masonry, reduced bonding capacity of mortar, accelerated corrosion of metal components, and loss of internal filling materials	Masonry repointing, roof-top maintenance, water-repellent treatment, and ground drainage improvement
Freeze–thaw and surface	Surface weathering of	Moisture ingress,	Surface spalling,	Surface strengthening,

weathering[23,24]	masonry, brick fall at eaves induced by freeze–thaw action, local plaster detachment, and surface degradation of bricks	temperature cycling, and long-term environmental exposure	brick powdering, falling eave components , and safety risks in high-altitude areas	local repair, eave maintenance, and improvement of the surrounding conservation environment
Corrosion-induced deterioration of metal components[25,26]	Severe cracking caused by corroded corner steel plates, expansion of previous reinforcement elements, and intensified masonry cracking due to water entering existing cracks	Ageing of earlier steel reinforcement , rainwater penetration, and long-term humid conditions	Expansion pressure on adjacent masonry, separation between protective layers and the original structure, and progressive local cracking	De-rusting of steel components, anti-corrosion treatment, local dismantling and inspection, and rebuilding with customized bricks
Biological deterioration[27,28]	Growth of weeds and small trees, with roots penetrating masonry joints and cracks	Moisture retention, loosened masonry joints, and insufficient routine maintenance	Joint loosening, crack widening, root-induced disturbance of local masonry, and recurrence	Vegetation inactivation and root removal, surface cleaning, joint repair, and regular follow-up inspection

			of biological colonisation	
Local masonry deformation and cracking[29,30]	Deformation of arched openings, open masonry joints, progressive local cracking, and severe brick loss at eaves	Long-term inclination, local stress redistribution, material ageing, and combined effects of moisture and freeze–thaw action	Local structural instability, enlarged pathways for rainwater ingress, and risk of component detachment	Reinforcement of arched openings, masonry repointing, local masonry repair, and eave maintenance

The five categories were strongly interconnected. Moisture-related conditions were associated with surface weathering, biological colonisation, and corrosion, while cracking and open joints created additional pathways for water and root penetration. Corrosion of earlier reinforcement further contributed to local cracking and separation of protective layers. The resulting deterioration pattern is therefore better represented as an interacting risk chain than as a collection of independent defects. This observation provided the basis for mapping individual interventions to both their target deterioration mechanisms and their subsequent verification needs.

3.3 Intervention records reveal mechanism-specific treatment and legacy reinforcement risks

The 2015 maintenance archive documented a set of targeted interventions corresponding to the deterioration conditions identified above. Rather than applying a single repair strategy, the campaign combined safety-related measures, treatment of previous reinforcement, moisture-control interventions, localized masonry strengthening, biological removal, and environmental improvement. The analysis therefore focuses on the relationship between documented deterioration, selected intervention, and subsequent verification needs rather than on construction sequence alone.

A detailed reconstruction of individual intervention procedures is provided in Supplementary Table S3.

The long-term inclination, height, octagonal plan, and fragile masonry condition made access itself a conservation constraint. Project records show that scaffolding was adapted to the inclined geometry to provide access for inspection and localized repair while

limiting disturbance to the historic fabric. Temporary works therefore formed part of the intervention strategy rather than merely serving as construction assistance.

The lightning-protection system was renewed in response to deficiencies documented before maintenance. Because the pagoda is a tall masonry structure on an elevated site, the intervention was treated as a preventive-safety measure addressing lightning-related risk to the finial, external components, masonry fabric, and visitors.

The recorded work included treatment of the existing lightning rod, replacement of down conductors, installation of additional circumferential bands, and improvement of the grounding and inspection system. These measures were intended to improve system continuity, redundancy, and future inspectability rather than to repair an existing masonry defect.

The intervention demonstrates that preventive conservation includes low-probability but high-consequence hazards in addition to visible material deterioration. Representative procedures are shown in Fig. 4.



Fig. 4. Representative procedures for renewal of the lightning-protection system of the Yunyan Temple Pagoda.

(a) lightning rod before and after polishing; (b) down conductor before and after replacement; (c) circumferential lightning bands at the finial and the seventh level; (d) circumferential lightning bands at the fifth and sixth eave-brick levels; (e) excavation and exothermic welding for step-voltage protection; and (f) insulated backfill layer and lightning-protection inspection box.

371 The treatment of corroded corner steel plates provided the clearest evidence that
372 previous conservation measures had become part of the later deterioration system. Steel
373 hoops and internal corner plates introduced in earlier campaigns remained relevant to
374 structural stabilization, but archival photographs and construction records documented
375 corrosion, expansion, and separation of adjacent protective layers. Each affected corner
376 column was measured and photographed before treatment to define the intervention
377 scope.

378 The archive distinguished between serviceable and severely deteriorated components.
379 Steel plates with limited corrosion were retained, cleaned, protected with anti-rust
380 coatings, and re-covered with masonry, whereas severely corroded elements were locally
381 supplemented or replaced using plates of the same size before masonry rebuilding. This
382 condition-dependent strategy prioritized retention where continued service remained
383 feasible.

384 Connection and crack-control measures, including wire mesh and tie bars, were used
385 during rebuilding to reduce recurrent cracking at the steel–masonry interface. Detailed
386 dimensions and construction procedures are retained in Supplementary Table S3 and
387 illustrated in Fig. 5.

388 The intervention therefore represents lifecycle reassessment rather than automatic
389 retention or removal of previous conservation additions. Earlier reinforcement can remain
390 functionally significant while simultaneously acquiring new deterioration risks, requiring
391 its condition, compatibility, and maintenance needs to be reconsidered during later
392 conservation campaigns.



393

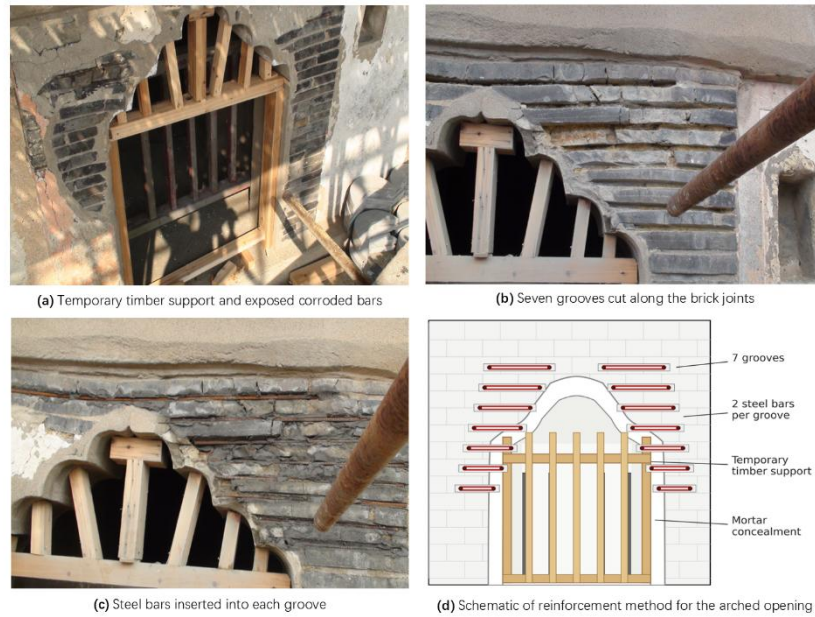
394 Fig. 5. Representative procedures for the treatment of corroded corner steel plates at the Yunyan
395 Temple Pagoda

396 Open masonry joints were cleaned and repointed to restore surface continuity and
397 reduce direct pathways for rainwater and internal material loss. The construction archive
398 records removal of loose material, cleaning of joints, preliminary filling, final repointing,
399 and surface finishing.

400 From a conservation perspective, repointing addressed more than surface appearance.
401 Open joints can facilitate rainwater, salts, roots, and environmental agents, and can
402 become weak zones for material loss and freeze–thaw–related deterioration. The
403 intervention therefore functioned as both localized masonry repair and moisture control.

404 Pre-maintenance records identified deformation and partial collapse at arched openings,
405 where local load redistribution, long-term inclination, material ageing, and moisture-
406 related deterioration affected masonry surrounding the openings. Local reinforcement
407 was therefore selected rather than extensive dismantling.

408 The recorded procedure used temporary timber support, grooves cut along masonry
409 joints, insertion of steel bars, and mortar concealment. This localized strategy sought to
410 improve local stability while maintaining visual continuity. The intervention sequence is
411 shown in Fig. 6, with detailed process information retained in Supplementary Table S3.



412

413 Fig. 6. Local reinforcement procedure for the deformed arched opening of the Yunyan Temple
414 Pagoda

415 (a) temporary timber support and exposed corroded bars; (b) seven grooves cut along the brick
416 joints; (c) steel bars inserted into each groove; and (d) schematic illustration of the reinforcement
417 method.

418 The 2015 campaign also combined surface consolidation, water-repellent treatment, and
419 ground drainage improvement. KSE300 consolidant was applied to weathered external
420 surfaces, SNL water-repellent treatment was used to reduce surface water absorption,
421 and the poorly draining brick paving around the tower was replaced with stone slabs to
422 improve runoff[31,32] .

423 These measures formed an integrated material-treatment and moisture-control strategy
424 rather than independent treatments. Surface strengthening addressed weakened
425 material, while water-repellent treatment, repointing, roof-top maintenance, and
426 drainage improvement targeted different pathways of water entry and retention.

427 The resulting moisture-control strategy operated across several spatial levels: the pagoda
428 top, external masonry surfaces, joints, localized structural openings, and the surrounding
429 ground. This distributed intervention pattern is important for interpreting later
430 monitoring needs.

431 Table 3 summarizes the relationship between documented deterioration and the selected
432 interventions. Each deterioration category is associated with a corresponding treatment
433 objective and a set of variables relevant to subsequent verification, translating the
434 maintenance campaign into a traceable conservation logic rather than a list of

435 construction measures.

436 Table 3. Deterioration–intervention matrix for the Yunyan Temple Pagoda.

Deterioration type	Representative manifestations	Conservation interventions	Conservation objectives	Subsequent monitoring indicators
Moisture-related deterioration	Leakage at the pagoda top, rainwater ingress into interior spaces, poor waterproofing capacity of masonry, and inadequate drainage around the tower base	Masonry repointing, roof-top maintenance, SNL water-repellent treatment, and drainage improvement through stone-slab paving	Reduce rainwater ingress, internal material loss, and long-term damp exposure	Moisture content, environmental humidity, leakage points, joint condition, and ground drainage performance
Freeze–thaw and surface weathering	Surface weathering, brick fall at eaves, local plaster detachment, and surface degradation of bricks	KSE300 surface strengthening, local repair, finial/eave maintenance, and maintenance of exposed eave components	Slow surface material degradation and reduce the risk of high-altitude component detachment	Extent of surface damage, spalling area, falling eave components, and surface material condition
Corrosion-induced deterioration	Severe cracking of corner steel plates, expansion of previous reinforcement elements, and separation between	Measurement and photographic recording, rust removal, anti-rust paint application, customized brick rebuilding, wire-	Control corrosion-induced cracking of metal components and restore local protective	Crack width, local deformation, corrosion state of steel components, and cracking at masonry–steel connection

	protective layers and the pagoda body	mesh crack control, tie-bar reinforcement, and replacement welding of severely corroded steel plates using same-size new plates	layers and connection stability	zones
Biological deterioration	Growth of weeds and small trees, with roots entering masonry joints and cracks	Vegetation inactivation and root removal, surface cleaning, joint repair, and follow-up inspection	Reduce root-induced disturbance to joints and masonry, and lower the risk of biological recurrence	Vegetation regrowth, root residues, joint loosening, and locally damp areas
Local masonry deformation	Collapse and deformation of arched openings, local cracking of the pagoda body, and severe brick fall at eaves	Temporary timber support, groove cutting and bar insertion at arched openings, mortar concealment, local masonry repair, and eave maintenance	Improve local structural stability and reduce deformation expansion and component detachment risk	Deformation amount, crack development, local displacement of arched openings, and condition of eave components

437 The mapping shows that the maintenance campaign generated not only physical
 438 interventions but also information requirements for later evaluation. Moisture-control
 439 measures correspond to moisture content, leakage, joint condition, and drainage
 440 performance; steel-component treatments correspond to corrosion state, crack
 441 development, and local deformation; biological-control measures correspond to
 442 vegetation recurrence; and arched-opening reinforcement corresponds to displacement
 443 and crack development. The intervention archive can therefore be interpreted as an
 444 intermediate link between deterioration diagnosis and subsequent monitoring.

3.4 Digital documentation and monitoring reveal an integration gap

Digital records associated with the Yunyan Temple Pagoda document a progressive extension of conservation information from conventional project records to spatial documentation and sensor-based monitoring. The value of these technologies in the present study lies primarily in their ability to provide a spatial and temporal basis for linking component condition, intervention history, and subsequent observation[33,34].

Fig. 7 summarizes the relationship among digital documentation, digital archives and information platforms, and real-time monitoring within the documented conservation system.

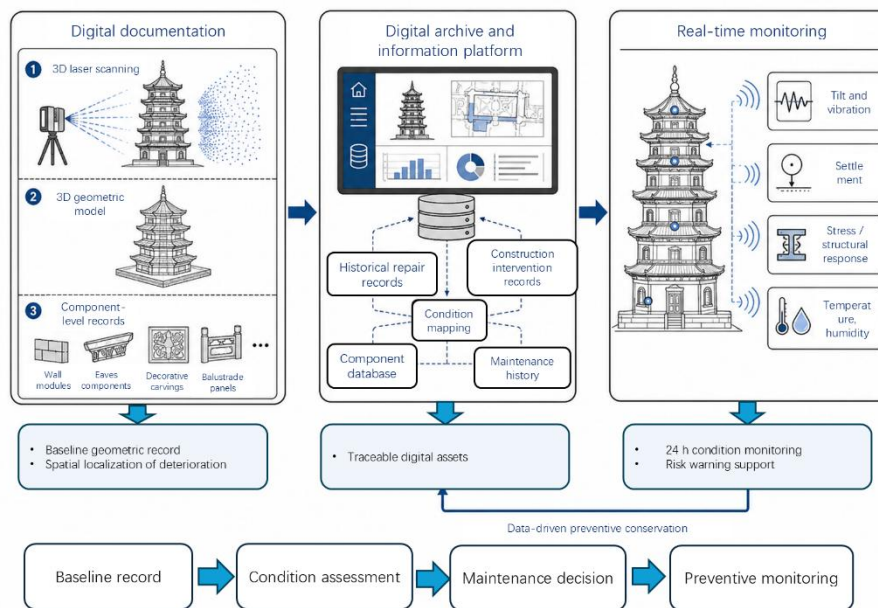


Fig. 7. Overall framework of the digital documentation and monitoring system for the Yunyan Temple Pagoda, linking 3D laser scanning, geometric modelling, component-level records, digital archives and real-time sensor-based monitoring.

During the 2015 maintenance campaign, three-dimensional laser scanning was used to document the exterior surface, internal structure, and local masonry components. Processing produced a geometric model, internal and external digital representations, and 503 three-dimensional models of painted relief elements. These records established a spatial baseline for later comparison and component-level documentation.

For a leaning masonry pagoda, the principal analytical value of the scanning record is its potential to support comparison of geometric condition over time. Façades, internal spaces, cracks, local deformations, decorative elements, and component loss can be referenced against a common spatial baseline rather than relying only on separate photographs and written descriptions.

Three-dimensional documentation can also improve the spatial localization of deterioration. Compared with conventional records, point clouds and digital models can associate deterioration and intervention information with specific positions, improving traceability between repair areas and future monitoring points.

Digital models and information platforms provide a structure for associating geometric records with component condition, intervention history, and maintenance information. Their value lies less in immersive display than in bringing otherwise dispersed drawings, photographs, repair records, and component information into a traceable spatial context[35,36] .

At the component level, such platforms can support links among past conditions, current problems, and future maintenance needs. In the present case, however, these resources remain only partially connected to later monitoring information and therefore function primarily as a spatial and documentary baseline rather than as a fully integrated predictive system.

Fig. 8 illustrates one form of spatial representation available within the digital archive. In this study, the Gaussian-splatting representation is treated as a documentation and visualization asset rather than as an independent source of quantitative deterioration data.

Project documentation indicates that a preventive-conservation monitoring system was established in 2020. The system comprised 44 sensors covering inclination, vibration, structural response, foundation and differential settlement, temperature, humidity, surrounding climate, masonry moisture, and material-condition variables. The documented configuration therefore extended conservation information from periodic inspection toward continuous condition sensing[37,38] .

Inclination and vibration monitoring address macro-level stability; settlement monitoring addresses foundation behaviour; temperature, humidity, and moisture observations relate to environmental and moisture-related deterioration. The present study did not analyse a complete sensor time-series dataset; the monitoring system was evaluated through its documented configuration and available monitoring information rather than through quantitative longitudinal performance analysis.

Intervention-specific monitoring indicators derived from the deterioration–intervention relationship are provided in Supplementary Table S4.

Comparison between the intervention archive and the documented monitoring system identified four integration gaps. First, monitoring primarily addresses global structural and environmental variables, whereas local conditions of masonry joints, treated steel–masonry interfaces, arched openings, eave components, and surface treatments are less

continuously recorded. Second, intervention records and monitoring outputs are not yet consistently linked at component level. Third, warning thresholds remain partly dependent on expert interpretation, particularly where moisture, corrosion, freeze–thaw–related deterioration, and biological growth may interact. Fourth, earlier drawings, photographs, and construction records require further spatial registration before they can be systematically compared with later digital models and monitoring information.

These gaps indicate that the principal challenge is no longer simply the acquisition of additional digital data, but the establishment of traceable relationships among archival evidence, intervention locations, component condition, and subsequent monitoring.



Fig. 8. Gaussian-splatting representation of the Yunyan Temple Pagoda and its surrounding landscape.

3.5 A closed-loop diagnosis–intervention–monitoring framework

Based on the relationships identified among archival deterioration records, documented interventions, digital assets, and monitoring information, a closed-loop diagnosis–intervention–monitoring framework was constructed for the Yunyan Temple Pagoda. The purpose of the framework is not to introduce additional technologies, but to organize existing forms of conservation evidence into a traceable sequence linking diagnosis, treatment, documentation, verification, and subsequent reassessment.

The framework follows a closed sequence from historical records through deterioration diagnosis, risk classification, intervention, documentation, monitoring, warning, and maintenance decision-making, after which monitoring results feed into the next round of diagnosis.

Historical records → Deterioration diagnosis → Risk classification → Conservation intervention → Intervention records → Digital archiving → Monitoring → Warning and maintenance decision → Next-round diagnosis.

Its analytical structure is based on three forms of association. Spatial association links deterioration locations, intervention areas, and monitoring points; temporal association links documented condition, treatment, and subsequent change; and logical association links deterioration mechanisms, selected interventions, and verification indicators. This structure addresses the common separation of historical archives, deterioration surveys, construction records, and monitoring data in heritage projects.

The overall structure is shown in Fig. 9, which organizes diagnosis, intervention, and monitoring as three connected layers supported by project archiving, digital assets, preventive-conservation data chains, and maintenance feedback.

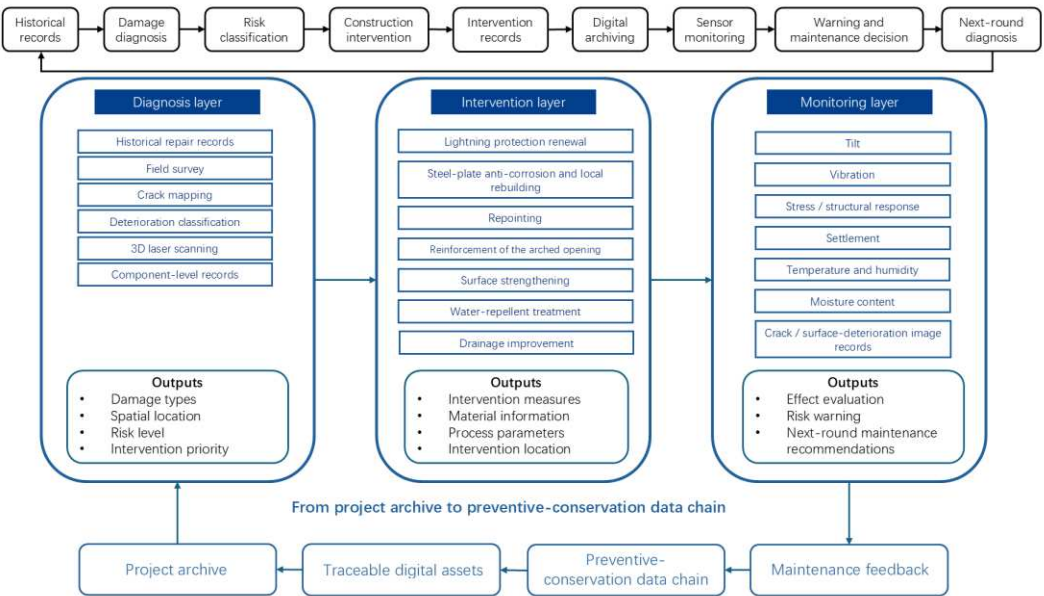


Fig. 9. Integrated diagnosis–intervention–monitoring framework for the preventive conservation of the Yunyan Temple Pagoda, transforming project archives, intervention records and monitoring data into a closed preventive-conservation data chain.

The diagnosis layer organizes historical records, field observations, spatial documentation, and component information into deterioration type, location, risk level, and intervention priority. For the Yunyan Temple Pagoda, this includes the effects of the 1957 reinforcement, 1986 foundation treatment, and 2015 maintenance campaign, because previous interventions form part of the present material and risk condition.

The intervention layer records the treatment applied to a specific location together with materials, procedures, conservation objectives, and completion information. Treating

intervention as a data-generation stage allows later moisture increase, crack development, spalling, or local deformation to be traced back to the earlier treatment and location.

The monitoring layer links subsequent structural, environmental, visual, and component-level observations back to treated locations and earlier diagnostic records. The existing 44-sensor system provides global and environmental information, while local crack records, image comparison, repeated 3D documentation, and manual inspection remain necessary for intervention-specific verification.

The data loop connects engineering archives with subsequent diagnosis and maintenance by establishing spatial, temporal, and logical associations among condition, treatment, and later change. For the Yunyan Temple Pagoda, this provides a means of linking the 2015 intervention archive with monitoring after 2020 without assuming that the available monitoring dataset already constitutes complete quantitative verification of treatment performance. The resulting logic shifts conservation from a linear sequence of problem identification, repair, and archiving toward diagnosis, intervention, monitoring, feedback, and re-diagnosis.

4. Discussion

The findings show that heterogeneous engineering records generated across successive conservation campaigns can be reorganized into a traceable conservation evidence chain when deterioration, intervention, location, and subsequent verification requirements are explicitly linked. The conservation trajectory of the Yunyan Temple Pagoda moved from emergency stabilization to foundation control, localized maintenance, and later continuous monitoring. This progression supports a preventive-conservation interpretation in which individual repair campaigns are understood as stages within a longer management process rather than as isolated technical events.

A central implication is that engineering archives can function as conservation evidence rather than merely as proof of project completion. As-built drawings, photographs, acceptance reports, deterioration records, and material information can reveal how risks were interpreted, why interventions were selected, and what later observations are needed. Their value increases when records are organized by location and time, because specific interventions can then be associated with materials, procedures, conservation objectives, and subsequent condition changes[39,40] .

The case also highlights the lifecycle implications of previous conservation interventions [41,42]. The corroded steel hoops and corner plates show that an intervention may remain structurally relevant while simultaneously becoming part of the later deterioration system. Maintenance therefore should not rely on a simple distinction between original

and added components. The current function, heritage significance, material condition, compatibility, and deterioration risk of earlier intervention components need to be evaluated together, with retention, repair, replacement, isolation, or monitoring selected according to their later condition .

Moisture-related conditions provide a second cross-cutting implication[43,44] . The archival evidence associates water ingress with surface weathering, biological colonisation, corrosion, joint opening, and local material loss. These relationships should not be interpreted as experimental causal verification, but they show why moisture control in the 2015 campaign was distributed across the pagoda top, masonry joints, external surfaces, localized repairs, and the surrounding ground. The resulting intervention pattern supports diagnosis and maintenance at multiple spatial levels rather than treatment of isolated symptoms.

Digital technologies are most useful when they preserve continuity between intervention history and subsequent condition assessment[45,46]. Three-dimensional scanning, digital archives, and sensor-based monitoring can provide geometric baselines, spatial records, and repeated observations, but additional data alone do not create an integrated preventive-conservation system. If digital models remain visualization products and monitoring outputs remain disconnected from intervention records, their ability to support lifecycle review is limited. The four integration gaps identified in this study therefore point toward component-level linkage of archival evidence, intervention locations, and later monitoring as the more important next step.

The proposed framework is transferable primarily as an analytical sequence rather than as a fixed technical prescription[47,48] . Historic masonry towers, pagodas, and related structures with repeated intervention histories can use the same spatial, temporal, and logical associations, but deterioration categories, monitoring variables, intervention thresholds, and acceptable treatment strategies require site-specific calibration. The study is also limited by its reliance on one case and on existing archives. It includes no new field testing, finite-element analysis, or material experiments, and no complete long-term sensor time series was available. Future work should test the framework across additional heritage structures and combine repeated 3D surveys, longer monitoring records, structural analysis, non-destructive testing, and material-performance assessment to evaluate the durability and effectiveness of individual interventions.

5. Conclusion

This study used the Yunyan Temple Pagoda as a long-term, multi-intervention masonry heritage case to examine how engineering archives can support preventive conservation. By reorganizing completion reports, as-built drawings, construction records, site

photographs, digital documentation, and available monitoring information, the analysis reconstructed the transition from emergency stabilization and foundation control to localized maintenance and preventive monitoring.

Five interacting deterioration categories were identified in the archival record: moisture-related deterioration, freeze–thaw-related deterioration and surface weathering, corrosion-induced deterioration of previous reinforcement, biological deterioration, and local masonry deformation. The records indicate that these categories were interconnected rather than independent, and that earlier reinforcement could itself become a later deterioration source requiring lifecycle reassessment.

The 2015 interventions were mapped to their target deterioration conditions, conservation objectives, and subsequent verification indicators. This mapping shows that intervention records can serve as an intermediate evidence layer between diagnosis and monitoring rather than remaining static descriptions of completed work.

The resulting closed-loop diagnosis–intervention–monitoring framework organizes conservation evidence through spatial, temporal, and logical associations. Its principal contribution is a traceable method for linking past conditions and interventions with future verification needs while explicitly respecting the limits of incomplete long-term datasets. For historic masonry structures with repeated intervention histories, preventive conservation should therefore combine lifecycle assessment of previous repairs, structured archival evidence, component-level traceability, and monitoring feedback rather than relying on one-time repair decisions alone.

Overall, the Yunyan Temple Pagoda case demonstrates that the conservation of leaning masonry pagodas should move beyond individual repair techniques and one-time engineering experience. A preventive conservation system should be centred on long-term condition management, traceable documentation, monitoring feedback and evidence-based decision-making. The framework proposed here provides a methodological reference for similar leaning masonry pagodas, tall masonry heritage structures and heritage buildings that have undergone multiple historical interventions. Future research should incorporate longer monitoring time series, structural analysis and material-performance assessment to further examine the applicability of this framework in different heritage contexts.

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Authors' contributions

Bingke Xiao: Conceptualization, methodology, investigation, archival organization, formal analysis, project administration, and writing—original draft.

Ming Zhang: Investigation, field documentation, construction-record organization, data curation, and validation.

Gemin Lu: Archival documentation, construction-documentation support, site-record organization, technical verification, and data curation.

Fangyong Wang: Conservation-strategy analysis, technical consultation, validation, and writing—review and editing.

Xingnan Zhu: Construction-technique interpretation, field-process verification, technical documentation, and validation.

Zhilong Liu: Heritage-value interpretation, cultural-context analysis, academic consultation, and writing—review and editing.

Ding Wen 'Nic' Bao: Methodological consultation, technical validation, supervision, and writing—review and editing.

Zeyu Chao: Conceptualization, methodology, formal analysis, manuscript organization, academic positioning, supervision, writing—review and editing, submission coordination, and author communication.

Cossima Cornado: Supervision, methodological consultation, and writing—review and editing.

All authors reviewed and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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Data availability statement

The structured data and selected documentary evidence supporting this study are provided in the Supplementary Information and Supplementary Tables. Certain original drawings, high-resolution photographs, project archives, and heritage-site records cannot be publicly shared due to institutional, heritage-protection, project, or third-party restrictions. Additional materials may be available from the corresponding author upon reasonable request and subject to relevant permissions.

Ethics declaration

Ethical approval and informed consent were not required because this study did not involve human participants, personal data, animals, or other procedures requiring ethical review.

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