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Identification and Risk Assessment of Erosion Characteristics of the Rammed-Earth Great Wall from the Perspective of Preventive Conservation

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Abstract

The rammed-earth Great Wall, a vital world heritage site, faces rapid erosion exacerbated by environmental change, demanding urgent erosion assessment as foundational conservation work. From a preventive conservation perspective, this paper develops an integrated digital 'census-quantification-assessment' methodology to systematically analyse rammed-earth wall erosion characteristics and enable risk assessment. Utilizing unmanned aerial vehicle (UAV) photogrammetry, comprehensive high-precision 3D modeling and multi-temporal imaging of the Ming Great Wall is achieved. This establishes a dynamic digital twin model, revealing the characteristic deterioration sequence of 'bottom hollowing → local collapse → overall destabilisation'. Quantitative morphological indicators (hollowing height, depth, area, rate) combined with 3D point cloud analysis map the evolution of wall-base hollowing within the digital twin. Integrating these morphological metrics enables the proposal of an erosion risk grading system, allowing precise location and dynamic monitoring of risks within individual wall sections. Compared to traditional approaches, this framework provides a data-driven decision basis for preventive protection. It implements a 'monitoring-assessment-warning' closed-loop management strategy applicable to the Great Wall and similar linear heritage. This promotes a shift in conservation strategy from post-event restoration towards proactive risk prediction, supporting the development of a holistic, lifecycle cultural heritage risk management system.

1. Introduction

As the world's largest linear cultural heritage site, the Great Wall has attracted worldwide attention since it was inscribed on the World Heritage List in 1987. Decades of human activity and changing natural conditions have accelerated its structural degradation, transforming what was once localized damage into large-scale loss. Variations in local terrain, climate, and resource availability led to the use of different construction techniques and materials—mainly rammed earth, brick, and stone—along its extensive trajectory. Rammed earth sections are most prevalent in the northwestern regions, accounting for more than half of the Ming Dynasty Great Wall's total length. Due to the inherent vulnerability of earthen structures, these segments are highly susceptible to wind erosion, water scouring, salt crystallization, and freeze-thaw cycles, rendering urgent conservation measures essential.

Current scholarship on Great Wall deterioration focuses on cataloguing damage patterns and probing their underlying causes. Built of compacted loess and left fully exposed, these northwestern ramparts endure abrasive spring and autumn sandstorms, intense summer downpours and solar heating, and winter freeze-thaw cycles with heavy snow. The combined assault triggers severe pathologies—surface pulverization, cracking, voids beneath the crust, and wholesale structural collapse—across extensive sections of the earthen barrier (Haiying et al. 2007). Among the various forms of deterioration observed in rammed earth sections of the Great Wall, basal hollowing stands out as one of the most damaging to the structural integrity of the site. This type of erosion leads to the formation of large cavities near the foundation, significantly weakening the wall's resistance to overturning forces. As a result, the structure becomes prone to large-scale collapse due to overall instability. Research into the underlying mechanisms attributes this hollowing phenomenon primarily to the effects of saline erosion (Elert et al. 2015; Guo et al. 2022). Most rammed-earth stretches of the Great Wall lie in arid or semi-arid zones, where scant rainfall and rapid evaporation drive dissolved salts to accumulate at the wall's base. Repeated crystallization and hydration within this saline band progressively weaken the earthen fabric, leading to loss of cohesion and the onset of hollowing and surface loss (Liu et al. 2023). Panoramic imagery collected along Gansu's Ming-era Great Wall from 2019 to 2024 reveals an accelerating loss: side-by-side photographs of the Shilibao segment show the structure collapsing and vanishing within just five years.

In the current heritage erosion status and protection context, the traditional "salvage restoration" model is difficult to cope with such persistent risks(Yang et al. 2017), there is an urgent need to establish a preventive protection mechanism based on risk prediction, so the preventive protection of heritage has become a core scientific issue of the architectural discipline, cultural heritage protection discipline(Gros et al. 2008) . China's 13th Five-Year Plan for cultural heritage shifted the country's approach from "rescue-only" to "rescue-plus-preventive" conservation, stressing early intervention and risk management. The 2018 joint directive of the CPC Central Committee and the State Council (Opinions on Reforming Protection and Utilization of Cultural Relics, Article 16) reaffirmed this pivot, calling for simultaneous safeguarding of monuments and their broader settings. By establishing an iterative "monitor-evaluate-intervene-re-evaluate" cycle, the policy aims to replace last-minute repairs with proactive, evidence-based control. This transition is both a practical response to the accelerating decay of the Great Wall and a strategic fulfillment of obligations under the World Heritage Convention (Elert et al. 2015).

Since 2007, China has initiated its most extensive survey of the Great Wall to document fundamental resource data. However, the scope of this investigation remained limited to spatial distribution, photographic documentation of surface features, and schematic plans and elevations, without systematically addressing the categories or spatial patterns of structural deterioration. Targeted research on preservation risks and defects has been lacking, resulting in an incomplete understanding of current conservation conditions and an absence of comprehensive risk mapping. This gap hinders efficient and rational allocation of limited restoration resources.

In response, this study proposes a integrated digital framework under the preventive conservation paradigm—structured around "investigation, quantification, and evaluation"—to translate

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theoretical conservation concepts into actionable engineering practices. First, a digital pathway is established for recording wall diseases, upgrading discrete historical data into a dynamic digital twin model capable of simulating temporal changes. Second, using multi-temporal imagery, the developmental stages and sequence of structural collapses are reconstructed, revealing typical deterioration patterns in rammed earth sections. Finally, high-resolution 3D point cloud modeling enables morphological fitting to quantify hollowing severity in representative areas. Through four metrics—hollowing height, depth, area, and morphological hollowing ratio—a comparative analysis across sections facilitates quantitative grading and assessment of preservation conditions (Wang et al. 2025).

Unlike traditional methods, this multi-dimensional technical approach not only offers a novel paradigm for analyzing deterioration mechanisms in earthen heritage but also establishes a closed-loop management system comprising "monitoring–evaluation–warning." This structurally enhances the efficiency of conservation resource allocation and provides a scientific foundation for diagnostic evaluation of heritage diseases, thereby contributing significantly to the advancement of restoration practices for immovable cultural relics.

2. Technical links for the digital survey of the Great Wall damage

In recent years, the use of digital technology for the surveying and documentation of cultural heritage has gained significant momentum worldwide. Between 2002 and 2009, Hadrian's Wall was comprehensively mapped along its entire length and within its surrounding buffer zone. This effort resulted in the collation, organization, and production of over 3,000 records of archaeological remains. Furthermore, in 2009, English Heritage initiated an annual aerial survey project aimed at discovering, documenting, and monitoring these historical sites. Emerging technologies—including laser scanning, digital photogrammetry for structural recording, and field digital acquisition systems—are increasingly being integrated into the conservation and monitoring of heritage assets.

The Great Wall of China represents an exceptionally extensive heritage system. The Ming Dynasty section alone spans a total length of 8,851.8 kilometers, traversing 156 counties across ten provincial-level regions: Liaoning, Hebei, Tianjin, Beijing, Shanxi, Inner Mongolia, Shaanxi, Ningxia, Gansu, and Qinghai. This vast distribution encompasses not only the main structure but also a rich array of associated relics and ancillary facilities, forming a heritage landscape of remarkable scale and diversity.

Figure 1 Technical links for digital survey of disease in the Great Wall.

3. Analysis of disease deterioration processes based on ephemeral monitoring images

Under the influence of natural environmental changes, the rammed earth wall undergoes the deterioration process of bottom hollowing out - local collapse - and overall destabilization and overturning. Using the low-altitude photogrammetric data of the Great Wall taken by the authors' team in 2019 and 2024, we summarize the locations where the main changes of the wall have occurred from the comparative photographs taken before and after five years at the same location, and then summarize the deterioration process of the rammed-earth Great Wall and the sequence of its collapse.

According to the comparison of the images of multiple points in the figure below, it can be summarized that the changes of the rammed earth wall mainly include three types: the spalling of earth blocks in the hollowed-out area at the bottom of the wall, the longitudinal layered collapse of the wall, and the overall collapse of the wall. Soil block falling mainly exists in the more intact wall surface, due to the wall bottom hollowing concave formation of cavity, along with the wind erosion effect of the prolonged period of time to make the soil body rammed layer between the connecting force weakened, the role of their own gravity to form a dangerous block, in the wind and sand under the action of the fall of (Chen et al. 2014) (Figure 2a). Longitudinal layered collapse of the wall exists in the hollowing increase, the upper part of its own gravity will be tilted to one side of the wall along the wall plate seam tendency, resulting in the bottom of the wall cavity there will be compressive cracks development, along with the gradual development of compressive cracks expansion of the confluence of the wall rammed earth plate seam, the unilateral wall due to the destabilization of the whole sliding, resulting in the longitudinal layered collapse (Figure 2b). Integral collapse is the overall destabilization of the wall structure after damage by erosion, which exists in the continued development of hollowing on both sides of the wall, with the increasing degree of inclination of the wall, and the gradual development of cracks at the bottom of the hollowing to the extent that they become continuous with the plate joints, the site body is unable to maintain its own stable state, and it breaks down from the middle of the plate joints into two parts, and tilts to the two sides of the wall to be destroyed under the action of its own gravity (Figure 2c).

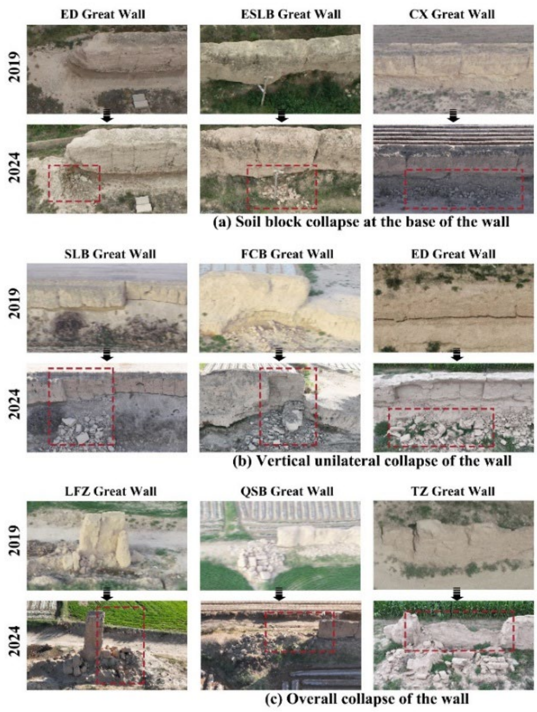

Figure 2 Comparison of disease development using multi-temporal data.

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Based on the comparison of the disease development of the above ephemeral pictures, combined with the systematic combing of the preservation status of the whole line of the rammed earth Great Wall, the chronology of the continuous deterioration and collapse of the rammed earth Great Wall can be summarized (Figure 3). First of all, the rammed earth wall in the intact state is trapezoidal in shape, collected and divided from bottom to top, and constructed by a layered ramming method(Zhang et al. 2023) (Figure 3a). After rain, water, wind and other factors continuously wash away the soil of the wall, the foot of the wall began to concave inward (Figure 3b), making the bottom of the formation of hollowing area cavity (Figure 3c). As the cavity grows, the upper block overhangs, and when the stress in the overhang exceeds the ultimate tensile strength of the soil, the block will fall (Figure 3d). And along with the falling of the soil block above the hollowing area of the wall, the lesion continued to develop and the line of the lesion shifted upwards. As the bottom hollowing lesion progressively develops upwards and deeper, and the erosion situation is different on both sides, one side of the wall will be peeled off along the central wall platen seam, which will result in the formation of a top-to-bottom through crack in the wall at the centerline (Figure 3 e). Under external camp forces such as earthquakes, rainfall, and windstorms, the eccentric forces increase the stresses at the weak points at the base of the wall or at the severe cuts in the cracks, leading to unilateral tipping damage of the wall toward the critical surface (Figure 3f). Eventually, with the increasing degree of wall spalling and tilting, the deteriorated wall is unable to maintain its own stable state and undergoes structural instability and complete overturning due to its own gravity and external natural action (Figure 3g-h). By sorting out the deterioration process and collapse time sequence of the wall, the typical deterioration pattern of rammed earth wall disease throughout the life cycle was clarified, and it is possible to evaluate the deterioration status of different sections of the site and clarify the stage of the disease, similar to the diagnosis of "early-mid-late" cancer, and then adopt targeted preservation strategies for walls in different stages of deterioration. The wall in different stages of deterioration can then be protected with targeted protection strategies.

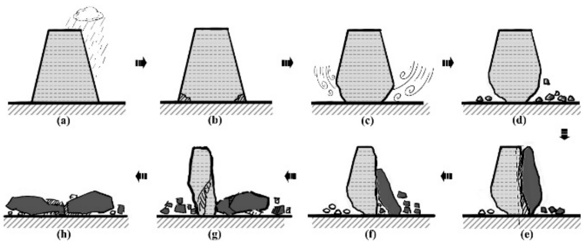


Figure 3 Time sequence of deterioration and collapse of rammed earth wall.

4. Risk assessment of disease deterioration based on morphological characterization indicators

Based on the digitized survey of structural deterioration along the Great Wall, this study employs high-precision 3D point cloud modeling to quantitatively assess erosion damage in representative sections through morphological feature fitting. A comparative analysis across different segments is conducted using four specific metrics: hollowing height, hollowing depth, hollowing area, and morphological hollowing rate. These indicators enable a quantitative evaluation and classification of erosion severity within individual sections.

The primary methodology consists of the following steps: First, a high-resolution 3D point cloud model of a typical section is constructed using unmanned aerial vehicle (UAV) close-range photogrammetry (Figure 4a). Second, the 3D model is longitudinally segmented at intervals of 5–10 meters according to section lengths, generating vertical profiles and extracting their contour lines (Figure 4b). Third, incomplete or obstructed profiles—such as those intersecting with beacon towers, collapsed wall segments, vegetation, or base piles—are filtered and excluded based on the contour morphology. Finally, the intact segments are used to reconstruct an ideal wall profile: the height is determined based on the existing parapet and continuous main wall top, while the closure angle and width are derived from well-preserved upper sections. This process allows for the fitting of a complete theoretical wall profile, with hollowed-out areas at the base clearly marked as shaded regions (Figure 4c).

Following the above model processing steps, the four indices—hollowing height, depth, area, and morphological hollowing rate—are computed based on the morphological attributes of the sections and the characteristics of the hollowing features. This approach facilitates a quantitative assessment and grading of hollowing damage within typical segments of the Great Wall.

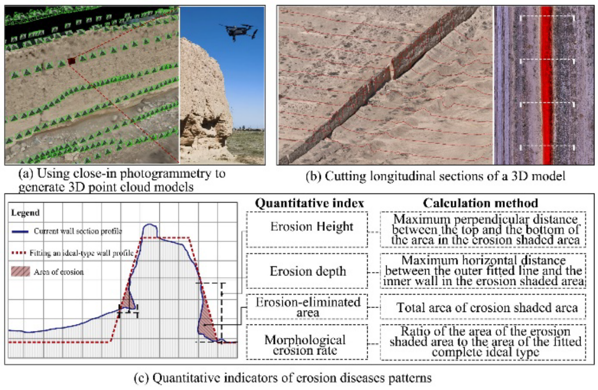
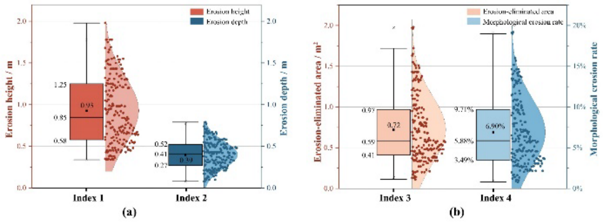


Figure 4 Morphological feature quantification using 3D point cloud.

Taking the Ming Great Wall in Gansu as an example, the quantitative indexes of the hollowing patterns of all sample sections are summarized, and box plots are drawn as shown inFigure 5. According to Figure 5a, it can be concluded that the overall hollowing height of each section is generally greater than the depth of hollowing, and the data of hollowing height is widely distributed and the data changes are more abundant, while the depth of hollowing is more stable and concentrated, and the data changes are small. Among them, the maximum value of the hollowing height is 1.98m (Erdun Great Wall of Gulang County), and the minimum value is 0.34m (Changfeng Great Wall of Wuwei City, with a difference of 1.64m; according to the values of the upper and lower boundaries of the box and line diagrams, the hollowing height is centrally distributed in the range of 0.58m-1.25m, with a mean value of 0.93m. The maximum value of the hollowing depth is 0.79 (Shilibao Great Wall of Shandan County), and the minimum value is 0.08m. The maximum value of hollowing depth is 0.79 (Shilibao Great Wall in Shandan County), and the minimum value is 0.08m (Liu Fuzhai Great Wall in Shandan County), with a difference of 0.71m, and the depth of hollowing is centrally distributed in the range of 0.27-0.52m, with an average value of 0.41m. The differences in the extreme values of hollowing height and depth indicators reflect that the deterioration of rammed-earth wall bodies exists in large differences in different sections, which may be affected by the natural environment in which walls are endowed, such as changes in topography, the moisture content of surrounding soil, and salt content, among other factors. and salinity, etc . According toFigure 5b, it can be concluded that the median of the data of hollowing area and overall hollowing rate are both higher, and the upper and lower boundaries of the box line have a large range, which indicates that the data are more widely distributed as a whole, further reflecting that the variability of the environmental conditions around the rammed-earth Great Wall may be an important factor affecting the hollowing.



(a) Statistics on the height and depth of hollowing

(b) Statistics on hollowing area and morphological hollowing rate

Figure 5 Morphological Indicators Statistics.

Based on the three-dimensional point cloud model of the Great Wall acquired through low-altitude photogrammetry, axial dissection and Z-axis calibration are performed to generate a pseudo-color depth map illustrating the concave and convex variations of the wall surface. This visualization intuitively highlights the recessed characteristics of hollowed areas at the base. By analyzing color gradients within the depth map, a continuous hollowing profile can be fitted, tracking the progression of erosion along the façade.

Using the quantitative indicators of hollowing morphology outlined in Section 3.1, cluster analysis is applied to the index values, enabling risk assessment of disease severity at any point along a wall section. This approach provides a scientific basis for establishing future grading standards for deterioration of immovable cultural relics. Based on the computed indicator values, the wall damage is categorized into four risk levels, from 1 (lowest) to 4 (most severe).

Taking the Shilibao segment of the Great Wall in Gansu as an example (Figure 6), the 3D point cloud model is sliced at 1-meter intervals to calculate the morphological hollowing rate for each profile. This enables precise grading of hollowing damage at a resolution of one meter, facilitating the creation of a detailed disease risk map that visually represents erosion severity within individual sections (Jarrah et al. 2020).

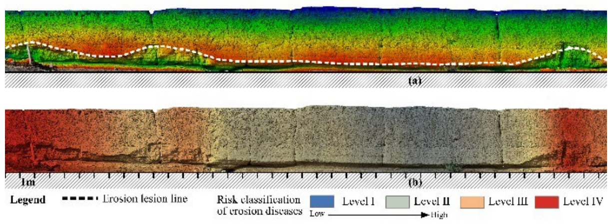


Figure 6 Grading of foci line fitting and deterioration of the hollowing out lesions.

According to the Construction and Protection Plan for the Great Wall National Cultural Parkissued in 2019, the aim is to fully complete the development of the Great Wall National Cultural Park by 2035 and establish a comprehensive system for the conservation, 传 承 , and utilization of the Great Wall. Quantitative risk assessment of the heritage structure itself enables effective risk management and offers foundational support for major decision-making in conservation projects. The findings of this research address the previous lack of methods for evaluating the progression of deterioration within individual sections and allow for risk assessment at any point along any segment. In the future, regular digital surveys can be used to monitor the condition of the structure in near real-time, providing timely risk warnings for ongoing deterioration. This will form a fundamental database for the conservation of heritage sites designated for protection, help identify critical areas for repair work, and offer technical support for the dynamic monitoring of the heritage structure.

5. Conclusion

Guided by the concept of preventive conservation, this study proposes a systematic approach for managing the erosion risks of the Great Wall throughout its entire lifecycle. By leveraging unmanned aerial vehicle (UAV) low-altitude photogrammetry, a digital workflow of “census–quantification–assessment” is established to support holistic heritage conservation. Compared to traditional reactive protection models, the methodology introduced here enhances preventive conservation through three key aspects:

First, a digital archive of structural deterioration, built using multi-temporal monitoring data, enables visualized and dynamic tracking of the heritage structure. This establishes an essential database for long-term monitoring of the structural health of the Wall.

Second, by analyzing full-lifecycle degradation patterns and assessing risk levels, the intervention point for conservation is shifted from traditional “emergency repair” to the stage of “risk prediction.” This allows for forecasting disease progression and issuing early warnings at different severity levels, thereby supporting tailored conservation strategies for sections based on their condition.

Third, a quantitative grading system for structural damage—based on point cloud modeling—overcomes the limitations of ambiguous qualitative descriptions used in the past. It transforms conservation decision-making from experience-based judgement to data-driven insight, offering a scientific foundation for developing differentiated and preventive maintenance plans(Vaknin et al. 2024).

The application of technologies such as low-altitude remote sensing and satellite remote sensing offers significant potential for establishing digital disease archives for large-scale cultural heritage sites. Digital disease surveys enable comprehensive documentation of deterioration, enhancing the archaeological investigation of heritage in all dimensions. Furthermore, by integrating computer vision and artificial intelligence, the retrieval, statistical analysis, and interpretation of database information can be automated. With continued research and practical development, this approach can facilitate real-time monitoring of structural conditions and early risk warnings.

This methodology not only supports the conservation and restoration of the Great Wall World Heritage Site but can also be extended to other archaeological excavation projects and cultural relic protection initiatives. Its versatility and broad applicability make it highly valuable for widespread adoption in the field of heritage conservation..

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