A Multi-Regional Cultural Heritage Risk Monitoring and Management Platform for Grotto Temple Sites

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Abstract

Grotto temples in China, with their wide distribution, rich historical heritage, and profound cultural significance, constitute one of the most distinctive categories in the list of World Heritage. In contrast to world-renowned sites such as the Mogao Caves, the vast majority of grottoes in China are of small to medium scale. These sites, often situated in remote regions with scarce conservation resources available, face more severe challenges in heritage protection. A multi-regional cultural heritage risk monitoring and management platform for grotto temple sites was constructed, aiming to address challenges faced by small and medium-sized grottoes – including non-standardized assessments of physical conditions, ineffective monitoring of risk factors, low resilience to natural disasters, and shortages of professional personnel and funds. This study first introduced the construction philosophy of a multi-regional monitoring and management platform for grotto temple sites. A hybrid system framework integrating regional-scale and site-specific monitoring was then designed, establishing a two-tiered "regional–site" risk-event response mechanism. Finally, it provided a detailed demonstration of how both regional-scale and site-specific monitoring and early-warning platforms are implemented. The system has been successfully applied to six grotto temples in China. It facilitates unified monitoring of natural disasters and the dynamics within protection zones, while also enabling targeted monitoring of deterioration risks specific to each site. Consequently, it significantly bolsters the overall conservation and management capacities of these sites. This approach provides a valuable reference for the systematic preservation of small to medium-sized cultural heritage sites, not only in China but also in other countries.

1. Introduction

1.1 Background

Cave temples, usually carved into cliffs, embody a unique synthesis of architecture, sculptures, murals, and calligraphy, and historically served as important venues for religious rituals. The cave temples are widely distributed in China and span a vast temporal range – from the Eastern Jin and Sixteen Kingdoms period in the 3rd century CE to the Qing Dynasty in the 19th century. The evolution of architectural forms and the stylistic features of murals and sculptures within these sites provide critical evidence of sustained cultural exchange between ancient China and other civilizations. Furthermore, the depictions of social life in murals offer invaluable primary sources for studying China's historical societal development. Consequently, cave temples possess an exceptional combination of historical, artistic, scientific, social, and cultural value. They constitute an integral part of China's cultural heritage and represent one of the most distinctive Chinese categories within the global corpus of World Cultural Heritage. Among them, internationally renowned sites such as the Mogao Caves and the Yungang Grottoes are exemplary (Wang and Guo, 2019).

The latest investigation conducted by the National Cultural Heritage Administration shows that there are a total of 5986 cave temples (including cliffside statues) in China (Zhao, 2023a). Among them, 288 are designated as major heritage sites protected at the national level, and 417 are protected at the provincial level. According to the survey results, over 88% of the sites fall below the provincial level and consist primarily of small to medium-sized cave temples. These sites are typically located in remote mountainous areas with weak institutional capacity for conservation and management. As the level of official protection decreases, these sites receive significantly less attention, with significantly fewer financial and human resources allocated for their conservation compared to nationally protected sites.

In recent years, the intensification of global climate change has exacerbated the vulnerability of cave temples to complex and dynamic natural hazards. Environmental factors including precipitation, windborne sand, and temperature fluctuations have led to structural instability, weathering, water infiltration, biological colonization, and other forms of deterioration, thereby posing escalating threats to the preservation of these cultural heritage sites. The lack of dedicated conservation institutions and the shortage of adequately trained personnel for many small and medium-sized cave temples impede the effective safeguarding of their invaluable cultural assets. Thus, the question of how to strengthen the conservation capacity of these numerous lower-tier sites – thereby mitigating their elevated risk exposure – has emerged as a critical challenge in the broader context of the systematic conservation of cave temples in China.

Addressing these challenges requires, first and foremost, the physical conditions of heritage elements need to be timeously and accurately assessed. Given the specific deterioration issues identified, targeted conservation strategies should be formulated and implemented. For instance, caves with compromised structural stability and facing risks of collapse, mural detachment, or sculpture toppling necessitate immediate

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emergency interventions. In cases where cliff surfaces exhibit weathering, seepage, or cracking – and where murals or sculptures are highly sensitive to environmental variables – continuous monitoring of risk factors is essential. Regular evaluations based on monitoring data can inform adaptive conservation planning and decision-making. Therefore, scientific assessment of the preservation state and sustained monitoring of environmental and structural risks are fundamental to strengthening the conservation and management capacities of small and medium-sized cave temples.

1.2 Related Work

Many leading international heritage institutions have developed systematic frameworks for conservation assessment and monitoring, which facilitates effective identification and management of heritage risks. These efforts aim to support preventative conservation and ensure the long-term sustainability of cultural heritage.

For instance, the archaeological site of Pompeii in Italy, due to its vast spatial extent and pronounced vulnerability, has adopted a comprehensive methodology for assessing and monitoring its preservation state. This approach involves general assessment surveys, microclimate monitoring (Merello *et al*., 2012), seismic risk assessments (Ruggieri *et al*., 2022), and photomosaic documentation (Boucherie, 2018). These efforts are ultimately integrated into preventative conservation measures, supporting the sustainable preservation of the site (Merello *et al*., 2013). Angkor Wat employed a multifaceted strategy to assess and monitor the condition of the site. This includes detailed documentation and analysis of the sandstone material for bas-reliefs and devatas (apsaras) (Leisen and Plehwe-Leisen, 2008), monitoring of structural stability using advanced remote sensing techniques (Chen *et al*., 2021a), and the development of flood hazard distribution maps (Liu *et al*., 2019). These assessments inform the implementation of targeted conservation measures to mitigate erosion and other forms of damage. In Istanbul, Hagia Sophia integrated environmental monitoring (Emrullah and Eser, 2018; Mizutani *et al*., 2021) with structural health monitoring techniques to observe the behavior of its massive central dome. Finite element modeling has also been employed to simulate structural responses under various load conditions, including seismic events (Ozkul and Kuribayashi, 2007). Additionally, non-invasive diagnostic methods were adopted to examine the mosaics in the south upper gallery, enabling the evaluation of their current preservation status and previous restoration efforts (Moropoulou *et al*., 2013).

Similarly, major heritage sites in China such as the Great Wall, the Palace Museum, and the Mogao Caves have adopted advanced monitoring and conservation strategies. For the Great Wall, the Small Baseline Subset Interferometric Synthetic Aperture Radar enables the monitoring of large-scale surface deformation (Chen *et al*., 2021b; Xu *et al*., 2021), while rainfall disaster and ecological risk models provide data-driven protection strategies (Zhao, 2023b; Li *et al*., 2021). At the Palace Museum, an indoor environmental monitoring network is used to track temperature, humidity, concentrations of carbon dioxide (CO_2), total volatile organic compounds, illumination, and ultraviolet intensity exposure across 60 historic buildings, guiding preventative conservation (Zhang *et al*., 2021). Targeted studies, such as crack monitoring via photogrammetry, further support structural health assessments (He *et al*., 2025). The Mogao Caves, managed by Dunhuang Academy, integrate meteorological, microclimatic, and structural data through an IoT-based monitoring and early warning system. This system assesses mural deterioration, cave stability, visitor impact, and environmental hazards, enabling science-based preventative measures (Wang, 2015). The system has since been extended to the Yulin Grottoes and Western Thousand-Buddha Caves, promoting holistic conservation across multiple cave temples.

1.3 Conservation Requirements

Building on its extensive expertise in cave temple conservation and management, the Dunhuang Academy has been entrusted with several additional heritage sites. In 2017, the Maijishan Grottoes and Bingling Temple Grottoes – both inscribed as part of the World Cultural Heritage property *Silk Roads: the Routes Network of Chang'an–Tianshan Corridor* – along with the North Grottoes, a nationally protected heritage site, were officially placed under the unified management of the Academy. As a result, Dunhuang Academy became the institution responsible for the largest number of cultural heritage sites in China (Figure 1).

Figure 1. Six cave temples managed by the Dunhuang Academy. (a) Mogao Caves, (b) Maijishan Grottoes, (c) Bingling Cave - Temple, (d) Yulin Grottoes, (e) Western Thousand-Buddha Caves, (f) North Grottoes. © Dunhuang Academy.

The six grotto sites are geographically dispersed, with the farthest located over 1500 km from the Mogao Caves. They are situated in varied geographical and climatic contexts and differ markedly in their levels of conservation and management capacity. This diversity makes them a representative microcosm of the broader challenges facing the conservation of cave temples in China.

A critical question now facing the Dunhuang Academy is how to transfer the capabilities developed at the Mogao Caves – particularly in condition assessment, risk monitoring, and early warning systems – to these other sites. The primary goal is to gain a dynamic understanding of preservation conditions, strengthen risk mitigation, and promote more balanced conservation practices across all six sites. This initiative serves as a valuable model for advancing the protection of numerous small and medium-sized cave temples across China.

1.4 Proposed Approach

Amidst the rapid advancement of emerging technologies such as cloud computing, big data, and artificial intelligence, there is a growing opportunity to transform heritage conservation practices. Drawing on the extensive experience of staff of Dunhuang Academy in the conservation and management of the Mogao Caves, and leveraging its established multi-site management framework, the design and implementation of a multi-regional risk monitoring and early warning platform are proposed for cave temple heritage sites.

This system adopts a two-tiered model comprising both regional-scale and site-specific monitoring platforms. At the regional scale, regional monitoring centers collaborate with specialized national institutions – including meteorological, seismic, and satellite remote sensing agencies – to provide targeted monitoring services for shared natural disaster risks. This enables comprehensive oversight and timeous intervention for major external threats facing cave temples. At the site level, heritage sites receive standardized software services for condition assessment, risk monitoring, early warning, data analysis, risk assessment, and response planning, delivered through the regional center. By simply deploying monitoring equipment tailored to their specific risk factors and connecting to the central platform, individual sites – especially small to medium-sized ones – can quickly and cost-efficiently establish a standardized, targeted risk monitoring and warning system, allowing for effective management of site-specific risk factors.

This framework not only promotes balanced conservation capacity across the six major sites under the jurisdiction of Dunhuang Academy, but also addresses widespread challenges faced by numerous small and medium-sized cave temples in China, including the limited resilience to natural disasters, lack of standardized condition assessment, insufficient monitoring and early warning capacity, and constraints in personnel and funding. Furthermore, this approach holds potential as a scalable model for enhancing cultural heritage management systems for small and medium-sized heritage sites both in China and abroad.

The remainder of this paper is organized as follows: Section 2 outlines the overall framework and core concepts of the proposed risk monitoring and management system; Section 3 presents the implementation outcomes and system demonstrations; Section 4 provides main conclusions.

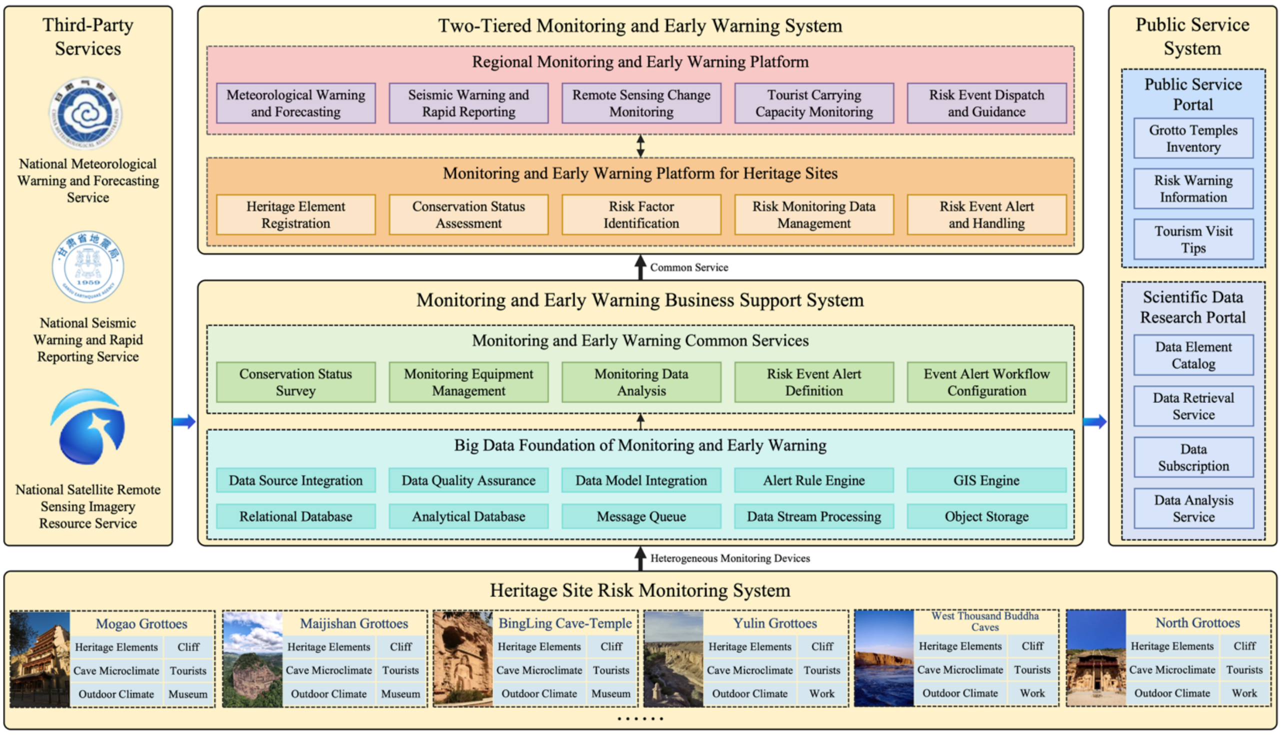

Figure 2. The framework of the multi-regional risk monitoring and management platform for cave temple heritage sites.

2. Methods

2.1 System Framework

The overall framework of the multi-regional risk monitoring and management platform for cave temple heritage sites is illustrated in Figure 2.

The framework comprises five core components: a two-tiered monitoring and early warning system, a monitoring and early warning business support system, third-party services, a public service system, and a risk monitoring system for heritage sites.

The two-tiered monitoring and early warning system is designed to support different levels of heritage management requirements by providing tailored software platforms. It is composed of both a regional-scale monitoring system for major shared risks – such as natural disasters – affecting groups of cave temples, and a site-specific monitoring and early warning system that addresses the unique risk factors of individual sites.

The monitoring and early warning business support system, that comprises a big data foundation and a suite of common services, provides foundational services for the two-tiered monitoring architecture.

The risk monitoring system for heritage sites is composed of a range of sensing devices installed at heritage sites. These devices are integrated into the monitoring and early warning business support system and deliver real-time data to support risk assessment and monitoring at each site.

The third-party services offer specialized early warning and rapid reporting capabilities for large-scale regional risks including natural disasters. These services include access to meteorological and seismic alerts issued by national agencies, as well as satellite remote sensing imagery and data products provided by relevant institutions.

Finally, beyond serving professional heritage managers, the proposed monitoring and early warning system also meets the needs of the general public through a public service system, which includes a public service portal and a scientific data research portal.

2.2 Two-Tiered Monitoring and Early Warning System

2.2.1 Regional Monitoring and Early Warning Platform: The regional monitoring and early warning platform comprises five core components: meteorological warning and forecasting, seismic warning and rapid reporting, remote sensing change monitoring, tourist carrying capacity monitoring, and risk-event dispatch and guidance.

First, the regional monitoring center collaborates with specialized third-party institutions to conduct natural disaster risk monitoring. Given that cave temples are typically built into mountain cliffs, they are especially vulnerable to environmental influences. In recent years, the increasing frequency of disasters under the impact of global climate change – such as earthquakes, floods, mudslides, and landslides – has posed severe threats to the preservation of these invaluable cultural sites. Due to the interconnected and regional nature of such events, a disaster influencing one site often impacts nearby cave temples as well. Considering the limited disaster response capacity of small and medium-sized cave temples, the establishment of a unified natural disaster monitoring system is proposed for regional cave temples. Through collaboration with national meteorological and seismic agencies, the regional monitoring center provides specialized services such as meteorological forecasting and earthquake early warning, significantly enhancing the disaster resilience of the cave temple network under its jurisdiction.

Second, the regional monitoring center utilizes national satellite remote sensing imagery resources to monitor changes in heritage sites. In accordance with Operational Guidelines of the UNESCO for the Implementation of the World Heritage Convention and China's cultural heritage protection laws, regular remote sensing monitoring of heritage protection zones enables the early detection and intervention of unauthorized developments or land use changes, thereby safeguarding the integrity of heritage values. Additionally, satellite imagery supports specialized monitoring of sites exposed to high disaster risks – such as flood-prone areas or unstable cliff faces – allowing for quantitative assessment of damage and providing essential data for informed conservation planning.

Third, the regional monitoring center monitors the visitor carrying capacity. Due to the fragile and irreplaceable nature of heritage elements including murals and sculptures, excessive tourism poses serious threats. Under national heritage protection and tourism regulations, all publicly accessible cave temples are required to ascertain and disclose their maximum daily visitor capacity. Exceeding this limit may jeopardize both the safety of the heritage and its visitors. In response to the rapid expansion of the cultural tourism sector, the regional monitoring center monitors the numbers of daily visitors by directly interfacing with the ticketing systems of each site, allowing for effective supervision of tourism operations and ensuring the protection of both the cultural assets and public safety.

In the event of a major disaster risk within the region, the monitoring center promptly issues early-warning notifications to affected heritage sites, and subsequently activates the risk-event dispatch and guidance mechanism to support and oversee local response initiatives.

2.2.2 Monitoring and Early Warning Platform for Heritage Sites: The monitoring and early warning platform for heritage site is designed to provide customized risk monitoring and early warning services for individual cave temples. It comprises five key components: heritage element registration, conservation status assessment, risk factor identification, risk monitoring data management, and risk-event alert and handling.

The process begins with heritage element registration, where heritage managers catalog the characteristics of heritage elements such as caves, murals, and sculptures – including their historical periods, content, and cultural significance. Following this, the conservation status assessment and risk factor identification modules support periodic investigations and assessments of the state of preservation of these elements, facilitating the identification and analysis of various risk factors. According to the observed deterioration phenomena and associated risks, targeted monitoring strategies are selected and implemented to construct a rational, element-specific monitoring system.

Through the risk-monitoring data-management module, professionals can analyze and interpret collected monitoring data, while the risk-event alert and handling module enables the timeous detection and resolution of risk events. In the case of major risks, the response process and outcomes are reported to the regional monitoring center via the platform to ensure coordinated intervention.

The monitoring system for cave temples consists of multiple components: health-condition monitoring for murals, sculptures, and other heritage elements (*e.g.*, chromaticity measurement, monitoring of mural surface temperature, visual detection of mural deterioration processes (Feng *et al*., 2021), and structural stability monitoring of sculptures); structural stability and weathering risk monitoring of cliff faces (*e.g.*, crack detection, water seepage, vibration, wind speed and direction, radiation levels); online monitoring of microclimatic risk factors within caves (*e.g.*, temperature, humidity, particulate matter concentration, and VOCs); real-time monitoring of external environmental factors (*e.g.*, ambient temperature and humidity, precipitation, wind conditions, and air pollutants); monitoring of visitor numbers within the caves; and environmental monitoring of display cases in on-site museums, with a particular focus on temperature and humidity risks affecting movable heritage. The platform can also track activities related to heritage research and conservation work processes.

Importantly, the monitoring and early warning platform for heritage sites is delivered as a Software-as-a-Service (SaaS) solution, enabling individualized management of monitoring systems for each site. When a new heritage site is added, administrators can simply create an account and configure the system following the standard workflow outlined above. This allows for the rapid deployment of tailored monitoring platforms with minimal cost and technical burden.

2.3 Monitoring and Early Warning Business Support System

2.3.1 Big Data Foundation of Monitoring and Early Warning: The big data foundation of monitoring and early warning (Figure 3) serves as the central data processing hub of the entire platform, encompassing several integrated components to support comprehensive data management and analysis. It consists of a relational database and an analytical database for structured data storage and analysis, as well as object storage for managing unstructured data. A message queue engine and data source integration services are responsible for integrating and transmitting data from heterogeneous monitoring devices. The foundation also incorporates a data stream processing engine and data quality assurance services to support data cleansing, real-time event alerts, statistical analysis, and data quality monitoring. Additionally, it incorporates a data model integration service for managing analytical and predictive models, an alert rule engine for defining and executing alert conditions for risk events, and a GIS engine for geospatial data analysis and visualization. Detailed technical specifications of the big data foundation, are provided elsewhere (Gong *et al*., 2025).

Figure 3. The architecture of the monitoring and early warning big data foundation (Gong *et al*., 2025).

2.3.2 Monitoring and Early Warning Common Services: Built upon the big data foundation, the monitoring and early warning common services module provides shared functionalities to support the operational needs of the two-tiered monitoring and early warning system, including services such as survey of the conservation status, management of monitoring equipment, analysis of monitoring data, definition of risk-event alerts, and configuration of event alert workflows. Specifically, the conservation status survey service delivers a standardized module for heritage element condition surveys, drawing upon the well-established survey specifications developed for use at the Mogao Caves. The monitoring equipment management service offers streamlined tools for managing a wide range of heterogeneous sensor devices, enabling rapid, efficient data ingestion, and maintenance of sensor status across diverse monitoring systems at various sites. The monitoring data analysis service offers powerful data retrieval and analytical capabilities to process the vast volume of risk monitoring data generated at each site. The risk-event alert definition service, built on the alert rule engine within the big data foundation, enables visual configuration of risk alert conditions tailored to the specific needs of each site. Finally, the event alert workflow configuration service supports the visual design of customized response workflows for various types of risk events, promoting efficient and standardized handling procedures.

2.4 Public Service System

2.4.1 Public Service Portal: The public service portal is designed to provide the general public with access to essential information related to regional grotto temples and their monitoring status. It includes features such as the inventory of grotto temples, risk-warning information, and tourism visit tips, offering an overview of heritage sites, real-time alerts, and practical guidance for visitors.

2.4.2 Scientific Data Research Portal: To meet the needs of researchers interested in monitoring data from grotto temples, the scientific data research portal has been developed to offer professional data services. This portal supports data element cataloging, a data retrieval service, data subscription, and data analysis services, enabling researchers to browse, query, download, and analyze monitoring data for scientific study and heritage conservation research.

3. Results

Using the six grotto sites under the jurisdiction of the Dunhuang Academy as pilot locations, a two-tiered monitoring and early warning business model was implemented based on the multi-regional risk monitoring and management platform framework for cave temple heritage sites proposed. This section presents the results related to the regional monitoring and early warning platform and the monitoring and early warning platforms for heritage sites.

3.1 Regional Monitoring and Early Warning Platform

The overview of the regional monitoring and early warning platform (hereafter referred to as the “regional platform”) is shown in Figure 4. Leveraging WebGIS technology, the platform displays the distribution of all grotto temple resources within Gansu Province where the Mogao Caves are located. It also integrates monitoring information related to natural disasters and tourist-carrying capacity for the six grotto sites managed by the Dunhuang Academy, presented on both sides of the interface.

Figure 4. The regional monitoring and early warning platform.

On the left-hand sidebar, the platform aggregates information including meteorological warnings, real-time weather conditions, and current risk alerts for each of the six sites. The right-hand sidebar displays the opening status of each site, real-time visitor load data, and updates on risk-event management.

For example, when the regional platform receives a major weather disaster warning issued by meteorological authorities for a specific grotto site, it immediately pushes the alert to the corresponding monitoring platform for heritage sites and notifies those personnel responsible via the mobile app. Simultaneously, the site in question is marked with a prominent symbol on the GIS map to draw attention to the risk. The platform also tracks and displays the handling process of the warning by heritage site managers in real time, ensuring that regional administrators can remain informed of the progress and responses being conducted at site level.

For earthquake early warnings and rapid reporting signals, the regional platform promptly pushes the relevant data directly to the corresponding monitoring and early warning platform for heritage sites, enabling local managers to make timely decisions. Simultaneously, the regional platform initiates real-time tracking of the earthquake response process.

As illustrated in Figure 5, the earthquake early warning interface of the heritage site presents a heatmap visualization showing the predicted intensity distribution from the earthquake epicenter to the heritage site across the affected spatial range. A pop-up window at the epicenter displays key details such as: the time of occurrence, epicenter location, magnitude, depth, and the distance between the epicenter and the heritage site, providing essential context for informed decision-making. Compared to traditional rapid reports that focus solely on magnitude and location, intensity prediction data offer a more precise basis for heritage site managers to assess the potential effects of an earthquake on grotto structures and artworks.

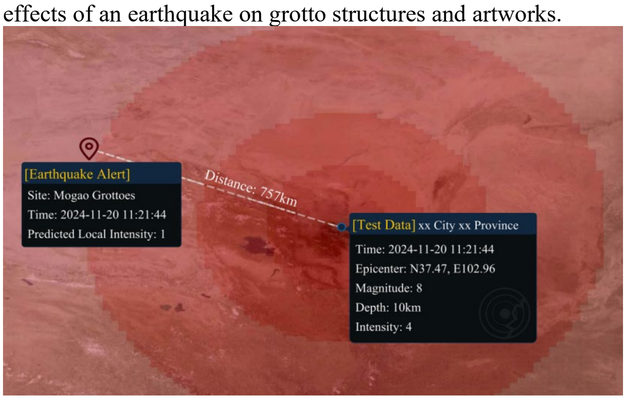

Figure 5. Visualization of earthquake early warning for the heritage site.

Upon receiving the earthquake early warning and rapid reporting signals, heritage site managers follow the earthquake response protocol defined by the regional platform (Figure 6) to manage the event. If the predicted seismic intensity exceeds level III, key caves and associated heritage elements at higher risk are prioritized for inspection. If the predicted seismic intensity reaches Level V, all heritage elements are comprehensively assessed.

Based on the inspection results, staff evaluate the extent and severity of the damage caused by the earthquake and develop targeted response strategies, including emergency stabilization or specialized monitoring. Once completing all assessments, a detailed earthquake incident response report is compiled and submitted to the regional platform for review and archiving.

In addition to the monitoring of disaster risks, the regional platform also provides remote sensing-based change detection services for heritage sites (Figure 7). By comparing multi-temporal satellite imagery, the system can identify changes in surface structures, vegetation, and even the heritage assets themselves within the protected zones. This capability offers valuable data support for the safety supervision of cultural heritage and the development of site-specific conservation and management strategies.

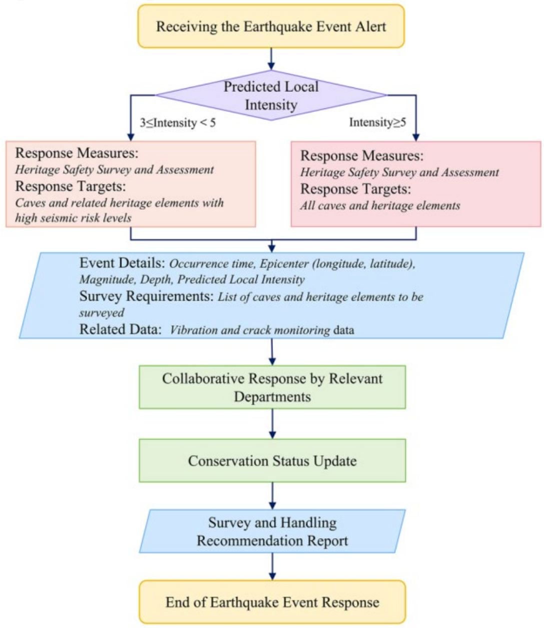

Figure 6. The flowchart through for the management of earthquake incidents.

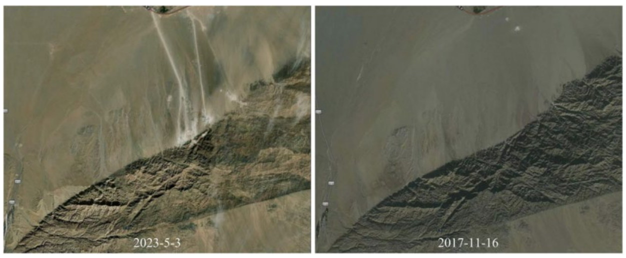

Figure 7. Monitoring results of remote sensing image changes in the Mogao Caves Protection Area.

3.2 Monitoring and Early Warning Platform for Heritage Sites

The monitoring and early warning platform for heritage sites consists of a front-end data visualization interface and a back-end business processing interface.

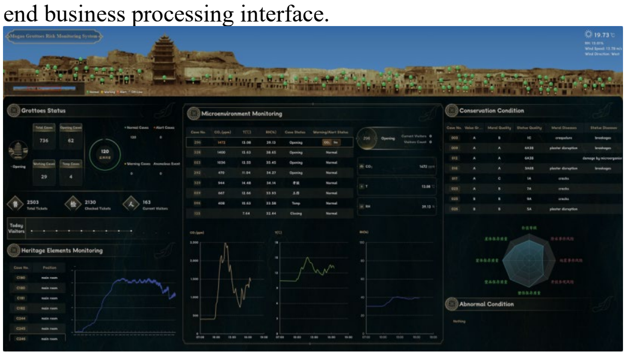

Figure 8. Front-end data visualization interface of the monitoring and early warning platform for Mogao Caves.

The front-end interface is designed to provide real-time visualization of various risk alerts and associated monitoring data from grotto temples, empowering site managers to promptly review and respond to emerging risks. Considering that grotto temples are frequently scattered across cliff faces, elevation diagrams of the grotto site are utilized to more intuitively display the alert status of individual caves.

For instance, as shown in Figure 8 – the dashboard for the Mogao Caves monitoring and early warning platform – each circular icon on the elevation diagram corresponds to a specific cave and indicates its current risk alert status. A green icon means that no alert is present; yellow signals a warning; and red suggests an active alert.

At the Mogao Caves, alert events are primarily triggered by fluctuations in two key monitoring indicators: the relative humidity and CO_2 concentration inside the caves.

Based on years of research, the critical threshold for the deliquescence and crystallization of soluble salts on the surface of Mogao Caves murals is approximately 67% relative humidity. When the relative humidity inside a cave exceeds this threshold, the activity of such salts may accelerate mural deterioration (Demas *et al*., 2015). Consequently, relative humidity is treated as a key monitoring parameter. Once the 67% threshold is surpassed, an alert is triggered, and the status indicator for the specific turns red, prompting site managers to take dehumidification measures to reduce the risk of damage to the murals.

The further to expound the influence of tourist presence – which can increase the humidity within the cave – a lower threshold of 62% has been set to trigger early warnings. When exceeding this pre-alert level, the status indicator changes from green to yellow, signaling that the cave is currently unsuitable for tourist visits.

Monitoring CO_2 levels inside the caves is primarily aimed at ensuring visitor comfort and safety. Most of the Mogao Caves have relatively small, enclosed spaces, with cave doors serving as the only point for air exchange. During peak tourist seasons, high visitor traffic leads to poor air quality, potentially causing discomfort. According to China’s national indoor air quality standards, the early warning and alert thresholds for CO_2 concentration are set at 1500 ppm and 2000 ppm, respectively. If exceeding these thresholds, the corresponding status indicator turns yellow or red, indicative of potential health risks for visitors.

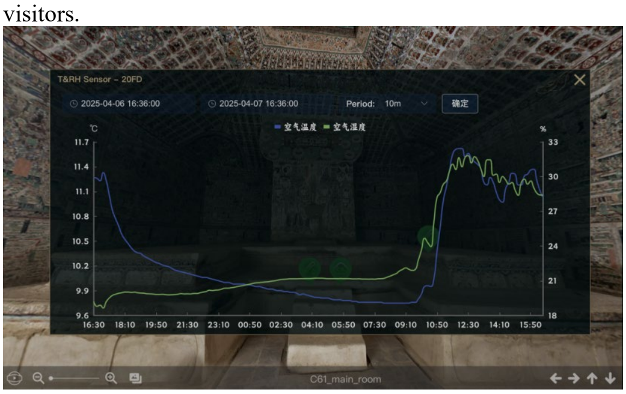

Figure 9. The monitoring interface for an individual cave.

By clicking on the status indicator of a cave, users can access the monitoring interface of the cave (Figure 9). This view includes a 360° panorama image of the cave interior, allowing for full spatial visualization and real-time monitoring data from installed sensors.

The back-end business processing interface primarily supports key functions such as heritage element conservation status assessment, monitoring equipment management, monitoring data analysis, and risk-event handling. As exemplified by the conservation status assessment of heritage elements (Figure 10), conservation professionals can conduct detailed inspections and record the condition of each component within a cave (*e.g*. murals, statues, floors, doors and windows, parapets, monitoring devices, and open/closed status). This process facilitates a comprehensive evaluation of the conservation status of heritage elements and enables the formulation of targeted conservation and management recommendations.

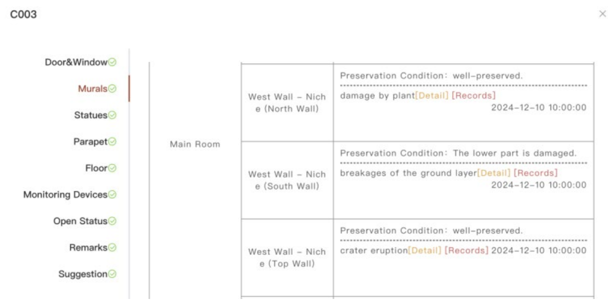

Figure 10. Investigation and evaluation module for the preservation status of heritage elements.

4. Conclusions

This study addresses key challenges faced by the conservation and management of China’s numerous small and medium-sized grotto temples, including the lack of standardized assessments of heritage element conservation status, limited capacity for effective risk monitoring, weak resilience to natural disasters, and shortages of professional personnel and funding. Using the six grotto temples under the administration of the Dunhuang Academy as case studies, a multi-regional cultural heritage risk monitoring and early warning platform was developed. This system enables centralized monitoring of natural disasters and protection zone changes across grotto temples through a regional platform, while also supporting standardized construction of site-specific monitoring systems by providing unified services such as conservation status assessment, monitoring equipment integration and management, data storage and analysis, and risk-event handling.

The main contributions of this study are as follows:

(1) A conceptual framework for a multi-regional preventative conservation platform for cave temple groups is established. By leveraging a shared software platform, the system enables the transfer of best practice from the Mogao Caves to other sites, including condition assessment, risk monitoring, and platform development experience;

(2) A hybrid monitoring and early warning framework integrating regional-scale and site-specific monitoring is designed. Rooted in conservation needs, this framework incorporates regional monitoring for natural disaster risks and customized monitoring for site-specific deterioration risks, thus addressing the challenge of scaling risk monitoring systems across large numbers of small and medium-sized cave temples;

(3) A two-tiered response mechanism, encompassing the regional monitoring center and individual heritage sites, is established. Based on real-time monitoring data, event-triggering strategies and graded response mechanisms are devised to align with the conservation requirements of different cave temples, thus closing the loop between monitoring and management actions;

The Dunhuang Academy's central monitoring and early warning platform, built upon this system, has substantially improved risk management for sites such as Mogao Caves and Maijishan Grottoes. The framework is currently being extended to underpin a province-wide monitoring platform across Gansu, offering a scalable foundation for the conservation and management of many more small and medium-sized grotto temples.

Acknowledgements

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