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Original Article

Modal Analysis of Earthen Heritage Sites: A Case Study of the Hanguang Gate Section of the Xi'an City Wall

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Abstract - *The Xi'an City Wall, a prominent earthen heritage site in China with over 600 years of history, holds significant cultural, economic, and archaeological value. Over centuries, it has undergone progressive deterioration due to natural weathering, seismic events, and environmental vibrations, with vibrations identified as a critical factor in structural degradation. Despite this, the dynamic characteristics of earthen heritage sites under vibration remain poorly understood. This study addresses this gap by employing a three-dimensional finite element model to investigate the modal behavior of the Hanguang Gate section of the Xi'an City Wall, China, providing new insights into the damage mechanisms induced by environmental vibrations. Results reveal that the wall's natural frequencies fall within a low-frequency range, with stress concentration occurring at geometric transitions and peak displacement observed at the upper regions. These findings enhance the understanding of vibrational damage mechanisms and provide a scientific foundation for developing targeted vibration isolation strategies to preserve earthen heritage structures.*

Keywords - *City wall, Earthen sites, Environmental vibrations, Modal analyses, Numerical simulations.*

1. Introduction

Earthen heritage sites are extensively distributed across China. They serve as invaluable assets for historical and cultural studies and also function as significant tourism resources with considerable economic value [1-3]. The Xi'an City Wall, a prominent cultural relic constructed more than 600 years ago during the Ming Dynasty, is a nationally protected heritage site [4]. Among its sections, the Hanguang Gate site (Figure 1) is the most well-preserved, highlighting the importance of its conservation for historical research and cultural heritage preservation.

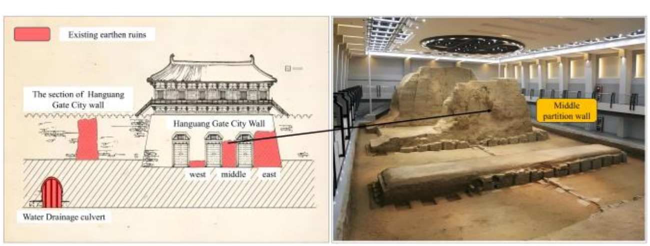

Fig. 1 Hanguang gate site

Although the Hanguang Gate earthen site of the Xi'an City Wall is housed within a museum, shielding it from weathering erosion, it remains susceptible to damage caused by earthquakes and environmental vibrations. Field monitoring and model experiments by Yang Ruijuan revealed that the top of the Hanguang Gate partition wall is subjected to environmental vibrations exceeding the standard vibration velocity for more than 19 hours daily, potentially leading to fatigue damage at the wall's top. Similarly, Ma Meng et al. [5] demonstrated through field monitoring and numerical simulations that the Xi'an City Wall and the Xi'an Bell Tower are affected by the vibration waves of subway operations. Due to their intense impact forces, Earthquakes pose a significantly greater threat to earthen heritage sites, often resulting in severe structural damage. For instance, the Wenchuan earthquake on May 12, 2008, in Sichuan, China, caused extensive destruction to numerous earthen buildings and towers [6], highlighting the vulnerability of such structures to seismic activity. Similarly, the Pisco earthquake [7] compromised the structural integrity of earthen constructions, while the Maule earthquake [8] led to widespread cracking and collapse of rammed-earth houses. Prolonged exposure to environmental vibrations can induce fatigue damage in earthen heritage sites, while sporadic seismic events have the potential to cause severe structural degradation. However, current research primarily focuses on three key aspects: the response of earthen heritage sites to vibration waves, the damage patterns and affected locations of these sites following seismic events, and the principles

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governing their failure under various types sof seismic waves. Notably, there is a significant gap in the study of the intrinsic dynamic characteristics of earthen sites themselves. Consequently, conservation and seismic mitigation measures are often implemented without conducting modal analysis, which limits their effectiveness in reducing vibration-induced damage.

Modal analysis is extensively applied in fields such as mechanical systems, bridges, and architectural structures, enabling the refinement and optimization of dynamic technical parameters to mitigate the adverse effects of vibrations on these structures [9]. Modal analysis is a fundamental approach for investigating the dynamic behavior of structures under vibratory conditions. By characterizing the inherent properties of a structure—namely, natural frequencies, mode shapes, and damping ratios—provides insights into the dynamic responses induced by external excitations [10, 11].

The key components of modal analysis encompass natural frequency, mode shape, and damping ratio [12]. Natural frequency represents the frequency at which a structure undergoes free vibration, independent of external excitation, with each vibrational mode corresponding to a distinct natural frequency. Mode shape delineates the deformation pattern exhibited by a structure at a specific natural frequency, capturing the relative motion among various points during vibration. At the same time, the damping ratio quantifies the energy dissipation rate, governing the attenuation of vibrational amplitudes over time [13].

The modal characteristics of a structure are significantly influenced by several factors, including material properties, geometric configuration, boundary conditions, loading scenarios, and structural defects [14]. Material properties [15], such as elastic modulus, density, and Poisson's ratio, together with structural geometry (shape, size, and mass distribution), play a critical role in determining natural frequencies and mode shapes. Boundary conditions [16] (e.g., fixed, hinged, or free) and applied constraints profoundly affect vibrational behavior. Environmental factors [15], such as prestress, temperature variations, and humidity, may alter material properties and geometric parameters, consequently modifying the modal characteristics. Structural defects, including cracks, damages, and nonlinear behaviors, introduce deviations in the vibrational modes, potentially degrading structural performance.

With the advancement of computer technology, Finite Element Analysis (FEA) has emerged as one of the pivotal techniques in modal analysis. For instance, Liu Zhicheng [17] validated the accuracy of the theoretical modal model for transmission line towers using a finite element model. Similarly, Wu Yingrui [18] employed finite element modeling to analyze the modal characteristics of a rammed earth dam, while Zhao Jingui [19] utilized finite element analysis to investigate the modal behavior of architectural structures. However, scholars have predominantly focused on failure patterns and mechanisms under seismic actions for earthen heritage sites. For example, Federica Greco [20] utilized numerical simulations to identify the vibration-induced damage distribution and failure mechanisms of earthen sites following earthquakes. Similarly, Karanikoloudis [21] employed numerical modeling to analyze the structural damage and inelastic behavior of the rammed earth structure, the Church of Kuño Tambo. Fernando Ávila [22] applied Finite Element Method (FEM) analysis to investigate the seismic response of the Tower of Muhammad, a rammed earth structure. These studies collectively underscore the effectiveness of numerical simulations as a robust tool for elucidating the failure mechanisms and damage characteristics of earthen heritage sites under seismic conditions. Nevertheless, there is a notable lack of research on the modal properties of earthen sites, and their seismic performance has not been adequately considered in the design of reinforcement strategies, thereby hindering the optimization of their maintenance and preservation approaches.

This study employs ABAQUS software to model and analyze the dynamic characteristics of the Hanguang Gate site, focusing on its natural frequencies, mode shapes and the response of displacement, acceleration, and stress to the environment vibration. Environmental vibration waves collected on-site were applied as input excitations. The findings of this study contribute to the refinement of reinforcement and maintenance strategies for earthen heritage sites, particularly in optimizing design parameters for seismic and vibration mitigation.

2. Methodology

2.1. Background

The Hanguang Gate, originally constructed in 582 AD during the establishment of Chang’an City in the Sui Dynasty, functioned as a ceremonial gateway for receiving envoys and foreign dignitaries during the Tang Dynasty. Notably, during the two phases of Xi’an City Wall construction in the Ming and Qing Dynasties, the gate was encapsulated within the newly built fortifications. This unique circumstance facilitated the preservation of the Tang Dynasty structure, safeguarding it as an archaeological relic. In 1986, systematic excavations of the city wall revealed the site of Hanguang Gate, leading to the establishment of the Xi’an Tang City Wall Hanguang Gate Site Museum in 2008 to protect and present this historical artefact.

Architecturally, the Hanguang Gate site exhibits a rectangular layout featuring three distinct doorways of varying widths. The central doorway measures 5.72 meters, while the eastern and western doorways each measure 5.35 meters. The gate pier spans 37.4 meters in length from east to west and 19.6 meters in width from north to south, oriented at 1°30′ north by east. Constructed using compacted loess rammed earth, the structure demonstrates a stratified elevation profile: the eastern section reaches a height of 8.2 meters, the central partition wall rises to 7.95 meters, and the partition wall itself has a thickness of 3.07 meters. These measurements and structural characteristics reflect the advanced engineering techniques of the Tang Dynasty, providing critical insights into the ceremonial and functional design of urban gates in ancient Chinese cities.

2.2. FEM Modeling

A three-dimensional finite element model of the interstitial walls at the Hangguang Gate site was established using Abaqus V.24, with a 1:1 scale corresponding to the prototype, as depicted in Figure 2. To enhance computational efficiency, the model excluded considerations of localized detachment observed at the wall end and sides and the influence of adjacent structures.

Table 1. The material properties of the earthen site

Density P (kg/m^3)	Elastic Modulus (E/MPa)	Poisson's Ratio (ν)
1550	11	0.29
1580	11	0.29
1610	11	0.29

Fig. 2 Finite element mesh diagram of hanguang gate partition wall

The primary objective of this study is to analyze the harmonic response of the earthen walls under ambient environmental vibrations. Given the low intensity of such vibrations, a linear elastic analysis approach was employed. To account for the non-uniformity of wall density, the model simulated three distinct density scenarios, with the linear elastic material properties of the earthen structure detailed in Table 1. To accommodate the geometric complexity and dynamic analysis requirements, the model was discretized into 37,088 hexahedral structured elements (C3D8). In regions with irregular protrusions and indentations, such as the wall edges and top sections, the mesh size was determined through a mesh sensitivity analysis. Specifically, the element size was set to 0.2 m, equivalent to one-tenth of the minimum geometric feature size, as illustrated in Figure 2.

2.3. FEM Analysis

The influence of ambient vibrations on the interstitial walls of the Hangguang Gate site was evaluated using the modal superposition method, executed in two sequential analysis steps. Step 1 involved a linear perturbation frequency analysis to extract the first five natural modes of the structure.

Step 2 utilized steady-state dynamic analysis under linear perturbation to investigate the influence of sinusoidal vibration waves with acceleration amplitudes on the wall. The frequency range of the sinusoidal waves was set to 0–500 Hz, with acceleration amplitudes of 0.03 m/s² applied sequentially. A preliminary modal analysis was conducted before the dynamic response analysis, serving as an essential step for verifying the model's validity and providing insights into its seismic performance.

Boundary conditions were imposed to fully constrain all six degrees of freedom at the foundation base (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0), thereby preventing both translations and rotations. Furthermore, vertical displacement was restricted for all nodes in the model (U2 = 0).

Ambient vibration waves were modeled to propagate from the foundation base to the top of the interstitial walls. The ground excitation load was applied as a base acceleration input at the foundation. The waveform data is presented in Table 2.

Table 2. Ambient vibration wave

Waveform	Acceleration (m/s²)	Frequency (Hz)	Angular Frequency (ω, rad/s)
Sine	0.03	9	56.549

In the modal analysis of the wall, the influence of three different densities on its first five natural frequencies and mode shapes was investigated. The dynamic effects of environmental vibration waves on the wall were analyzed based on three indicators: wall displacement, vibration acceleration, and stress.

By comparing the wall's response under vibration waves in the range of 0–500 Hz, the frequencies and mode shapes corresponding to the peak values of displacement, vibration acceleration, and stress were analyzed, thereby identifying the wall's vibration-sensitive frequencies and vulnerable locations.

3. Results and Analysis

3.1. Modal Result and Validate

The modal analysis of the partition wall at the Hanguang Gate earthen ruins reveals that the natural frequencies of its first five modes are all below 10 Hz. The detailed natural frequencies are listed in Table 3, while the corresponding mode shapes are depicted in Figure 3.

Table 3. Natural frequencies of the first five modes for the earthen wall with different density

Density / Modes	1550	1580	1610
First (Hz)	1.9361	1.9177	1.8997
Second (Hz)	5.3257	5.2749	5.2256
Third (Hz)	6.0508	5.9930	5.9369
Fourth (Hz)	7.5684	7.4963	7.4261
Fifth (Hz)	7.7024	7.6289	7.5575

To further validate the three-dimensional finite element model, the modal analysis results were compared with the velocity monitoring data of the Hanguang Gate city wall reported in previous studies. The dominant frequency of 9 Hz obtained from the monitoring data showed close agreement with the simulated frequency of 7.5575 Hz, thereby validating the accuracy and reliability of the proposed model. Any minor discrepancies could be attributed to uncertainties in material properties and boundary conditions, which will be further investigated in future studies.

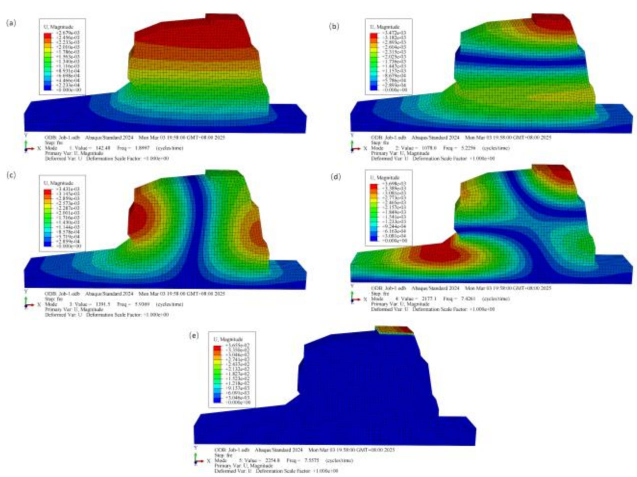

Fig. 3 The first five modes of the hanguang gate sites

The mode shapes for the first and second modes indicate that the maximum displacement occurs at the top of the partition wall, progressively diminishing with decreasing height. For the third mode, the maximum displacement, observed at the end of the partition wall under a vibrational frequency of 5.9369 Hz, reaches a magnitude of 3.431 mm. The fourth mode highlights that the maximum displacement is localized at the junction between the left end of the wall and the base. In the fifth mode, the top of the partition wall demonstrates the largest displacement, reaching a peak value of 36.5 mm. These results provide critical insights into the dynamic behavior of the partition wall, emphasizing areas of potential vulnerability under vibrational loads.

By comparing the natural frequencies and mode shapes under different densities, it was found that the first five natural frequencies of the wall decreased gradually with increasing density, as shown in Table 3. However, the mode shapes remained consistent. Figure 3 illustrates the first five mode shapes for a density of 1610 kg/m³.

3.2. Displacement

Under the excitation of ambient vibrations at the base, the walls of the Hanguang Gate earthen ruins exhibit notable displacements at specific frequencies, namely 1.353 Hz, 1.9 Hz, 5.251 Hz, and 6.128 Hz, while the displacements at other frequencies remain relatively minor. The displacement distribution is illustrated in the contour maps shown in Figure 4.

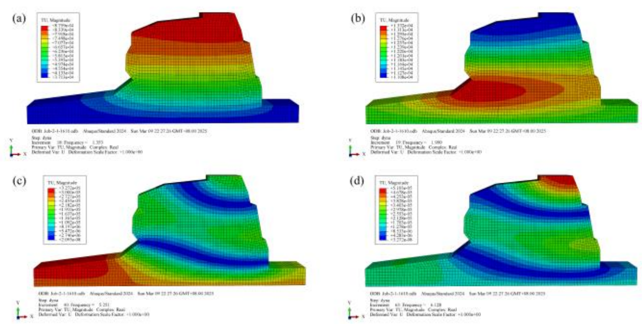

Fig. 4 The displacement responses of the hanguang gate sites under different frequency

At a frequency of 1.353 Hz, the maximum displacement, measured at 0.87 mm, occurs at the upper middle of the wall and increases with wall height. At 1.9 Hz, the displacement is most pronounced at the junction of the left end of the wall and the base. At a frequency of 5.251 Hz, the left bottom corner of the wall exhibits the greatest displacement. Conversely, at 6.128 Hz, the maximum displacement is observed at the top of the wall.

These results highlight that, despite identical acceleration amplitudes and waveforms, variations in vibration frequency significantly influence the location of maximum displacement and the corresponding areas of potential structural vulnerability. This underscores the frequency-dependent nature of structural responses under dynamic excitation.

3.3. Acceleration

The acceleration response of the walls at the Hanguang Gate earthen ruins under ambient base vibrations at frequencies of 1.353 Hz, 1.9 Hz, 5.251 Hz, and 6.128 Hz is presented in the contour maps shown in Figure 5. At other frequencies, the acceleration response is minimal and deemed negligible.

At a frequency of 1.353 Hz, the maximum acceleration, reaching 63.29 mm/s², is observed in the upper-middle portion of the wall, with acceleration increasing proportionally to wall height. At 1.9 Hz, the peak acceleration occurs at the junction between the left end of the wall and the base. At 5.251 Hz, the highest acceleration is concentrated at the left bottom corner of the wall, whereas at 6.128 Hz, the top of the wall exhibits the maximum acceleration.

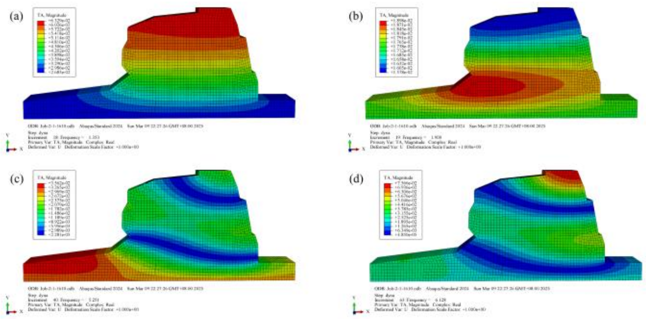

Fig. 5 The acceleration responses of the hanguang gate sites under different frequency

A comparative analysis of the displacement and acceleration contour maps indicates that the two share identical spatial distribution patterns at corresponding frequencies, highlighting a strong correlation between displacement and acceleration responses under vibrational excitation. The acceleration spectrum response of the Hanguang Gate partition wall is illustrated in Figure 6. At vibration frequencies below 0.01 Hz or above 10 Hz, the wall exhibits negligible acceleration response. In the frequency range of 0.01 Hz to 1 Hz, the acceleration response gradually increases. When the vibration frequency falls within the range of 1 Hz to 10 Hz, the response becomes significantly amplified, exceeding five times the excitation acceleration.

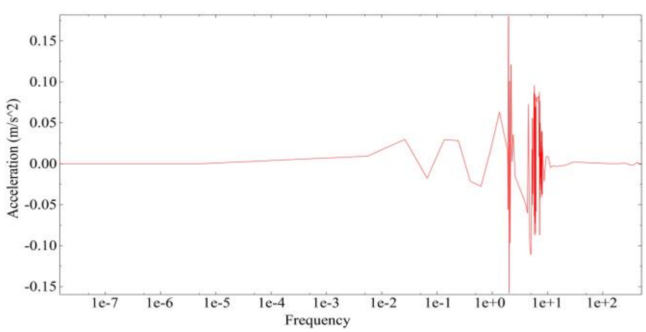

Fig. 6 Acceleration spectrum

This pronounced amplification is primarily due to the alignment of the first five natural frequencies of the partition wall within the 1–10 Hz range, rendering the structure highly susceptible to resonance effects. These results underscore the critical influence of natural frequencies on the dynamic amplification behavior under vibrational excitation.

3.4. Stress

The stress response of the walls at the Hanguang Gate earthen ruins under ambient base vibrations at frequencies of 1.353 Hz, 1.9 Hz, 5.251 Hz, and 6.128 Hz is illustrated in the contour maps presented in Figure 7. At frequencies outside this range, the stress response is negligible and thus considered insignificant.

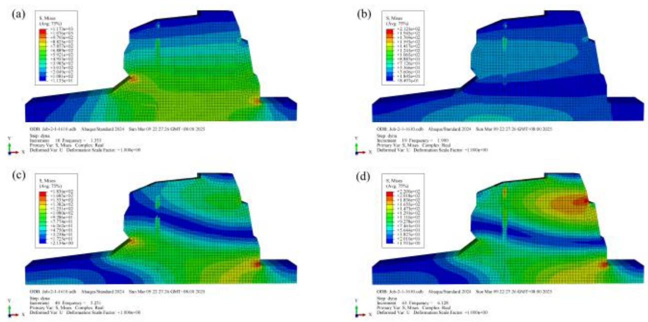

Fig. 7 The stress responses of the hanguang gate sites under different frequency

At a frequency of 1.353 Hz, the maximum stress concentration occurs at the location of an abrupt shape transition in the middle-lower section of the wall. For 1.9 Hz, the peak stress is observed in the middle-upper and bottom regions. At 5.251 Hz, stress is predominantly concentrated in the middle-lower and top sections of the wall. In contrast, at 6.128 Hz, the stress distribution becomes nearly uniform across the entire wall surface. Notably, stress intensity diminishes with increasing distance from the location of the shape transition. Under identical vibration amplitudes but varying frequencies, stress concentration in the wall consistently occurs at points of shape discontinuity; however, the specific locations of these concentration points differ across the frequencies. The 6.128 Hz excitation results in the most widespread stress distribution, whereas the highest stress magnitude is recorded at 1.353 Hz.

4. Discussion

The displacement, acceleration, and stress responses of the partition wall at the Hanguang Gate earthen ruins under sinusoidal vibration waves with different frequencies and the same vibration acceleration amplitude exhibit distinct variations. However, the displacement and acceleration contour maps show remarkable similarity (shown in Figures 4 and 5), suggesting that both displacement and acceleration exhibit a consistent response to the applied vibration. The stress contour map highlights that stress concentrations are localized at the points of shape discontinuity within the wall. A comparative analysis of the contour maps of displacement, acceleration, and stress reveals that the highest values for all three parameters are predominantly observed at the top of the wall and the junction between the wall and the base. This finding indicates that the most significant damage from vibration occurs at these critical locations, emphasizing the need for focused reinforcement in these areas. The peak values of displacement, acceleration, and stress at the top of the partition wall vary with frequency, as shown in Figure 7. At 1.353 Hz, the peak values for displacement, acceleration, and stress are observed to be the highest. As the frequency increases, both displacement and stress decrease progressively, while acceleration experiences a sharp increase at 6.128 Hz, reaching its maximum. However, as illustrated in Figure 6, the wall undergoes varying degrees of resonance between 1 and 10 Hz.

To mitigate the potential damage caused by vibrations from sources such as earthquakes, traffic, and construction activities and to enhance the preservation of the earthen ruins, it is essential to implement vibration isolation measures targeting the 1-10 Hz frequency range to avoid resonance-induced damage.

The study identified critical zones of stress concentration, displacement sensitivity, and vibration sensitivity within the earthen heritage site, highlighting areas that require prioritized attention for maintenance and reinforcement. Furthermore, the results revealed that variations in wall density significantly influence the modal properties of the earthen structure. Consequently, prior to the application of any maintenance interventions, it is crucial to assess the potential impact of such structures on the site's modal behavior and to evaluate the continued efficacy of existing vibration isolation and damping systems. This comprehensive approach will enable the refinement and optimization of maintenance and reinforcement strategies.

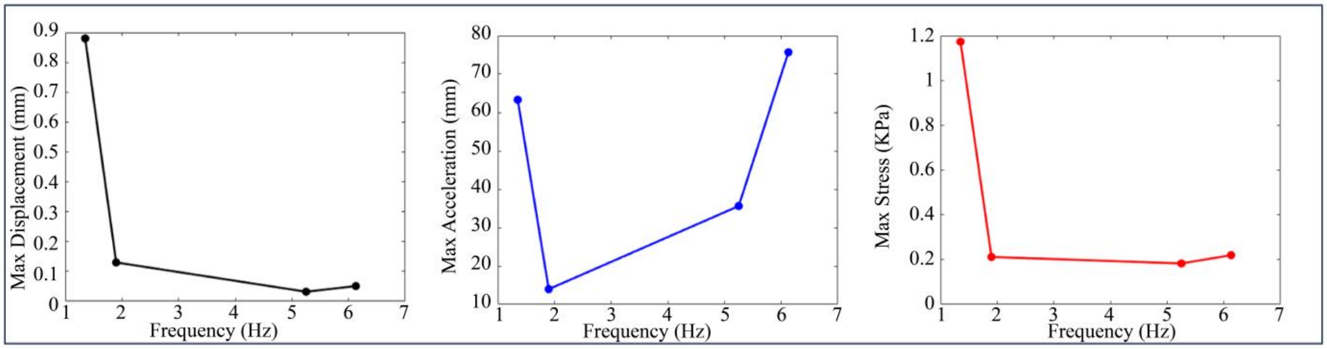

Fig. 8 The max displacement, acceleration and stress spectrum

5. Conclusion

A 3D finite element model of the Hanguang Gate partition wall earthen ruins in Xi'an City was developed in this study to perform modal analysis and harmonic response analysis under environmental vibration waves. The key findings are as follows:

- The first five natural frequencies of the partition wall were determined to be 1.8997 Hz, 5.2256 Hz, 5.9369 Hz, 7.4261 Hz, and 7.5575 Hz, indicating that the structure predominantly exhibits low-frequency vibrations below 10 Hz.
- Acceleration, displacement, and stress responses were negligible for vibration waves above 10 Hz but exhibited amplification within the 1-10 Hz frequency range due to resonance effects.
- The peak values of acceleration, displacement, and stress were localized at the top of the partition wall and the junction between the wall and its base. These critical areas are the most susceptible to vibration-induced damage and should be prioritized in conservation and reinforcement strategies.

This analysis underscores the importance of addressing low-frequency vibrations to mitigate potential damage and preserve the structural integrity of earthen ruins.

Limitation

In order to improve computational efficiency and simplify the model, the unevenness of the wall surface was not considered in the modeling.

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