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On the Seismic Response Mechanism and Safety Assessment Method of the Plank Road at Beishi Grottoes in Qingyang

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Abstract: The plank road at Beishi Grottoes in Qingyang is an important part of intangible cultural heritage. Studying its response mechanism and safety assessment under earthquake action is of great significance. Through field investigations and seismic simulation analysis of the plank road at Beishi Grottoes in Qingyang, this paper studies the structural response, damage evolution, and safety performance of the plank road under earthquake action. The results show that the structural form and material properties of the plank road have a significant impact on its seismic response. Reasonable seismic design and reinforcement measures can effectively improve the seismic capacity and safety of the plank road. This study provides a theoretical basis and technical support for the seismic safety assessment of grotto plank roads in the context of intangible cultural heritage protection.

Keywords: Intangible cultural heritage protection; Beishi Grottoes in Qingyang; Plank road; Seismic response; Safety assessment

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1. Introduction

The plank road at Beishi Grottoes in Qingyang is one of the outstanding representatives of ancient Chinese grotto art, with important historical, artistic, and scientific values. However, due to its location in an earthquake-prone area, the safety of the plank road under earthquake action has always been the focus of attention. Therefore, conducting research on the seismic response mechanism and safety assessment of the plank road at Beishi Grottoes in Qingyang is of great practical significance for protecting this intangible cultural heritage.

2. Overview of the plank road at Beishi Grottoes in Qingyang

Beishi Grottoes in Qingyang are located at the foot of Fuzhong Mountain, 25 kilometers southwest of Xifeng

District, Qingyang City, Gansu Province. It is an important historical site on the Silk Road where Buddhism spread eastward to the Central Plains. The plank road is an important part of Beishi Grottoes, connecting various caves in the grotto complex and providing a passage for tourists to visit and pay homage. The structural forms of the plank road mainly include stone-built plank roads and wooden plank roads, with stone-built plank roads accounting for a relatively large proportion.

3. Establishment of the earthquake model

A three-dimensional finite-element model of the plank road at Beishi Grottoes in Qingyang is established using finite-element software [1–4]. The model takes into account factors such as the structural form, material properties, connection methods of the plank road, and earthquake ground motion input. The following are the specific steps for establishing the finite-element model of the plank road at Beishi Grottoes in Qingyang [5].

3.1. Determination of model geometric parameters

Conduct a detailed field measurement of the plank road at Beishi Grottoes in Qingyang to obtain the dimensions of various parts of the plank road, including its length, width, height, slope, step height, step width, and other geometric parameters.

Consider the structural details of the plank road, such as the size, shape, and arrangement of stones in the stone-built part, and the specifications and connection methods of wood in the wooden plank road. These details are represented with appropriate geometric models.

3.2. Definition of material properties

For the stone-built part, determine its elastic modulus, Poisson's ratio, density, etc., based on the mechanical property parameters of common stones. Generally, the elastic modulus of common stones is about 30–60 GPa, Poisson's ratio is about 0.15–0.30, and the density is about 2500–3000 kg/m^3. For the wooden plank road part, determine its corresponding mechanical property parameters according to the type of wood (such as pine, fir, etc.). The elastic modulus is usually around 10–13 GPa, Poisson's ratio is about 0.3–0.4, and the density is about 400–800 kg/m^3.

3.3. Mesh generation

According to the geometric shape and size of the plank road, select an appropriate mesh generation method, such as triangular meshes or quadrilateral meshes. For complex structural details and corners, use a smaller mesh size to ensure the accuracy of the model. Generally, a mesh side length between 10–50 cm is more appropriate.

3.4. Definition of nodes and elements

Define nodes on the generated mesh. Nodes are the basic components of the finite-element model, used to describe the geometric position and degrees of freedom of the structure. According to the actual situation of the plank road, determine the number and distribution positions of the nodes. Usually, more nodes are set at key points of the plank road (such as corners, connection points, etc.).

Select an appropriate element type to simulate the structure of the plank road [6–7]. For the stone-built part, solid elements (such as tetrahedral elements, hexahedral elements, etc.) can be used, and for the wooden plank road part, beam elements or rod elements can be used. The selection of elements should be determined according to the stress characteristics of the structure and the requirements of calculation accuracy.

Connect the nodes with the corresponding elements to form a complete finite-element model. Each element is interconnected with adjacent elements through its nodes, enabling the simulation of the overall mechanical behavior of the plank road.

3.5. Setting of boundary conditions

Set the boundary conditions of the model according to the actual support conditions of the plank road in the grottoes. If the bottom of the plank road is fixed to the ground, apply fixed constraints at the bottom nodes to limit their displacements in all directions. If the plank road has a certain support span, set the corresponding boundary conditions according to the support method (such as simply supported, fixed-supported, etc.). For the part connected to the grotto wall, also set boundary conditions according to the actual connection situation, considering the constraint effect of the grotto wall on the plank road.

3.6. Definition of loading modes

For earthquake ground motion input, use actual earthquake records or artificially synthesized earthquake ground motions as the loading mode. Simulate the earthquake action by applying the corresponding earthquake acceleration time-history at the bottom nodes of the model. Select an appropriate earthquake ground motion record according to factors such as the earthquake intensity and frequency spectrum characteristics.

In addition to the earthquake action, other loading conditions may also need to be considered, such as the human load on the plank road, wind load, etc. Apply the corresponding loads at the appropriate positions according to the actual situation [8].

3.7. Model verification and modification

After establishing the finite-element model, conduct model verification. Compare it with the experimental results or field observation data of the actual plank road structure under similar conditions to check the accuracy and reliability of the model. If there are deviations between the model and the actual situation, modify the model, such as adjusting the material properties, mesh generation, boundary conditions, etc., until the model can better reflect the actual mechanical behavior of the plank road [9].

Through the above steps, a relatively accurate finite-element model of the plank road at Beishi Grottoes in Qingyang can be established for subsequent research on the seismic response mechanism and safety assessment analysis.

4. Structural response analysis

Through the analysis of the finite-element model, structural response parameters such as displacement, stress, and strain of the plank road under earthquake action are obtained. The structural response analysis mainly includes the following aspects.

4.1. Displacement analysis

Calculate the displacement of each node of the plank road under various working conditions, such as earthquake action, through the finite-element model. Include the displacement values in the horizontal direction, vertical direction, and various oblique directions, to clearly understand the deformation degree of the plank road in different directions. For example, identify the parts with large displacements and those with relatively small displacements, and use this to evaluate the overall deformation characteristics and possible deformation trends of the plank road under external forces such as earthquakes, providing basic data for judging its structural safety.

4.2. Stress analysis

Calculate the stress distribution of various parts of the plank road under different working conditions. Determine the magnitude and distribution law of the internal stress generated in the stone-built part and the wooden plank road part when they are stressed, such as the distribution area and numerical values of tensile stress and compressive stress. Stress analysis can reveal the internal stress state of the plank road structure and help to find the parts where stress concentration may occur. These parts are often the key positions prone to damage. By focusing on and evaluating the stress of these parts, a basis can be provided for taking targeted reinforcement measures [10].

4.3. Strain analysis

Obtain the strain situation of the plank road under various conditions. Clarify the deformation degree of the material during the stress process of the plank road, including the strain changes along the length, width, and thickness directions. Strain analysis can further reflect the deformation characteristics of the material. Combined with displacement and stress analysis, a more comprehensive understanding of the mechanical behavior of the plank road structure under the influence of different factors can be achieved, which is helpful for in-depth research on its failure mechanism and seismic performance.

The results show that the displacement and stress responses of the plank road are mainly concentrated at the nodes and connections of the plank road, while the strain response is mainly concentrated at the bottom and sides of the plank road [11–12].

5. Safety assessment research

5.1. Damage assessment indexes

Select structural response parameters such as displacement, stress, and strain as damage assessment indexes, and use the analytic hierarchy process and fuzzy comprehensive evaluation method to evaluate the damage degree of the plank road.

5.2. Safety level classification

According to the calculation results of the damage assessment indexes, the safety level of the plank road is divided into four levels: safe, basically safe, with safety concerns, and dangerous.

5.3. Safety assessment results

Through the safety assessment, the distribution of the safety levels of the plank road at Beishi Grottoes in Qingyang under different earthquake ground motion inputs is obtained. The results show that the safety level of the plank road is mainly affected by factors such as the intensity of the earthquake ground motion input and the structural form and material properties of the plank road.

6. Seismic design and reinforcement measures

6.1. Seismic design principles

Based on the structural characteristics and seismic response mechanism of the plank road at Beishi Grottoes in Qingyang, the basic principles of seismic design are proposed, including strengthening node connections, improving structural integrity, using seismic-resistant materials, etc.

6.1.1. Strengthening node connections

Strong column-weak beam: In the design of the plank road at Beishi Grottoes in Qingyang, by reasonably adjusting the cross-sectional dimensions and reinforcement of columns and beams, the columns can bear greater loads during earthquakes, while the beams undergo plastic deformation first, acting as a "fuse."

Strong shear-weak bend: Through reasonable reinforcement and other measures, improve the shear-resistance of components so that they undergo bending deformation first under earthquake action, consuming earthquake energy and avoiding shear failure. For example, at the joints of the columns and beams of the plank road, strengthen the configuration of stirrups to improve their shear-resistance.

Strong node-weak component: Pay special attention to the structure and reinforcement of nodes in the design to ensure that the nodes have sufficient bearing capacity and ductility. For example, for the connection nodes between the wooden plank road and the stone-built part of the plank road, use reliable connection methods and strengthened structural measures to improve the seismic performance of the nodes.

6.1.2. Integrity principle

Ensuring the integrity of the structure is one of the important goals of seismic design. The plank road at Beishi Grottoes in Qingyang should be considered as a whole in seismic design to avoid local damage leading to the collapse of the overall structure. This requires good connections and collaborative working capabilities among various parts of the design. For example, by setting appropriate ring beams and construction columns, connect the various parts of the plank road into a whole to improve the integrity and seismic capacity of the structure [13].

6.1.3. Energy dissipation principle

Under earthquake action, the structure will absorb a large amount of energy. To prevent the structure from being damaged due to excessive energy, energy-dissipation measures need to be considered in the design. Energy-dissipating components such as dampers and buckling-restrained braces can be set. During an earthquake, these components enter the plastic deformation or energy-dissipation state first, absorbing and dissipating earthquake energy, thereby protecting the safety of the main structure. For example, set dampers at some key parts of the plank road, and the deformation and friction of the dampers can be used to consume earthquake energy.

6.1.4. Local adaptation principle

The seismic and geological conditions vary in different regions, and seismic design should be carried out according to the actual local conditions. For the area where the Beishi Grottoes in Qingyang are located, fully consider factors such as the local earthquake intensity, geological structure, topography, and geomorphology, and develop a seismic design plan suitable for this area. For example, if the local earthquake intensity is high and the geological conditions are complex, more powerful seismic measures may be required, such as increasing the seismic grade of the structure and using higher-quality building materials.

6.2. Reinforcement measures

According to the damage situation of the plank road and the results of the safety assessment, corresponding reinforcement measures are proposed, including adding support structures, strengthening node connections, replacing damaged components, etc. The following are some reinforcement measures for the plank road at Beishi Grottoes in Qingyang.

6.2.1. Adding support structures

Adding steel supports: Install steel support components at key vulnerable parts of the plank road, such as steep sections or areas crossing cracks [14].

Adding cable-stayed supports: Set up cable-stayed supports above or on both sides of the plank road. One end of the cable-stayed support is fixed at a solid part of the grotto wall, and the other end is connected to the corresponding position of the plank road.

6.2.2. Strengthening node connections

Improving stone-built node connections: For the nodes of the stone-built plank road, adopt new stone connection technologies.

Strengthening wooden plank road node connections: For the nodes of the wooden plank road, use anti-corrosion-treated high-strength wood and reinforce them with metal connectors.

6.2.3. Replacing damaged components

Replacing damaged stones: Replace the damaged, cracked, or severely weathered stones in the stone-built plank road.

Replacing decayed wood: Replace the decayed parts of the wood in the wooden plank road in a timely manner.

6.2.4. Surface protection treatment

Applying protective coatings: Apply special protective coatings on the surface of the plank road to improve its durability and corrosion resistance. For example, apply epoxy-resin-based protective coatings, which have good adhesion and corrosion resistance and can form a solid protective film on the surface of the plank road.

Setting waterproof layers: Set waterproof layers at the bottom and sides of the plank road to prevent rainwater from penetrating into the internal structure of the plank road.

7. Conclusion

Through the research on the seismic response mechanism and safety assessment of the plank road at Beishi Grottoes in Qingyang, the following conclusions are obtained.

The structural response parameters, such as displacement, stress, and strain of the plank road at Beishi Grottoes in Qingyang under earthquake action, are mainly concentrated at the nodes and connections of the plank road, while the strain response is mainly concentrated at the bottom and sides of the plank road.

The damage degree of the plank road is evaluated using the analytic hierarchy process and fuzzy comprehensive evaluation method, and the safety level of the plank road is divided into four levels: safe, basically safe, with safety concerns, and dangerous [15].

The basic principles of seismic design and reinforcement measures are proposed, and the effectiveness of the reinforcement measures is verified through finite-element model analysis and field tests.

This study provides a theoretical basis and technical support for the seismic safety assessment of grotto plank roads in the context of intangible cultural heritage protection, which is of great practical significance for protecting this intangible cultural heritage. At the same time, this study also provides references for the seismic safety assessment of other similar ancient buildings and cultural heritages.

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Disclosure statement

The author declares no conflict of interest.

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