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Study on Deformation Analysis and Reinforcement Measures of Feifeng Castle in Hailongtun, Guizhou

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***Abstract* - Most existing ancient masonry structures in China suffer from various forms of deterioration, making their conservation extremely challenging. To investigate scientifically sound conservation techniques for ancient masonry structures within the Hailongtun ruins, the representative Feifeng Castle was selected for analysis. Firstly, through field investigation and survey, the existing deterioration conditions of Feifeng Castle and the engineering geological context were analyzed. Then, numerical simulation using the finite difference software FLAC3D, combined with field survey data, was employed to analyze the causes of structural deformation. Finally, integrating the findings from the field survey and numerical simulation, reinforcement measures suitable for this type of castle structure were proposed. The conclusions drawn from this study can provide a reference for the reinforcement and restoration of other castles within Hailongtun and similar types of ancient masonry structures.**

Keywords - Ancient masonry structure; Heritage conservation; Deformation analysis; Reinforcement measures; Numerical simulation

I. INTRODUCTION

Hailongtun was initially constructed during the Southern Song Dynasty (1127-1279 AD). The fortress encompassed a mountaintop area approximately 5 kilometers wide, surrounded by three layers of earthen walls and crescent walls, containing buildings, warehouses, and water dungeons within. Nine passes, including Tongzhu (Bronze Pillar), Tiezhu (Iron Pillar), Feilong (Flying Dragon), Feifeng (Flying Phoenix), Chaotian (Facing Heaven), and Wan’an (Eternal Peace), were established at the front of the fortress, connected by protective walls stretching over 10 kilometers along the mountain terrain. The city walls, pass towers, checkpoints, and stone structures retain their form from 400 years ago, making it the only well-preserved medieval military fortress in China. Its layout, spatial composition, architectural settings, and artistic expression incorporate elements of traditional Chinese culture, reflecting the fusion of diverse cultural arts. It holds immense value for researching medieval military, political, technological, and craft aspects [1, 2]. On July 4, 2015, at the 39th UNESCO World Heritage Committee meeting in Bonn, Germany, the Hailongtun Tusi Site in Zunyi, Guizhou, was inscribed on the World Heritage List.

Over its long history, changes in the regional environment of Hailongtun, coupled with the continuous impact of adverse natural and human factors, have altered the geological substrate supporting the cultural relics within the area. The pass structures in the region commonly suffer from deterioration such as collapse, structural instability, crack development, wall bulging, water seepage, and foundation settlement. These issues severely threaten the integrity of the Hailongtun military fortress and the long-term survival of the entire historic site.

Current research on the stability analysis and conservation techniques for stone masonry structures is relatively limited. He Manchao [3], based on field surveys and engineering geological investigations, used FLAC3D to simulate stress field changes and deformation/failure patterns of the Goguryeo General’s Tomb under self-weight, local foundation softening, and groundwater seepage conditions. Lu Xiao [4] used the finite element software MARC to establish a detailed 3D model of a stone arch bridge, simulated its entire collapse process, analyzed potential causes of collapse, and evaluated the importance of various bridge components. Yu Tianhe [5] established an elastoplastic contact finite element model for a city gate platform, calculated the main causes of cracks in the outer brick masonry, and explored the relationship between crack distribution, lateral deformation, and the deterioration of

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the masonry's mechanical performance. Chun Qing [6] conducted field surveys to analyze damage to a Ming Dynasty stone arch bridge in Nanjing, identified visible deterioration, then used ANSYS finite element analysis to assess structural performance, identify potential deterioration, and perform importance analysis of structural components. Integrating damage survey and numerical simulation results, they proposed conservation techniques suitable for Ming Dynasty stone arch bridges. Lei Honggang [7], through analysis of the current condition of the Pingyao ancient city wall and considering World Heritage conservation requirements, proposed repair and reinforcement principles for brick-earth wall structures, and reinforcement methods for masonry and rammed earth wall structures. Other scholars have also predominantly used numerical simulation methods for structural analysis of stone masonry structures and stone arch bridges [8-14], which will not be listed exhaustively here.

This study focuses on the representative Feifeng Castle within Hailongtun. Through field investigation and survey, the existing deterioration and engineering geological conditions of Feifeng Castle were analyzed. Combining field survey data, numerical simulation using the finite difference software FLAC3D was performed to analyze the causes of structural deformation. Integrating the field survey and numerical simulation results, scientifically sound and rational reinforcement measures for the castle structure were proposed, providing a reference for the reinforcement and restoration of other castles within Hailongtun and similar types of ancient masonry structures.

II. CURRENT CONDITION OF FEIFENG CASTLE

A. *Preservation Status*

Feifeng Castle was initially built during the Southern Song Dynasty and reinforced/rebuilt during the Ming Dynasty. It is the easternmost pass of Hailongtun. Its main structure is constructed with bluestone blocks and lime-sticky rice mortar laid in staggered joints. The internal fill consists of crushed stone and soil with flagstones. The foundation is made of bluestone slabs. The top of the castle originally housed a gate tower, and the gateway features a single-passage semi-circular arched stone structure. Due to its long history and the effects of natural weathering, rainwater erosion, geological environmental changes, and human factors, its preservation status is precarious, exhibiting multiple severe and interrelated structural deteriorations.

Wall bulging is one of the most prominent and serious deteriorations of Feifeng Castle. The south wall exhibits significant outward bulging deformation, with the maximum bulging occurring at the mid-height of the wall (Fig. 1a). This bulging not only causes surface unevenness but also severely compromises the structural integrity and stability. The bulging deformation induces tensile stresses within the wall, directly contributing to the formation of numerous surface cracks. The north wall has suffered partial or large-area collapse (Fig. 1b), resulting in the complete or partial loss of that section of the castle structure. The collapse removes or weakens the load-bearing capacity and constraint provided by that wall section, exacerbating the force imbalance and instability of the remaining structure. The aging and failure of the bonding material, along with cracking and localized collapse of the arch crown, have led to loosening and deformation of the gateway arch. Furthermore, a series of destructive factors such as block weathering, rainwater infiltration, biological deterioration, and crack development have accelerated the destruction of Feifeng Castle. In summary, the deterioration of Feifeng Castle is a complex systemic problem. Wall bulging, crack development, rainwater seepage, internal fill degradation, and localized collapse interact and collectively lead to severe structural deformation, instability, and safety risks. The loosening, cracking, and localized collapse of the arch are direct consequences of the progression of these deteriorations. These issues pose a serious threat to the long-term preservation of Feifeng Castle as a significant cultural heritage site.

Fig. 1 Typical structural deterioration of Feifeng Castle a. Cracks and bulging on the south wall, b. Collapse of the north wall, c. Loosening of the arch

B. *Engineering Geological Conditions*

Based on the field survey, a typical geological profile of Feifeng Castle was drawn, as shown in Fig. 2. The castle exterior consists of block masonry, while the interior is filled with crushed stone and soil containing flagstones. The wall foundation is a bluestone slab foundation resting on marl, which overlies bedrock. The profile shows that the east wall has collapsed, while the west wall exhibits bulging deformation, with the maximum displacement occurring at the mid-height of the wall. The survey also revealed that the flagstones within the internal crushed stone and soil fill were originally oriented roughly vertically. However, in areas that are loose or have collapsed and become unstable, the flagstones are chaotically arranged and have rotated from their original positions, as shown in Fig. 3.

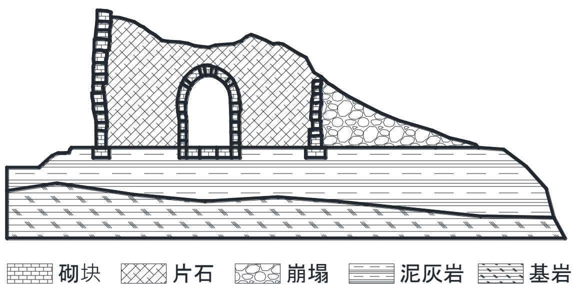

Fig.2 Geological section map of Feifeng castle

Fig.3 Rotate of flag stone in the instability region

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III. NUMERICAL ANALYSIS

A. Model Establishment

To deeply analyze the causes of structural deterioration in Feifeng Castle, scientifically evaluate its stability under current preservation conditions, and provide a quantitative basis for subsequent reinforcement design, this study constructed a three-dimensional numerical analysis model of Feifeng Castle based on detailed field survey data. Given the significant longitudinal consistency of the Feifeng Castle structure along its thickness direction, a plane strain model was adopted for simplified analysis. A representative 1m thick typical cross-section was selected for numerical simulation. Based on high-precision survey results (including topography, castle outline, internal structure, and geological stratification), modeling and meshing were performed in the finite element pre-processing software ANSYS. The finite element model was then imported into the finite difference software FLAC3D for calculation. The model was divided into five material groups according to the geological profile: Masonry Blocks, Flagstones, Collapsed Material, Marl, and Bedrock, as shown in Fig. 4. The coordinate system was defined with the east-west direction as the x-axis, the north-south direction (thickness direction) as the y-axis, and the vertical direction as the z-axis. Vertical displacement constraints were applied at the model bottom. Displacement constraints in the x-direction were applied on the x-axis boundaries, and displacement constraints in the y-direction were applied on the y-axis boundaries. The castle structure in the model is subjected only to gravity, with no additional loads applied on top.

B. Parameter Selection

Combining field inspection and laboratory test data, and considering that the Masonry Blocks and Flagstones groups are discontinuous media, the cohesion and tensile strength of these two material groups were reduced. To reflect the nonlinear characteristics of the geomaterials, the Mohr-Coulomb model was selected, with parameters assigned as follows:

1) Masonry Blocks: Density = 2480 kg/m^3, Bulk Modulus = 18.7 GPa, Shear Modulus = 9.15 GPa, Cohesion = 67.2 MPa, Friction Angle = 42.1° , Tensile Strength = 2.46 MPa.

2) Flagstones (Crushed Stone & Soil Fill): Density = 2180 kg/m^3, Bulk Modulus = 12.3 GPa, Shear Modulus = 12.3 GPa, Cohesion = 21.7 MPa, Friction Angle = 13.4° .

3) Collapsed Material: Composed of collapsed flagstones and masonry blocks, parameters were assigned based on the Flagstones group.

4) Marl: Density = 2070 kg/m^3, Bulk Modulus = 4.71 GPa, Shear Modulus = 2.94 GPa, Cohesion = 49.5 MPa, Friction Angle = 28° .

5) Bedrock: Density = 2580 kg/m^3, Bulk Modulus = 5.56 GPa, Shear Modulus = 3.17 GPa, Cohesion = 81.4 MPa, Friction Angle = 40° .

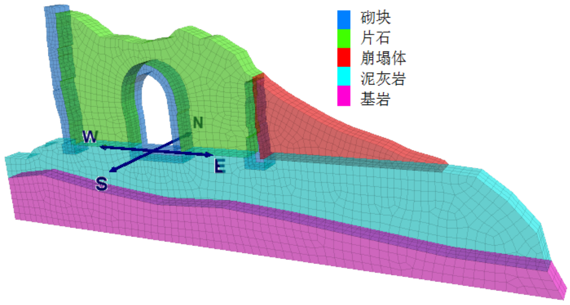

Fig.4 Numerical model and groups

C. Result Analysis

1) Vertical Displacement

As Feifeng Castle is built on a mountainside and exhibits wall deformation, many scholars speculate that uneven foundation settlement might be the cause. However, field pit exploration revealed that the foundation slabs of Feifeng Castle are intact, with no significant misalignment or fractures. To analyze the cause of structural deformation, vertical displacement related to foundation settlement was first analyzed, as shown in Fig. 5. The figure shows that although the height of the upper castle structure varies, and the deformation of the flagstone fill is greater than that of the walls, the vertical displacement of the foundation' s left and right parts is essentially symmetrical about the axis through the center of the arch. At the foundation elevation, due to the absence of load above the gateway arch, the vertical deformation at the arch base is less than on either side, resulting in a slight uplift at the arch base, consistent with the current condition of Feifeng Castle and commonly observed in other passes and ancient gate towers. The area below the foundation shows consistent displacement at the same elevation, indicating that the foundation settlement of Feifeng Castle is essentially uniform. Therefore, it can be inferred that the bulging deterioration is primarily caused by relative displacement-induced deformation. To eliminate the influence of overall foundation displacement in subsequent bulging deformation analysis, only the castle structure above the foundation was analyzed.

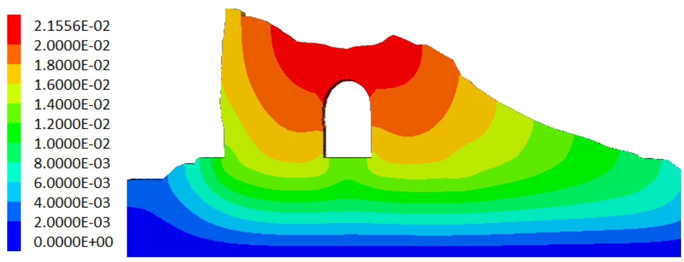

Fig.5 Vertical displacement contour

2) Bulging Deformation

The castle structure was selected for analysis, and its horizontal displacement contour is shown in Fig. 6. The figure reveals the deformation characteristics of the castle walls. The west wall exhibits outward displacement, with the maximum displacement occurring at the mid-height position. The arch haunches also show some bulging deformation, particularly significant on the west side, consistent with the survey results.

The bulging deformation of the walls on both sides of the arch haunches alters the arch axis, inducing bending moments and shear forces in the arch ring. Combined with the collapse of the east castle structure, which reduces the constraint on the arch ring, this is one of the reasons for the cracking of the arch crown and even localized collapse and spalling.

Based on field survey and numerical calculation results, the bulging deformation, coupled with the pore space created by rainwater seepage carrying away fine particles, causes the internal flagstones to rotate. The uneven settlement of the internal flagstones has two main consequences: firstly, in areas with larger settlement, the structural centroid and center of gravity form an angle, generating a horizontal thrust component from the self-weight; secondly, the granular fill material exhibits the "silo effect," causing part of the gravity load from the internal flagstones to disperse laterally, generating pressure on the walls and leading to wall bulging and cracking. The bulging deformation further creates space for flagstone rotation and fine particle seepage, exacerbating the ongoing structural deformation.

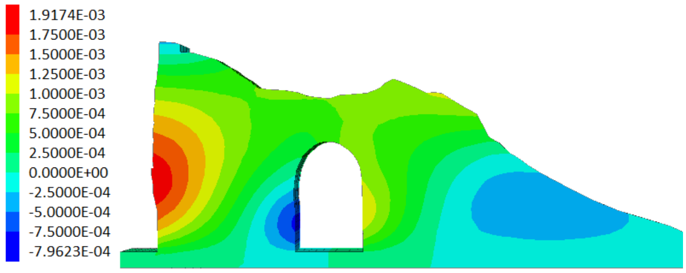

Fig.6 Horizontal displacement contour

IV. ANALYSIS OF REINFORCEMENT MEASURES

A. Conservation Principles

Adhering to the conservation principles of preserving the integrity and authenticity of cultural relics, ensuring recognizability and sustainability (reversibility), the aim is to preserve as much genuine historical information as possible, restore Feifeng Castle to its original appearance, and provide possibilities and convenience for future conservation and research. Based on the analysis of field deterioration and structural deformation, a conservation plan for Feifeng Castle was formulated.

B. Conservation Plan

1) Steel Grid Confinement and Anchor Rods for Temporary Restraint

Before undertaking engineering measures such as arch resetting, replacement of insufficiently strong masonry blocks in the outer walls, and re-laying of bulged blocks, temporary restraint of the castle structure using steel grids and anchor rods is implemented, as shown in Fig. 7. A spatial grid confinement system is formed using Q345B grade channel steel. Prestressed anchor rods are welded to the grid, creating a three-dimensional constraining force field. The channel steel closely follows the wall surface, with gaps wedged tight using steel or wooden wedges, forming an integrated support frame to inhibit further deformation.

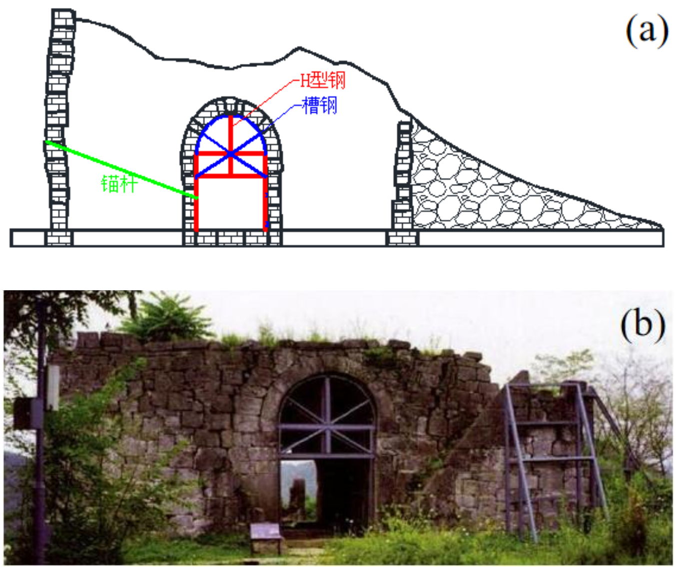

Fig.7 Temporary supporting measure a.Design drawing of temporary restraint support measures,b. Actual effect of temporary restraint support measures

2) Arch Resetting

After the confinement effect is established, the loosened and deformed arch is carefully and gradually reset. Operations include jacking, adjusting the position of arch stones, and removing loose fill material. After resetting, permanent reinforcement of the arch is achieved through joint grouting and adding internal connecting elements to prevent re-loosening. This repairs the loosened arch structure due to deformation and restores its load-bearing capacity.

3) Block Replacement and Reinstatement

- Conduct on-site inspection of all stone masonry blocks of the castle using methods like rebound hammer testing and visual assessment of weathering degree to precisely identify blocks with degraded strength that cannot meet load requirements.
- Replace these degraded blocks with new stone materials matching the original in material, specifications, and appearance.
- Before reinstating collapsed wall blocks, detailed archaeological data, historical photographs, and survey records must be thoroughly studied to verify the original position and arrangement of the collapsed blocks.
- Systematically number the scattered collapsed blocks, recording their positions and characteristics.
- Based on the verification results, precisely return the numbered blocks to their original positions, restoring the wall's original appearance and structural continuity.

4) Hydraulic Lime Grouting for Internal Fill and Wall Cracks

After block replacement and reinstatement, inject hydraulic lime grout into the internal fill of the castle structure. Hydraulic lime possesses the breathability of lime and the strength of cement, with better water resistance and faster setting speed, making it suitable for Guizhou's rainy and humid climate. Its mineral composition is closer to ancient masonry,

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ensuring excellent long-term stability. Grouting enhances the integrity of the internal flagstone fill, reducing the thrust on the walls caused by flagstone rotation, and allowing the weight of the internal masonry to be transferred more effectively to the foundation.

5) Joint Repointing of Outer Walls

To maintain the material authenticity, compatibility, and reversibility of the cultural relic fabric, use traditional modified lime mortar, such as sticky rice-lime mortar, for repointing the outer walls of the castle. Before repointing, remove existing loose and failed mortar from the joints. Then, carefully fill all joints in the outer wall masonry with the prepared sticky rice-lime mortar, compacting and smoothing it. This prevents rainwater seepage through the joints, which causes internal fine particle loss and flagstone rotation, while simultaneously enhancing the integrity and stability of the outer wall masonry.

6) Water Damage Control for the Castle Structure

Given the small catchment area on the castle top, and guided by the principle of minimal intervention, water damage control on the top focuses primarily on drainage. Use local clay mixed with a clay stabilizer to create a slope on the castle top for waterproofing and rapid drainage. Prevent rainwater infiltration into the walls using the aforementioned crack grouting and wall repointing treatments. Construct aprons and drainage blind ditches at the wall base using materials identical to the castle's outer walls, ensuring new engineering measures harmonize as much as possible with the original cultural relic fabric.

C. Establishment of a Long-Term Monitoring Mechanism

1) Monitoring System Design and Installation:

a) Deploy a sensor network at key locations: significant bulging deformation areas, arch crown and haunches, newly replaced block areas, crack development zones, foundation settlement sensitive points, etc.

b) Monitoring content should include:

- Displacement Monitoring: Use crack gauges, displacement transducers, total stations, or 3D laser scanning to precisely measure wall bulging deformation, crack width changes, overall settlement, and tilt.
- Stress/Strain Monitoring: Embed strain gauges in key blocks, steel grids, anchor rods, and internal fill to monitor changes in internal stress states.
- Environmental Factor Monitoring: Record temperature, humidity, rainfall, and other environmental parameters to analyze the impact of environmental changes on structural deformation.
- Hydrogeological Monitoring: Monitor groundwater level changes, internal wall humidity, and seepage conditions to evaluate the effectiveness of water damage control measures.

2) Data Collection and Analysis:

- Establish a regular data collection schedule, with high frequency initially and extended intervals once stability is observed.
- Utilize specialized software for data processing and analysis. Focus on analyzing deformation rates, stress development trends, and the correlation between environmental factors and structural response.

3) Early Warning and Assessment:

- Set safety thresholds. Issue timely alerts when monitoring data approaches or exceeds these thresholds.
- Regularly compile structural safety assessment reports to evaluate reinforcement effectiveness and overall structural health.

4) Guiding Maintenance Decisions Based on Monitoring:

- Determine subsequent maintenance and repair work based on monitoring data and analysis results.
- Adjust maintenance strategies based on data feedback, performing local repairs or other interventions where necessary.

Field monitoring over the two years following the implementation of the temporary restraint measures described in this paper showed no further deformation in the Feifeng Castle structure, and existing cracks did not propagate further. This indicates that the temporary restraint measures effectively enhanced the overall integrity and stability of Feifeng Castle, providing a strong guarantee for the implementation of further conservation measures.

V. CONCLUSION

This study focused on the structural instability risks facing Feifeng Castle, a core pass within the World Heritage site of Hailongtun. Employing a multidisciplinary research approach, it systematically conducted detailed field surveys, comprehensive deterioration investigation, and refined numerical simulation analysis based on FLAC3D. This revealed the intrinsic mechanisms behind its complex deformation and failure, leading to the proposal of a scientific, systematic, and targeted reinforcement and conservation technical system. The research results not only provide direct and reliable technical support for the emergency conservation of Feifeng Castle, but the revealed deformation patterns and proposed reinforcement concepts and methods can also serve as important theoretical and practical references for the conservation of other passes within the Hailongtun site complex and for cultural heritage protection projects worldwide with similar geological conditions and structural characteristics.

Systematic research is the prerequisite for scientific conservation. Conservation design for complex ancient masonry structures must be based on thorough on-site deterioration surveys, precise engineering geological investigations, and in-depth structural mechanics analysis. This study, by coupling field measurement data with numerical simulation technology, clearly revealed the spatial distribution characteristics, evolution process, and underlying driving factors of Feifeng Castle's deterioration, providing a solid scientific basis for subsequent reinforcement design and avoiding the blindness of empirical conservation.

Numerical simulation results corroborated field surveys, revealing that the loosening, cracking, and even localized collapse of the arch were not caused by a single factor, but by the coupling of multiple mechanical effects. The large-area collapse of the east castle structure significantly weakened the effective lateral constraint at the east springing of the arch ring,

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leading to incompleteness in the arch structural system and deterioration of boundary conditions. Significant outward bulging deformation of the walls on both sides of the arch haunches directly caused asymmetric changes in the arch axis. This geometric alteration induced non-negligible additional bending moments and shear forces within the originally compression-dominated arch structure, forming stress concentrations particularly at the crown and haunches. The aging and failure of bonding materials, weathering of the blocks themselves, and localized spalling further reduced the effective load-bearing area and integrity of the arch cross-section, accelerating cracking and instability under the action of these additional internal forces.

Wall bulging is the most prominent deterioration of Feifeng Castle, and its cause exhibits significant "structure-material-environment" interaction characteristics. Continuous bulging deformation combined with rainwater seepage created pore spaces between the wall and internal fill, and within the fill itself. This caused the originally vertically oriented internal flagstones to rotate and rearrange, becoming chaotically oriented and undergoing uneven settlement. The rotation behavior of the flagstones is a key link in the ongoing deformation development. The uneven settlement of the internal fill caused the overall structural centroid and center of gravity to misalign, forming an angle. The self-weight of the structure consequently generated a horizontal thrust component pointing in the direction of the bulge, continuously acting on the already damaged wall. More importantly, the internal fill, as a typical granular material, exhibits mechanical behavior governed by the "silo effect" principle. The gravity of the flagstones is not transmitted entirely vertically downward; instead, part of it disperses laterally through particle friction and arching effects, transforming into sustained lateral pressure on the walls. This pressure, inherent to the granular material's properties, is the core mechanical mechanism inducing and maintaining wall bulging. The bulging and cracking of the wall, in turn, provide pathways and space for further rainwater infiltration, fine particle loss, and more significant flagstone rotation, forming a self-reinforcing vicious cycle that accelerates the overall structural failure.

Both numerical simulation and field practice have proven that effective three-dimensional spatial temporary restraint is crucial for structures experiencing ongoing deformation and instability before implementing any permanent repair measures, such as arch resetting or block reinstatement/replacement. The technical solution proposed in this study, using Q345B grade channel steel to form a spatial grid confinement system connected by prestressed anchor rods to create an integrated constraining force field, successfully halted further deformation development over a two-year monitoring period, verifying its reliability and effectiveness as a "surgical platform." This provides the absolutely essential stable and safe conditions for subsequent delicate repair operations and is the core guarantee for the successful implementation of the entire reinforcement technical system.

Based on a profound understanding of the deterioration mechanisms, the reinforcement scheme proposed in this study is not a mere collection of isolated techniques, but a logically rigorous, interconnected systematic solution: from temporary support (steel grid and anchor rod restraint) → core structural repair (arch resetting) → masonry fabric repair (block inspection, replacement, reinstatement) → internal integrity enhancement (hydraulic lime grouting) → surface protection and waterproofing (traditional modified lime mortar repointing) → water damage control (drainage, aprons, blind ditches) → long-term health monitoring. This system fully embodies cultural heritage conservation principles such as minimal intervention, authenticity, and reversibility. Its technical approach holds significant value for popularization and reference in solving stability problems of similar ancient masonry structures, especially walls, passes, fortresses, and retaining walls containing loose internal fill.

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