Seismic performance simulation of Pingyang Fujun watchtower after repaired by discrete element method

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Abstract. The cushion material is used to renovate the Pingyang Fujun watchtower and the discrete element method is employed to analyse the earthquake response after the repair. Discrete element software is applied to establish three-dimensional models of the watchtower with cushion material, and the dynamic response of the watchtower under the Qingping seismic wave is recorded and analysed. The results show that the cushion material can effectively relieve the earthquake response of Pingyang Fujun watchtower. Under the action of earthquake, the torsion angle of the watchtower with cushion material increases, but the material of the cushion material remains to be in the stage of elastic deformation and the watchtower is not affected by twist.

1. Introduction
Watchtower is a landmark standing by both sides of palaces, ancestral halls, temples and mausoleums in ancient China, prevailing in the Han Dynasty. Pingyang Fujun watchtower consists of the southern and northern watchtowers, which are about the same in type, structure and size. Built in the late Eastern Han Dynasty (about 195 A.D.), the watchtower, as one of the most completely preserved double-chamber tomb landmarks among the 45 existing stone watchtowers of the Han Dynasty in China, has a history of more than 1,800 years. The tectonic structure of the watchtower in Mianyang is located at the junction of platform subside in Western Sichuan and that in Northern Sichuan of Sichuan platform downwarp in Yangtze paraplatform, that is, the junction between the Longmenshan piedmont depression and Dabashan piedmont depression [1]. There is no record of intense earthquake activity in the history of the city, but it is often affected by the frequent earthquakes in the west fault-fold belt of Longmenshan. “5•12 WenChuan Earthquake” led to distortion of the body, rock dislocation and component fracture of Pingyang Fujun watchtower, exerting a serious impact on the stability of watchtower structure. It is urgent to carry out scientific renovation and evaluate its dynamic stability.

At present, the studies of domestic scholars in stone watchtowers mainly focus on the aspects of weathering disaster, chemical composition and physical property of watchtower stones to explore the comprehensive treatment techniques of chemical grouting, rebar installation and foundation stabilization. Cao [1, 2] put forward the methods of foundation reinforcement according to the local subsidence and fissure of Pingyang Fujun watchtower and Gaoyi watchtower. Zeng [3] explored the repair technology of Gaoyi watchtower according to the structure of Gaoyi watchtower, the climate in
Yaan, the chemical composition and physical properties of watchtower stones. Li et al. [4] studied the weathering disaster of Dingfang watchtower and Wuming Watchtower in Zhongxian County. Tian et al. [5] reinforce and repair Wuyanghan watchtower made of stones by rebar installation and other comprehensive treatment techniques, achieving the ideal effect. Tang and Lu [6] construct the monitoring and protection system of the three watchtowers in the Han Dynasty through digital sensors and other information technologies. Li and Ma [7] observe and report the status of Pingyang Fujun watchtower after the treatment by polymethacrylate vinegar materials. Up to now, there are seldom research achievements on the dynamic stability evaluation and seismic isolation measures of stone watchtowers. In view of this, based on the repair report of Pingyang Fujun watchtower, a sacrificial cushion material is developed based on the principle of sacrifice [8] to ensure the uniform stress between the rocks of stone watchtowers. A three-dimensional discrete element model of the watchtower is established with the code 3DEC for dynamic analysis to evaluate the effect of seismic isolation of sacrificial cushion material and the seismic stability of the watchtower after repair. Besides, for the repair and stability estimate of similar stone relics, the results of research could provide valuable experience to learn.

2. Development of sacrificial cushion material

The particularity of the Pingyang Fujun watchtower is that it is constituted by many discrete rock blocks without any cementing material [1]. Each layer is composed by two to six pieces of stone stripes. Horizontally, the dovetails are used to connect blocks as a whole. Vertically, lines of 1.5cm wide are chiseled flat on the edges of two sides of the stones, and the middle is chiseled into a roughened concave-convex shape. The measures could help the stones to be tightly integrated.

Due to the uneven surface of rocks on stone watchtower without filling material, it is serious in stress concentration on point contact between blocks. The damage of Pingyang Fujun watchtower is attributed primarily to the effect of rock collision under the WenChuan earthquake. In order to avoid the stress concentration, prevent the collision of the blocks and reduce the seismic response of the watchtower, a sacrificial cushion material is developed to fill the voids within the joints between the upper and lower blocks to release stress concentration, which can not only serve the purpose of "soft protection" of the block of cultural relics, but also meet the principle of "least intervention" for the renovation of cultural heritage assets.

As a sacrificial cushion material for the protection of stone relics, it must comply with the following principles:

(i) To protect the integrity of weathered watchtower, the strength of material must be lower than that of stone components, which could ensure that the cushion material is destroyed first under the seismic load.

(ii) The stiffness of the material should be far less than that of the stone components to reduce and isolate the vibration for the purpose of reducing the seismic response of the upper member.

(iii) It is well compatible with stones, easily cleaned without residue and exhibit strong reversibility [9].

Based on the abovementioned principles, the material strength are dominated considered in the development of the sacrificial cushion material.

2.1. Determination of mixing ratio of the cushion material

Clay, sand, gypsum and lime are employed as raw materials for the sacrificial cushion material in this study. The clay excavated and screened on the site of Pingyang Fujun watchtower, the river sand for construction and the lime for general road engineering are used. The specification for the fineness of desulphurized gypsum is 300mesh. On the basis of the relevant literature and engineering experience, the matching proportion of the six components of the initial cushion material is given in Table 1. Then, clay, sand, gypsum and lime are mixed according to the mix ratio, and the water is added based on the water cement ratio of 0.3 to mix. Finally, the required sacrificial cushion material is obtained. In order to test the strength of the sacrificial cushion material, the cubic specimens of 100mm × 100mm ×
100mm are poured. Cubic specimens are cured for 28 days at constant temperature (around 22°C) after stripping, and then the uniaxial compressive strength test is carried out.

Table 1. Physical and mechanical properties of cushion material with different composition ratio.

| Group | Mix Proportion               | Compression Strength (MPa) |
|-------|------------------------------|----------------------------|
| 1#    | Clay: Gypsum: Lime=80:8:12   | 2.63                       |
| 2#    | Clay: Gypsum: Lime=80:10:10  | 2.35                       |
| 3#    | Clay: Gypsum: Lime=80:12:8   | 1.84                       |
| 4#    | Clay: Gypsum=90:10           | 2.12                       |
| 5#    | Clay: Lime=90:10             | 2.04                       |
| 6#    | Clay:Sand:Lime=42:31:27      | 1.50                       |

2.1.1. Uniaxial compressive strength test of sacrificial cushion material. The YZW50 ShearTest apparatus, at the Sichuan Higher Education Engineering Research Center for Disaster Prevention and Mitigation of Village Construction in Sichuan Agricultural University, is used to implement uniaxial compressive strength test. Three samples of 100mm×100mm×100mm are prepared for each group of mix proportion. Typical uniaxial compression stress-strain curves are shown in Figure 1 (Limited to length, here is only the test curves of 3 specimens in Group 1). The 28-day cube strength of the sacrificial cushion material, the mean strength of three samples, is listed in the third column of Table 1.

According to the requirement of the material, 6# material is selected for further testing.

2.2. Mechanical properties of rock joints in filling cushion materials

Pingyang Fujun watchtower is stacked by stones, and the adjacent upper and lower rocks constitute artificial rock joints, of which mechanical properties are the key factors that affect the stability of watchtower.

In the same way, the artificial rock joints will form when the sacrificial cushion material fill the gap between the upper and lower blocks of the watchtower. To obtain the essential parameters for numerical simulation, the joint shear test is carried out in the sandstone, which is near the site of the stone watchtower. By cutting the sandstone into 200mm×100mm×100mm rectangular specimen and smearing the 6# cushion material evenly on surface of the specimen, the test gets prepared after the curing of 28d. The curves of stress and strain test are obtained in Figure 2. The normal stiffness and tangential stiffness are calculated by the following formula.

\[
\begin{align*}
K_n &= \frac{\Delta \sigma_n}{\Delta \delta_n} \\
K_s &= \frac{\Delta \tau}{\Delta \delta_s}
\end{align*}
\]

In the formula, \( \Delta \sigma_n \) and \( \Delta \delta_n \) are respectively normal stress and normal deformation increment, \( \Delta \tau \) and \( \Delta \delta_s \) are respectively shear stress and shear displacement increment in the pre-peak stress rise area.

The parameters of the joints are listed in Table 2. It is evident that the cushion material added to the rock, which can significantly reduce the stiffness of joint surface and the vibration response of the upper block, offers benefit to the stability of the watchtower. Joint parameters of the rock without cushion material reference the literature\([11,12]\).
### Table 2. Physical and mechanic parameters of sandstone and joints.

| Content       | Density (g/cm³) | Shear modulus (GPa) | Bulk modulus (GPa) | Normal stiffness (GPa) | Tangential stiffness (GPa) | Internal friction angle (°) | Cohesive strength (MPa) | Tensile strength (MPa) |
|---------------|-----------------|---------------------|--------------------|------------------------|---------------------------|---------------------------|-------------------------|-----------------------|
| Sandstone     | 2.5             | 7.71                | 8.45               | \           | \                         | \                        | \                      | \                     |
| Unfilled joints | \               | \                   | \                  | 1.5             | 1.5                       | 23                       | 0                      | 0                     |
| Filled joints | \               | \                   | \                  | 1.39            | 0.309                      | 30                       | 0.01                   | 0.12                  |

### 3. Numerical analysis model of vibration response of stone watchtower

The south watchtower is 5.45m tall and that of the north is 5.29m. The foundations of the two watchtowers stacked by sandstones are composed of four layers of sandstones, at a total height of 1.9m. The models are built according to the actual size of the north and south watchtowers (Figure 3).

In the numerical simulation, the Y axis is the vertical axis; the X axis and the Z axis are the horizontal axes. The elastic-homosexual constitutive model is applied to the rock block, and the Coulomb sliding constitutive model is used in the joints. The mechanical parameters of sandstone refer to *Rock Mechanics and Engineering* (Cai M F 2013). For the mechanical parameters of sandstone, the specific parameters are listed in Table 2.
3.1. Selection of damping and boundary conditions
In the 3D numerical analysis of watchtower, the parameters of local damping selected to dissipative energy are obtained by the following formula\[^{[12]}\].

\[
\alpha_L = \pi D
\]  

(2)

In the formula, \(\alpha_L\) is local damping value, \(D\) is critical damping ratio. Referring to \(\xi_{\text{min}}\) in Rayleigh damping, the value of \(D\) is 0.05, so the local damping is 0.157.

The free field boundary is applied around the model to simulate the infinite field in the dynamic analysis for the purpose of reducing the reflection of the wave on the model boundary. The bottom boundary of the model is a vertical displacement constraint.

3.2. Input of seismic wave
The seismic wave adopts the Qingping wave recorded in Wenchuan earthquake. The high frequency of seismic wave is filtered to avoid too small division of grids in the subsequent simulation. And the baseline correction is carried out to eliminate draft of velocity time history. After adjustment, the velocity time history is obtained by the integral of Qingping wave acceleration time history (Figure 4). The seismic wave of 35s-55s is intercepted for simulation based on the efficiency of numerical analysis and the amplitude distribution of seismic wave. The north-south and east-west velocity time histories are applied to the x-direction and z-direction of the watchtower models respectively.

3.3. Determination of the cell dimensions
In the 3DEC simulation, the rock block is generally cut into triangular elements with finite difference. Kuhlemeyer and Lysmer\[^{[13]}\] suggest that the size of the grid unit should meet the following formula.

\[
\Delta l \leq \left(\frac{1}{10}\right)^{\frac{1}{8}} \lambda
\]  

(3)

\(\Delta l\) is the maximum size of cell grid, \(\lambda\) is the minimum wavelength (the shortest wavelength after filtering is 70.25m). The maximum size of the cell grid should be less than 7.025m. The average dimension of the north watchtower units is 0.6m, besides the north watchtower is divided into 3058 tetrahedral units and contains 1410 nodes. With 2336 units and 1212 nodes contained in the model of south watchtower, the average dimension of the south watchtower unit is 0.7m.

4. Simulation results and analysis of stone watchtower under seismic action

4.1. Watchtower gaps under seismic action
Under the seismic actions, the gap between blocks in the stone watchtower increases with height. The reason for the gap is that the friction resistance caused by overlying weight is not enough to resist the action of horizontal earthquake force. The PGA amplification factor (the ratio of the acceleration peak at the measured points on the stone to the acceleration peak of the upper part of foundation) to characterize the horizontal seismic force of the rock block.

As the height increases, the friction of the lower rock block is reduced for the decrease of the self-weight of the overlying rock blocks. With the elevation amplification effect, the PGA magnification coefficient of the test point (Figure 3) is increased (Figure 5). It is shown that with the height increasing, the friction of the rock blocks to resist the horizontal seismic force decreases, which results in the increase of the gap width between the rocks.

Compared with PGA amplification factors of the stone watchtower without the cushion material, the PGA amplification factors of the watchtower added cushion material reduce. The stiffness of cushion material is low, which is equivalent to adding a flexible spring at the bottom of rock blocks, playing a role in separating the transmission of seismic energy to the upper. Moreover, the cushion material combines the upper and lower rock blocks tightly and enhances the ability of the watchtower to resist the horizontal seismic force.

4.2. Rock fragmentation under seismic action

Under the seismic action, shear slip failure occurs to the rocks of NQ-M-S-3-2 and SQ-Z-S-1-1 (SQ-South watchtower, NQ-North watchtower, M-Main watchtower, Z-Subwatchtower, J-Base, S-Body, L-Building, D-Cap, 1~5 values indicate the number of layers of the rock; 1, 2, 3, and W1, W2, W3, E1, E2, E3 represent the number of each layer of rock on the main watchtower or the sub-watchtower, and the letter in front of number represents the West or the East). The result of shear stress is listed in Table 3, simulation shows that the maximum shear stress of NQ-M-S-3-2 is 1.09MPa, and that of SQ-Z-S-1-1 is 2.08MPa. The compressive strength of sandstone is 29.82MPa, and the shear strength is about 1/10 of compressive strength. The shear strength of rocks weathered for more than 1,800 years falls below the shear stress, which leads to shear failure.

Under the seismic action, the maximum shear stress of the rock blocks with the cushion material decreases in varying degrees. The maximum shear stress of NQ-M-S-3-2 and SQ-Z-S-1-1 is 0.90MPa and 1.87MPa, respectively, and the decrease is 17.43% and 10.10%. The addition of the cushion material is proved to effectively reduce the maximum shear stress of the watchtower.
Table 3. Shear stress of watchtower

| Watchtower rocks | Maximum shear stress (Mpa) | Amplitude reduced (%) |
|------------------|---------------------------|-----------------------|
|                  | No material | With material |                |
| NQ-M-S-3-2       | 1.09        | 0.90          | 17.43           |
| NQ-M-S-2-2       | 1.08        | 0.90          | 16.67           |
| NQ-M-S-3-E1      | 0.66        | 0.48          | 27.27           |
| SQ-Z-S-1-1       | 2.08        | 1.87          | 10.10           |
| SQ-M-S-1-W2      | 0.83        | 0.71          | 14.46           |
| SQ-M-S-2-1       | 0.73        | 0.67          | 8.22            |

4.3. Rock torsion under seismic action

The watchtower blocks are unconnected vertically but connected horizontally with the dovetails, so the horizontal integrity is better than vertical integrity. Under horizontal seismic force, horizontal layer of rocks has relative horizontal displacement as a whole, causing the horizontal torsion between layers (Figure 6).

The watchtower rocks resist the horizontal seismic force by the friction generated by gravity. With the increase of the height, the decrease of vertical compressive stress of the rock block accounts for the decrease of friction, which leads torsions of the tower to increase. As shown in Figure 8, both the numerical simulation and the actual situation show that torsion occurs in the rocks of NQ-M-S-2-2 and SQ-Z-S-1-1. The simulation results show that the rock of NQ-M-S-2-2 twists at a horizontal angle of 4.50°, and the rock of SQ-Z-S-1-1 twists at a horizontal angle of 1.69°.

With cushion material added, the twisting angles of NQ-M-S-2-2 and SQ-Z-S-1-1 blocks increase by horizontal angles of 0.80° and 0.33°, mainly because the cushion material reduces the tangential stiffness of the contact surface. The contact between the rock blocks is point contact for the absence of cushion material, and the stress concentration causes the destruction of contact positions, so that the torsion of rocks cannot be recover. Adding the cushion material turns the point contact between the rocks into the surface contact, which helps to relieve the stress concentration.

In the earthquake, the stress in the cushion material is not satisfied with the yield stress, so the material is supposed to remain in the elastic domain, and the blocks of watchtower can reset after torsion.

Figure 6. Schematic diagram of relative torsion angle of rock block.
5. Conclusions

The discrete element method is used to analyse the seismic response of the watchtower, and the following conclusions are obtained:

(i) The numerical simulation shows that the dynamic response of the Pingyang Fujun watchtower is reduced effectively after the repair, and the aim of the restoration is achieved.

(ii) Under seismic action, the cushion material is in the stage of elastic deformation, the watchtower blocks can reset after torsion. Under the action of Qingping seismic wave, the simulation shows that the torsion angle of the watchtower increases, but the cushion material remains to be in the elastic deformation stage, and the torsion of the watchtower can be restored.

References

[1] CAO D 1996 Cultural Relics of Sichuan 50-4
[2] CAO D 2010 Preservation of cultural relics (1981~1991) ed LIU S L (Beijing: Science Press)
[3] ZENG Z M 1993 Sciences of Conservation and Archaeology 36-40
[4] LI Z Y, ZHAN X G, LI H S 1995 Earth Science-Journal of China University of Geosciences 378-82
[5] TIAN P G, CHEN P, ZHAO D and WANG Y 2005 Journal of Xi'an University of Architecture & Technology (Natural Science Edition) 37 492-5
[6] TANG Z, LU Y 2009 Architecture & Culture 63-5
[7] LI X Wand MA J Y 2010 Preservation of cultural relics (1981~1991) ed S L LIU (Beijing: Science Press)
[8] DAI S B, CHEN Y, ZHONG Y 2016 China Cultural Heritage 68-72
[9] SUN X J 2013 Characterization of Stone Relic Conservation Materials and Studies on the Mechanism, Lanzhou: Lanzhou University of Technology
[10] Stefanou I, Psycharis I, Georgopoulos I O 2011 Construction & Building Materials 25 4325-37
[11] Papastamatiou D, Psycharis L 2010 Terra Nova 5 591-601
[12] LAI J, ZHENG Y R, LI X D and LIU Y 2016 Journal of Vibration and Shock 35 175-80
[13] Kuhlemeyer R L, Lysmer J 1973 Journal of Soil Mechanics & Foundations Div 99 421-7