Experimental Study on Structure Water Support Interaction of Large Aqueduct

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Abstract. Based on the large-scale shaking table model test of aqueduct, the interaction and influence of large-scale aqueduct structure-water-damping bearing were studied. Through the dynamic detection of white noise, the free vibration characteristics of aqueduct model under different working conditions were obtained. Based on the comparison of seismic responses of aqueduct under three conditions of water, half water and normal water level and two states of locking and releasing damping bearing, the influence of water quality and damping bearing on natural frequency, dynamic water pressure and dynamic strain of aqueduct structure was studied. By inputting Ricker waves with different frequencies, the correlation among the input wave frequency, the fundamental frequency of aqueduct structure and the frequency of water sloshing and the influence on the aqueduct response were studied. The experimental results show that with the increase of water quality, the interaction between water and aqueduct structure enhanced, which had a great influence on the fundamental frequency of aqueduct structure, and the influence of water level presented an obvious nonlinear. The hydrodynamic pressure decreased along the middle section elevation of the aqueduct, and the acceleration increased with the increase of the tank elevation, which reflected the complexity of the interaction between water and aqueduct structure. The results provide support for the seismic design of aqueduct and the application of shock absorption bearing.

1. Introduction

Aqueduct, as an important water conveyance structure that can cross river, canyon, highway and other obstacles, has been widely used in water conservancy projects, especially in the water conveyance projects in Southwest China with complex geological and topographical conditions. However, aqueducts often have unfavourable structural safety factors, such as large span and large top quality. Especially in Southwest China, the seismic safety of large-scale elevated aqueduct is often the controlling factor of seismic safety in the whole water diversion project [1].

Under the earthquake load, the interaction between the tank structure, water body and support has a certain correlation with the seismic response of the structure, and it also presents nonlinear characteristics under the strong earthquake action. Therefore, the research on the interaction of aqueduct structure, water body and support is of great significance to the seismic safety of aqueduct structure.

There are two different views on the fluid structure coupling in structural dynamic analysis: one is that water sloshing can absorb and consume energy, and act as a damping effect similar to tuned fluid damper (TLD), so as to reduce the seismic response of aqueduct structure [2,3]. Another point of view is that there is strong fluid solid coupling between the water body and the aqueduct body, and the water sloshing frequency is difficult to be consistent with the natural vibration frequency of the aqueduct, and
it is difficult to meet the TLD effect conditions in the actual engineering, so the fluid solid coupling
dynamic interaction is usually not conducive to the aqueduct earthquake resistance [4].
For the interaction between tank and water, scholars at home and abroad have also carried out a lot
of research. According to the simplified model of Hausner theory [5], under the action of transverse
seismic load, the interaction force between fluid and tank body should include fluctuating pressure and
convective pressure. Wu Yi et al. [6] studied the influence of cross-section shape and size on the dynamic
characteristics of water body. The research shows that the influence of section width depth ratio on the
dynamic force of water body in the tank is more significant, and the smaller the depth width ratio of
water body in the tank is, the more obvious the water sloshing is The larger the influence on the stability.
The frequency of external excitation is an important factor affecting the interaction between aqueduct
and water body. Jung et al. [7] applied different frequency reciprocating loads on two-dimensional and
three-dimensional rectangular water tanks. It was found that when the ratio of excitation frequency to
modal frequency of water body was 1, the water body would shake violently, while when the frequency
ratio reached 2, the shaking of water surface would weaken rapidly.
At present, there are few experimental studies on the U-shaped Aqueduct, and the comprehensive
research on the interaction of aqueduct, water body and damping support is rare. Therefore, through the
large-scale shaking table model test of aqueduct, the experimental research on the interaction of
aqueduct structure water bearing is carried out, which provides data support for engineering practice.

2. Test model and measuring point layout

2.1. Test model
The large-scale elevated aqueduct of a water diversion project is located in the southwest high-intensity
area. The structural design section of the aqueduct is U-shaped, with a total width of 8.30m, an inner
diameter of 3.50 m, and a side wall thickness of 0.35m. A tie rod is arranged every 2.5 m along the top
of the trough. The cross-section size of the tie rod is 0.5 m × 0.5 m. The design water level in the groove
is 5.46 m under normal use.
The single span aqueduct above the aqueduct support is taken as the research object, and the model
includes the aqueduct support, aqueduct and water body. The U-shaped Aqueduct has a single span of
30m, a width of 8.3m and a height of 7.6m. C50 concrete is used. Considering the size of shaking table,
the physical model of 1/10 geometric scale was adopted, and the test water body was ordinary water (i.e.
$C_\rho=1$). The tank body of the test model is made of weighted rubber material with a static modulus of
2400MPa. The measured density and elastic modulus meet the requirements of similar scale. The main
similarity scales of the test model are shown in Table 1.

Table 1. Similarity scale of the model

| Scale                  | Numerical value |
|------------------------|-----------------|
| Geometric scale*       | $c_r = 10$      |
| Density scale*         | $c_p = 1.0$     |
| Acceleration scale*    | $c_a = 1.0$     |
| Strain scale*          | $c_\varepsilon = 1.0$ |
| Deformation scale      | $c_\delta = c_r c_\varepsilon = 10$ |
| Stress scale           | $c_\sigma = c_r c_p c_a = 10$ |
| Elastic modulus scale  | $c_E = c_r c_p c_\varepsilon = 10$ |
| Force scale            | $c_F = c_r c_p c_a = 1000$ |
| Time scale             | $c_t = \sqrt{\frac{c_E}{c_r}} = 3.1623$ |
| Frequency scale        | $c_\omega = \frac{1}{c_t} = 0.3162$ |

*Represents the basic similarity scale, and the others are derived scales.
2.2. Layout of test equipment and measuring points
A large three-dimensional six degree of freedom shaking table is used in the test. The table size is 5 × 5m, the maximum load weight is 20t, the working frequency range is 0.1 ~ 120Hz, the maximum horizontal acceleration is 1.8g, the vertical maximum acceleration is 1.3g, the horizontal maximum acceleration is 1.0g, and the vertical maximum acceleration is 0.7g.

In order to monitor the dynamic response of each position of the tank body under earthquake action, 45 strain measuring points are arranged along the 5 sections along the axial direction of the tank body, and 5 hydrodynamic pressure sensors are evenly arranged along the height direction of the central section of the tank body to understand the dynamic changes of the water body in the tank during the test. The layout of measuring points is shown in Fig. 1.

![Figure 1. Layout of the test model points - strain](image)

The top of aqueduct buttress is connected with aqueduct by damping bearing, and 4 bearings are used for each span. During the test, the damping effect of the bearing is analysed by locking and releasing the shear pin.

In order to monitor the dynamic response of each position of the tank under earthquake action, 15 three-dimensional acceleration sensors are arranged along the top of the tank, the middle section, the bottom of the support and the shaking table; in order to obtain the stress distribution and dynamic change of the support during the test, four three-dimensional force sensors are used at the bottom of the aqueduct support. The arrangement of support force sensor and partial acceleration measuring points is shown in Fig. 2.
2.3. Test conditions

In the model test, three different water levels are considered, empty, half water level and normal water level, as well as the locking and releasing of bearing.

(1) Using 0.1g horizontal steady-state white noise excitation.

(2) Inputting three groups of artificial seismic waves, the horizontal peak acceleration is taken as 50 years 5% exceeding probability level value of 0.358g, vertical 0.239g, respectively named A1YZ, A2YZ, A3YZ.

(3) After the natural frequency of the structure is obtained by white noise, Ricker waves with different frequencies are input to study the influence of frequency on the overall seismic response of aqueduct. The main working conditions of the test are shown in Table 2.

| Test conditions | Loading wave | Water level | Bearing status |
|-----------------|--------------|-------------|----------------|
| 1.              | White noise  | Empty       | Lock           |
| 2.              | White noise  | Normal      | Lock           |
| 3.              | White noise  | Empty       | Unlock         |
| 4.              | Artificial wave(A1YZ, A2YZ, A3YZ) | Empty | Unlock |
| 5.              | White noise  | Half        | Unlock         |
| 6.              | Artificial wave(A1YZ, A2YZ, A3YZ) | Half | Unlock |
| 7.              | White noise  | Normal      | Unlock         |
| 8.              | Artificial wave(A1YZ, A2YZ, A3YZ) | Normal | Unlock |
| 9.              | Ricker wave(1Hz) | Normal | Unlock |
| 10.             | Ricker wave(5Hz) | Normal | Unlock |
| 11.             | Ricker wave(10Hz) | Normal | Unlock |
3. Test results and analysis

3.1. Influence of bearing locking state on dynamic characteristics of aqueduct

Under the condition of no water and full water, the self-vibration characteristics of aqueduct structure under two states of locking and releasing self-reset damping support are obtained through the dynamic detection test of 0.1g low-level white noise.

The transfer function of acceleration measuring point A1 on the top of the middle section of the aqueduct model was studied, and the influence of different water level and support locking state on the dynamic characteristics of aqueduct was compared.

![Figure 3. Transfer functions under different bearing states and different water levels (real and imaginary)](image)

The natural frequencies of the aqueduct body under water free condition and normal water level are 11.597 Hz and 9.399 Hz respectively. When the damping support is released, the natural frequencies of the tank body under no water and normal water level are 11.475 Hz and 9.277 Hz respectively.

From the shape of transfer function in the figure, it can be seen that in the low-level white noise test of aqueduct under the condition of no water, the locking and releasing of self-reset damping support has little influence on the first-order frequency of aqueduct structure, the fundamental frequency only decreases by 1.0%, and the influence on the second-order frequency is weak. It shows that the locking and releasing state of self-reset bearing has little influence on the natural vibration characteristics of aqueduct structure under low-level earthquake action.

It can be seen from Fig. 3 that in the white noise test of aqueduct under full water condition, locking and releasing of self-reset damping support has little effect on the first-order frequency of aqueduct structure, the fundamental frequency only decreases by 1.298%, and the second-order frequency is greatly affected (the second-order frequency decreases by 6.418% when opening), which may be related to the enhancement of interaction between water body and tank body.

By applying artificial waves to the aqueduct model under normal water level by shaking table, the influence of four self-reset supports loosening and locking on the support reaction force of aqueduct is studied.
It can be seen from Fig. 4 that the horizontal force on the bearing is significantly reduced (the four bearing forces are reduced to 66.431%, 81.752%, 90.917% and 51.168% respectively). The results show that, under the earthquake action, the shock absorption bearing in the loose state can effectively reduce the influence of seismic load on the aqueduct structure.

3.2. Influence of different water levels on dynamic characteristics of aqueduct

Under the normal working state of aqueduct structure, the damping support is in the non-locking state. The influence of different water levels on the dynamic characteristics of aqueduct structure is studied through white noise detection and seismic test under three working conditions of no water, half water and normal water level.

Through the low-level white noise dynamic detection test, the fundamental frequencies of the tank body under the condition of no water, half water and normal water level are 11.475Hz, 11.108Hz and 9.277Hz respectively, as shown in the figure 5.

It can be seen from Figure 5 that the fundamental frequency of aqueduct model under half water and normal water level is reduced by 3.198% and 19.155% respectively compared with that without water. It shows that with the increase of water quality, the interaction between water body and aqueduct structure will have a great impact on the fundamental frequency of aqueduct structure, and the influence of water level is obviously nonlinear.
At the same time, by applying the same seismic load to the aqueduct structure model under different water levels, the strain difference on the middle section of the aqueduct under different water levels is compared, as shown in Fig. 6.

![Figure 6. Maximum strain of longitudinal measuring points at the middle section of tank body under different water levels](image)

It can be seen from the figure that the maximum strain of No. 19-24 does not change much under the condition of no water or half water. However, at normal water level, the effect of water body on the tank increases significantly, and the strain growth and water level growth present obvious nonlinear relationship, which is related to both the increase of water quality and the interaction between water and tank.

### 3.3. Seismic response of aqueduct structure under normal water level

In order to further study the influence of water body on the aqueduct under earthquake action, three groups of YZ bidirectional synthetic seismic wave loads randomly generated by the same response spectrum are applied to the aqueduct model. The corresponding relationship between hydrodynamic pressure and strain along the elevation direction of the middle section of the aqueduct under normal water level is studied, as shown in the figure 7.

![Figure 7. Relationship between the maximum strain at different elevations and hydrodynamic pressure at the middle section of the tank](image)
It can be seen from Figure 7 that the hydrodynamic pressure at the bottom is obviously smaller, which is mainly affected by the vertical movement of the tank body. Other measuring points are mainly affected by the horizontal movement of the tank body. The hydrodynamic pressure decreases with the increase of the elevation of the tank body. The maximum value of the dynamic strain has a good correlation with the maximum value of the hydrodynamic pressure, and also decreases with the increase of the elevation.

Hydrodynamic pressure mainly reflects the joint influence of wave height variation and water tank interaction. In order to study the relationship between tank acceleration and hydrodynamic pressure, the maximum acceleration and hydrodynamic pressure along the elevation direction of the tank are compared and analysed, as shown in Fig. 8.

![Figure 8. The relationship between the acceleration of different elevation and hydrodynamic pressure in the middle section of the tank](image)

It can be seen from the figure that the hydrodynamic pressure gradually decreases along the elevation direction of the middle section of the tank body, while the acceleration increases with the increase of the tank elevation, which reflects the complexity of the interaction between water and aqueduct structure.

3.4 Influence of input wave frequency on aqueduct structure

Because Ricker wavelet has the characteristics of simple shape, only one positive peak, short duration and fast convergence [8], it is easy to generate waveform with a certain frequency as the main frequency, so it is widely used in seismic waveform input.

In order to study the influence of input wave frequency, aqueduct structure frequency and water sloshing frequency on the aqueduct structure, the Ricker waves of 1Hz (measured water body shaking frequency), 5Hz and 10Hz (the natural vibration base frequency of aqueduct structure are 9.277 Hz) are input respectively for aqueduct model under water level and water level, and the dynamic response of support force of aqueduct structure is compared, as shown in Figure 9.
As can be seen from Fig. 9, at basically the same 1Hz Under the excitation of Ricker input wave, due to the close frequency of wave and water sloshing, the interaction between water body and tank is strong. The support force under normal water level is obviously different from that under no water condition. Not only the support force increases more, but also there is obvious delay phenomenon with excitation, which reflects the strong nonlinear relationship between water body and tank structure. Under the excitation of 5Hz Ricker input wave, the influence of water on the bearing force is weakened, but there is still a regular reciprocating motion of the support after the excitation stops; under the excitation of 10Hz Ricker input wave, the water has little influence on the bearing force, and the bearing force and excitation are basically consistent in time. After the excitation disappears, the movement of the support stops quickly.

4. Conclusion
Based on the large-scale shaking table model test of aqueduct, the interaction and influence between large-scale aqueduct structure, water body and damping support are studied.
Based on the above research, the following conclusions are drawn.

1) Under low-level earthquake, the locking and releasing state of self-reset support has little influence on the natural vibration characteristics of aqueduct structure. In the white noise test of aqueduct under full water condition, the first-order frequency of aqueduct structure is little affected by locking and releasing of self-reset damping support. The fundamental frequency decreases by 1.298%, and the second-order frequency is greatly affected (the second-order frequency decreases by 6.418% when the aqueduct is released), which may be related to the enhancement of the interaction between water body and the aqueduct.

2) With the increase of water quality, the interaction between water body and aqueduct structure will have a great impact on the fundamental frequency of aqueduct structure, and the influence of water level is obviously nonlinear.

3) At normal water level, the effect of water body on the tank increases significantly, and the strain growth and water level growth show a significant nonlinear relationship, which is related to both the increase of water quality and the interaction between water and tank.

4) The hydrodynamic pressure decreases gradually along the elevation direction of the middle section of the aqueduct, while the acceleration increases with the increase of the tank elevation, which reflects the complexity of the interaction between water and aqueduct structure.

5) For the aqueduct with the same mass of water body and tank body, the excitation close to the water sloshing frequency has a great influence on the support of aqueduct.

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