The influence of large mass water on the seismic response of large-scale aqueduct

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Abstract. The large mass water inside a large-scale steel structure aqueduct will have a significant impact on the response of the structure system under seismic conditions. Centrifuge shaking table model tests are carried out in this article. The results show that water insides has a damping effect similar to TLD effect on the acceleration response of the upper aqueduct and the stress response of the lower pier, but it will increase the seismic stress response of the aqueduct steel truss member to a certain extent.

Keywords: seismic response; large-scale aqueduct; TLD effect; centrifuge shaking table test

1 Introduction

The weight of water in large-scale aqueduct is great, which is equivalent to or even exceeds the structural weight. Under seismic excitation, the movement of the massive water in the aqueduct will have a significant influence on the dynamic characteristics and seismic response of the aqueduct structure. When the aqueduct system vibrates, the fluid will sway with the vibration of the structure. The huge inertia force generated by the large mass water body may increase the overall displacement of the structure and the stress of the members, resulting in serious consequences such as falling beam and instability of the members.

Many equivalent analysis methods for the description of water sloshing in tanks have been proposed, including the Westergaard additional mass method[1], Housner equivalent spring-mass method[2], and nonlinear method[3]. The effect of water on the overall energy dissipation and vibration reduction of aqueducts was further studied, with reference to the TLD (tuned liquid damper) effect used in towering structures. Some scholars believe that the water in the tank has a TLD effect on the lower support structure of the aqueduct, which shows that a stronger the water shaking leads to a better shock absorption effect[4,5]. However, some other scholars believe that TLD effect of water in the tank under earthquake depends on the lateral hydrodynamic

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pressure generated by the water sloshing, which is related to many complex factors, including the frequency spectrum characteristics of seismic waves, the vibration characteristics of the water in the tank, and the fundamental frequency of the aqueduct structure. Whether super large water bodies have the TLD seismic reduction effect or adverse effects in large-scale aqueduct seismic systems, has always been a confusion for engineering builders.

2 Engineering profile

In the project of diverting water from the Yangtze River to the Huaihe River, a large-span steel structure aqueduct was built to enable the existing Pi River main canal to cross the Jianghuai communication channel. A beam arch combination structure is adopted for the large single span of 110 meters, the largest span of steel navigation aqueduct of the world, as Fig.1 shows.

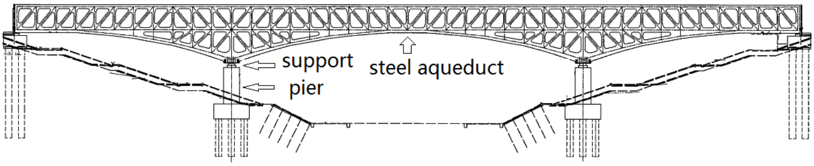

Fig. 1. Schematic diagram of aqueduct

The aqueduct steel structure weighs 10,000 tons, while the maximum weight of the water inside reaches 20,000 tons, which is twice as its own weight. Referring to general bridge structures design, the aqueduct is equipped with friction pendulum bearings to reduce the frequency of the structure and dissipate seismic energy. The large water to structure mass ratio and the setting of friction pendulum bearings make the effect of water on the seismic response of aqueducts a concern for the project constructors. Therefore, series of centrifuge shaking table model tests were conducted at the Tianjin Research Institute for Water Transport Engineering, M.O.T., to study the effect of water on the seismic response of the aqueduct, utilizing the similarity advantage of high gravity field.

3 Similarity ratio design

The first step in designing a centrifuge vibration table model is to determine the similarity ratio of the model. The dimensional analysis method is adopted in this experiment model design to determine the similarity ratio, which needs to meet the Cauchy formula as below.

$$S_E(S_\rho S_a S_l)^{-1} = 1 \tag{1}$$

According to the size of the prototype and the size of the model box, the gravity acceleration scale of this test is determined to be 1/30. The following Table.1 shows similarity ratio (model to prototype) designed in the experiment.

Table 1. Centrifuge Similarity Ratio

Symbol	Physical Quantity	Formula	Ratio of Similitude
S_l	Length	S_l	1/30
S_a	Acceleration	S_a	30
S_E	Elastic modulus	S_E	1
S_ρ	Density	$S_\sigma/(S_a \cdot S_l)$	1
S_σ	Stress	$S_\sigma = S_E$	1

4 Model design and processing

The aqueduct model considered in this experiment includes the internal water, the steel structure aqueduct, eight friction pendulum bearings and four main piers.

4.1 Pier Model

The fine aggregate concrete of C40 grade is used to modeling the aqueduct pier. The strength and reinforcement ratio of the internal steel bar in the concrete model are consistent with the prototype.

4.2 Steel Aqueduct Segment Model

The steel aqueduct test model selects a partial structure on the main pier as the research object, with 4 truss lengths in the longitude direction. The model is manufactured with steel, the same material with prototype structure. And the main components of the prototype structure are dimensionally scaled to 1/30 according to the principle of equivalent axial stiffness, with an error controlled within 5%. Due to the segmented model, sealing steel plates are installed at both ends of the inner wall of the channel. There is a 5mm gap between the steel plate and the side wall, which is sealed with flexible glass glue, which can not only prevent water leakage during the experiment, but also reduce the influence on the vibration of both sides.

4.3 Friction Pendulum Bearing

In the designing of a scaled friction pendulum support model, it is necessary to ensure that the frequency and stiffness of the model satisfy a similarity relationship with the prototype structure[6]. According to the mechanical model of the friction pendulum support[7], the basic parameters of the model were obtained under the ratio of similarity conditions in this experiment, as shown in the following Table 2.

Table 2. Friction Pendulum Bearing Parameters

Physical Quantity	Unit	Prototype	Model
Coefficient of friction	-	0.03	0.03
Effective radius	mm	4000	133.33

A double spherical surface type of friction pendulum bearing is designed for the model experiment. The effective radius is the center distance between the two spherical surfaces of slider, which is covered with polytetrafluoroethylene (PTFE) sheets, used in the prototype structure, to ensure the same friction coefficient as prototype. The whole test model of aqueduct segment is shown in the following Fig. 2.

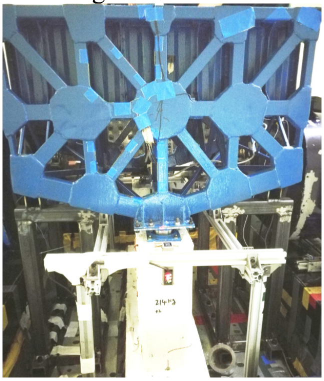

Fig. 2. Aqueduct segment test model

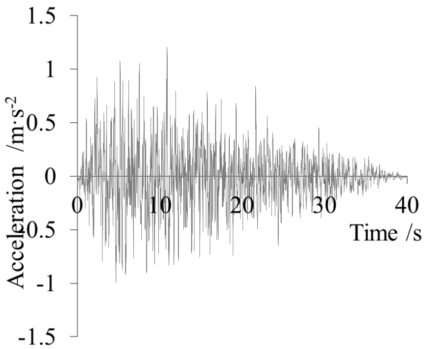

Fig. 3. Acceleration time history of E1

5 Test conditions

In the seismic safety assessment report of the aqueduct site, three E1 and E2 artificial waves of earthquake action are provided according to the ground motion acceleration response spectrum of the site, with acceleration peak values of 0.123g and 0.237g for exceedance probability of 10% and 2% in 50 years, respectively. The typical seismic acceleration time history curve is shown in Fig. 3. In the test, the lateral ground motion was applied at the bottom of the pier by the centrifuge shaking table to study the seismic response of the pier and aqueduct segment models. In order to study the effect of water in the seismic response of the aqueduct, three experimental conditions were carried out: waterless, full water (the highest water level considered in the design), and fixed mass (steel weights of the same mass as full water condition).

6 Test data analysis

All results analyzed in this section are converted back to the prototype structure based on similarity ratio.

6.1 Acceleration

The acceleration response time history curves of the base, pier top, and aqueduct under waterless conditions are shown in Fig. 4.

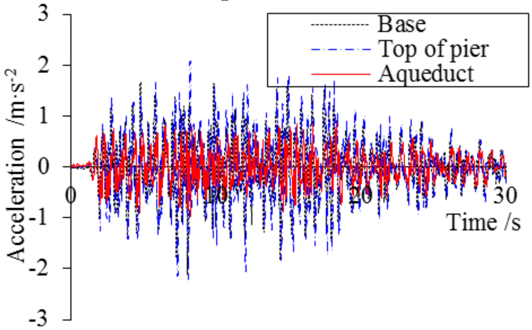

Fig. 4. Acceleration time history of structure

It can be seen that the acceleration and phase at the top of the pier are basically consistent with the base, indicating that the amplification effect of the pier on the seismic acceleration is not significant, which is mainly due to the small height and large stiffness of the pier. Secondly, the peak acceleration of the aqueduct is significantly smaller than that of the pier top, which is mainly due to the installation of friction pendulum supports between the pier top and the aqueduct, indicating that the friction pendulum supports have a good seismic isolation effect. The acceleration Fourier spectrum of the upper aqueduct under three test conditions of waterless, full water, and fixed mass are shown in Fig.5.

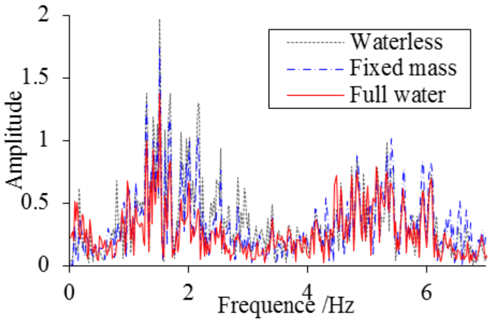

Fig. 5. Fourier spectra of acceleration at different test conditions

From the diagram, it can be seen that the seismic acceleration response is the highest under waterless conditions, and the lowest under water condition within the main frequency range of vibration, especially significant from 1.5Hz to 4Hz. This indicates that an increase in the mass of the upper structure will reduce the seismic acceleration response of itself. At the same time, under the condition of increasing the same mass, the acceleration response of the water condition is smaller than that of the fixed mass, indicating that the water sloshing and the fluid solid coupling effect with the aqueduct wall will further reduce the seismic acceleration response of the upper structure. Therefore, the water plays a certain role similar to the TLD effect in the seismic energy dissipation in the aqueduct structure system.

6.2 Truss member stress

Amplitude of the stress change of the member is obtained through the strain gauge during the test, which can represent the influence of water on the seismic response of the steel structure aqueduct.Due to the discreteness of the data collected in the experiment, the average values of stress variation amplitudes of typical members under three artificial waves of E1 and E2 earthquake actions were taken for comparison, as shown in Fig. 6.

It can be seen from the diagram that the stress variation amplitude of the members in the aqueduct under full water condition is greater than that under waterless condition, and the increase amplitude is more significant under E2 earthquake action compared to E1. The experimental results indicate that water inside the aqueduct increases the stress response amplitude of the structure member, with some members having a particularly significant increase effect under strong earthquake conditions.

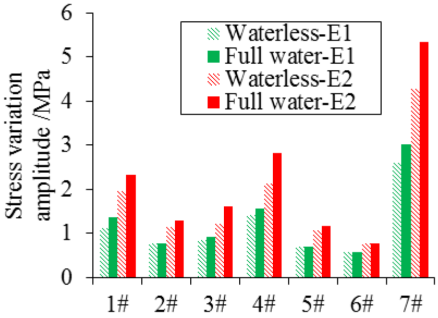

Fig. 6. Stress variation amplitude of typical members

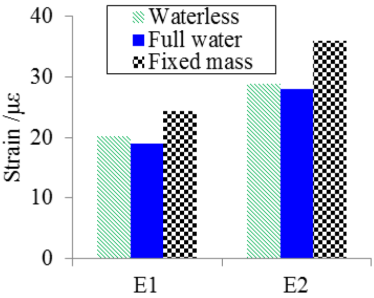

Fig. 7. Strain variation amplitude of pier

6.3 Pier strain

The seismic response of the pier is obtained through the strain gauge laid on the concrete surface at the bottom of the pier during the test. The average data processing method in the previous section is used to obtain the impact of water on the seismic response of the aqueduct pier, as shown in Fig. 7. It can be seen from the diagram that the seismic response of the pier is the smallest under full water condition, while the largest under fixed mass condition. The experimental results indicate that for the aqueduct pier, the water inside also plays a TLD seismic reduction effect, which similar to the impact on the acceleration of the upper aqueduct.

7 Conclusions

The effect of great water mass on seismic response of large steel aqueducts was studied through centrifuge shaking table tests. The following conclusions can be drawn by analyzing the stress and acceleration results of the structure. The friction pendulum supports have a good seismic isolation effect in large-scale aqueduct system. Water inside the aqueduct has a damping effect similar to TLD effect on the acceleration response of the upper aqueduct and the stress response of the lower pier, but it will increase the seismic stress response of the aqueduct steel truss member to a certain extent. A fixed mass with the same mass of water will increase the acceleration response of the upper aqueduct and the stress response of the pier. The above conclusions are specific to the structural system and load characteristics of aqueducts, and can provide reference for similar projects. For aqueducts with significant differences in structural systems, the centrifuge model testing methods in this article can be used for analysis.

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