Investigation on Fluid-Structure Interaction of a Steel Truss Aqueduct under Seismic Force

Haocheng Chang¹, Zhigang Wu², Yu Zhu², Rujin Ma¹, *
¹Department of Bridge Engineering, Tongji University, Shanghai, China
²Anhui Transport Consulting & Design Institute Co., Ltd., Anhui, China
*Corresponding author e-mail: rjma@tongji.edu.cn

Abstract. Aqueduct, one special kind of bridge, has quite different loads from traditional bridge. In this paper, we study the fluid-structure interaction characteristics of a steel truss aqueduct under seismic force using finite element method (FEM). The additive mass method is used to get the acceleration of key sections under E2 earthquake wave. Then the acceleration is applied on the FSI model to obtain the influence of unbalance hydrodynamic load and hydrodynamic pressure on structure. A simplified linear relationship between earthquake acceleration and pressure on the wall is also proposed. The conclusions and approach provided by this study could serve as significant references for anti-seismic design and control of similar steel truss aqueducts.

1. Introduction

Aqueduct [1-3] is a significant structure for water delivery in the Water Transfer Project from Yangtze River to Huai River in China. The water inside the aqueduct has large weight and could be even heavier than the self-weight of structure. Moreover, once motivated by the earthquake, the water inside aqueduct would have significant influence on the dynamic characteristics of the aqueduct. Thus, study on complex fluid-structure interaction (FSI) of the aqueduct is an important aspect of the design process. The Pi river aqueduct studied in this work is the first steel truss aqueduct in China. The structural behaviours of such kind could be found in several references [4, 5], but the investigations on the FSI problems [6,7] are limited.

In this work, we first establish an FSI model of a steel truss aqueduct using finite element method (FEM). Then the accelerations of mid-span and support under E2 earthquake are calculated by the additive mass method [8]. Applying the earthquake accelerations to FSI model, linear fitting of pressure and earthquake acceleration are analysed as well as maximum hydrodynamic load condition.

2. FSI Simulation on the Aqueduct under seismic force

2.1. FSI Model

The total length of the aqueduct is 246 m and the main span is 110 m long. The width of the container of water of the aqueduct, groove, is 16 m. The height of groove is 7 m. The check water level is 5.05 m and sets 5 m here for simplicity. As a steel aqueduct, the groove has the unchanged cross section along the aqueduct and could be seen as an opening water tank. The walls are thin and flat, and thus shell element is used to model the walls of water container. For simplicity, assume the stiffness of wall
infinitely large. The water and wall are simulated by two separate elements, which are also meshed separately. The meshed fluid-structure interaction model is shown in Figure 1. In the initial state, the nodes of two different types of element on the interfaces should be coincide. Free slip boundary condition is applied. When aqueduct is sloshing, the water inside it tend to return to an equilibrium position under gravity. In order to restore this effect, spring element is applied to the free surface.

Figure 1. Meshed fluid-structure interaction model.

2.2. Earthquake Acceleration
Two key locations are investigated: mid-span and support. Due to the lack of the observed seismic wave, the calculation is based on the artificial waves generated by the reaction spectrum. Additional mass method is used to calculate the earthquake accelerations at these two locations with seismic waves generated. The results are shown in Figure 2. The total duration is 40 seconds and time internal is 0.01 second.

Figure 2. The curves of earthquake accelerations of mid-span and support.

3. Results and Discussion
3.1. Linear Fitting of Wall Pressure and Earthquake Acceleration
In this section, the linear fitting of wall pressure (the pressure of left and right bottom corners) and earthquake acceleration are studied, which could facilitate the dynamics analysis of similar structure.

In order to eliminate the influence of date instability, the data of the first second in Figure 2 is ignored. The scatter diagrams of water pressure-earthquake acceleration of mid-span and support are shown in
Figure 3 and Figure 4, respectively. Linear fitting was performed on the data to obtain the fitting line as shown in Figure 3 and Figure 4 as red lines. Various indicators of four linear fitting are listed in Table 1.

![Figure 3](image1.png)

**Figure 3.** Linear fitting between earthquake acceleration of mid-span and bottom pressure of two sides.

![Figure 4](image2.png)

**Figure 4.** Linear fitting of earthquake acceleration of support and bottom pressure of two sides.

**Table 1.** Indicators of linear of pressure-earthquake acceleration

| acceleration | intercept value | intercept standard deviation | slope value | slope standard deviation | statistics value |
|--------------|----------------|-------------------------------|-------------|--------------------------|-----------------|
| mid-span     | left 48556.17  | 22.86                         | 3493.11     | 13.61                    | 0.94408         |
|              | right 48555.82 | 23.28                         | -3494.45    | 13.86                    | 0.94218         |
| support      | left 48556.11  | 22.90                         | 3500.17     | 19.20                    | 0.89502         |
|              | right 48555.88 | 23.32                         | -3503.33    | 19.55                    | 0.89175         |

In Table 1, the adjusted R2 are 0.94408, 0.94218 and 0.89502, 0.89175, which are all close to 1 and represent good agreement of fitting. For these two different locations, the intercept and slope are almost the same. Thus, we can get the following equations.

\[
P_{\text{left}} = 3500a + 48566.2 \quad (1)
\]

\[
P_{\text{right}} = -3500a + 48555.8 \quad (2)
\]

Where, \(a\) is the earthquake acceleration. In the simplified model, the water depth is 5 meters. When the earthquake acceleration is zero, the hydrostatic pressure is 49490 Pa. Amplification coefficient is
49490/48566.2 ≈ 1.01902. Using amplification coefficient 1.02 to modify Eqs. (1) and (2), we can get:

\[ P_{\text{left}} = 3570a + 49490 \]  \hspace{1cm} (3)

\[ P_{\text{right}} = -3570a + 49490 \]  \hspace{1cm} (4)

Assume the pressure along the side wall linear-distributed. The pressure at free surface is zero and thus the pressure along the side wall could be approximated.

3.2. Maximum Hydrodynamic Load Condition

The time history curve of water pressure at the left bottom corner is shown in Figure 5. It could be found from Figure 5 that the pressure on left side wall reaches its peak 70202.5 Pa at 15.28 s and the pressure on right side wall gets its lowest value at the same time. The water shape and pressure nephogram at 15.28 s are shown in Figure 6.

![Figure 5. Time history curve of water pressure at the left bottom corner](image)

![Figure 6. The water shape and pressure nephogram at 15.28 s.](image)

The pressures on the bottom surface along the transverse direction of aqueduct and on the left side wall along vertical direction are shown in Figures 7 and 8, separately.
Figure 7. The pressure on the bottom surface along the transverse direction of aqueduct.

Figure 8. The pressure on the left side wall along vertical direction.

It is conservative to assume that the pressure is changed linearly and the pressure gradients along the transverse direction of aqueduct, vertical direction on the left and right side wall are 8664.6 Pa/m, 14040.5 Pa/m and 5375.9 Pa/m, respectively. Apply this load on the structure as static load and the displacement nephogram of the whole aqueduct is shown in Figure 9. The displacements on the key locations are listed in Table 2. The “origin” represents aqueduct’s state when self-weight and hydrostatic pressure are applied. It could be seen from Table 2 that the displacement along the tranverse direction of aqueduct changed the most proportionately. One reason for this is that the application of corrugated steel web reduces the lateral stiffness. However, the displacements are still acceptable.

Figure 9. Displacement nephogram of the whole aqueduct under seismic force.
Table 2. Displacements at different locations under seismic force.

| Location          | Left expansion joint (mm) | Right expansion joint (mm) | Support (mm) | Deflection at mid-span (mm) | Displacement along the transverse direction of aqueduct (mm) |
|-------------------|---------------------------|----------------------------|--------------|----------------------------|-----------------------------------------------------------|
| Origin            | 27.596                    | 5.680                      | 33.838       | 142.828                    | 4.291                                                      |
| Unbalance load    | 28.641                    | 5.641                      | 33.339       | 142.078                    | 6.462                                                      |
| Deviation (%)     | 3.79                      | 0.69                       | 1.47         | 0.53                       | 50.60                                                      |

4. Conclusion
In this work, a fluid-structure interaction analysis of a steel aqueduct with water inside under seismic force was conducted using FEM method. The time history curve of pressure and displacement nephogram under maximum unbalance load were obtained. A linear relationship was found between earthquake acceleration of support and bottom pressure of two sides, which could facilitate the analysis of FSI on aqueduct. It is concluded that the deflection at mid-span, displacements at expansion joints and support are relatively small, which indicates that the unbalance loading under seismic force has relatively little influence on the structural behaviour along the aqueduct and vertical direction; however, the displacement along the transverse direction of aqueduct under seismic force increases by 50.6% and special earthquake resistant measurements are needed at this direction. The maximum displacement along the transverse direction of the aqueduct occurs at the top truss of the aqueduct.

Acknowledgments
This work was financially supported the National Natural Science Foundations of China [grant Number 51878493].

References
[1] Bai, X.L.; Fan, Y.Y.; Yu, W.; Wang, D.F. Dynamic Response Analysis of Large Aqueduct Structure. In Advanced Materials Research; Trans Tech Publications: Zurich, Switzerland, 2011; Volume 255, pp. 1159–1162, doi:10.4028/www.scientific.net/AMR.255-260.1159 W. Strunk Jr., E.B. White, The Elements of Style, third ed., Macmillan, New York, 1979.
[2] Rossi, M.; Righetti, M.; Renzi, M. Pump-as-Turbine for energy recovery applications: The case study of an aqueduct. Energy Procedia 2016, 101, 1207–1214.
[3] Cheng, G.; Zhang, Y.; Huang, J.; Liu, J.; Zhang, J. Vulnerability analysis of aqueduct structure based on boundary method. In Proceedings of the IOP Conference Series: Earth and Environmental Science, IOP Publishing: Shanghai, China, 7-9 August 2020; Volume 567, p. 012036. Available online: https://iopscience.iop.org/article/10.1088/1755-1315/567/1/012036/meta (accessed on 25 September 2020).
[4] Resnik, B.; Ribakov, Y.; Berlin, B. Implementation and analysis of vibration measurements obtained from monitoring the Magdeburg water bridge. In Proceedings of the 7th International Conference on Material Technologies and Modelling, Melbourne, Australia, 14–17 July 2012.
[5] Suprobo, P.; Febry, A. Infrastructure Health Monitoring System SHM Development, a Necessity for Mainance and Investigation. In Proceedings of the International Conference on Engineering and Technology Development ICETD, Lampung, Indonesia, 27–29 August 2013.
[6] Sbeinati M R, Meghraoui M, Suleyman G, et al. Timing of earthquake ruptures at theAl Harif Roman aqueduct (Dead Sea fault, Syria) from archaeoseismology and paleoseismology[J]. Ancient Earthquakes, 2010, 243.
[7] Xu X, Liu X, Zhang C, et al. STUDY ON EARTHQUAKE DAMAGE MECHANISM OF AQUEDUCT STRUCTURE BASED ON DIFFERENT BOUNDARY[J]. Civil Engineering Journal, 2020 (4).
[8] Pei-wu L I. ADDITIVE MASS METHOD MEASURED DYNAMICALLY FOUNDATION BEARING CAPACITY [J]. Chinese Journal of Geophysics, 1993, 5.