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Finite element analysis of the aseismicity of a large aqueduct

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ABSTRACT

Finite element analysis has been applied to a large aqueduct to investigate the efficiency of lead rubber bearings (LRBs) in reducing the effects of earthquake shocks. Theoretical relationships have been derived for dynamic interaction of a coupled fluid-solid system such as an aqueduct. A numerical program has been developed by considering the coupled fluid-structure dynamics between the water in the aqueduct and the side wall of the aqueduct and the bilinear deformation characteristics of LRB. The numerical analysis shows that the incorporation of LRBs is a valuable technique in creating aseismicity for a variety of conditions. Since aseismic efficiency varies with LRB type, it is feasible to have an optimal design. The analyses show that LRBs work best with large earthquakes, however, the displacement of the trough sat on top of the LRBs is enhanced so the design of joints within the aqueduct needs special attention.

1. Introduction

Aqueducts are hydraulic structures that transport water across valleys, rivers, traffic lines and other obstructions, played an important role in utilization and allocation of water resources. A large number of major aqueduct projects are to be undertaken in China as part of the South-North Water Transfer Project, including an aqueduct with a total length of 3.5 km and maximum flow rate of 500 m^3/s across the Yellow River [1], the Diao River Aqueduct [2] with a design flow capacity of 610 m^3/s. These projects are so large that their equivalents are rarely found in the world. Most of these large aqueducts are located in areas of intense earthquake activity and ensuring that the aqueducts are safe when subjected to seismic load is an issue that must be addressed.

To date little research work has been undertaken into the seismic design of large aqueducts. However, it is readily apparent that there are a lot of similarities between the structural form of an aqueduct and a bridge and there has been a lot of research conducted into bridges in seismic areas [3–5] and some of the findings may be applicable to aqueducts. The specific difference between bridges and aqueducts is that the latter carries a large body of water at the top of the structure. This causes two significant problems, i.e., how to account for the behaviour of the water when subjected to seismic load, how to reduce the effect of the large water body which makes the aqueduct structure 'top-heavy' by comparison to a normal bridge. The presence of the large quantify of water at the top of the aqueduct is very detrimental under the action of an earthquake. The use of a passive "resistance" strategy is not economic, it is very difficult to guarantee the safety of the structure.

At present, the effect of the water in an aqueduct which is subjected to seismic excitation can be accounted for in four ways: 1) the added mass approach [6], 2) the spring-mass system approach [7] as put forward by Housner [8–10], 3) the fluid-solid coupling approach with the trough of the aqueduct being treated as a rigid body [11], 4) the fluid-solid coupling approach with the trough being considered as an elastic body [12].

The added mass and spring-mass system approaches are relatively simple and practical to apply. In Chinese code NB 35047-2015 [10], based on the general Housner model, the improved formula of the dynamic water pressure and the added mass of the trough wall and the trough bottom are given. Analytical results show that the fluid-solid interaction is more intense when the trough of the aqueduct is comparatively thin and flexible compared to when the trough is rigid. When the trough of the aqueduct is treated as an elastic body the analytical results have better correlation with actual behaviour. Disaster investigation of earthquake shows that the steel storage tank in the earthquake occurred a serious damage, especially round thin-walled steel tanks, prone to nonlinear local buckling [13–15]. Aqueducts are concrete structure, its materials and shapes are different from steel tanks, the existing literature shows that the main failure occurs in the supporting part [12], and so far, there has been no instance of trough failure during earthquakes, so elastic body was considered in this paper.

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2. Seismic resistance using lead rubber bearings

Seismic isolation and absorption technology for bridges, which has been the subject of much research and is in an advanced state of development [3–5,16,17], would seem to be worth applying to aqueduct structures.

There are three kinds of common used isolation bearings: laminated rubber bearings, sliding friction isolation bearings, viscous damping bearings [18,19]. The bridge isolation device which is composed of laminated steel plate and rubber bearing is the main bridge seismic isolation system. The plate type rubber bearing is made of thin rubber sheet and thin steel plate, and is formed by bonding with each other. In the middle or centre of the plate type rubber bearing, the lead core is pressed into the lead core with a purity of 99.9%, and the lead rubber bearing (LRB) is formed. Its function of dissipation vibration energy through the shear deformation of the lead core. The principle of sliding friction isolation bearing is that when the structure is subjected to a small ground vibration, the static friction force can prevent the structure sliding and keep the structure stable, when the ground excitation exceeds a certain limit that is more than the maximum static friction, the sliding surface begins to slip, at this time, even the ground excitation is increasing the seismic force to the upper structure will not be increased. Now there are resilient-friction base isolator (R-FBI) and friction pendulum system (FPS). The viscous damping bearing is a viscous damping energy dissipation device. The vibration isolation principle is to achieve the purpose of absorbing and dissipating the vibration energy through the viscous shear of the viscous material. Its damping effect is more ideal, but its structure and processing complex.

The lead rubber bearing is a well-established seismic isolation system for use in buildings and bridges. It consists of a laminated rubber bearing with a lead core pressed into its centre as depicted in Fig. 2-1. The rubber/steel laminated part of the bearing is designed to carry the weight of the structure and provide post-yield elasticity. The lead core deforms plastically under shear deformations and its size can be chosen to provide the required amount of damping. This type of bearing has the advantage of being a simple structure and has been used widely throughout the world. [3].

A large number of quasi-static experiments have shown that the load-deformation behaviour of an LRB is in the form of a hysteresis curve [4,16] which can be represented by the bi-linear model shown in Fig. 2-2, where Q and Δ are horizontal force and displacement, respectively. In this Figure Q_y represents the characteristic strength which is elastically related to the yield stress of the lead, K_1 and K_2 are the elastic and post-elastic shear stiffness, respectively.

The small amount of research which has been undertaken on aqueducts [20,21], has utilised the added mass or spring-mass system approaches wherein the water is treated as part of the aqueduct. This paper concerns numerical study of the aseismic behaviour of a large aqueduct structure to assess the feasibility and effectiveness of using LRBs within such a structure.

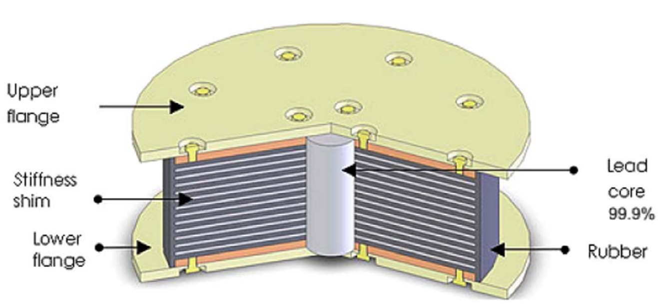

Fig. 2-1. Lead rubber bearing (LRB).

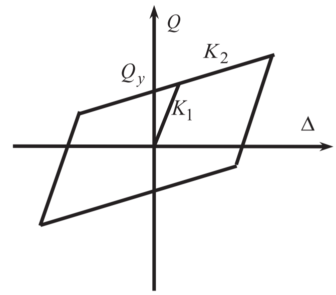

Fig. 2-2. LRB Load-deformation model.

3. Fluid-structure dynamic interaction

A coupled fluid-solid dynamic model, which considers the water container as an elastic body, was used to simulate the behaviour of the water in the aqueduct. This fluid-structure system must satisfy the controlling equations and the general boundary conditions in the fluid and structural fields, it must also satisfy the constraint conditions at the fluid and structure interface. The generalised variable energy function for the coupled fluid-structure dynamic system has been given by Liu et al. [22] as:

$$\Pi = \Pi_0 + Q_C + Q_L \tag{3-1}$$

where, Π_0 is the generalised variable energy function of the fluid-solid system; Q_C and Q_L represent the internal work done during non-slip and slip conditions, respectively.

The specific form of Π_0 is:

$$\Pi_0 = \Pi_0^f + \Pi_0^s - \iint_{V_f} (\rho F_{if}\dot{u}_i + p\frac{\partial \dot{u}_i}{\partial x_i} - \mu\frac{\partial \dot{u}_i}{\partial x_j}\cdot\frac{\partial \dot{u}_i}{\partial x_j})dV - \int_{\Gamma_{f\sigma}} \overline{T}_{if}\dot{u}_i d\Gamma - \iint_{V_s} F_{is}\dot{u}_i dV - \int_{\Gamma_{s\sigma}} \overline{T}_{is}\dot{u}_i d\Gamma \tag{3-2}$$

wherein,

$$\delta\Pi_0^f = \iint_{V_f} \rho(\frac{\partial \dot{u}_i}{\partial t} + \dot{u}_k\frac{\partial \dot{u}_i}{\partial x_k})\delta\dot{u}_i dV \tag{3-3}$$

$$\delta\Pi_0^s = \iint_{V_s} (\rho_s \ddot{u}_i \delta\dot{u}_i + \sigma_{ij}\delta\dot{\varepsilon}_{ij})dV \tag{3-4}$$

In this paper, the superscript and subscript f and s represent the fluid domain and solid domain, respectively.

ρ and ρ_s represent the fluid and solid densities, respectively.
$\dot{u}$ and $\ddot{u}$ represent the system velocity and acceleration, respectively.
$\overline{T}_{if}$ and $\overline{T}_{is}$ represent the known surface force at the fluid and solid interface, respectively.
F_{if} and F_{is} represent the fluid unit mass volume vector and the solid volume force vector, respectively.
$\dot{\varepsilon}_{ij}$ represents the strain rate tensor for small deformations of the solid and is equal to $\frac{1}{2}(\frac{\partial \dot{u}_i}{\partial x_j} + \frac{\partial \dot{u}_j}{\partial x_i})$.

If the non-slip region of the internal contact boundary is taken as Γ_{fsc} and the slip contact region is denoted by Γ_{fsl}, then,

$$Q_C = \int_{\Gamma_{fsc}} \pi_i(\dot{u}_i^f - \dot{u}_i^s)d\Gamma \qquad (i = n, \tau) \tag{3-5}$$

$$Q_L = \int_{\Gamma_{fsl}} \pi_n(\dot{u}_n^f - \dot{u}_n^s)d\Gamma + \int_{\Gamma_{fsl}} g(\lambda_\tau - a_{st})d\Gamma + \int_{\Gamma_{fsl}} \lambda_\tau(\dot{u}_\tau^f - \dot{u}_\tau^s)d\Gamma \tag{3-6}$$

where π_i, π_n and g are Lagrangian multipliers which import constraint conditions. The final term in Eq. (3-6) is the work generated by the internal contact force along the slip direction in unit time.