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Dynamics of submerged intake towers including interaction with dam and foundation

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ABSTRACT

The dynamics of a coupled concrete gravity dam-intake tower–reservoir water–foundation rock system is numerically studied considering two hollow slender towers submerged in reservoir of gravity dam. The system is investigated in the frequency-domain using frequency response functions of the dam and the towers, and in the time-domain using time-history seismic analysis under a real earthquake ground motion. The analyzes are separately conducted under horizontal and vertical ground motions. The coupled system is three-dimensionally modeled using finite elements by Eulerian–Lagrangian approach. It is shown that presence of the dam significantly influences the dynamic response of the towers under both horizontal and vertical excitations; however the dam is not affected by the towers. When the dam is present in the model, the water contained inside the towers has different effects if the foundation is rigid, but it alleviates the towers motion if the foundation is flexible. It is concluded that the effects of foundation interaction are of much importance in the response of tall slender towers when they are located near concrete gravity dams.

1. Introduction

The assessment of dynamic response of concrete dams and their intake–outlet towers during earthquakes is important, because they are related to the continuity of water supply in many regions around the world [1]. Destruction of either dam or intake tower may cause catastrophic consequences. Many of actual intake–outlet towers are axisymmetric; i.e. towers of circular plan with radius varying over the height [2]. These towers may be constructed freestanding supported by concrete blocks on foundation rock or soil; or may be structurally connected to the ground or to the upstream face of dams [1]. They are usually located close to dams, and in some cases, there are more than one intake tower in reservoir, for example in Hoover dam site there are two closely spaced intake towers in stream direction near this arch-gravity dam (Fig. 1).

Extensive researches have been previously done separately on the dynamics of gravity dams and intake towers, but little done on dam–tower interaction including hydrodynamic and foundation interaction effects. The dynamic behavior of gravity dams and their interaction with reservoir water and foundation rock have been broadly studied in the literature [3–19]. Water compressibility and foundation deformability alter the steady-state dynamic response of the dam to harmonic excitations. In particular, this influence is prominent when the excitation frequency approaches to the natural frequencies of the reservoir. Both interactions reduce the resonant natural frequencies of the dam and increase its effective damping [5–8]. Here, the assumption of water incompressibility and hence the added mass method would lead to misleading responses.

Many researchers have studied the dynamic behavior of hollow intake towers considering different components affecting the problem and various geometries ranging from squat to slender towers with circular and non-circular cross-sections [1,2,20–30]. Most of these researches investigated the dynamics of towers assuming their interaction with surrounding water, inside water and foundation rock but ignored their interaction with adjacent dam. They showed that surface waves and water compressibility effects are negligible in the dynamic response of submerged towers. Therefore, the pressure field effect on the tower can be simply represented by added mass attached to the tower. The interaction of the towers with infinite reservoir, inside contained water and foundation rock decreases their resonant frequencies. The effects of tower–foundation interaction are dependent on the geometric and dynamic properties of tower and foundation. These effects are more obvious for squat towers than tall slender ones [2].

The intake towers are commonly located near dams. The presence of the dam causes the hydrodynamic pressure waves to reflect back to the tower. This may change the dynamic response of the tower. So the vibration properties and effective damping of

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Fig. 1. Hoover arch-gravity dam and its intake towers.

the submerged intake towers are modified due to the presence of the dam, surrounding and contained (inside) water, and deformability of supporting foundation rock [1,24]. As the water compressibility could not be neglected in the dynamic analysis of dam–water interaction, it should be considered in the analysis of dam–tower–water systems. Therefore, the simple added mass approach could not be utilized. In a research by Millan et al. [1] the seismic response of an intake tower considering its interaction with a concrete and an earth dam was investigated. They showed that the presence of the dam has significant effects on the seismic response of the tower. They considered the dam–tower–surrounding water interaction on rigid foundation rock by coupled finite element-boundary element model. The hollow intake tower was modeled as solid by changing the concrete's unit mass and elastic modulus such that both hollow and solid towers have the same fundamental frequency. So they did not model the inside water and ignored the effects of foundation flexibility.

The objective of this paper is to numerically investigate the dynamics of a gravity dam and its intake tower(s) considering their interaction themselves, and with surrounding reservoir, water contained inside the tower(s), and foundation rock. For this purpose, the steady-state dynamic response of the dam–tower (s) system to horizontal and vertical harmonic excitations is presented in the form of frequency response functions for various cases: with and without surrounding and inside water; rigid and flexible foundation rock. These cases characterize the dynamics of the coupled dam–water–tower–foundation system and show the significance of various interactions presented in the model. Finally, based on the results of the frequency-domain analysis, the time-history seismic response of some selected cases is studied under horizontal and vertical components of a real earthquake ground motion.

2. Governing equations and boundary conditions

This section outlines the governing equations of the coupled fluid-solid interaction and its boundary conditions. From Fig. 2, the solid domain, Ω_S, consists of three sub-domains: the dam, Ω_{SD}, the tower, Ω_{ST}, and the foundation Ω_{SF}. The governing differential equation of the solid domain in displacement-based Lagrangian formulation, assuming no static gravity load, is:

$$\nabla.\sigma-\rho_s\ddot{u}=0 \quad (1)$$

where σ is the Cauchy stress tensor, u is the displacement vector, ρ_s is the solid mass density, ∇represents the Del operator, and $(\ddot{\bullet})$ represents the second derivative with respect to time [31]. The governing equation of the fluid domain, Ω_F, using the pressure-based Eulerian formulation, assuming that the fluid is linearly compressible, neglecting its internal viscosity and having small amplitude irrotational motion, can be represented as:

$$\nabla^2 p-\frac{1}{c^2}\ddot{p}=0 \quad (2)$$

where p is the hydrodynamic pressure in excess of hydrostatic pressure, c is the acoustic wave speed in the fluid, and ∇^2represents the Laplacian [6]. Three main boundary conditions of the fluid domain are (Fig. 2): fluid free surface, Γ_{FF}, fluid–structure interaction, Γ_{FSI}, and truncated far-end, Γ_{TF}. In practice, the effects of surface gravity waves can be neglected in analysis of high gravity dams, so the zero-pressure boundary, $p=0$, can be assigned to $\Gamma_{FF,}$ which is an essential boundary condition [9].

The boundary condition on Γ_{FSI}, considering no flow across the fluid–solid interface, can be written as:

$$\frac{\partial p}{\partial n}=-\rho_F\ddot{u}_n \quad (3)$$

where ρ_F is the fluid density, and n is the normal vector on Γ_{FSI}. From Fig. 2, it would be defined on the dam–reservoir (D–R), foundation–reservoir (F–R), tower–reservoir (T–R) and tower-inside water (T-I) interfaces [2]. It is assumed that solid faces of the fluid–solid interfaces are impermeable, so there is no wave absorption in these boundaries. In the finite element formulation, the infinite fluid domain should be truncated in a sufficient distance from the fluid–solid interface. The transmitting boundary condition has to be assigned to the truncated far-end boundary, Γ_{TF}, to absorb pressure waves going away from the system. It could be taken into account using the Sommerfeld boundary condition [32]:

$$\frac{\partial p}{\partial n}=-\frac{1}{c}\dot{p} \quad (4)$$

Eqs. (3) and (4) represent the natural boundary conditions of the fluid domain.

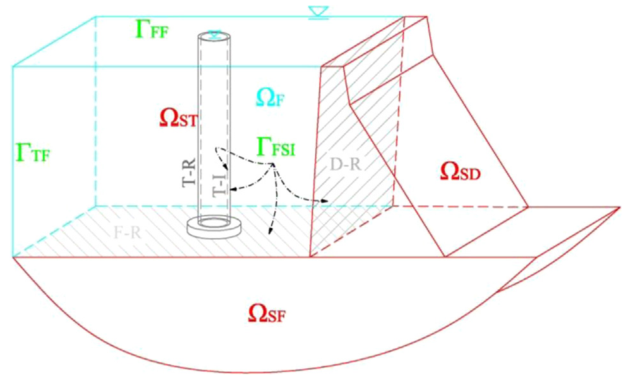

Fig. 2. The coupled system of dam–water–tower–foundation rock and its boundary conditions.

3. System and cases analyzed

The whole system considered, as shown in Fig. 3, consists of a concrete gravity dam, its reservoir, and two hollow reinforced concrete intake–outlet towers fully submerged in the reservoir supported through a flexible concrete block on horizontal surface of a flexible foundation rock. The hollow towers are fully filled with the water. The idealized section of the gravity dam, 85 m high, is considered as tapered triangle with inclined upstream and downstream faces. The tower is an idealized common concrete tower which may be used as intake–outlet tower in a dam site. It is 80 m high, having tapered geometry with a hollow circular cross