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Earthquake response of solitary slender freestanding intake towers

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ABSTRACT

Earthquake response of solitary slender intake towers is investigated considering an idealized hollow intake tower with its circular footing submerged in water. The tower is studied in anchored (fixed base) and unanchored (freestanding) states placed on undeformable soil foundation. The water-structure interaction is modeled by the Eulerian-Lagrangian approach, using the pressure-based elements for the water and the displacement-based elements for the structure. The only source of nonlinearity is the contact at the base joint between the tower's footing and the ground. This contact is modeled using Coulomb friction model which allows the tower to slide and uplift. The system is three-dimensionally analyzed using finite element method under static and dynamic earthquake loads. A detailed parametric study is conducted to assess the importance of system characteristics including surrounding and inside water levels, ratio of tower height to footing radius, base joint friction coefficient, water compressibility, footing flexibility, and vertical ground motion.

1. Introduction

Most previous research on submerged intake-outlet towers has considered towers that are anchored to the supporting foundation rock or soil [1–14]. Such towers, however, may be constructed freestanding, without any structural connections to the ground [13]. The seismic safety of intake towers is important for ensuring continuity of water supply for the public utilities. The dynamic response of unanchored freestanding structures has been widely studied for various tower and block types assumed to be rigid or flexible, and several simplified analytical procedures have been developed for their dynamic analysis [15–20]. They may slide, uplift, rock and even overturn during a dynamic excitation. Their rocking response is very sensitive to their geometry and mass distribution as well as to the nature of the ground motion. It may occur for interfaces with larger coefficient of friction and for more slender structures. Earthquakes with longer dominant period have larger overturning capability than earthquakes with shorter dominant period [15]. Rocking and overturning spectra have been generated for different unanchored structures excited by various records and pulses on rigid and flexible foundations [21–28]. Smaller friction coefficient of the interface between structure base and ground generally results in larger sliding displacement but smaller rocking response. The problem of simultaneous sliding and rocking (uplift) motions is highly nonlinear, and energy can be dissipated both due to friction and due to impacts during sliding and rocking motions, respectively. It has been shown that the rocking and the sliding can be used as seismic response modification technique characterized by residual displacements and forces transmitted to foundations [26].

Clear evidence of uplift has been observed during strong earthquakes [21]. However, no definite conclusion has been indicated on its benefits [25–28]. The uplift can be of considerable concern for the design of unanchored freestanding intake-outlet towers subjected to strong ground motions [29]. Excessive rocking and sliding response is undesirable. The uplift during the rocking motion may lead to mechanical damage or total loss in the event of overturning. It also generates high acceleration spikes developed during impact of the rocking structure [15]. The sliding could damage the equipment connected to the tower, such as penstocks, gates and water pipes extended from the intake towers.

It is common to design intake towers as fully fixed-base to transmit the plastic-capacity tower forces to their footings. The footings are designed to transmit these forces to the underlying soil without uplift, sliding or soil failure. For most soil types, this requires extending the footing substantially beyond the tower section footprint, and sometimes anchoring it into the soil using piles [16]. The foundation uplift can reduce the magnitude of the seismic forces in the tower and its footing. However, it may cause permanent soil deformations which should be avoided [30–32].

The effects of water compressibility can be neglected in dynamic analysis of submerged anchored hollow intake towers specifically for slender ones [1–4]. Their earthquake response is increased because of hydrodynamic effects due to the presence of

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surrounding (outside) and inside water. The effects of tower-foundation interaction are generally lower than the tower-water interaction specifically when the relative stiffness of the foundation soil to the tower structure becomes greater which is the case for slender towers on stiff soils [1].

The problem of coupled tower-water system allowed uplifting and sliding is a rather complex one that requires involving physical problems such as unbounded extent of the water, the geometry and flexibility of the structure, uplift, sliding and friction, and stochastic nature of the earthquake ground motion. Spyrakos and Xu [29] showed that the hydrodynamic effects increase the response of intake towers considering footing uplift but decrease the footing rotation. In the case of short towers, footing uplift is unlikely to occur, but for slender towers, uplift is more likely to occur, especially for footings supported by stiff soil. They modeled the soil as frequency-independent spring-dashpot system connected to the tower's footing. They neglected the slippage of the footing and considered the tower to deflect only in its fundamental flexural vibration mode.

In this paper, the seismic response of a slender intake tower in anchored and unanchored states is investigated using a three-dimensional model and strong earthquake excitations. A hollow intake tower is considered submerged in water and with its footing placed on undeformable soil foundation. The entire system is modeled using the finite element method. The contact between the tower's footing and the rigid ground is modeled assuming Coulomb friction, which allows the tower to slide and uplift. Results are shown of a parametric study aiming to assess the effects of the presence of water inside and surrounding the tower, and various model parameters such as the ratio of tower height to footing radius, the water level, the coefficient of friction between the footing base and the ground, horizontal and vertical ground motions, water compressibility, and footing stiffness. The objective is to show the relative importance of the system characteristics that affect the tower seismic response.

2. Governing equations and numerical modeling

2.1. Finite element formulation of the water-structure interaction

Let us consider a solid hollow intake tower submerged in an infinite water reservoir, as shown in Fig. 1. The governing equation of motion of the structure domain, Ω_S, which may contain the tower, its footing and underlying soil, in the displacement-based Lagrangian formulation is

$$\frac{\partial \tau_{ji}}{\partial x_j} + F_i = \rho_s \frac{\partial^2 u_i}{\partial t^2} \tag{1}$$

where $\tau_{ji}=\tau_{ij}$ is the Cauchy stress tensor, u_i is the displacement, ρ_s is the structure mass density, and F_i is the body force per unit volume [33]. The governing equation of the water domain, Ω_W, which may contain the surrounding and inside water, 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 wave equation

$$\frac{\partial^2 p}{\partial x_i^2} = \frac{1}{c_w^2}\frac{\partial^2 p}{\partial t^2} \tag{2}$$

where p is the hydrodynamic pressure in excess of hydrostatic pressure, and c_w is the acoustic wave speed in the water [6]. As shown in Fig. 1, the four main boundaries of the water domain are: the water free surface Γ_{WF}, the water-structure interface Γ_{WSI}, the truncated far-end Γ_{TF}, and the lateral faces Γ_{LF}. In practice, the effects of the surface waves can be neglected for both surrounding and inside water, because sloshing is not important for slender towers. Accordingly, zero-pressure boundary, $p=0$, can be assigned to Γ_{WF} [4].

The boundary condition on Γ_{WSI}, considering no flow across the water-structure interface, can be written as

$$\frac{\partial p}{\partial x_i} n_i = -\rho_W \frac{\partial^2 u_i}{\partial t^2} n_i \tag{3}$$

where ρ_W is the water density, and n_i is the normal vector on Γ_{WSI}. It is assumed that the solid faces of the water-structure interfaces are impermeable, so there is no wave absorption in these boundaries. In the finite element formulation, the infinite water domain should be truncated in a sufficient distance from the water-structure interface. The transmitting boundary condition has to be assigned to the truncated far-end boundary Γ_{TF}, in direction of earthquake ground motion to absorb pressure waves going away from the system. It could be taken into account using the Sommerfeld boundary condition [34]

$$\frac{\partial p}{\partial x_j} n_j = -\frac{1}{c_w}\frac{\partial p}{\partial t} \tag{4}$$

where n_j is the normal vector on Γ_{TF}. If the ground motion is applied parallel to the lateral faces of the water domain, then rigid boundary condition can be assigned to Γ_{LF} as

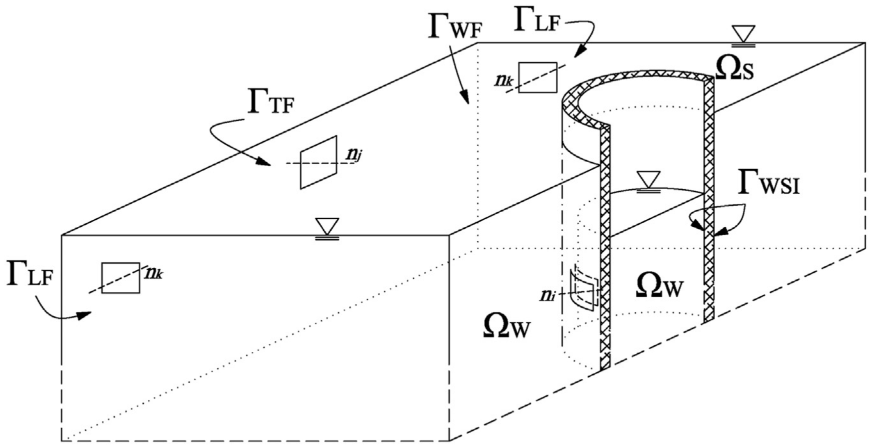

Fig. 1. The coupled system of tower-water and its boundary conditions.