Analysis and investigation of the response of free-standing intake tower under the effect of seismic pulses with variable frequencies and accelerations

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ABSTRACT

This study investigates the behavior of free-standing intake towers subjected to seismic pulses with different amplitudes and frequencies. The effects of loading amplitude and frequency on the dynamic response of the surrounding reservoir and the water inside the tower, as well as their subsequent influence on the structural behavior of the intake tower, are also examined. To provide a comprehensive assessment, five numerical models representing different configurations of the surrounding reservoir and internal water presence or absence were developed and analyzed. The analyses covered various pulse-loading conditions with different acceleration amplitudes and frequencies, resulting in a total of 80 linear analyses. The numerical models were developed using ABAQUS to investigate the linear dynamic behavior of the intake towers. Each analysis consisted of two stages: a static step followed by a pulse-loading step. The time-history analysis method was employed to evaluate the structural response. The intake tower and its interactions with the surrounding reservoir and internal water were modeled using the Coupled Eulerian–Lagrangian (CEL) formulation. The results indicated that, for each model, increasing the loading acceleration and frequency had increasing and decreasing effects, respectively, on the structural responses. The presence of the surrounding reservoir and internal water increased the structural responses under all investigated loading amplitudes and frequencies. Furthermore, the influence of the internal water and its elevation on the intake tower response was strongly dependent on the loading frequency. Notably, at certain loading frequencies, the partially filled tower exhibited more critical structural responses than the fully filled tower.

KEYWORDS

Intake tower, Seismic pulse, Fluid- structure interaction, Frequency effect, Water-level effect.

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1. Introduction

Intake towers are critical components of dam systems, and their safety under extreme conditions, particularly earthquakes, is essential for maintaining water supply. They can be designed as free-standing structures or integrated with the downstream dam. Lia and Chopra pioneered studies on the modal behavior of axisymmetric intake towers surrounded by a reservoir, introducing the added hydrodynamic mass concept. However, soil–structure–reservoir interaction and hydrodynamic pressures were not considered [1,2]. Alembagheri and Hajirezaei investigated the overturning and rocking responses of free-standing towers under sinusoidal pulses with different periods and acceleration amplitudes. Their results showed that surrounding water significantly affects overturning response and reduces tensile stresses by more than 50% compared with anchored towers [3]. Ravikumara studied intake towers considering internal and surrounding water, showing that water presence, structural slenderness, and flexibility increase the natural period [4]. Chen et al. examined reinforced concrete intake towers under near-fault motions, focusing on forward-directivity and fling-step pulses. Their results revealed considerable displacements and damage concentration in the lower tower region [5]. Su et al. analyzed Pine Flat Dam under pulse-like and non-pulse-like motions using linear and nonlinear analyses. Their findings showed that pulse-like motions impose greater seismic demands at the same PGA [6]. In this study, five cylindrical intake tower configurations were analyzed using the Coupled Eulerian–Lagrangian (CEL) approach. Eighty linear dynamic analyses were performed considering five water-level configurations, four frequencies, and four acceleration amplitudes. The results showed that increasing PGA amplifies structural responses, whereas increasing frequency generally reduces maximum displacement and principal stresses. Internal water effects were strongly frequency-dependent, with the half-filled configuration producing greater amplification at higher frequencies. Critical hydrodynamic pressure also varied with excitation frequency and reservoir level.

2. Numerical modeling and Methodology

The boundary conditions of the intake tower, including the surrounding reservoir and internal water, are illustrated in “Fig. 1.” The governing equations for the structural domain are formulated based on the Lagrangian formulation and are expressed as follows:

$$\nabla.\sigma - \rho_s \ddot{u} = 0 \tag{1}$$

In this equation, σ denotes the Cauchy stress tensor, u represents the displacement vector, and ρ is the density of the solid material. The governing equation for the fluid domain is derived using a pressure-based Eulerian formulation, assuming small displacements and inviscid fluid behavior, while neglecting temporal and spatial variations in water density. The equation is expressed as follows:

$$\nabla^2.p - \frac{1}{c^2}\ddot{p} = 0 \tag{2}$$

Here, P denotes the fluid pressure, while C represents the speed of sound in water. The fluid domain is subjected to the following boundary conditions:

- S1 (Free Surface): The hydrodynamic pressure at the free surface is assumed to be zero (P=0), based on the assumption that free-surface fluctuations are negligible.
- S2 (Fluid–Structure Interface): The impermeability of the structural boundary requires the fluid and structure to have identical normal velocity components. Accordingly, no relative flow is permitted across the interface.

Where ρ is the fluid mass and n is the normal vector on S2.

- S3 (Far-Field Boundary): The Sommerfeld radiation condition is imposed at the truncated outer boundary to simulate the propagation of outgoing plane waves into the far field, thereby minimizing artificial wave reflections from the computational domain boundaries [7].

$$\frac{\partial p}{\partial n} = -\frac{1}{c}\dot{p} \tag{3}$$

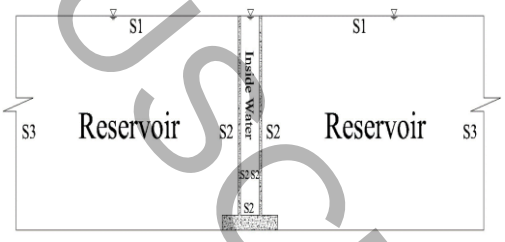


Fig.1. Boundary conditions of the tower, reservoir, and internal water

The intake tower is a cylindrical structure with a total height of 100 m and a uniform cross-section along its entire height, consistent with the configuration adopted by Alembagheri [8]. The tower is supported by a foundation with a height of 5 m and a radius of 12.5 m.

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The inner and outer radii of the tower are 4.5 m and 5.5 m, respectively. The material properties of the intake tower and the fluid are provided in Table 1. Tables 2 and 3 summarize the geometrical characteristics of the investigated models and the corresponding loading conditions applied to the intake tower analyses for the five configurations considered.

3. Results and Discussion

The results indicated that, for each model, increasing the loading acceleration and frequency had increasing and decreasing effects, respectively, on the structural responses. The presence of the surrounding reservoir and internal water increased the structural responses under all investigated loading amplitudes and frequencies. Furthermore, the influence of the internal water and its elevation on the intake tower response was strongly dependent on the loading frequency. Notably, at certain loading frequencies, the partially filled tower exhibited more critical structural responses than the fully filled tower.

Table 1. Properties of Intake tower and water

Intake tower		
Poisson ratio	Density	Modulus of Elasticity
0.15	2400Kg/m3	30GPa
Water		
Density		Bulk Modulus
1000Kg/m3		2.07GPa

Table 2. Characteristics of Intake tower

Internal Water	Reservoir	Intake tower
0	0	A
0	50	B
50	50	C
0	100	D
100	100	E

4. Conclusions

1- Increasing PGA amplifies the maximum displacement, principal stresses, and hydrodynamic pressure in all intake tower models.

2- Increasing excitation frequency generally reduces the maximum structural responses and shifts the peak displacement toward the beginning of loading.

3- The effects of internal water on structural responses are strongly frequency-dependent, with the half-filled configuration exhibiting greater amplification at higher frequencies.

4- Increasing the surrounding reservoir level consistently increases the maximum structural responses, while the influence of internal water varies with excitation frequency.

5- The maximum hydrodynamic pressure increases linearly with PGA, with its critical location depending on the excitation frequency and reservoir water level.

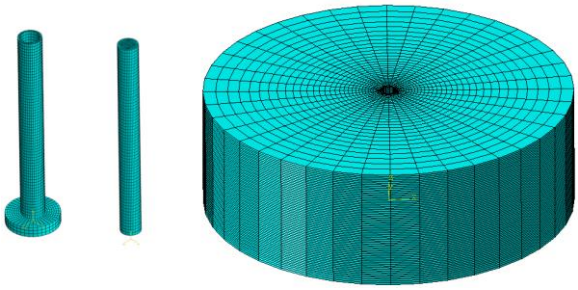


Fig.2. Finite element model of the intake tower, internal water, and reservoir

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