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Seismic response sensitivity analysis of intake towers interacting with dam, reservoir and foundation

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Abstract. In this paper, parameter sensitivity analysis of the dynamic response of cylindrical intake towers interacting with the concrete dam, foundation, internal and surrounding water is performed. The tower is modelled and verified using three-dimensional finite elements according to the Eulerian-Lagrangian approach in the time domain. In order to carry out a parametric study, the Taguchi optimization method is employed to distinguish the most influential parameters. Thus, the iteration algorithm and number of numerical tests are designed. The models are tested under longitudinal horizontal excitation of selected reference accelerograms for either hard soil or hard rock. The evaluation of the results indicated that the two parameters, i.e. tower's slender ratio, and the surrounding water depth are the most effective factors on both intake tower's top drift and the base shear coefficient under seismic excitations on hard soil. It is observed that the elasticity modulus of the foundation is another influential factor in the seismic response, as the tower's drift increases with the foundation's flexibility. Furthermore, the effect of dam interaction on the tower drift reduces as the distance from the dam increases and stays relatively constant for any distance higher than twice the tower's height. Interesting to note that the intake tower did not show notable sensitivity to the reference hard rock ground motion compared with that of the hard soil ground motion.

1. Introduction

Intake towers are of most importance among hydraulic structures in a dam-reservoir system. These are rather lean structures with either cylindrical or rectangular cross-sections at the vicinity of large dams, and surrounded by their reservoir water and usually containing internal water as well. However, in highly seismic areas, they are so much prone to damages due to both direct ground motion and the induced hydrodynamic pressure. In this paper, we study the sensitivity of free-standing intake towers to several geometric and material parameters.

In previous works, researchers first analytically evaluated the effects of water compressibility, surface waves and the popular "added mass" method on seismic response of the cylindrical intake tower with the fixed cross-section due to rigid ground harmonic motion. They have found that in the lower-frequencies of excitation, the effects of surface waves and water compressibility on slender towers are ignorable [1]. The latter has been found when the dam is not present in the vicinity of the tower. Liaw and Chopra used Finite-element method for the hydrodynamic solution of Laplace equation and developed an incompressible fluid formulation with reasonable boundary conditions [2]. Other works presented simplified added mass approach for calculating the hydrodynamic pressure on intake towers, while accounting for dynamic tower-water-foundation [3]. However, in their researches, the considered added mass for creating hydrodynamic pressure only included the effect of the tower vibration, and the effect of the large dam near the tower ignored. Moreover, the linear responses of the intake towers under the harmonic ground motion for different parameters, including geometry, internal and surrounding water and foundation system were idealized. Previous research on intake towers has analyzed towers that are anchored to the supporting foundation. Their results used in *engineering manuals* [4–11]. Milan et al. studied the dam body effect on the seismic response of a cylindrical intake tower on a rigid

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foundation in the reservoir-tower system. They observed an unpredicted resonance created on the tower response due to a modified added mass, caused by the tower-dam-reservoir interaction. This event was interpreted as the results of the added mass induced by reflective waves from the dam. Additionally, the phenomenon could alter the natural frequencies of the tower and thus, the seismic response of the tower [12, 13]. Alembagheri studied the seismic response of a sample intake tower with a cone frustum, including the dam and its foundation under different conditions of the reservoir water compressibility, distance from the dam, and foundation material. Furthermore, in the absence of the dam, vertical excitation did not affect the tower response, and for slender towers, foundation interaction was intensified when the dam was absent [14, 15]. However, in his research, the effects of the tower geometry, as well as the different internal and surrounding water depths, were not evaluated. Indeed, simultaneous consideration of influential factors including the geometry of the tower has been less studied. In a recent research, an analytical solution for hydrodynamic pressure on the cylindrical tower with elliptical cross-section on a rigid foundation has been derived but without the presence of the dam [16].

The goal of the current research is to examine the effects of different parameters on the seismic response of intake towers, the consistency of the idealized model of the system of the intake tower is first verified under the Taft earthquake. After that, using Taguchi optimization method, the required test cases for a cylindrical intake tower with variable conditions including geometry, internal and surrounding water depth, foundation material and dam body distance are established in order to distinguish the most crucial parameters on the seismic response of the complete system.

2. Methods

2.1. Governing equations and boundary conditions

This section outlines the governing equations of the coupled fluid-solid interaction and its boundary conditions. The governing differential equation of the solid domain in the displacement-based Lagrangian formulation, assuming no static gravity load, is:

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

where σ is the Cauchy stress tensor, u is the displacement vector, ρ_s is the solid mass density, ∇ represents the Del operator, and $(\ddot{u})$ represents the second derivative with respect to time [17]. Using the pressure-based Eulerian formulation, assuming that the fluid as inviscid, linearly compressible, with small amplitude irrotational motion, the governing equation of the fluid domain can be represented as:

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

where p is the hydrodynamic pressure in excess of hydrostatic pressure, c the acoustic wave velocity in the water, and ∇^2 the Laplacian operator. In practice, the effects of surface gravity waves can be neglected in the analysis of high and slender intake tower, so the zero-pressure boundary, $p = 0$ [1]. The boundary condition on the fluid–structure interface, considering no flow through the fluid–solid interface, can be written as:

$$\frac{\partial p}{\partial n} = -\rho_w \ddot{u}_n \tag{3}$$

where ρ_w water mass density, and n is is the boundary surface outward normal vector. In the finite element formulation, the upstream infinite fluid domain should be truncated at a sufficient distance from the fluid–solid interface, where Non-reflective Sommerfeld boundary condition is employed [18]:

$$\frac{\partial p}{\partial n} = -\frac{1}{c}\dot{p} \tag{4}$$

The wave reflection at the bottom of the reservoir in the absence of the vertical and transversal direction acceleration can be written as [20]:

$$\frac{\partial p}{\partial n} = -\frac{1}{\beta.c}\dot{p} \tag{5}$$

β is acoustic impedance ratio of bottom to water acoustic impedance:

$$\beta = \frac{\rho_b.c_b}{\rho.c} \tag{6}$$

where c is the water wave velocity, is represented in a simplified way using an absorption coefficient α.

$$\frac{1}{\beta} = \frac{1-\alpha}{1+\alpha} \tag{7}$$

That $\alpha = 0$ implies a non-reflective boundary and implies a fully reflective boundary. c_b is the P-wave velocity in the bottom of reservoir.

The tower is decidedly smaller than the foundation, so the foundation is modelled massless with eight nodes elements as a rectangular shape with a depth more than two times of the tower's height for observing the interaction behaviour.

2.2. System Model Verification

The initial validity of the model is verified against Chopra and Goyal, for the case of the intake tower of the Briones dam response time history under Taft's earthquake [4]. Although they employed a novel added mass concept, instead of our rigorous hydrodynamic model, the considerable agreement is achieved between the two analyses as depicted in Figs. 3.

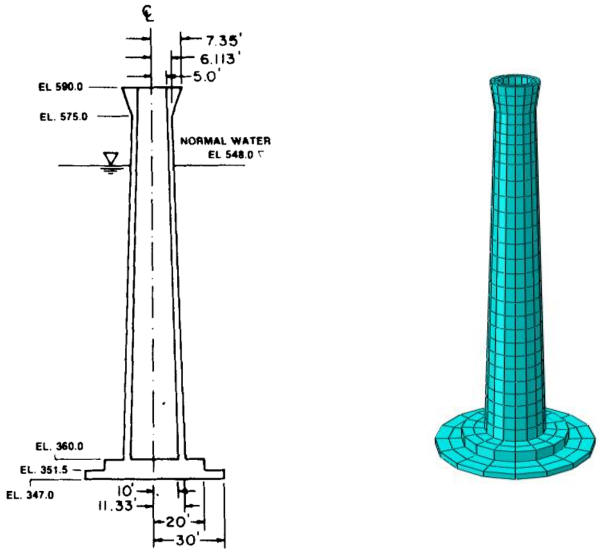


Figure 1. Geometry and the Finite element model of Briones Dam Intake Tower.

In this research, concrete Young's modulus of elasticity E_s is 31 GN/m^2, unit weight is 24.3 kN/m^3 and Poisson's ratio 0.17. The material properties of the foundation material include; shear wave velocity C_f = 305 m/s, unit weight = 25.9 kN/m^3, Poisson's ratio = 0.33 and a constant hysteretic damping factor of η_f = 0.10.

Table 1. Different cases of analysis of Briones Dam Intake Tower to Taft ground motion.

Case	Surrounding Water Level	Inside Water Level	Foundation
1	none	none	Rigid
2	normal	none	Rigid
3	none	normal	Rigid
4	normal	normal	Rigid
5	none	none	flexible
6	normal	normal	flexible

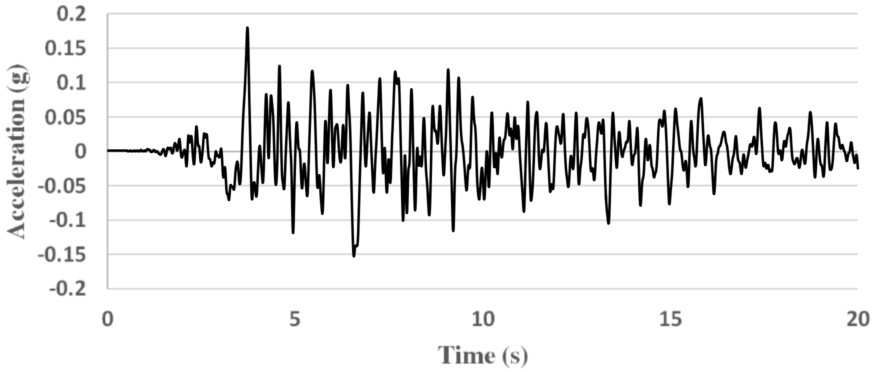
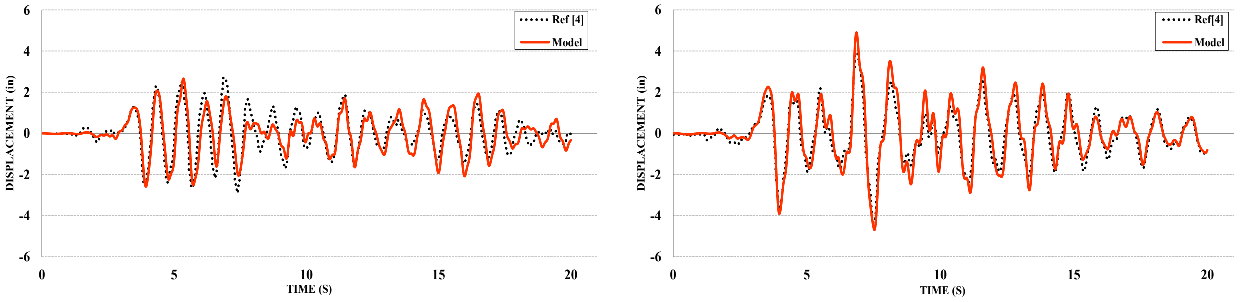
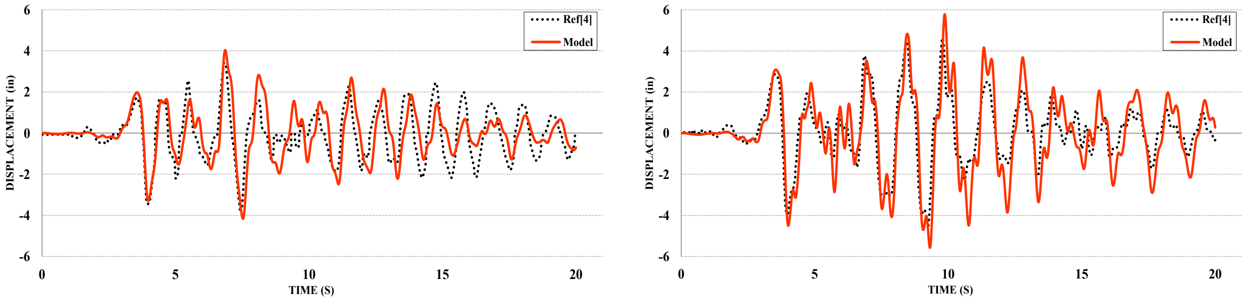


Figure 2. Ground motion recorded at Taft, California, on hard soil, Earthquake July 21, 1952 [20].



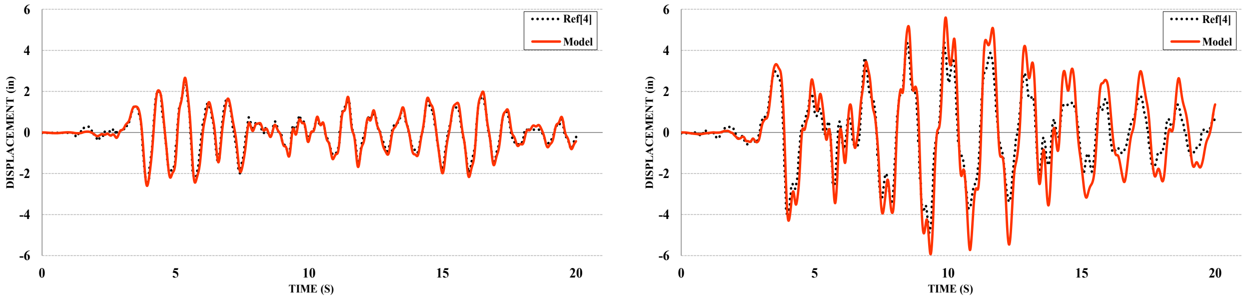
(a). No water – rigid foundation

(b). Surrounding water only – rigid foundation



(c). Inside water only – rigid foundation

(d). Surrounding and inside water only – rigid foundation



(e). No water – felexible foundation

(f). Surrounding and inside water only – felexible foundation

Figure 3. Horizontal displacement at the Briones Tower top due to Taft (1952) excitation in model and reference [4].

2.3. Numerical Values and Analysis Cases

2.3.1. Model and Parameters

Different parameters effects on the seismic response of the cylindrical intake tower with hydrodynamic, structural, and foundation interactions under horizontal longitudinal components of the Taft ground motion (a hard soil record) and the Loma Prieta ground motion (a hard Rock record) are studied [21]. The dam geometry is assumed as a triangular one with a vertical upstream face and a 0.8:1 slope at the downstream face. The dam and the tower heights are always the same, but variable in different cases. Reservoir transverse dimension is assumed to equal to B = 300 meters.

Effects of eight different parameters are studied according to Table 1-1 and Figs. 4, 5 [22]. Tower height H, along with some dimensionless parameters r/H and t/r corresponding the tower section internal radius r, and wall thickness t are considered. Moreover, for evaluating the transverse location of the tower in the reservoir, b/B parameter is used where b is the shortest distance of the tower from the reservoir vertical side banks. The effects of internal and surrounding water depths, di and D respectively, are also studied, using di/H and D/H quantities. Reservoir end boundary is always three times the tower height far from it, and foundation model extension is two times the tower's height. Foundation material parameter is considered by the E_c/E_f ratio where E_c and E_f are the concrete and the foundation elasticity moduli, respectively. Tower distance from the dam L, is also considered by the L/H ratio. For all the 8 latter parameters three different values belonging to appropriate ranges of variation are considered, as depicted in Table 2.

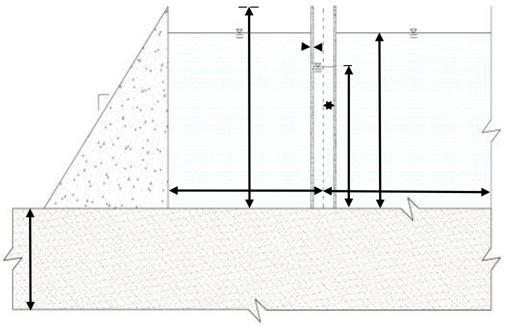


Figure 4. The geometry of the intake tower, dam, water and foundation system.

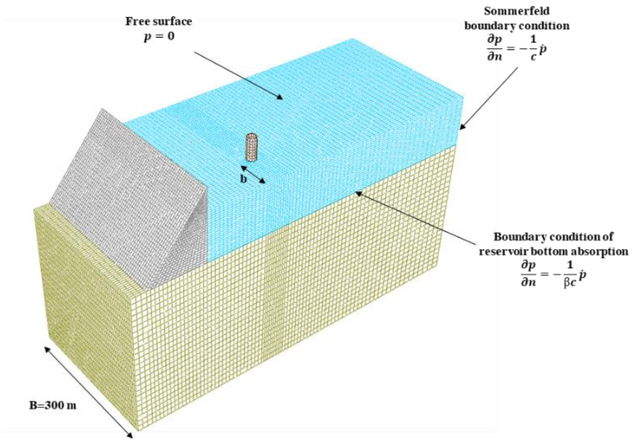


Figure 5. Three-dimensional finite element model of the whole system.

Table 2. System parameters and their selected values.

level	1	2	3
b/B	0.25	0.5	–
H (m)	50	100	150
r/H	0.03	0.05	0.07
t/r	0.15	0.175	0.2
D/H	0.4	0.7	1
di/H	0	0.4	1
E_c/E_f	0	1	3
L/H	1	2	3

The assumed material properties for the dam and the intake tower are constant, including concrete modulus of elasticity $E_c = 3.45\times10^{10}$ N/m^2, Poisson ratio $\nu = 0.17$, mass density $\rho = 2480$ kg/m^3, and damping ratio $\xi = 0.05$. Water acoustic velocity C, and the mass density ρ_w, are equal to 1440 m/s and 1000 kg/m, respectively. The wave reflection coefficient at the bottom and the lateral boundaries of the reservoir α, is assumed equal to 0.9.

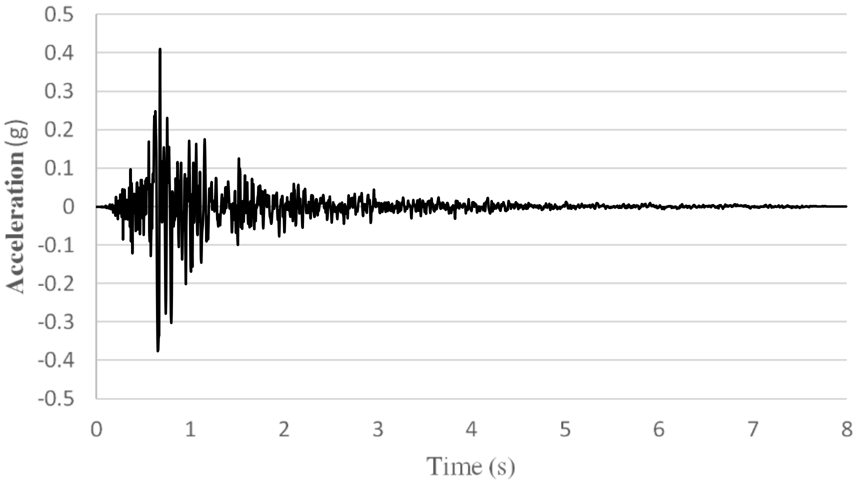


Figure 6. Ground motion recorded at Loma-Prieta, California, on hard rock, Earthquake October 18, 1989 [20].

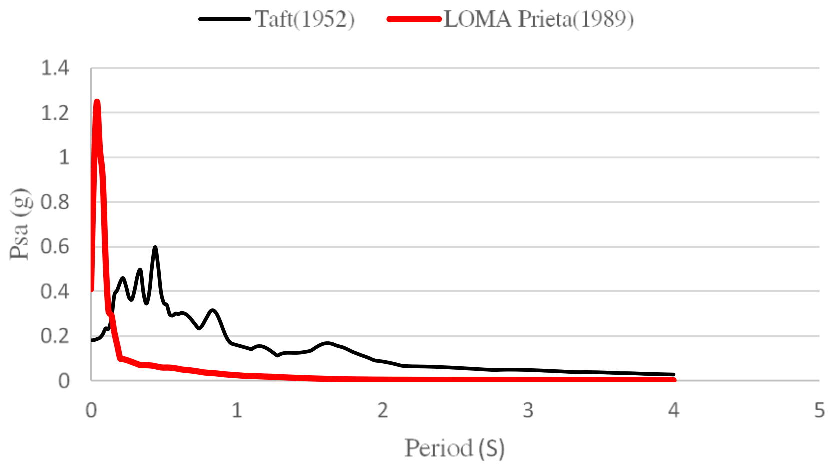


Figure 7. Response Spectra for Taft (1952) and Loma-Prieta (1989) Ground motions [20].

2.3.2. Optimizing the number of numerical experiments

There are *a* variety of methods for designing experiments. The first is the full factorial method. However, this method requires quite a large number of cases far from and is expensive. Therefore, optimization of the number of the experiments should be considered. One of the practical techniques for optimum design of experiments is the Taguchi method, in which a selected group of orthogonal arrays of parameters values is presented [23].

The standard orthogonal arrays would prepare instruction for partial factorial experiments that includes several combined experiments. While the combinations of levels for all factors are in discussion, the standard orthogonal arrays would satisfy most of the experimental design requirements. Based on the selected eight parameters and their levels in the Taguchi method, the orthogonal arrays $L_{18}(2^1 \times 3^7)$ are selected corresponding to seven parameters with three levels and a single parameter with two levels as seen in Table 3.

Table 3. Test cases investigated according to the Taguchi method.

case	b/B	H (m)	r/H	t/r	D/H	di/H	E_c/E_f	L/H
1	0.25	50	0.03	0.15	0.4	0	0	1
2	0.25	50	0.05	0.175	0.7	0.4	1	2
3	0.25	50	0.07	0.2	1	1	3	3
4	0.25	100	0.03	0.15	0.7	0.4	3	3
5	0.25	100	0.05	0.175	1	1	0	1
6	0.25	100	0.07	0.2	0.4	0	1	2
7	0.25	150	0.03	0.175	0.4	1	1	3
8	0.25	150	0.05	0.2	0.7	0	3	1
9	0.25	150	0.07	0.15	1	0.4	0	2
10	0.5	50	0.03	0.2	1	0.4	1	1
11	0.5	50	0.05	0.15	0.4	1	3	2
12	0.5	50	0.07	0.175	0.7	0	0	3
13	0.5	100	0.03	0.175	1	0	3	2
14	0.5	100	0.05	0.2	0.4	0.4	0	3
15	0.5	100	0.07	0.15	0.7	1	1	1
16	0.5	150	0.03	0.2	0.7	1	0	2
17	0.5	150	0.05	0.15	1	0	1	3
18	0.5	150	0.07	0.175	0.4	0.4	3	1

In the following, different parameters are investigated in two groups of dynamic time history analysis, first 18 tests for hard soil under Taft acceleration record, and then 18 more tests for hard rock under Loma Prieta acceleration record.

3. Results and Discussion

Sensitivity analyses of the parameters are carried out in terms of the normalized maximum displacement of the tower top node (tower drift), and also in terms of the maximum dynamic base shear force of the intake tower normalized by the tower weight (tower base shear coefficient). Also, the first frequency mode of each model are been dimensionless according to the first frequency mode of the single intake tower with the rigid foundation. The latter two quantities are believed as the most decisive responses for the seismic design of the tower structure.

3.1. Main effects of parameters on the tower drift

a) Cases of hard soil

According to Fig. 8, tower drift increases considerably when the tower position is more distant from the reservoir bank. This might be due to the effect of the reservoir bank partial absorption of the hydrodynamic energy. Interesting to notice that the higher the intake tower, the less its drift gets.

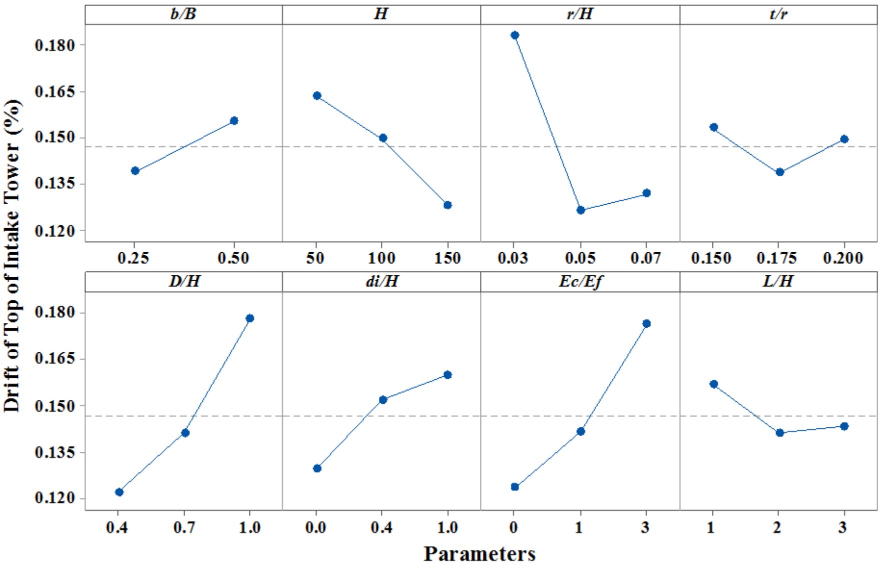


Figure 8. Main effects of different parameters on the tower drift based on hard soil (Taft 1952 record).

Table 4. Contribution of parameters due to variance analysis.

Parameters	Contribution (%)
b/B	5.75
H (m)	9.43
r/H	28.78
t/r	1.70
D/H	23.79
di/H	7.21
E_c/E_f	21.18
L/H	2.15
Total	100%

According to the statistical analysis on test results of the hard soil cases, the r/H ratio is the most critical parameter for the tower drift, with a share value of 28.78 %. The response of slender intake tower with r/H = 0.03 has more than to the other as with past research. The other important note is that the reducing trend from r/H = 0.05 stays nearly constant. Of course, it requires other ratios to evaluate carefully. The tower wall thickness parameter, t/r ratio has the least effect on the seismic response of the intake tower with only a 1.7 % share. However, the tower's thickness has a minimum amount, that is mean the optimized thickness of the tower for minimum drift is t/r = 0.175 for any similar situation to this experiment. According to the results, the second most effective parameter in the seismic response of the intake tower is the D/H ratio with 23.79 %, pertaining increased drift with increased reservoir depth, or hydrodynamic significance. Generally, the most critical drifts of the towers happen when the reservoir of the concrete dam is at its highest level.

Moreover, the tower internal water level parameter, i.e., the di/H ratio is also directly increasing the tower drift but with a lower rate than that of the surrounding reservoir. The foundation flexibility parameter, E_c/E_f ratio, is the third most effective parameter with a 21.18 % share by a direct proportion, similar to previous researches results [4].

According to Fig. 8 when the distance from the concrete gravity dam increases, the drift reduces, but remains approximately constant for distances more than twice the height of the tower. Of course, this result corresponds to horizontal actuation, as described in the past researches, while the vertical or combined excitation requires additional studies [14].

b) Cases of hard rock

According to Fig. 9, Intake tower response does not show much parametric sensitivity when a hard rock ground motion record is applied. Generally, this might be attributed to the issue of the high-frequency content of the ground motion in respect to the natural frequencies of the system. The only effective parameter in the case of the rock motion Loma Prieta record excitation is the tower height, by which the tower drift reduces for higher towers, a trend similar to the cases of hard soil, i.e., due to the Taft record.

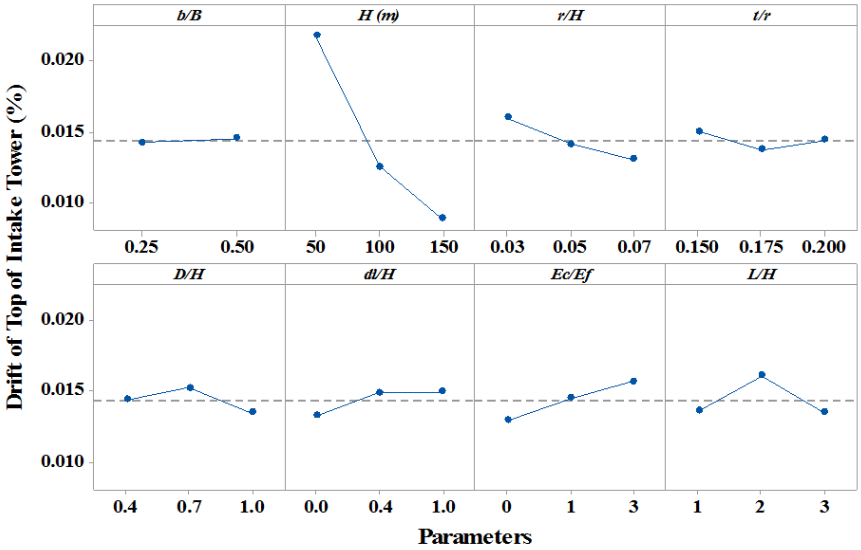


Figure 9. Main effects of different parameters on the tower drift based on the hard rock (Loma Prieta 1989 record).

3.2. Main effects of parameters on the tower base shear coefficient

a) Cases of hard soil

As shown in Fig. 10, the position of the tower in the reservoir width has the minimum effect on the shear coefficient, and thus could be neglected. As the height of the tower increases, the shear coefficient reduces, which can be explained with the tower's more pronounced weight. Moreover, it can be seen that effect of the height remains approximately constant for any height above 100 meters. Similar to the cases of tower drift, the shear force applied to the base of the tower increases for higher ratios of r/H in other words, for fatter towers, higher seismic shear force coefficient is expected. The radius ratio is the most influential parameter.

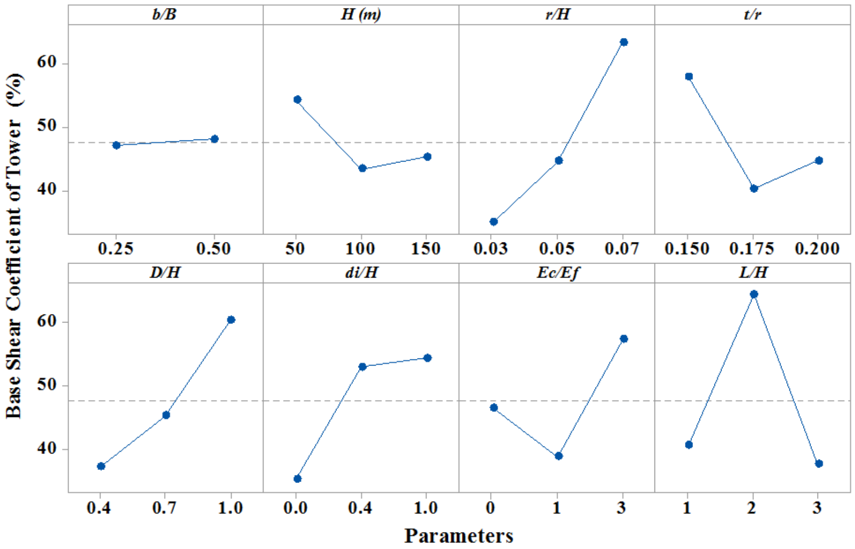


Figure 10. Main effects of different parameters on the tower base shear force coefficient based on hard soil (Taft 1952 record).

Moreover, the effect of the t/r ratio is minimum for the experiment domains, in other hands, for the lowest base shear force for similar conditions, the optimized tower thickness could be considered t/r = 0.175. The second effective parameter on the shear coefficient is the D/H ratio of the tower corresponding to the reservoir depth and is similar to the drift cases.

As shown in Fig. 10, the internal water parameter, di/H is again directly affecting the base shear coefficient. The effects of E_c/E_f ratio in shear coefficient is different from the drift case. When the elasticity module of the foundation and the tower were the same, the applied shear force to the tower's base is minimum, and as the foundation became flexible in comparison with the tower, the shear increased.

As for the dam distance ratio, the base shear coefficient maximizes for L/H = 2. This is an interesting observation that should be studied further as the hydrodynamic action could more intensively affect the tower when it is at an intermediate distance from the dam body.

b) Cases of hard rock

As shown in the Fig. 11, the reservoir water depth parameter is not effective on the shear coefficient of the intake tower. However, the most critical parameter on the base shear coefficient is the height of the tower as similar to the drift results.

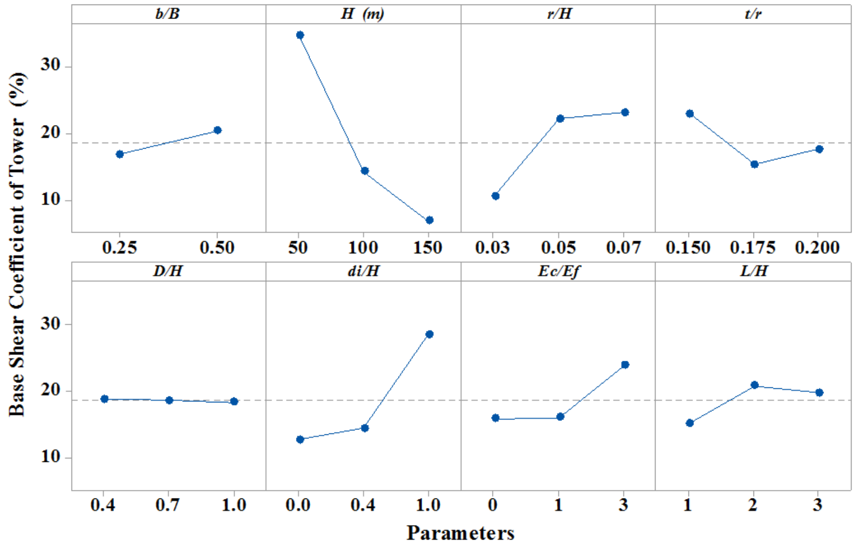


Figure 12. Main effects of different parameters on the tower base shear force coefficient based on hard rock (Loma Prieta 1989 record).

4. Conclusions

In this article, different parameter sensitivities on the dynamic response of cylindrical intake tower interacting with its internal and surrounding water, foundation, and the nearby concrete dam, is studied. For this purpose, the effect of different geometrical, material and loading parameters on the tower top drift, and tower base shear coefficient are studied after verification of the model employed through 3D-dimensional finite elements using Eulerian-Lagrangian approach in the time domain. The parameters in the current research include the height, the section radius and the wall thickness of the tower, as well as its internal and external water depth, foundation material flexibility, and the transverse and longitudinal positioning of the structure in the reservoir for a range of possible variations.Taguchi optimization method for the design of experiments is employed to reduce the number of the experiments drastically, and distinguish the most influential parameters in terms of the two major decisive response components. The study corresponds to longitudinal horizontal excitations records of both hard soil and hard rock conditions. The following conclusions are drawn based on the findings of this study:

1. The investigation of the results indicated that the two parameters of the slender tower ratio and the surrounding water depth were the most effective factors on both intake tower top drift, and the base shear coefficient, respectively under Taft record on hard soil.

2. According to the experimental results, t/r = 0.175 is selected as the optimized thickness for designing the tower wall thickness

3. For horizontal excitation, the effect of the tower placement in the reservoir width could be neglected.

4. The presence of the internal water is influential but weaker than the effect of the surrounding water.

5. It is observed that the foundation material, is another influential factor on the seismic response, and the tower drift increases with its flexibility.

6. The dam body interaction effect on the tower drift reduces as the distance from the dam increases and stays relatively constant for any distance higher than twice the height of the intake tower.

7. Interesting to note that the intake tower did not show notable sensitivity to the reference hard rock ground motion compared with that of the hard soil ground motion. The most critical parameter is the height of the tower when studying both the top drift and the base shear coefficient results.

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