Seismic Performance Analysis of the Elevated RC Tanks under Strong Far- and Near-Fault Ground Motions Considering Fluid–Structure Interaction

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Abstract: The elevated reinforced concrete tanks assessed in the current work were the subject of a nonlinear sloshing analysis resulting from fluid–container interactions. The primary response quantity of interest was the height of free surface sloshing. To achieve this aim, the effect of the liquid contents on the seismic behavior of tanks subjected to various sets of far- and near-fault ground motions were measured. The variables considered in this study included bidirectional loading, the earthquake’s frequency content, water sloshing, and the three-dimensional geometry. The primary goal of this work was to analyze these crucial parameters through a parametric analysis using a finite element method considering the influence of nonlinear fluid–structure interactions under the influence of different ground motions. By contrasting the numerical results obtained by previous studies and those of the current investigation, the applicability of the current simulation in seismic analyses of the elevated reinforced concrete tanks was then examined, and significant conclusions were formed. The findings showed that the nonlinearity of sloshing may significantly affect the seismic performance of the liquid–container interactions and that failing to properly account for it may pose a severe threat to these structures’ ability to perform satisfactorily for a particular class of tanks, particularly under the influence of near-fault events.

Keywords: elevated concrete tank; earthquake records; finite element method; fluid–structure interaction; nonlinear analysis; sloshing effect; ABAQUS; seismic resilience

1. Introduction

In recent decades, engineers from many different domains have shown a significant interest in the dynamic characteristics of fluid–structure interactions. It has been discovered that the fluid–structure interaction significantly influences the safe design of structures, including dams, storage tanks, offshore structures, and nuclear facilities. Numerous analytical and experimental investigations have already been conducted to develop a precise model to predict the dynamic effects of fluid–structure interactions on various structures with highly accuracy [1–3]. The safety of all types of structures with potentially immediate and long-term catastrophic risks to people and the environment has gained attention in recent years [4–6]. Therefore, structures such as elevated tanks containing fluids should be constructed to meet the necessary performance objectives and continue to be secure and functional during a natural disaster such as an earthquake. This has been greatly motivated by the poor performance of liquid tanks during seismic excitations, which have suggested the need for more precise mechanical models and numerical simulations to better understand the seismic response of the structures [7–12]. In this regard, the model proposed by Housner [13] is one of the well-known techniques used to assess the seismic behavior of tanks. This model is based on the linear theory of sloshing. Some people have argued that the relevant guidelines are inaccurate for estimating the sloshing behavior of fluids and the seismic loads induced on the tank. In addition, numerous studies have been...
carried out on sloshing in liquids that considered the linearized theory of sloshing. On the nonlinear effects of fluid–structure interactions under the influence of dynamic loads, not many studies were identified.

The nonlinearity of the boundary conditions at the liquid’s free surface or the change in the free surface boundary using the finite element method is the cause of the nonlinearity of sloshing. Even though sloshing shows a nonlinear behavior in nature, the majority of prior research considered the linear theory of sloshing, which assumes that the free-surface elevation is low and uses the linearized free-surface boundary condition. One of the studies that considered the nonlinear sloshing behavior in liquid reservoirs was carried out by Chen et al. [14]. To capture the finite-element fluid sloshing in 2D tanks during seismic events with a huge amplitude, the authors presented a novel approach to the analysis. The work dealt with the nonlinearities by considering the high-order differential terms and the time-varying surface of the liquid. The findings demonstrated certain shortcomings of the linear wave theory in comparison with the more precise nonlinear scheme when it came to addressing the reaction of seismically activated tanks [15–21].

To examine the nonlinear behavior and damping characteristics of fluid sloshing in rectangular storage tanks, Akyildiz [22] carried out an experimental investigation. The author also looked into the hydrodynamic pressure distribution of various portions of the tank. The results showed that bracing might significantly reduce the consequences of liquid sloshing. The tank’s configuration, the amplitude and type of the excitation, and the frequency content of the record concerning the natural frequency of the contained liquid were some of the main variables introduced by Akyildiz and Ünal [23]. A study on the linear and nonlinear sloshing responses of rectangular tanks subjected to harmonic excitation in a 2D domain was carried out by Virella et al. [24]. By measuring the natural periods and mode shapes of the tanks, they measured the characteristics of the free vibration response of the tanks. They proposed that the pressure resulting from the rectangular tanks’ nonlinear sloshing effect might differ significantly from what would be predicted based on the linear sloshing assumption. Numerical and experimental studies on the performance of liquid sloshing in partly filled 2D containers under the effect of dynamic loads were investigated by Pal and Bhattacharyya [25]. The nonlinear response of prismatic liquid tanks was calculated using the meshless local Petrov–Galerkin method. Additionally, they used experiments to study the sloshing behavior. They suggested that when the vibration amplitude is high and the motion frequency is close to the natural frequency of the vibrated liquid’s volume, the nonlinearity of the sloshing response may be significant.

Goudarzi and Sabbagh-Yazdi [26] studied the nonlinear sloshing effect in partly filled liquid storage tanks that were seismically excited. Both linear and nonlinear circumstances were simulated. While a series of experimental tests were used to validate the nonlinear simulation, the linear numerical model was checked against the available analytical solution. They suggested that under nonlinear sloshing conditions, the positive amplitude increased more quickly than the negative one, and that at the liquid’s free surface, the maximum wave height of the upward sloshing response was greater than the downward sloshing response. The Eulerian, Lagrangian, or coupled Eulerian–Lagrangian formulations are generally used in finite element methods to model the incompressible Newtonian fluid domain. The coupled Eulerian–Lagrangian approach is primarily intended to integrate the benefits of both the Eulerian and Lagrangian techniques, but its implementation is quite difficult and it is thought to be inappropriate for considering sloshing behavior, which is quite likely in problems of normal fluid–structure interactions with a large amplitude [23–28]. The Lagrangian fluid formulation is preferable to the Eulerian one for fluid–structure interactions due to its simple free surface tracking capability, lower numerical difficulties, and—most importantly—its adherence to Lagrangian formulations of structural mechanics.

According to the literature, various limited studies have been carried out to assess the performance of elevated tanks subjected to a specific ground motion. Previous studies [1–3,29] have recommended that a parametric study should be carried out to determine the effect of different ground motions on the responses. Therefore, based on the
literature’s recommendations, this study aimed to assess the effects of fluid–structure interactions on the seismic performance of elevated concrete tanks subjected to various strong far- and near-fault ground motions using finite element methodology.

2. Model Characteristics

In the section, the models of the elevated concrete tank with a variable amount of fluid were analyzed by the FEM software package ABAQUS, considering the stress–strain behavior of the materials. To define the structural properties, the behavior of concrete under compression stress is considered, as shown in Figure 1. For analyzing the tank, the isotropic SOLID C3D8R element of the ABAQUS software was used for the concrete shaft and the steel wall of the container. It should be stated that this criterion is the generalized state of the Drucker–Prager collapse criterion, which considers the definition of the failure of concrete. To determine the compressive stress–strain relationship of concrete, the nonlinear strain–compression damage \( (d_c) \) and the corresponding strain were considered. According to Equation (1), the real strain values were converted to a nonlinear strain, as follows [29]

\[
\bar{\varepsilon}_c^m = \varepsilon_c - \varepsilon_c^e
\]

where \( \bar{\varepsilon}_c^m \) is the inelastic strain, \( \varepsilon_c^e \) is the elastic strain, and \( \varepsilon_c \) is the concrete strain at different loading steps. Furthermore, the plastic strain was calculated to correspond to the instantaneous compressive strength of the concrete using Equation (2), in which, \( \varepsilon_c^{pl} \), \( \sigma_c \), and \( E_c \) denote the plastic strain, compression stress, and modulus of elasticity, respectively [29].

\[
\varepsilon_c^{pl} = \bar{\varepsilon}_c^m - \frac{d_c \sigma_c}{(1-d_c) E_c}
\]

**Figure 1.** Stress-strain relationship of concrete under the effect of compression stress.

The formula below was used for compression damage [29]:

\[
d_c = 1 - \left[ \frac{\varepsilon_c}{0.2\bar{\varepsilon}_c^m + \frac{\sigma_c}{E_c}} \right]
\]

To determine the tensile stress–strain relationship of concrete, the actual tensile strain was changed to a nonlinear strain according to Equation (3). In Figure 2, the stress–strain relationship of concrete under the effect of tensile stress is shown. In this study, the values
of the plastic strain, corresponding to the tensile strength of the concrete at any given moment, were calculated using the equation below.

\[
\varepsilon_{t}^{pl} = \varepsilon_{t}^{in} - \frac{d_t}{(1 - d_t)} \frac{\sigma_t}{E_c}
\]  

(4)

According to Figure 3, the tensile behavior of concrete after cracking was defined using the formula below

\[
u_{t0} = 2G_1 / \sigma_{t0}
\]  

(5)

where \(G_1\) is the area under the curve. Moreover, \(d_t\) is the failure cracking factor in elasticity and could be calculated using the following formula:

\[
d_t = 1 - \frac{\sigma}{f_{t}}
\]  

(6)

The natural periods of vibration and the effective masses corresponding to seismic behavior were compared with the values obtained by Housner’s approximation [30]. First, the Newton–Raphson numerical method was used for verification [31–36]. In this analysis,
solid elements were utilized, the elements’ shear modulus was set to zero, and the fluid’s bulk modulus, $K$, was used to establish the elastic stress–strain relations as reported by Moslemi et al. [37]. The Lagrangian and Eulerian techniques are two of the analysis methods that the finite element method offers. The current simulation of fluid–structure interactions used an arbitrary Lagrangian–Eulerian technique to prevent significant finite element distortion. The continuity of the analysis was provided by the mesh’s reduced distortion. To analyze the liquid sloshing and the nonlinear behavior of the isolation system, the Abaqus/Standard dynamic explicit operator already provided by ABAQUS was used. This operator permits the large deformation theory, which permits huge rotations and deformations of the elements, in the simulation.

3. Nonlinear Dynamic Analysis

To design elevated fluid reservoirs, the ACI 350.3 [38] codes were utilized in combination with ASCE 7 [39], as completely described by Moslemi et al. [37]. In this study, the seismic performance of elevated concrete tanks was assessed under the effect of various ground motions. To achieve this aim, a fixed base connection was considered for the structure. The influence of the rigidity of the container’s wall and the sloshing behavior of the fluid were considered as well. The geometric characteristics of the tank are indicated in Figure 4 according to Moslemi et al. [37], as a benchmark utilized in this study for verification and further study. Based on the results presented by Moslemi et al. [37], the geometric properties given in Figure 4 were as follows:

- The thickness of the side shell: 8.8 mm;
- The thickness of the shaft: 380 mm;
- The thickness of the floor: 330 mm.

Figure 4. Geometric properties of the elevated concrete tank.

It should be noted that the water nodes should be joined at all boundaries with a containing structure; consequently, all water nodes at the interface with the tank floor should be restrained in the vertical direction. To define the fluid domain’s boundary condition properly, shell nodes should be coupled to the conforming water nodes in two orthogonal directions. The finite element configuration of the reservoir model is indicated in Figure 5. Other characteristics of the materials have been used, as per Moslemi et al. [37].
the study of Moslemi et al. [37] study of the El Centro earthquake. As is shown in Figure 6, the horizontal component of the 1940 El Centro earthquake’s ground motion, with a peak ground acceleration of 0.32 g, was utilized for the dynamic analysis. All the results obtained are shown in Table 1 and Figure 7. For a further study, seven common ground motion records, which have been used by other investigators, were utilized in this study. According to Moslemi et al. [29], a constant damping ratio of 5% and 0.5% are considered for the impulsive and sloshing modes, respectively. It should be noted that both impulsive and convective responses are considered in the analysis. The exact descriptions of the impulsive and convective modes can be found in the study of Moslemi et al. [37]. Additionally, the deformation contour of the whole tank and the fluid are presented in Figure 8. Regarding this figure, the greatest influence of fluid sloshing on the container’s performance was observed at the middle of the container’s height and at the location of the joint between the container and shaft where a plastic joint might happen.

4. Verification

To show the ability and efficiency of the proposed dynamic method, the model was verified by the study of Moslemi et al. [37] study of the El Centro earthquake. As is shown in Figure 6, the horizontal component of the 1940 El Centro earthquake’s ground motion, with a peak ground acceleration of 0.32 g, was utilized for the dynamic analysis. All the results obtained are shown in Table 1 and Figure 7. For a further study, seven common ground motion records, which have been used by other investigators, were utilized in this study. According to Moslemi et al. [29], a constant damping ratio of 5% and 0.5% are considered for the impulsive and sloshing modes, respectively. It should be noted that both impulsive and convective responses are considered in the analysis. The exact descriptions of the impulsive and convective modes can be found in the study of Moslemi et al. [37]. Additionally, the deformation contour of the whole tank and the fluid are presented in Figure 8. Regarding this figure, the greatest influence of fluid sloshing on the container’s performance was observed at the middle of the container’s height and at the location of the joint between the container and shaft where a plastic joint might happen.
Table 1. Maximum absolute time history response values for the elevated tank model.

|                  | Convective | Impulsive | Total |
|------------------|------------|-----------|-------|
| **Base shear**   | Max value (kN) | Max value (kN) | Max value (kN) |
| Moslemi et al. [29] | 2487      | 35,548    | 34,842 |
| **Base moment**  | Max value (kN-m) | Max value (kN-m) | Max value (kN-m) |
| Moslemi et al. [29] | 94,023    | 1,290,592 | 1,293,880 |
| **This study**   | Max value (kN) | Max value (kN) | Max value (kN) |
| **Base shear**   | 2435      | 35,025    | 34,135 |
| **Base moment**  | 93,158    | 13,005,879 | 1,288,975 |

**Figure 7.** Time history results for the tank: (a) Moslemi et al. [29] and (b) this study.

**Figure 8.** Deformation of the tank and the water content under the influence of El Centro earthquake’s ground motion.
According to Figure 7, there is great agreement between the obtained results and those reported by Moslemi et al. [37]. It is worth emphasizing that the simulation performed in this study had an error of only $1.8 \times 10^{-4}$ and very good agreement with the benchmark results. Table 2 presents the basic information about the ground motions used. Furthermore, the spectrum of the ground motion records used for a 5% damping ratio is provided in Figure 9.

Table 2. Used ground motion properties.

| Record          | Station                  | Year | $M_w$ | Fault Distance (km) | $V_{s30}$ (m/s) | Comp. | PGA (g) | PGV (m/s) | PGA / PGV |
|-----------------|--------------------------|------|-------|---------------------|-----------------|-------|---------|-----------|-----------|
| **Far-fault records** |                          |      |       |                     |                 |       |         |           |           |
| Northridge      | Ferndale City Hall       | 1954 | 6.50  | 27.02              | 219.31          | 44    | 0.160   | 0.30      | 0.53      |
| Kocaeli, Turkey | Duzce                    | 1999 | 7.51  | 15.37              | 281.86          | 180   | 0.312   | 0.58      | 0.53      |
| Loma Prieta     | Hollister—South and Pine | 1989 | 6.93  | 27.93              | 282.14          | 0     | 0.370   | 0.63      | 0.58      |
| El Centro       | El Centro Imp. Co. Cent  | 1987 | 6.54  | 18.2               | 192.05          | 0     | 0.357   | 0.48      | 0.74      |
| Imperial Valley-06 | Delta                  | 1979 | 6.53  | 22.03              | 242.05          | 262   | 0.235   | 0.26      | 0.89      |
| Kobe            | TAZ090                   | 1995 | 7.14  | 31.62              | 269.26          | 0     | 0.294   | 0.35      | 0.84      |
| **Near-fault records** |                          |      |       |                     |                 |       |         |           |           |
| Northridge      | Newhall—W Pico Canyon Rd | 1994 | 6.69  | 5.48                | 285.93          | Normal | 0.425   | 0.87      | 0.48      |
| Kocaeli, Turkey | YPT                      | 1999 | 7.40  | 4.80                | 297.00          | Normal | 0.235   | 0.89      | 0.26      |
| Loma Prieta     | Hollister City Hall      | 1989 | 7.10  | 5.80                | 333.85          | Normal | 0.529   | 0.502     | 1.05      |
| El Centro       | LA-SFA                   | 1987 | 6.90  | 6.20                | 315.06          | Normal | 0.452   | 0.398     | 1.13      |
| Imperial Valley-06 | EC County Center FF     | 1979 | 6.53  | 7.31                | 192.05          | Normal | 0.179   | 0.540     | 0.33      |
| Kobe            | TCU052                   | 1995 | 7.60  | 3.70                | 479             | Normal | 0.694   | 0.590     | 1.17      |

Table 2 only presents the specifications of the ground motion records used. In this study, pairs of the selected records were scaled on the basis of ASCE 7–16 [38] for the risk-targeted Maximum Considered Earthquake (MCER), with a probability of exceedance of 2% in 50 yrs. Scaling was performed in the range of $0.2 T_{min}$ to $1.25 T_{max}$, which is $2.5 T_{min} = 2.5 T_s$ and $T_{max} = 4.5 T_s$, and their impact was taken into account through the impact factor. The scaling method was described in detail by Sadeghi Movahhed et al. [4].
5. Results and Discussion

In this investigation, both free and compulsive vibrations were performed on the 3D reservoir model. The results obtained for the natural frequencies and the structure’s performance for both the impulsive and convective responses are represented in Table 3. Additionally, the central sloshing and impulsive responses were measured with the maximum participation factors ($\beta$). Moreover, the effective modal mass ratio ($R_i$) of the studied tank is presented in this table. It should be stated that the maximum participation factors were normalized with the use of the maximum values given in this table [37].

**Table 3.** Result of the free vibration analysis of the tank.

| Mode   | Frequency (Hz) | Effective Mass $\times 10^3$ kg | $\sum R_i$ (%) | $\beta$ (Normalized) |
|--------|----------------|---------------------------------|----------------|----------------------|
| Number | Type           | This Study Code                 |                |                      |
| 1 *    | Convective     | 0.163                           | 4302.55        |                      |
| 2      | Impulsive      | 1960                            | 228.16         |                      |
| 3      |                | 1958                            | 918.39         |                      |
| 4      |                | 1960                            | 3367.54        |                      |
|       |                | 1979                            | 285.93         |                      |

* Fundamental mode.

It should be also stated that the vertical displacement of the fluid was considered in the sloshing modes. In this study, the influence of the fluid on different critical responses of the tank was studied, including the base shear force, the overturning moment, sloshing displacement, and roof displacement. As seen, different earthquake data yielded various maximum reactions. The time history responses obtained for each parameter are shown, and their consequences were examined. Figure 10 shows the variance in the base shear as a function of the elevated water content under the effect of various earthquake records. According to this figure, the base shear is highly dependent on the water content and the characteristics of the earthquake record. For the Kobe and Northridge records, the highest base shear force would occur in a half-full container, according to the change in the base shear forces. This could be associated with the PGA of these records, in comparison with other motion records. In addition, this might be because filling tanks to half-full results in...
higher hydrodynamic pressure than fully filling tanks, according to the characteristics of the motion records. The earthquake records do not all exhibit the same variational pattern, which shows the necessity of investigating the behavior of reservoirs for different regions according to the conditions of the area. However, for other records, the maximum base shear occurred when the container was completely filled with water. It is interesting to note that the magnitude of the base shear forces was significantly influenced by the dynamics and hydrodynamic factors of the structure. On the other hand, the base shear responses for near-fault records were higher than those subjected to far-fault motion records. Regarding these results, the base shear increased by 47% and 62% when a half-filled container was subjected to the far-fault Kobe and Northridge motion records, respectively. These results increased by 45.7% and 68% when a half-filled container was subjected to the near-fault Kobe and Northridge motion records, respectively. Furthermore, examples of the effect of sloshing on the distribution of von Mises stress for a tank subjected to the Kobe and Northridge ground motions are presented in Figure 11.
Figure 11. Effect of sloshing on the distribution of von Mises stress for a tank subjected to the (a) Kobe and (b) Northridge ground motions.

Additionally, Figure 12 shows the maximum displacement for the various elevations of the fluid in the container subjected to different far- and near-fault ground motion records. Regarding this figure, the Kobe earthquake produced the largest displacements recorded for the earthquake records (the fully filled case); however, the lowest value was observed under the influence of the Kocaeli earthquake. According to the results, the connection between the column and the container was where the greatest displacement occurs. The greatest displacement in tank systems on somewhat softer soils occurs in the ceiling, contrary to Dogangun and Livaoglu’s [40] observation that maximum displacement occurs in the joint of the column and container in tanks on stiffer soils. Moreover, the influence of near-fault ground motions on the maximum displacement was greater than that of far-fault motions. Therefore, the maximum displacement under the influence of the Kobe earthquake was observed at 39 cm and 58 cm for far- and near-fault ground motions, which was about 143.75% and 190% greater than those obtained for the Kocaeli earthquake, respectively. Figure 13 shows the influence of the El Centro earthquake’s ground motion and the sloshing of fully filled water on the maximum displacement. Regarding this figure, the maximum displacement occurred at the joint region and at the mid-height of the container part, which indicates the important role of the connection region and the container’s stiffness. Moreover, the influence of the water content on the displacement–time history behavior of the tank was assessed, as presented in Figures 14 and 15. These figures show the variation across time for empty, half-filled, and full water containers.
Figure 12. Differences in maximum displacement based on the filling ratio in full tanks with various elevations for (a) far-fault ground motions and (b) near-fault ground motions.

Figure 13. Example of the effect of sloshing on the distribution of maximum deformation for the tank subjected to the El Centro earthquake record.
Figure 14. Time history of maximum displacement under various far-fault ground motions: (a) Imperial Valley, (b) Kobe, (c) Kocaeli, (d) Loma Prieta, (e) Northridge, and (f) El Centro.

Figure 15. Cont.
As can be observed from Figures 14 and 15, increasing the amount of water significantly affected the maximum responses, while the difference between the empty and full displacement responses was slight for the Loma Prieta record, which shows the importance of the ground motions’ characteristics in fluid–structure analyses. Additionally, the influence of near-fault motions on the displacement–time history responses was greater than that of far-fault motions. Moreover, the maximum increment in terms of displacement versus time was observed under the effect of the Kobe record, which increased by 27.8 cm (about 248%) for the full tanks in comparison with empty containers. This could be associated with the characteristics of the PGA and Kobe ground motion records. Additionally, the mode of behavior of the tank changed under the influence of the Imperial Valley and El Centro earthquakes, where the maximum displacement history for the empty tank was negative but it switched to positive when the container was filled with water. This indicates the significant role of fluid sloshing and fluid–structure interaction analyses. Almost the same consequences were observed under the influence of near-fault ground motions. For example, the maximum displacement was amplified by 263% (41.9 cm) under the influence of the near-fault Kobe ground motion record (see Figure 15b).

For a better understanding of the influence of water and the sloshing effect, the maximum displacement considering the filling ratio for both far- and near-fault ground motions is provided in Figure 16. As can be seen from Figure 16, for the three ground motion records, the pattern of fluctuation and variations in the displacement is not the same. Therefore, for the Imperial Valley, El Centro, and Kocaeli Valley records, the maximum displacement was observed when the container was half-filled with fluid. However, for the other records, the maximum displacement was obtained for the full tank, which shows the important role of the characteristics of the ground motion records. Additionally, the highest displacement happened in full elevated concrete tanks under the influence of the Kobe record, which resulted in the displacement increasing by about 263% and 82% in comparison with the empty and half-filled cases, respectively. The variation in the displacement versus the percentage of tank capacity increased under the effect of near-fault
ground motions. According to Figure 16b, although it is not crucial, displacement of the container does not always happen in a full container under the influence of near-fault ground motions. The highest displacement for half-filled tanks happened in Kocaeli and Loma Prieta, respectively, increasing by about 40% and 150% relative to the case of empty tanks. The effects were caused by the characteristics of the earthquakes and the specified frequency content in addition to the frequency composition of the records as well as the periods of the various impulsive and convective masses.

**Figure 16.** Differences in maximum displacement based on the filling ratio for (a) far-fault ground motions and (b) near-fault ground motions.
Furthermore, Figure 17 shows the maximum value of the overturning moment for both far- and near-fault ground motion records, considering various fluid percentages. An increase in filling causes the overturning moment to rise. In addition, essentially identical variation patterns of the overturning moment exist for systems subjected to far- and near-fault ground motions. Therefore, the highest overturning moment occurred for the Loma Prieta record and particularly the Kobe record for the full containers. This might be connected to these recordings’ PGA in relation to other motion records. Additionally, this might be the case since, according to the characteristics of the motion records, half-filling tanks results in larger hydrodynamic pressures than filling tanks fully. There, the value of the overturning moment is very dependent on the water fraction in the container part and the characteristics of the ground motion record. Because not all earthquake records have the same variational pattern, it is important to look into how reservoirs behave in various regions according to local variables. However, for other records, the highest overturning moment happened when the container was half-filled with water. It is interesting to note that the magnitude of the overturning moment was significantly influenced by the dynamics and hydrodynamic factors of the system. On the other hand, the results of the overturning moment for near-fault records were higher than those subjected to far-fault motion records. Regarding these results, the overturning moment was increased by 143% and 43% when a full container was subjected to the far-fault Kobe and Loma Prieta motion records, respectively, while these results increased by about 192% and 44% when a full container was subjected to the near-fault Kobe and Loma Prieta motion records, correspondingly. Additionally, Figure 18 shows the stress distribution for the elevated concrete tank. It can be seen from the figures that the density of the stress contour is primarily focused at the base of the container in the region of connection between the concrete shaft and the container during earthquakes; moreover, as the magnitude of the sloshing height becomes more prominent, the stress density becomes amplified at the top of the shaft’s walls.

![Graph](image_url)

**Figure 17. Cont.**
Figure 17. Differences in the overturning moment based on the filling ratio for (a) far-fault ground motions and (b) near-fault ground motions.
1. The effect of the fluid sloshing on the overall reaction could be either increasing or reducing because the impulsive and sloshing components of the response did not reach their highest values at the same time. As a result, for design and implementation purposes, elevated concrete tanks should be analyzed and designed according to the environmental conditions and the construction region.

2. Depending on the features of the ground motion records, the critical response of elevated tanks may occur even when there is only a small amount of fluid in the (almost) empty tank. As a result, it is always necessary to check all situations for the fluid content.

3. The most crucial variables affecting the severity of or reduction in a tank’s responses are the earthquake’s frequency content and the physical characteristics of the natural frequency ranges.

4. The maximum seismic responses, displacement, base shear, and overturning moment do not occur at the same time and depend on the aforementioned factors due to differences in the impulsive and convective mass periods, the frequency content, and other attributes used to monitor earthquakes. Additionally, the maximum responses of a tank under the effect of near-fault ground motions were greater than those for far-fault earthquakes.

5. Among the earthquakes considered in this study, for the Kobe and Northridge records, the maximum base shear force occurred in the half-full container; however, the maximum base shear occurred when the container was completely filled with water. Therefore, the base shear increased by 47% and 62% when a half-filled container was subjected to the far-fault Kobe and Northridge motion records, respectively, while the

**Figure 18.** Example of the effect of the overturning moment resulting from sloshing on the distribution of maximum stress.

6. **Conclusions**

This study aimed to study the effect of fluid–structure interactions on the crucial structural responses of elevated concrete tanks under strong far- and near-fault ground motions using a comprehensive parametric analysis in the finite element method software package ABAQUS, which can take nonlinearity into account. The applicability of the current code rules in seismic analyses of such structures was then examined, and important conclusions are drawn as shown below.

1. The effect of the fluid sloshing on the overall reaction could be either increasing or reducing because the impulsive and sloshing components of the response did not reach their highest values at the same time. As a result, for design and implementation purposes, elevated concrete tanks should be analyzed and designed according to the environmental conditions and the construction region.

2. Depending on the features of the ground motion records, the critical response of elevated tanks may occur even when there is only a small amount of fluid in the (almost) empty tank. As a result, it is always necessary to check all situations for the fluid content.

3. The most crucial variables affecting the severity of or reduction in a tank’s responses are the earthquake’s frequency content and the physical characteristics of the natural frequency ranges.

4. The maximum seismic responses, displacement, base shear, and overturning moment do not occur at the same time and depend on the aforementioned factors due to differences in the impulsive and convective mass periods, the frequency content, and other attributes used to monitor earthquakes. Additionally, the maximum responses of a tank under the effect of near-fault ground motions were greater than those for far-fault earthquakes.

5. Among the earthquakes considered in this study, for the Kobe and Northridge records, the maximum base shear force occurred in the half-full container; however, the maximum base shear occurred when the container was completely filled with water. Therefore, the base shear increased by 47% and 62% when a half-filled container was subjected to the far-fault Kobe and Northridge motion records, respectively, while the
base shear was increased by 45.7% and 68% when a half-filled container was subjected to the near-fault Kobe and Northridge motion records, respectively.

6. In terms of maximum displacement, considering the earthquake records in the current investigation, for the Imperial Valley, El Centro, and Kocaeli Valley records, the maximum displacement was observed when the container was half-filled with fluid. However, the maximum displacement was obtained for the full tank, which showed the important role of the characteristics of the ground motion records. Additionally, the maximum displacement happened in full elevated concrete tanks under the influence of the Kobe records, which resulted in increasing the displacement by about 263% and 82% in comparison with the empty and half-filled cases, respectively.

It should be mentioned that this investigation was limited to one specific elevated concrete tank that was subjected to various ground motions. A parametric study might be conducted as an extension of this research study to ascertain the impact of various tank and shaft diameters on the seismic responses of tanks.

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Abbreviations

Notation

\( d_c \)  
nonlinear strain compression damage

\( d_f \)  
failure cracking factor in elasticity

\( E_c \)  
modulus of elasticity

\( g_1 \)  
area under the curve

\( K \)  
fluid bulk modulus

MCER risk-targeted maximum considered earthquake

\( R_i \)  
effective modal mass ratio

\( \beta \)  
maximum participation factors

\( \varepsilon^{in}_c \)  
inelastic strains

\( \varepsilon^{el}_c \)  
elastic strain

\( \varepsilon^{pl}_c \)  
plastic strain corresponding to the instantaneous compressive strength of the concrete

\( \varepsilon^{pl}_c \)  
plastic strain

\( \sigma_c \)  
compression stress

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