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EFFECTS OF NEAR-FIELD EARTHQUAKES ON ELEVATED CYLINDRICAL WATER TANKS

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ABSTRACT

Seismic vulnerability of elevated water tanks has been proven in past earthquakes, and some of the observed damages seem to be due to the effects of near-field excitations. This is while most of seismic design codes are still based on far-field earthquake excitations. Near-field earthquakes can cause eccentric vertical loading on the tanks structure, which creates some additional moments resulting in damages to both the tank supporting structure and its foundation. These damages can be more crucial in case of tank with a shaft-type structure. To investigate this problem, in this study two existing cylindrical tanks, designed based on the conventional code requirements, each in two states of relatively tall, with h/D more than 0.5, and two states of relatively short, with h/D less than 0.5 (h is the height of the water in that tank and D is the tank radius) were considered. Two series of earthquakes, one including far-field events, and the other including near-field events, were selected with a specific frequency range and long period strong pulse, to excite the sloshing modes of the tanks, and with PGA values varying in a wide range of 0.2g to 0.7g. Time history analyses were performed by using a powerful finite element analysis program, in which the flexibility of the tank wall and the resulting water-tanks interaction can be taken into consideration. The results show that in some cases, particularly for relatively short states, the combined effects of sloshing and vertical ground acceleration result in large values of overturning moments, which are beyond the values obtained by the code requirements. This is more crucial for the tanks which have a shaft structure. On this basis it can be said that the codes requirements for seismic design of elevated tanks need some modifications to take into account the near field effects.

Keywords: Seismic Design Codes, Time History Analysis, Finite Element Analysis, Sloshing

1. INTRODUCTION

Elevated water tanks are used for providing the required hydraulic pressure in water distribution networks all over the world, and their seismic vulnerability has been proven in past earthquakes, and some of the observed damages seem to be due to the effects of near-field excitations. This is while most of seismic design codes are still based on far-field earthquake excitations. In near-field earthquakes usually there are relatively high values of vertical acceleration, which in combination

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with sloshing effects can result in eccentric vertical loading on the tanks structure. This eccentric vertical loading can create some additional moments which can result in damages to both the tank supporting structure and its foundation. These damages can be more crucial in case of tank with a shaft structure. Some researchers have tried to investigate the effects of near-field excitations, included extensive vertical excitation, on the elevated tanks response and corresponding sloshing phenomenon. One of the first studies in this regard, which goes back to mid 80s was performed by Gau (1985), however, that study was limited to sinusoidal harmonic excitation.

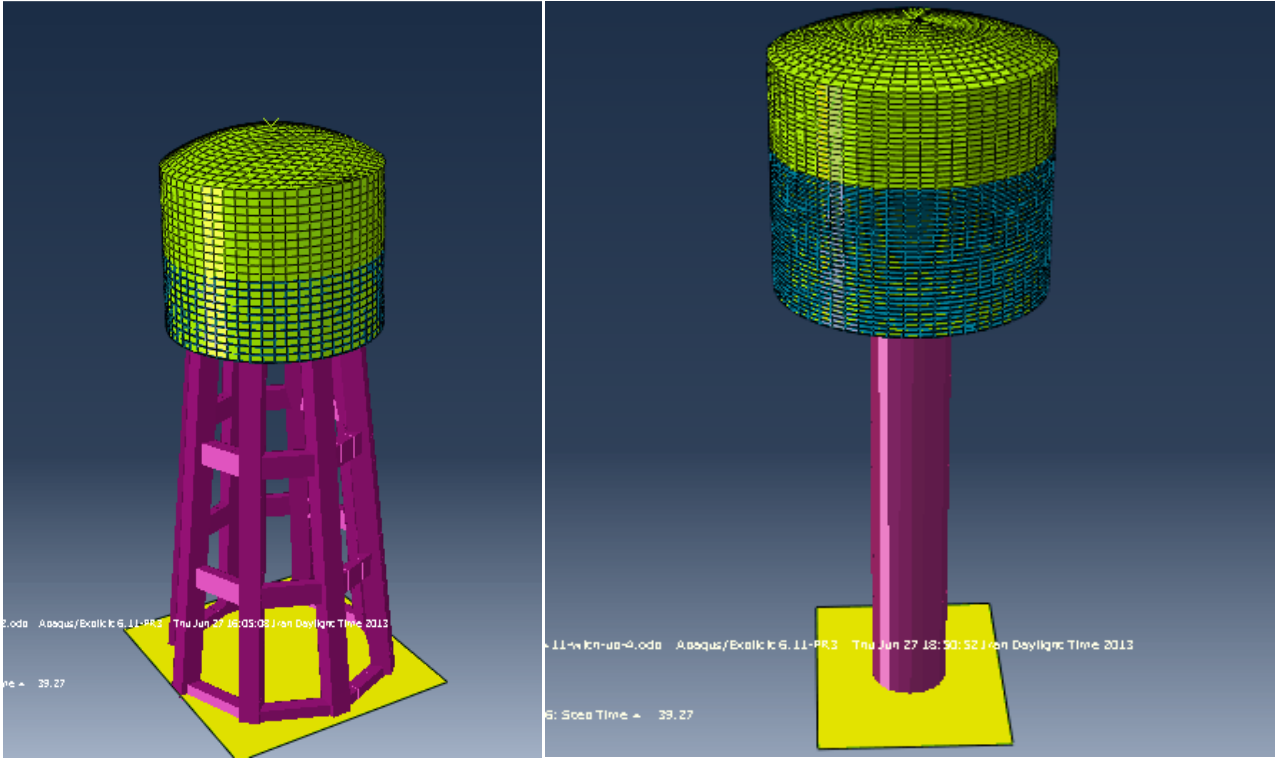
In recent years the soil-structure-interaction effect on the sloshing response of cylindrical elevated tanks has been also taken into consideration. Livaoglu and Dogangun (2008) conducted an investigation in this regard, in which the elevated tanks with two different types of supporting systems, built on six different soil profiles, were analyzed for both embedded and surface foundation cases. They modeled fluid-elevated tank-soil/foundation systems with the finite element (FE) technique. In their models fluid-structure interaction was taken into account by implementing Lagrangian fluid FE approximation into the general purpose structural analysis computer code ANSYS. A 3-D FE model with viscous boundary was used in their analyses of elevated tanks-soil/foundation interaction.

More recently Patel et al. (2012) studied the influence of frame type tapered staging on sloshing behavior of elevated water tank. They studied the sloshing behavior under different time history records using software SAP2000. Finally, Waghmare and Madhekar (2013) studied the behavior of elevated water tank under sloshing effect. In that study they have noted that under nonlinear conditions, sloshing heights are larger than those calculated under linear condition, and have investigated the sloshing effect by using Finite Element Method, using ANSYS program, by considering depth of water in tank to be 30%, 50%, 70% and full.

It is seen that in the previous studies no specific attention has been paid to the near-field effects. To investigate this problem, in this study two existing cylindrical tanks, one of 12 m diameter, supported on a space frame structure of 20 m height with eight columns, and another one of 20 m diameter supported on a shaft type structure of 36.2 m height were considered. Some minor geometrical modification was applied for simplification of numerical modeling of tanks, which was performed by a powerful finite element computer program. Several time history analysis cases were performed by using both far-and near-field earthquake records with PGA values varying in a wide range of 0.2g to 0.7g, and the results were compared. Details of the study are presented in the following section of the paper.

2. INTRODUCING THE CONSIDERED TANKS

Two existing cylindrical tanks, with some minor geometrical modifications, were considered for the study, including: 1) a tank with diameter of 12 m having a supporting structure of space frame type with eight columns (Figure 1-a) with two values of 7m and 4 m water height, and 2) a tank with diameter of 20 m having a supporting structure of shaft type (Figure 1-b) with two values of 11m and 7 m water height. Considering two values for water height in each case is for inclusion of both relatively short tanks (h/D more than 0.5), and relatively tall tanks (h/D less than 0.5) (h is the height of the water in that tank and D is the tank radius).



(a) Tank with space frame structure (b) Tank with shaft type structure

Figure 1: The two considered tanks for the study

For calculating the sloshing period in cylindrical tanks the following formulas can be used (IITK-GSDMA 2007).

$$K_c = 0.836 \frac{mg}{h} \tanh^2 \left(3.68 \frac{h}{D} \right) \quad (1)$$

$$\frac{m_c}{m} = 0.23 \frac{\tanh \left(3.68 \frac{h}{D} \right)}{\frac{h}{D}} \quad (2)$$

$$T_c = 2\pi \sqrt{\frac{m_c}{K_c}} \quad (3)$$

where h is the water height in the tank, D is the tank diameter, and m is the mass of the impounded water. By using these equations the sloshing periods of the four considered case are obtained as shown in Table 1.

Table 1: Parameters and the period of sloshing in the two considered tanks for the two values of water height

Parameters	Tank with space frame supporting structure		Tank with shaft type supporting structure	
	$h = 7$ m	$h = 4$ m	$h = 11$ m	$h = 7$ m
m_c (kg)	303,313	262,326	1,393,328	1,238,417
K_c (N/m)	876,690	655,712	2,399,249	1,895,741
T_c (sec)	3.696	3.974	4.788	5.078

The sloshing periods given in Table 1 were used to select appropriate earthquake records, as explained briefly in the following section.

3. THE TIME HISTORY ANALYSES

To find out the effects of near-field earthquakes on the seismic behavior of tanks in comparison with far-field earthquakes, the 3-component records of two set of earthquakes, one including far field events, and the other including near field events, were selected with a specific frequency range and long period strong pulse, to excite the sloshing modes of the tanks, and with PGA values varying in a wide range of 0.2g to 0.7g. Figure 2 shows a sample of the time series and displacement spectrum of the considered earthquakes, which relate to the main component of the Imperial Valley earthquake.

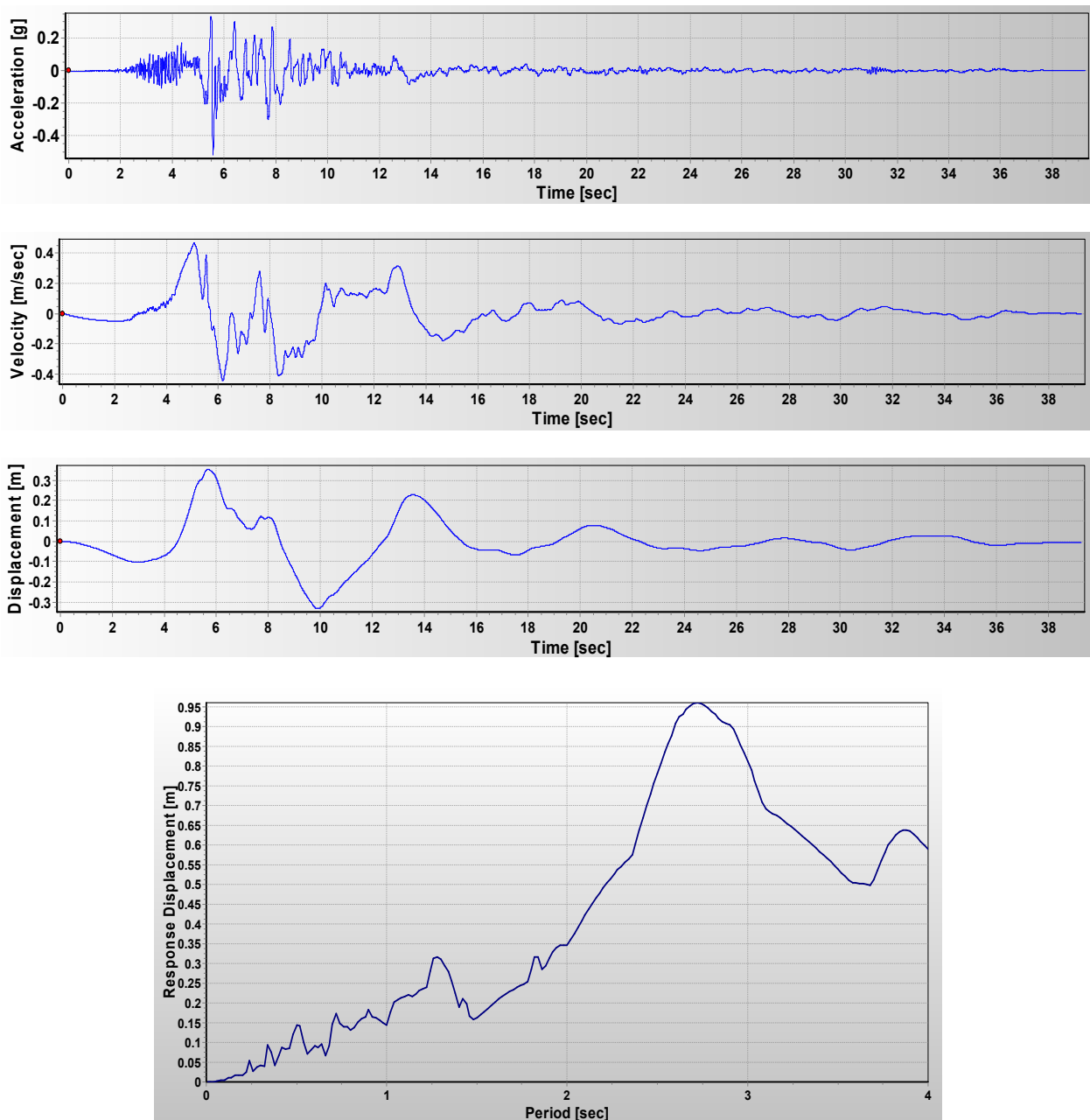


Figure 2: Time series and displacement spectrum of the main component of Imperial Valley earthquake

The tanks and the impounded water were modeled by using a powerful finite element analysis program (Figures 3 and 6), and after verification of the numerical modeling, the time history analyses were performed. The internal forces and moments in the major elements of the tank supporting structure and the water level variation near the tank wall were considered as the main response values for comparing the effect of far- and near-field records. Only some samples of the results are presented here, due to of lack of space, and more results can be found in the main report of the study (Soleymani 2013). Figures 4 and 5 show, respectively, sample section forces and water level variation near the tank wall for various states in case of tank with frame supporting structure, subjected to Imperial Valley earthquake.

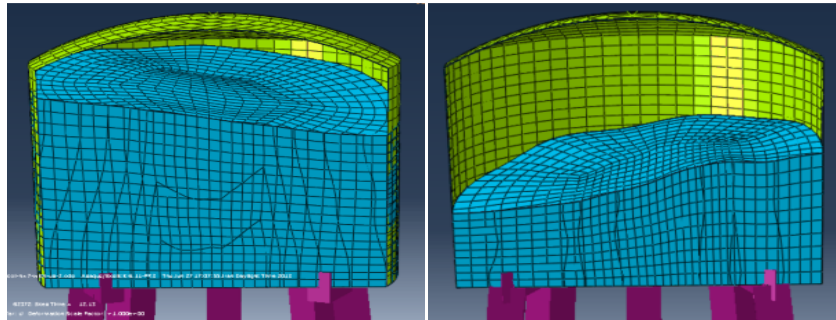


Figure 3: An instant deformed shape of the tank with frame supporting structure, and the impounded water in two states of $h=7\text{m}$ (left) and $h=4\text{m}$ (right)

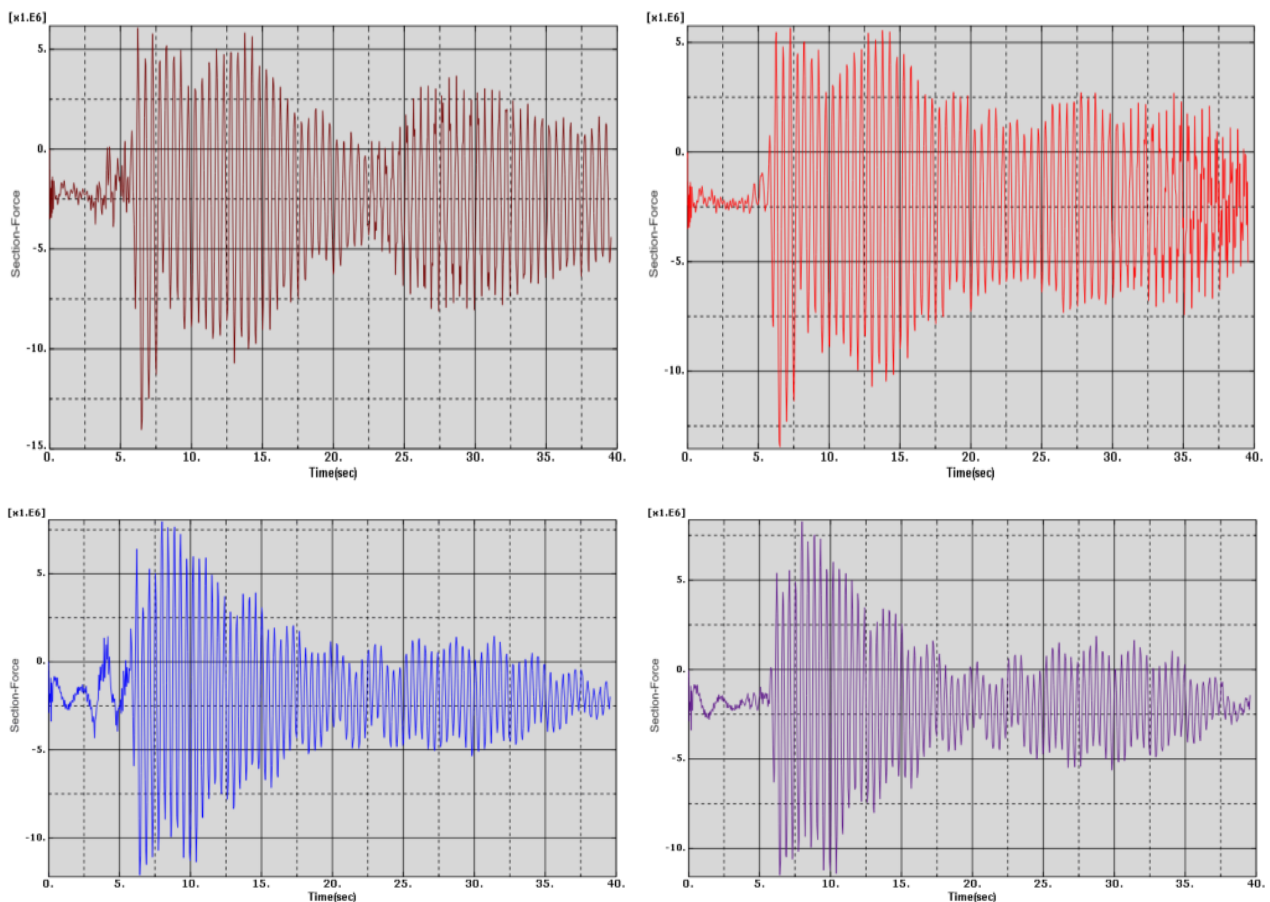


Figure 4: Sample column section force for $h=7\text{m}$ (upper graphs) and $h=4\text{m}$ (lower graphs) in presence of vertical ground excitation (left graphs) and its absence (right graphs)

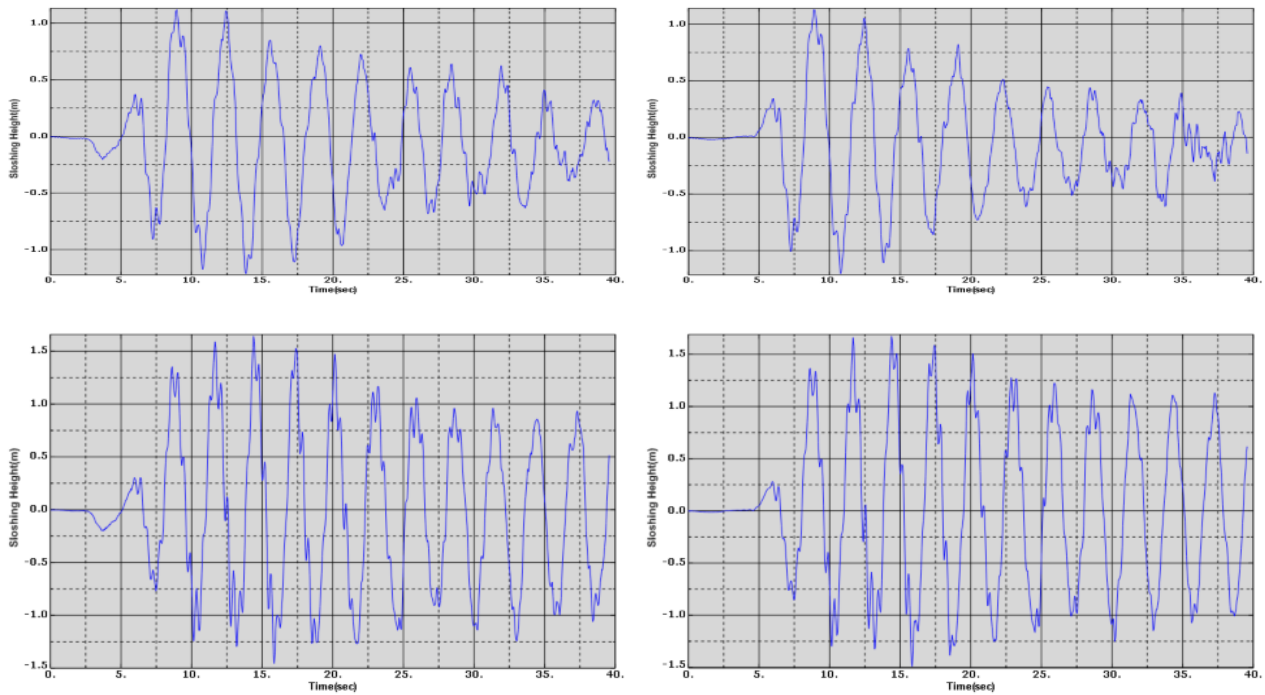


Figure 5: Water level variation near the tank wall for $h=7\text{m}$ (upper graphs) and $h=4\text{m}$ (lower graphs) in presence of vertical ground excitation (left graphs) and its absence (right graphs)

It can be seen in Figure 4 that due to extensive vertical excitation the section force in the supporting structure of the tank increases. However, Figure 5 shows that the water level variation may increase with lower height of water in the tank. This can be because of the change of the sloshing frequency due to the change in the water height in the tank, and therefore, becoming far from the dominant frequency of applied earthquake excitations. Of course, there are other earthquake records which can cause significant increase in the sloshing height with increase in the height of the water in the tank (Soleymani 2013).

Figures 6 to 8 relates to the tank with shaft type supporting structure. Figure 7 and 8 show, respectively, sample section forces and water level variation near the tank wall for the four various considered states in case of tank with shaft type supporting structure, subjected to Imperial Valley earthquake, in both cases of presence and absence of vertical excitations.

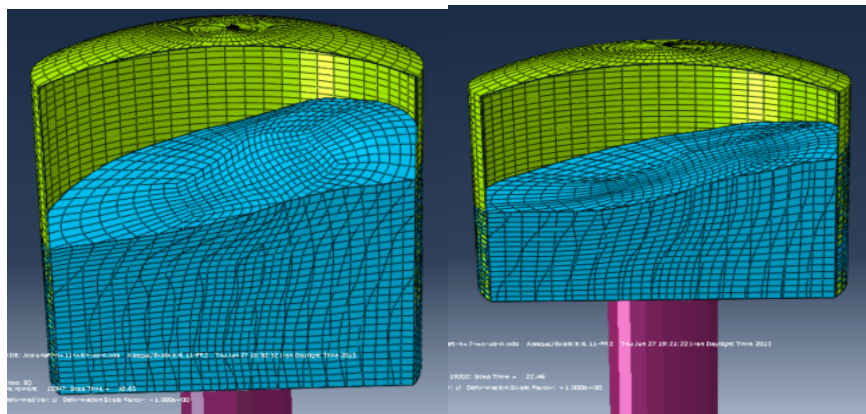


Figure 6: An instant deformed shape of the tank with shaft supporting structure, and the impounded water in two states of $h=11\text{m}$ (left) and $h=7\text{m}$ (right)

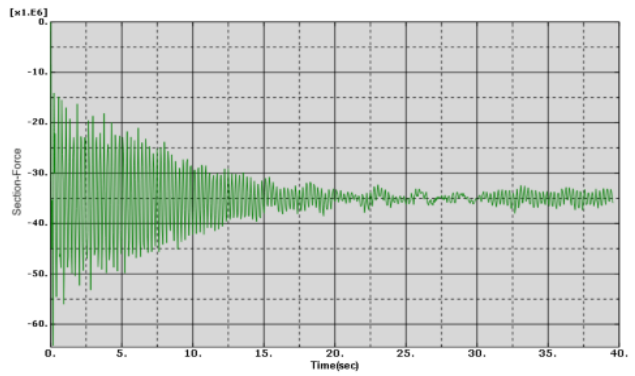
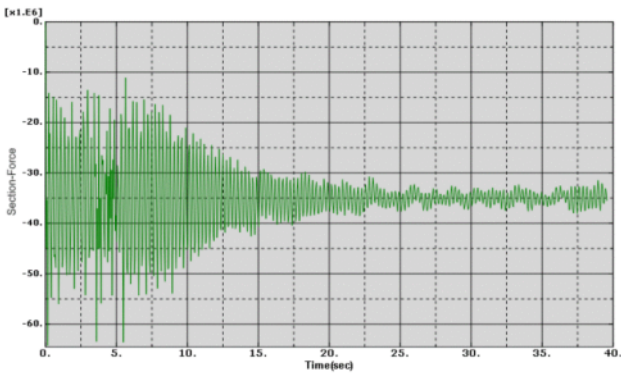
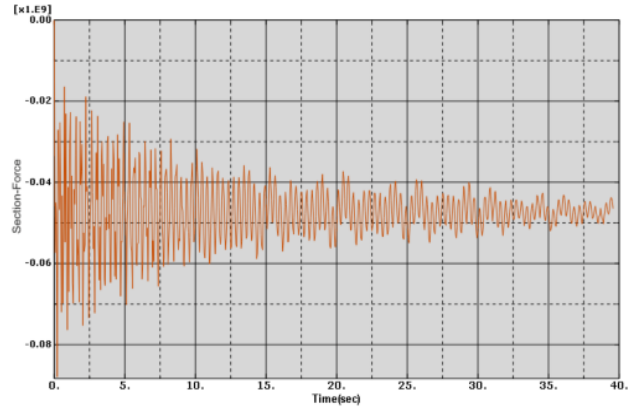
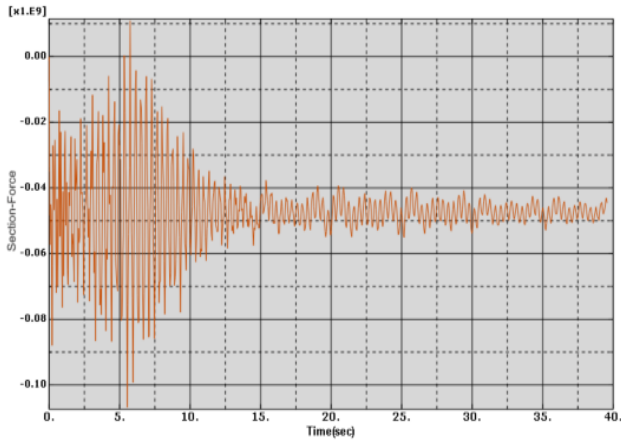


Figure 7: Sample shaft section force for $h=11\text{m}$ (upper graphs) and $h=7\text{m}$ (lower graphs) in presence of vertical ground excitation (left graphs) and its absence (right graphs)

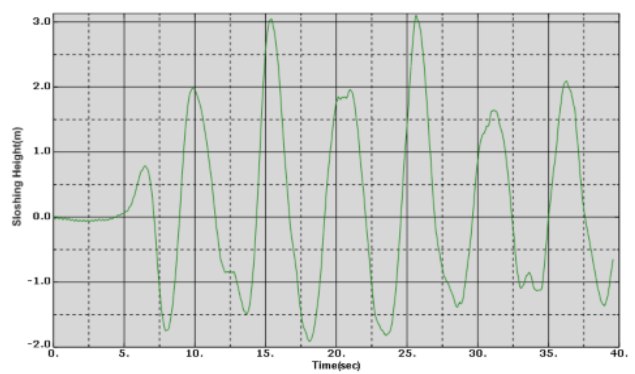
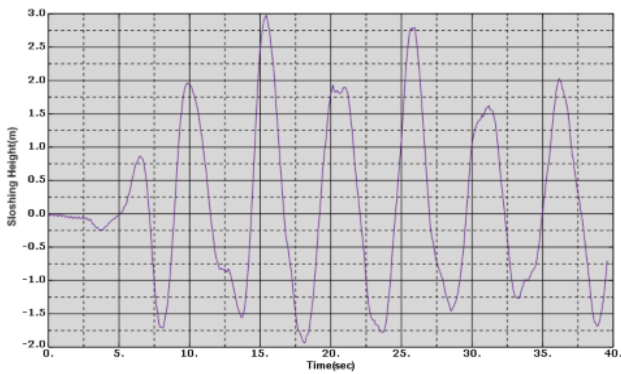
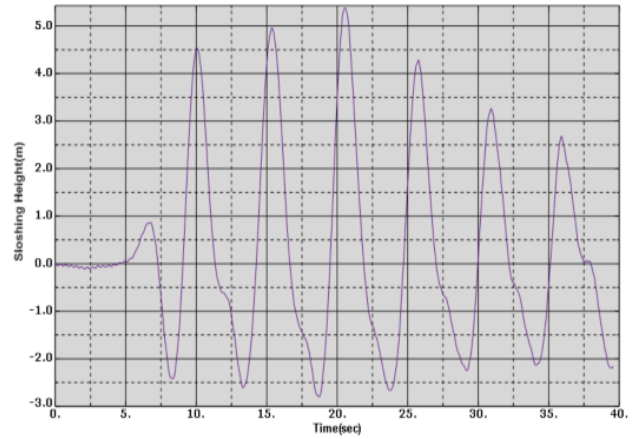
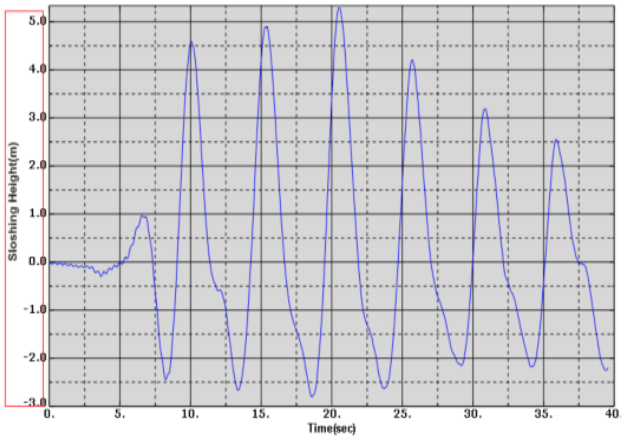


Figure 8: Water level variation near the tank wall for $h=11\text{m}$ (upper graphs) and $h=7\text{m}$ (lower graphs) in presence of vertical ground excitation (left graphs) and its absence (right graphs)

It can be seen in Figure 7 that the existence of extensive vertical excitation can increase the section force in the supporting structure of the tank up to 20%. Figure 8 shows that the water level variations are much more in case of larger water height in the tank, contrary to the case of tank with space frame supporting structure subjected to the same earthquake.

4. CONCLUSIONS

Based on the numerical results obtained from several cases of time history analysis, it can be concluded that:

- In some cases, particularly for relatively short ones, the combined effects of sloshing and vertical ground acceleration result in large values of internal forces and moments in the major elements of the tank supporting structure, which are beyond the values obtained by the code requirements.
- As expected these increases are more crucial for the tanks which have a shaft structure.
- The sloshing height may either increase or decrease with increase in the height of water in the tank.

Based on the above conclusions it can be said that the code requirements for seismic design of elevated tanks need some modifications to take into account the near-field effects.

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