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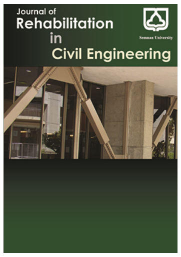

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Seismic Behavior Assessment of Concrete Elevated Water Tanks

S. Bozorgmehrnia[1*], M.M. Ranjbar[2] and R. Madandoust[2]

1. M.Sc., Civil Engineering Department, Guilan University, Rasht, Iran.
2. Ph.D., Civil Engineering Department, Guilan University, Rasht, Iran.

* Corresponding author: *saeed.bozormehr@gmail.com*

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ABSTRACT

Elevated tanks are very important structures and consist of various types. Water supply is vital to control fires during earthquakes. Also they are utilized to store different products, like petroleum supplies in cities and industrial zones. Damage to these structures during strong ground motions may lead to fire or other hazardous events. Elevated tanks should stay functional after and before earthquakes. However their dynamic behavior differs greatly in comparison with other structures. In this research, a sample of reinforced concrete elevated water tank, with 900 cubic meters capacity, exposed to three pair of earthquake records have been studied and analyzed in time history using mechanical and finite-element modeling technique. The liquid mass of tank is modeled as lumped masses known as sloshing mass, or impulsive mass. The corresponding stiffness constants associated with these lumped masses have been worked out depending upon the properties of the tank wall and liquid mass. Tank responses including base shear, overturning moment, tank displacement, and sloshing displacement have been calculated. Results reveal that the system responses are highly influenced by the structural parameters and the earthquake characteristics such as frequency content.

1. Introduction

Elevated tank structures are normally used to store water for domestic activities and also fire fighting purposes. Their safety performance is a critical concern during strong earthquakes. The failure of these structures may cause serious hazards for citizens due to the shortage of water or difficulty in putting out fires during earthquakes. Some elevated tanks have shown insufficient seismic resistance in pervious earthquakes which had prevented the fire fighting process and other emergency response efforts [1-3]. There have been several studies in which the dynamic behavior of liquid storage tanks have been analyzed; however most of them have focused on ground level cylindrical tanks, and very few of them have concentrated upon behavior of elevated tanks.

They are heavy structures which a greater portion of their weight is concentrated at an elevation much about the base. Critical parts of the system are columns and braces through which the loads are transmitted to the foundation. Due to the high sensitivity of elevated water tanks to earthquake characteristics such as frequency contents, peak ground acceleration and effective duration of the earthquake records, it seems necessary to ponder the earthquake loading as a non-stationary random pattern.

2. Past Experiences

Some of the major studies on the elevated liquid tanks are presented here. Haroun and Ellaithy [4] developed a model including analysis of a variety of elevated rigid tanks exposed to shifting and rotation. Resheidat and Sunna [5] investigated the behavior of a rectangular elevated tank considering the soil-foundation structure interaction during earthquakes. They neglected the sloshing effects on the seismic behavior of elevated tanks and the radiation damping effect of soil. Haroun and Temraz [6] analyzed two-dimensional x-braced elevated tanks supported on the isolated footings to investigate the impact of dynamic interaction between the tower and the supporting soil-foundation system but they also neglected the sloshing effects. Marashi and Shakib [7] carried out an ambient vibration test for the evaluation of dynamic characteristics of elevated tanks. Dutta [8] purposed alternate tank staging configurations for reduced torsional vulnerability. Dutta [9] studied the supporting system of elevated tanks with reduced torsional vulnerability and suggested approximate empirical equations for the lateral, horizontal and torsional stiffness for different frame supporting systems. Dutta [10] also investigated how the inelastic torsional behavior of tank system with accidental eccentricity varies with increasing number of panels. Subsequently, Dutta [11] showed that soil-structure interaction could cause an increase in base shear particularly for elevated tanks with low structural periods. Livaoglu and Dogangun [12] investigated seismic behavior of fluid-elevated tank-foundation-soil systems in domain frequency. Livaoglu and Dogangun [13] suggested a simple analytical procedure for seismic analysis of fluid-elevated tank-foundation-soil systems, and they used this approximation in selected tanks. Livaoglu [14] conducted a comparative study on the seismic behavior of elevated tanks considering both fluid- structure and soil-structure interaction effects. Livaoglu and Dogangun [15] studied the impact of foundation embedment on the seismic behavior of elevated tanks taking fluid-structure- soil interaction into account.

3. Elevated Tank Characteristics

In this research, a reinforced concrete elevated tank with support systems has been considered. This elevated tank is placed on framed structure and the elevation of this tank reaches to 32 meters and its capacity is 900 cubic meters. Detail of the elevated tank is shown in Fig. 1. and Fig. 2. vessel loading pattern and the shape of tank are symmetric. This sort of tanks and supporting system is widely used in recent years worldwide. The specifications of this tank are explained in Table 1. Also, mechanical properties considered for the steel, concrete and water are given in Table 1.

4. Modeling

A Finite Element Model (FEM) is used to model the elevated tank system. Columns and beams in the support system are modeled as frame elements (with six degrees-of-freedom per node) and the truncated cone and container walls are modeled with quadrilateral shell elements (with four nodes and six degrees of freedom per node). Fluid-structure interaction problems can be investigated using different techniques such as added mass (AM)[16, 17, 18], Lagrangian (LM) [19], Eulerian (EM)[20, 21, 22, 23], and Lagrangian–Eulerian (L-E M) [24] approaches in the FEM or by the analytical methods like Housner's two-mass representation [25] or multi-mass representations of Bauer [26] and EC-8 [27]. In this research, Housner's added mass approach is selected. In Housner's analytical model of mass-spring, [25] the fluid is modeled as a centered mass model and two impulsive and convective mass are used instead of the fluid. The parameters of the fluid are calculated using Housner's relations, which are stated in Table 2. Three cases of completely filled, half filled, and empty tanks are considered in this study.

In added mass method, the fluid mass being calculated through different methods such as Housner or Bour's is added to the structure mass in the common level of the structure and fluid. For a system under the earthquake motions, equation of motion can be written as:

$$M\ddot{u} + C\dot{u} + Ku = -M\ddot{u}_g \qquad (1)$$

Where M, K, and C are the mass, stiffness and damping matrix respectively, $\ddot{u}_g$ and u indicate the gravity acceleration and displacement varying with time, respectively. If the added mass approach is used, the above Eq.1 can be written as Eq.2:

$$M^*\ddot{u} + C\dot{u} + Ku = -M^*\ddot{u}_g \qquad (2)$$

Where M* is the total mass matrice that includes M as the structure mass matrix and M_a as the added mass. In this method, it is assumed that M_a is vibrated simultaneously with the structure. Hence, M is added due to the fluid effects while C and K do not change significantly.

Performing the free vibration analysis, the tank's dynamic properties consisted the period and modal partnership mass ratio are obtained and illustrated in Table 3. Sum of the structure's first six modes partnership is more than 90 percent. Considering the appropriate model of mass-spring that models the tank in two masses of impulsive and convective, there will be two different and various modes. The convective mass is jointed to the container's wall as a spring and the impulsive mass is considered to be rigid.

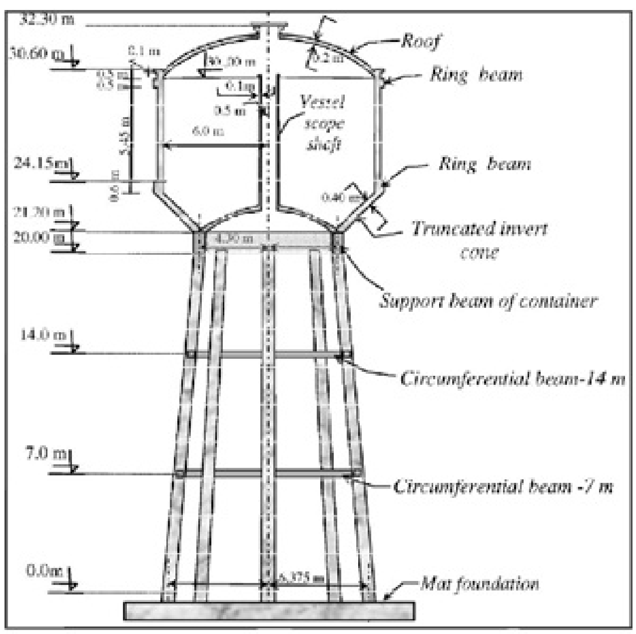

Fig. 1. Details and elevation of the tank

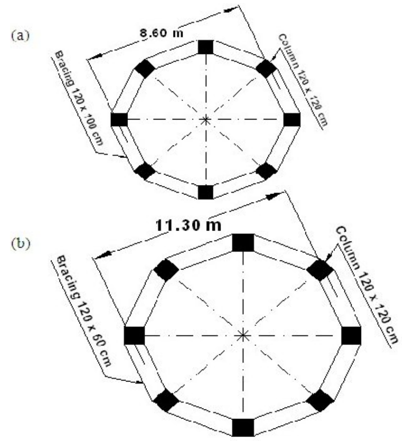

Fig. 2.(a) Arrangement of the columns and beams under the tank container;
(b) Arrangement of the columns and beams on the first story

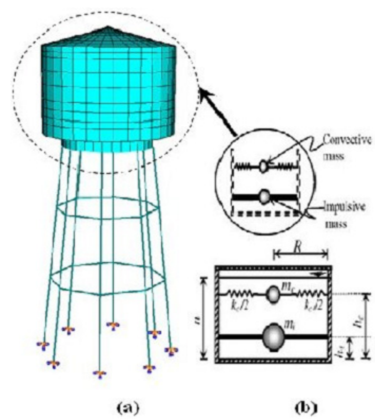

Fig. 3. (a) Modeling the elevated tank;
(b) Housner's mass-spring model [25]

Table 1. Mass-spring model parameters for filled and half filled cases

	Filled	Half-filled	Unit
mi	6.30×10^4	1.87×10^4	kgf
mc	2.79×10^4	2.47×10^4	kgf
hi	3.30	1.65	m
hc	5.95	2.48	m
kc	83.96	65.30	kN/m
H	8.80	4.40	m
R	6.0	6.0	m

Table 2. Tanks and material property

Tank vessel properties (m)		Tank staging properties (m)	
Geometry and section	Dimensions	Geometric and section	Dimensions
Inner diameter	12	Columns dimensions	1.20 ×1.20
Height	10.6	Columns height	7+7+6 = 20
Top Ring Beam	0.6 × 0.6	Staging inner diameter in top	8.60
Bottom Ring Beam	0.8 × 0.6	Staging inner diameter in bottom	12.75
Roof thickness	0.20	Beams dimensions in first floor	1.20 × 0.60
Vessel thickness	0.40	Beams dimension in second floor	1.20 × 0.60
Bottom slab thickness	0.50	Beams dimension in third floor	1.20 × 1.0
Material properties			
	Concrete	Steel	Water
E (MPa)	2.3 × 10 4	2.1 × 10 5	--------
(MPa) f_c'	30	--------	--------
Weight per unit volume (kN/m3)	25	78.5	10
Fy (MPa)	--------	240	--------

5. Ground Motions

Three cases including filled, half filled, and empty are considered to assess the dynamic response of elevated tanks. Time history analysis has been done using the above-mentioned equations. Rayleigh Damping is used in the analysis. In time history analysis, the tank is assumed in a C type soil according to UBC-97 classification. Three pair of earthquake records are used; their earthquake record properties are given in Table 4. The horizontal components of Kocaeli earthquake acceleration are presented in Fig. 5. and the important values of response spectrum acceleration of three pairs of earthquakes is also given in Table 4. In accordance with Table 5, the maximum PGA on the basis of acceleration gravity for Kocaeli, Imperial Valley and Northridge records are equal to 0.349, 0.485, and 0.843, respectively. The maximum PGV for the Kocaeli, Imperial Valley and Northridge records are equal to 65.7, 76.6, 129.6 cm/sec. According to UBC-97 code, the earthquake records should be scaled to 0.2T and 1.5T considering the amount of natural frequency.

Table 3. Modal properties of the tank in filled, half filled, and empty cases

	Mode	1	2	3	4	5	6
Filled	T (sec)	3.68	1.03	0.73	0.20	0.13	0.12
	MPMR	**8.60**	**83.90**	**0.00**	**2.90**	**3.60**	**0.00**
Half-filled	T (sec)	4.04	0.95	0.72	0.19	0.13	0.12
	MPMR	**8.11**	**83.42**	**0.00**	**3.55**	**3.83**	**0.00**
Empty	T (sec)	0.92	0.72	0.19	0.14	0.11	0.08
	MPMR	**90.4**	**0.00**	**3.51**	**4.80**	**0.00**	**0.03**

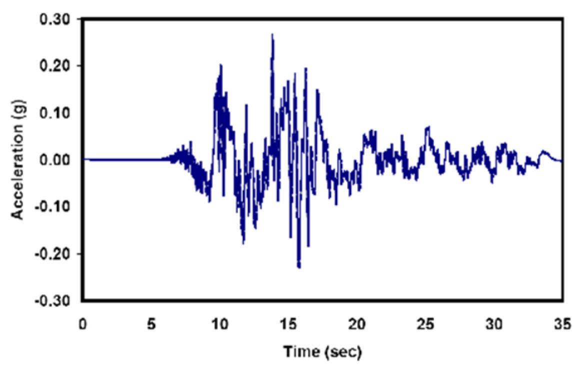

Fig. 4. Acceleration transverse component of Kocaeli earthquake

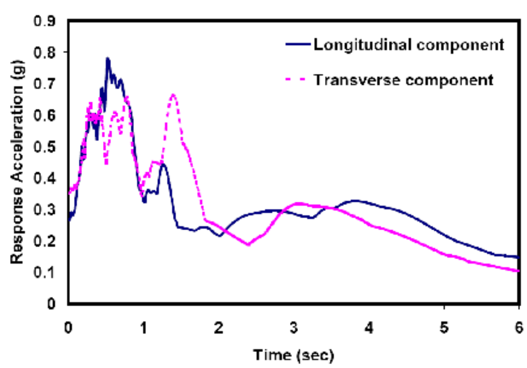

Fig. 5. Response spectrum acceleration of Kocaeli earthquake by 5% damping

Table 4. Used record properties

Record	Imperial Valley 1979		Northridge 1994		Kocaeli, Turkey 1999	
Station	El Centro	El Centro	Sylmar - Olive	Sylmar - Olive	Yarimca	Yarimca
Component	H-E04 -140	H-E04 -230	SYL -090	SYL -360	YPT- 060	YPT- 330
PGA (g)	0.485	0.36	0.604	0.843	0.268	0.349
PGV(cm/s)	37.4	76.6	78.2	129.6	65.7	62.1
PGD (cm)	20.23	59.02	16.05	32.68	57.01	50.97
Duration (sec)	36.82	36.82	40	40	35	35
M	6.5	6.5	6.7	6.7	7.4	7.4

Table 5. Seismic analysis results

Parameter	Imperial Valley,1979		
Case of Filling	Full	Half Full	Empty
HW / HL †	1.00	0.50	0.00
Maximum Roof Displacement (cm)	20.33	17.96	16.99
Maximum Floor Container Displacement (cm)	24.19	21.58	23.29
Maximum Sloshing Displacement (cm)	101.20	67.50	0.00
Maximum Base shear (ton)	682.53	638.66	627.40
Maximum Overturning Moment (ton.m)	13300.81	12832.28	9510
Parameter	Northridge, 1994		
Case of Filling	Full	Half Full	Empty
HW / HL †	1.00	0.50	0.00
Maximum Roof Displacement (cm)	17.79	20.33	19.58
Maximum Floor Container Displacement (cm)	21.11	24.94	23.29
Maximum Sloshing Displacement (cm)	121.7	54.81	0.00
Maximum Base shear (ton)	620.50	750.44	445.12
Maximum Overturning Moment (ton.m)	11821.73	11821.73	10270
Parameter	Kocaeli, Turkey,1999		
Case of Filling	Full	Half Full	Empty
HW / HL †	1.00	0.50	0.00
Maximum Roof Displacement (cm)	10.63	9.76	10.52
Maximum Floor Container Displacement (cm)	12.62	14.65	18.25
Maximum Sloshing Displacement (cm)	186.67	219.18	0.00
Maximum Base shear (ton)	564.50	474.65	480.83
Maximum Overturning Moment (ton.m)	7781.12	6375.54	5280.12
† Hw: Water height in vessel; HL T: Vessel Height			

6. Results

The maximum responses are determined for different parameters of the elevated water tanks subjected to three pair of the acceleration earthquake records. Table 5 reports the obtained maximum responses. These responses include base shear force, overturning moment, sloshing displacement, and roof displacement. As it can be seen, the obtained maximum responses were different in three earthquake records. The maximum response in base shear is for Northridge record in half filled case; however, the maximum response in roof displacement is for Northridge record in filled case. Obtained time histories responses for each parameter are presented and their implications are studied.

6.1. Base Shear Force

Fig. 6. shows variation of base shear forces against the percentage of capacity for the elevated water tanks in three earthquake records. The variation of base shear forces over the percentage of filling show that the maximum base shear force would happen in the half full and full filling. This may be due to the greater hydrodynamic pressures for half full filling compared to full filled tanks. This pattern of variations is not the same for all the three earthquake records. Interestingly, the dynamic characteristics of system and hydrodynamic influences considerably affects the amount of base shear forces. Also, the maximum time history of the base shear force for Northridge earthquake records in half-filled case is presented in Fig. 7.

6.2. Overturning Moment

The variation of maximum overturning moment against the percentage of tank capacity is presented in Fig. 8.The maximum response happens in a case that the tank is full filled. Increase in the percentage of filling, results in overturning moment rising. The pattern of overturning moment variation is almost the same for the system with different earthquake records. Also, the maximum time history of overturning moment for Imperial Valley earthquake records in full filled tank is presented in Fig. 9.

6.3. Roof and floor displacements

The maximum displacements obtained along the height of elevated tank for three earthquake records are shown in Fig. 10. and Table 5. The maximum displacements for three earthquake records occurred in Northridge earthquake in three cases (full, half full and empty). The results indicate that, in relatively stiff soils, the maximum displacement happens at the joint place of the column and the container. As Dogangun and Livaoglu [15] observed maximum displacement occurs in the joint of column and container in tank on stiffer soils, however, maximum displacement in tank systems on relatively softer soils occurs in the roof.

The variation of floor slab displacement against the percentage of tank capacity is presented in Fig. 11. As it can be seen in Fig. 11 , floor displacement of the container does not always occur in the filled case and it is not critical. Container’s maximum floor displacement occurs in Northridge record in half filled case and in Imperial Valley record on empty case. The results are due to the earthquake properties and the given frequency content. Container’s floor displacement curve against the time of Northridge earthquake in half full case is illustrated in Fig 12.

6.4. Sloshing displacement

The variation of displacement sloshing versus the percentage of the storage tank filling is presented in the Fig. 13. The results show that the sloshing displacement does not always occur in full tank and it is not critical. As it can be seen in Table 5 and Fig. 13, the pattern of variations of sloshing displacement is not same for the three earthquake records. Thus, in Northridge and Imperial Valley records, as the percentage of the tank fluid increases, the sloshing displacement increases and in Kocaeli record it decreases. Maximum sloshing displacement for three earthquake records and three cases of filling occurred Kocaeli earthquake in half filled case. Time history of sloshing displacement under Kocaeli earthquake in half filled case is illustrated in Fig.14. Also, the time history of sloshing displacement and roof for Northridge and Imperial Valley are presented in Figs. 15 and 16. As shown in Figs. 14 through 16, occurrence time of maximum roof and sloshing displacement are different for each earthquake record. The reason is related to the different periods of impulsive and convective mass and also the frequency content of used records.

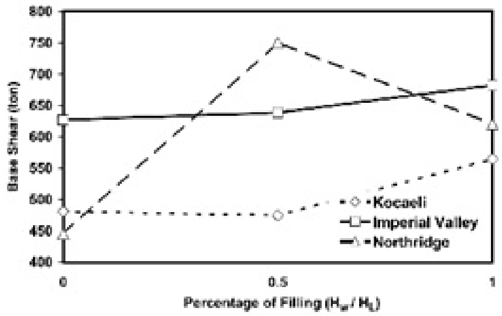

Fig. 6. Base shear variation based on the filling percent

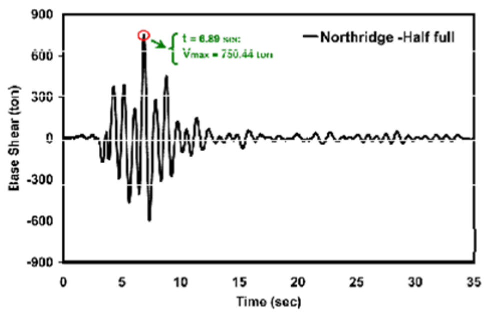

Fig. 7. Time history of base shear force under the Northridge earthquake in half full case

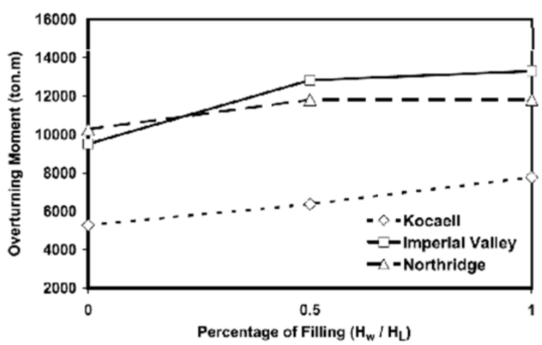

Fig. 8. Overturning moment variation based on the filling percent

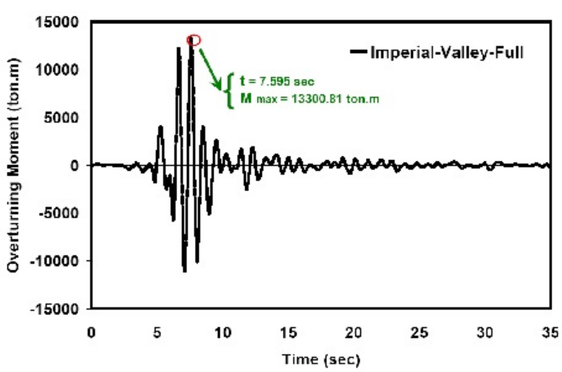

Fig. 9. Time history of overturning moment under the Imperial Valley earthquake in full case

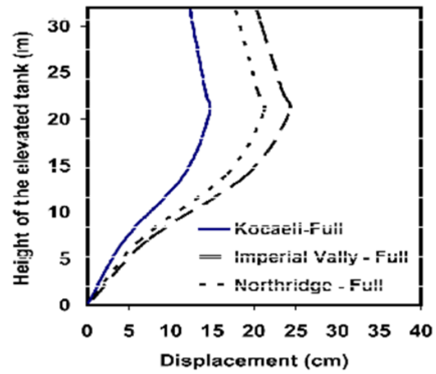

Fig. 10. Maximum displacements in full case

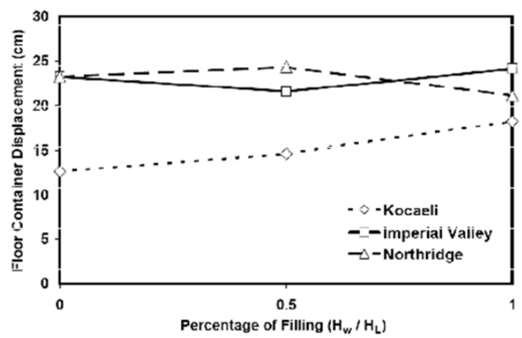

Fig. 11. Floor displacement variation based on filling percent

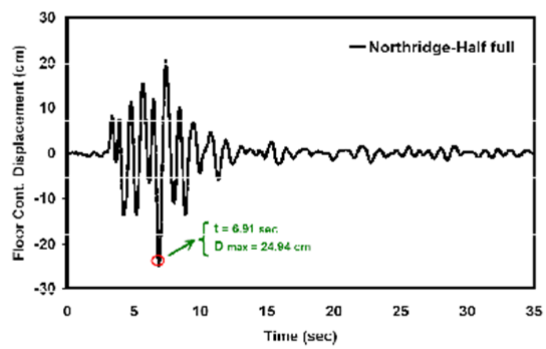

Fig. 12. Time history of floor displacement under the Northridge earthquake in half full case

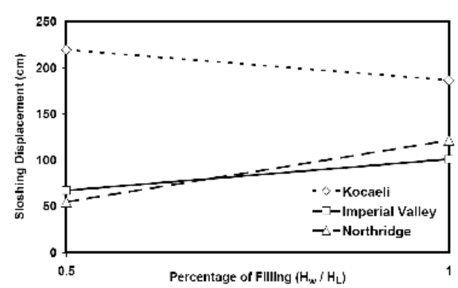

Fig. 13. Sloshing displacement variation based on filling percent

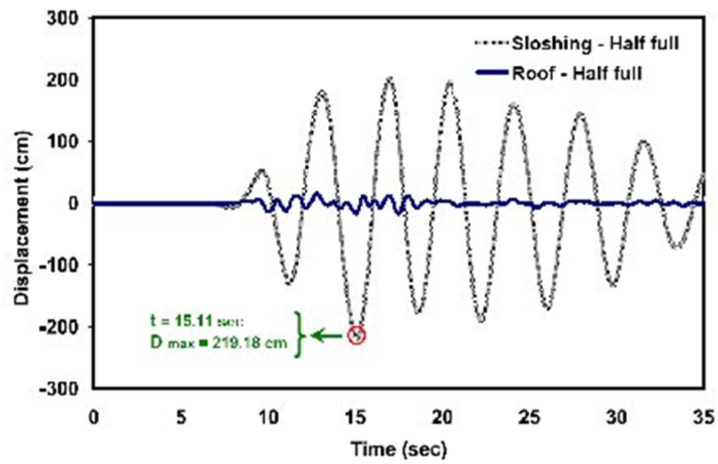

Fig. 14. Time history of roof and sloshing displacement under the Kocaeli earthquake in half full case

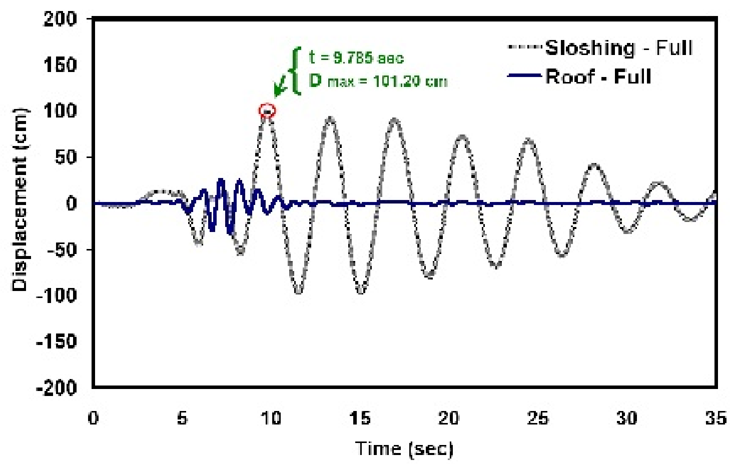

Fig. 15. Time history of roof and sloshing displacement under the Imperial Valley earthquake in full case

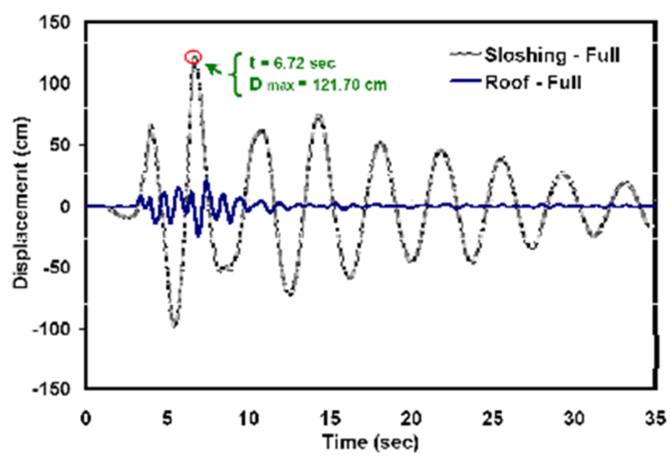

Fig. 16 Time history of roof and sloshing displacement under the Northridge earthquake in full case

7. Conclusion

In this study, an elevated 900 m^3 water tank which was supported by moment resisting frame was considered. Using Housner two-mass models, dynamic responses including base shear, overturning moment, roof and floor displacement, and sloshing displacement were assessed under three earthquake records. The dynamic responses of tank have been determined using time history analysis in three cases, i.e. empty, half-full and full. The obtained results are summarized as follows:

- The critical response of elevated tanks does not always occur in full case of tanks and it may happen in lower percentage of fluid and even in empty case of the tank depending on the earthquake characteristics.
- Frequency content and properties of the earthquake in ranges of natural frequency are the most important factors in reduction or intensity of tank responses.
- Freeboard considered for this tank (190 cm), the sloshing displacement obtained in Kocaeli record was 219 cm which is more than the considered value. This point is confirmed in reference [12] that investigated the tank considering fluid–structure–soil interactions.
- Maximum displacement of the elevated tank which is in a C type soil according to the UBC-97 classification occurs in the support system joint with the container.
- Due to the difference between the impulsive and convective mass periods and also among the frequency contents and utilized earthquake records properties, the occurrence time of maximum roof and sloshing displacements are not the same and they depend on the aforementioned parameters.

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