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Seismic Analysis of Elevated Water Storage Tanks Subjected to Six Correlated Ground Motion Components

L. Kalani Sarokolayi, B. Navayi Neya, J. Vaseghi Amiri and H. R. Tavakoli

Department of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran

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Abstract: In this work, rotational components of ground motion acceleration were defined according to improved method from the corresponding available translational components based on transversely isotropic elastic wave propagation in the soil. With such improvement, it becomes possible to consider frequency dependent wave velocities on rotational components of ground motion. For this purpose, three translational components of El Centro earthquake (24 January 1951) were adopted to generate their relative rotational components based on SV and SH wave incidence by Fast Fourier transform with 4096 discrete frequencies. The translational and computed rotational motions were then applied to the concrete elevated water storage tanks with different structural characteristics and water elevations. The finite element method is used for the nonlinear analysis of water storage tanks considering the fluid-structure interaction using Lagrangian-Lagrangian approach and the concrete material nonlinearities have been taken into account through William-Warnke model. The nonlinear response of these structures considering the six components of ground motion showed that the rotational components of ground motion can increase or decrease the maximum displacement and reaction force of the structure. These variations are depending on the frequency of structure and predominant frequencies of translational and rotational components of ground motion.

Key words: Elevated water storage tank · Six correlated components · Fluid-structure interaction · Lagrangian approach

INTRODUCTION

The kinematics of any point in a medium is ideally expressed in terms of three translational and three rotational components. The issue of rotational strong ground motion have been studied theoretically by several investigators, including Newmark [1], Ghafory-Ashtiany and Singh [2], Trifunac [3], Lee and Trifunac [4,5], Castellani and Boffi [6, 7] and based on constant plane wave velocity. Nouri *et al*. [8] have also compared different methods of torsional ground motion evaluation. Some researchers such as Hong-Nan Li, Li-Ye Sun and Su-Yan Wang [9] proposed an improved approach which included the effect of the relative contributions of the P, SV and SH waves, frequency dependent on wave velocity and angle of incident waves in each frequency to calculate time histories of rotational components. Lee and Liang [10] have also used the method introduced by Lee and Trifunac [4, 5]. Kalani Sarokolayi *et al*. [11] have generated the rotational components of six ground motions using improved method by Hong-Nan Li *et al.* [9] and their empirical scaling for high frequencies.

During the past two decades, numerous studies have continued to show the significance of the rotational components in strong motion excitation on the structural response [12, 13] and improved approach for empirical scaling of rotational spectra [14, 15]. Some researchers such as Bielak [16], Gupta and Trifunac [17], Goel and Chopra [18] and Takeo [19], Awad and Humar [20], Ghayamaghamian *et al*. [21] have shown the importance of the rotational components in the seismic behavior of building structures. They have shown that during an earthquake, even symmetric structures can be expected to undergo substantial torsional excitation and in the case of stiff building structures, the torsional components can increase the displacements up to four times.

Corresponding Author: B. Navayi Neya, Faculty of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran
Tel & Fax: +98-111-3231707. E-mail: Navayi@nit.ac.ir

In the particular case of nonlinear dynamic analysis of concrete tanks, the constitutive model of concrete material and water-structure interactions are also important issues. Numerous materials models were developed to simulate the complex nonlinear behavior of concrete structures subjected to dynamic loading [22, 23]. The Lagrangian approach to consider fluid-structure interaction has been used also by several researchers such as Hamdi [24], Khalvati and Wilson [25], Ahmadi and Navayineya [26], Kalani Sarokolayi and Navayineya[27], Akkose, Adanur, Alemdar and Dumanoglu [28].

In this paper, the response of elevated water storage tanks created by six correlated components of ground motion were obtained; where rotational components generated using improved approach with considering frequency dependent waves velocity based on SV and SH wave incidence. In addition, fluid-structure interaction using the Lagrangian-Lagrangian approach and nonlinearity of tank material using William-Warnke constitutive model are considered for different shapes and characteristics of the structure. The calculations are taken into account with some assumptions such as: foundation of structre is rigid and displacements are small; the tank materials are homogenous, isotropic and theory of three-dimensional isotropic elastic wave propagation is also considered in the soil medium.

Theory

Rotational Component: The seismic grounds motions are generated by plane harmonic waves occur at the site close to the earthquake source. The direction of propagation of the waves is assumed to lie in the vertical (x, z) plane. The waves in the plane perpendicular to the direction of propagation are decomposed into in-plane components of amplitude A_{SV} due to the SV waves and out-of–plane components of amplitude A_{SH} due to the SH waves. The incidence and reflection of in-plane waves in three dimensional structures will originate two rotational components of the ground motion at the free surface: ϕ_{gx} and ϕ_{gy} that are referred to as the rocking components. The incidence and reflection of out-of-plane waves will originate one the torsional component of the ground motion at the free surface, ϕ_{gz}.

SV Wave Incidence: Figure 1 shows the coordinate system, ground motion amplitudes *u, w* and the ray direction with the assumed positive displacement amplitudes of incident (A_S), reflected P(A_{SS}) and SV(A_{SP}) waves. For the incident ray of SV waves in $x=0$ plane,

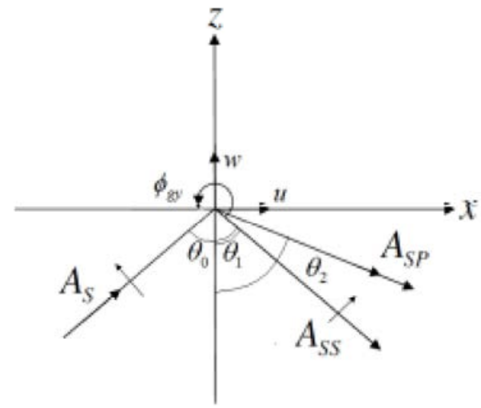


Fig. 1: Coordinate system for incident SV wave.

the only non-zero components of motion are *u*, *w* and ϕ_{gy} (Figure 1). These characteristics are also defined for the plane $y=0$, where the only non-zero components of motion are *v*, *w* and ϕ_{gx}.

Refer to Figure 1, the angle of incidence, θ_0 and reflected SV waves, θ_2, are equal. The angle of reflected P wave is also denoted as θ_1.

For harmonic waves of frequency ω, the potential functions are:

$$\psi_{SV} = A_S \exp i\omega\left(\frac{\sin\theta_0}{\beta}x - \frac{\cos\theta_0}{\beta}z - t\right) \tag{1}$$

$$\varphi_{SP} = A_{SP} \exp i\omega\left(\frac{\sin\theta_1}{\alpha}x + \frac{\cos\theta_1}{\alpha}z - t\right) \tag{2}$$

$$\psi_{SS} = A_{SS} \exp i\omega\left(\frac{\sin\theta_0}{\beta}x + \frac{\cos\theta_0}{\beta}z - t\right) \tag{3}$$

where α and β are the propagation velocities of P and S waves, respectively [29].

The particle displacement *u, w* in the *x, z* directions are given by:

$$u = \frac{\partial\varphi_{SP}}{\partial x} + \frac{\partial(\psi_{SV} + \psi_{SS})}{\partial z} \tag{4}$$

$$w = \frac{\partial\varphi_{SP}}{\partial z} - \frac{\partial(\psi_{SV} + \psi_{SS})}{\partial x} \tag{5}$$

By imposing the free shear stress condition at the ground surface:

$$\tau_{xz}\Big|_{z=0} = \left[\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right]_{z=0} = 0 \tag{6}$$

The rocking component can be written as:

$$\phi_{gy} = \frac{1}{2}\left(\frac{\partial w}{\partial x} - \frac{\partial u}{\partial z}\right) \tag{7}$$

The resulting rocking component can be obtained from Eq. 1 to 7 as:

$$\phi_{gy} = \frac{\partial w}{\partial x} = \frac{\partial^2 \varphi_{SP}}{\partial z \partial x} - \frac{\partial^2 (\psi_{SV} + \psi_{SS})}{\partial^2 x}$$
$$= i\omega \frac{\cos\theta_1}{\alpha} i\omega \frac{\sin\theta_1}{\alpha} \varphi_{SP} - [(i\omega \frac{\sin\theta_0}{\beta})\psi_{SV}$$
$$+(i\omega \frac{\sin\theta_0}{\beta})^2 \psi_{SS}] \tag{8}$$

According to the Snell's law, (sin θ_0)/α, one can also obtain:

$$\varphi_{gy} = \frac{i\omega}{C_x} w \tag{9}$$

in which $C_x = \beta/\sin\theta_0$.

These equations are also applied for the other rocking component, φ_{gx}.

SH Wave Incidence: For incident SH waves, there is no mode conversion and hence there is only one reflected SH wave with $\theta_2 = \theta_0$ and $A_2 = A_0$ according to Figure 2.

The potential functions of incident and reflected waves are [29]:

$$V_{SH} = A_0 \exp i\omega\left(\frac{\sin\theta_0}{\beta}x - \frac{\cos\theta_0}{\beta}z - t\right) \tag{10}$$

$$V_{SH'} = A_1 \exp i\omega\left(\frac{\sin\theta_0}{\beta}x + \frac{\cos\theta_0}{\beta}z - t\right) \tag{11}$$

The displacement field v caused by the incident and reflected waves in the y direction is:

$$v = 2V_{SH} = 2A_0 \exp i\omega\left(\frac{\sin\theta_0}{\beta}x - t\right) \tag{12}$$

Using Eq. 12, the torsion ϕ_{gz} is obtained by:

$$\phi_{gz} = \frac{1}{2}\left(\frac{-\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) = \frac{1}{2}\frac{\partial v}{\partial x}\bigg|_{z=0} = \frac{\partial V_{SH}}{\partial x}$$
$$= i\omega \frac{\sin\theta_0}{\beta}\frac{v}{2} = \frac{i\omega}{2C_x} v \tag{13}$$

in which $C_x = \beta/\sin\theta_0$.

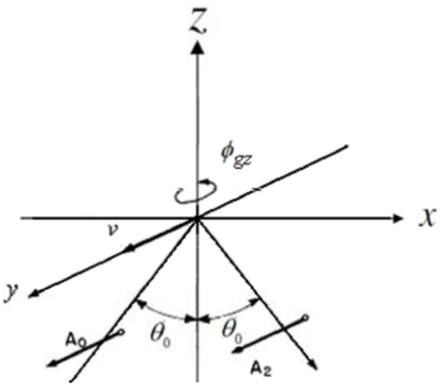


Fig. 2: Coordinate system for incident SH wave.

Assuming that the translational components *u, v* and *w* of the ground motion at the free surface can be measured, the rocking and torsional components of ground motion are obtained from Eqs. 9 and 13, respectively. In these equations, the frequency dependent angle of incident waves, (sin θ_0) need to be obtained.

Angle of Incidence: The improved approach developed as reported in literature [9], is used to calculate the angle of incident waves. Using this approach, introducing (x = sin θ_0) and based on Snell's law, Eqs. 14 and 15 are used to obtain the angle of incident SV and SH waves.

$$G = \frac{2x\sqrt{1-K^2x^2}}{K(1-2x^2)}, \qquad \theta_0 \prec \theta_C \tag{14}$$

$$G = -\frac{2x\sqrt{1-K^2x^2}}{iK(1-2x^2)}, \qquad \theta_0 \succ \theta_C \tag{15}$$

where $G = tg\bar{e} = w/u$ and $G = tg\bar{e} = w/v$ for rocking component in *x-z* and *y-z* plane due to SV waves; $G = tg\bar{e} = v/u$ for torsional component in *x-y* plane due to SH waves; K = α/β and θ_C the incident critical angle.

Constitutive Model of Material and Finite Element Method: In water storage tanks, concrete, steel and water have different rheological behaviors. The major nonlinear behavior that can affect the tank response is crack propagation in concrete. Reinforcement rebar can also exhibit plasticity flow and low pressure water can produce cavitation. In this research, the steel and water are considered linear. The nonlinear behavior of concrete is considered through the William-Warnke constitutive model [25].

Table 1: Geometrical characteristics of water storage tanks

FEM	t_u (m)	R_u (m)	H_u (m)	t_b (m)	R_b (m)	H_b (m)	H_r (m)
M1	0.3	2.7	3.5	0.5	1	6	0
M2	0.3	2.7	3.5	0.5	1	7	0
M3	0.3	2.7	3.5	0.5	1	8	0
M4	0.3	2.7	3.5	0.5	1	13	0
M5	0.3	2.7	3.5	0.5	1	8	0.4full
M6	0.3	7	6.5	0.5	1.5	30	0
M7	0.3	7	6.5	0.5	1.5	30	0.2 full
M8	0.3	7	6.5	0.5	1.5	30	0.6full

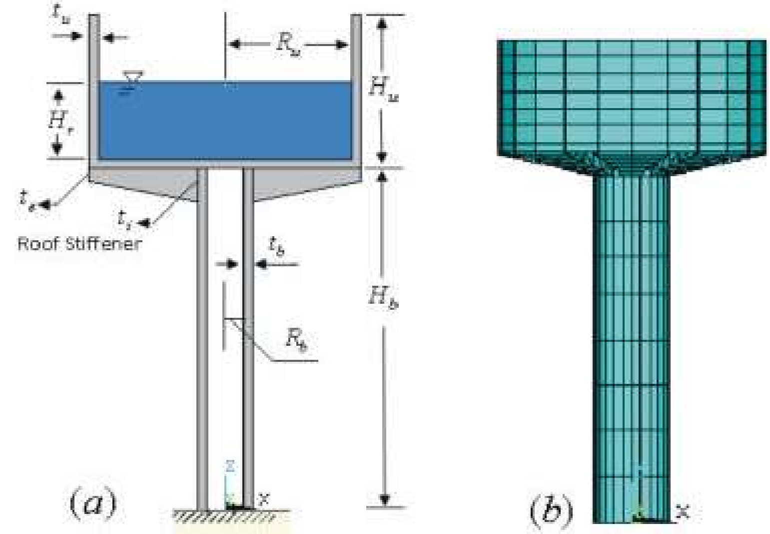


Fig. 3: (a) Geometrical characteristics, (b) Finite element model of elevated water storage tank.

Within the displacement-based finite element methodology (Lagrangian-Lagrangian method), the displacement is taken as the principal variable for the solid and fluid domains. The application of Lagrangian-Lagrangian method for coupled fluid-structure systems, leads to the follwing governing dynamic equation [30]:

$$M\ddot{u} + C\dot{u} + Ku = F(t) \tag{16}$$

in which M,C and K, are mass, damping and stiffness matrices for the coupled system, respectively. $\ddot{u},\dot{u},u$ and $F(t)$ are vectors of accelerations, velocities, displacements and external loads of the coupled system, respectively. The force vector of $F(t)$ must be defined as a way to consider the six ground motion components [31].

Numerical Results: The elevated water storage tanks considered to have a cylindrical shape and a central shaft. Some stiffeners are used in the cylinder's base to avoid in-plane flexural stresses. The geometrical characteristics and finite element model of considered structures are shown in Figure 3. The geometrical characteristics symbols are defined as t_u, R_u, H_u, t_b, R_b, H_b, t_e, t_i and H_r in Figure 3(a) and the related values are listed in Table 1. The tank finite element model is also shown in Figure 3(b). Eight models of water storage tanks named from M1 to M8 are considered in the present study; where three of them are allocated to effect of fluid. Height of water level in these three cases are 0.2, 0.4 and 0.6 height of full reservoir named M5, M7 and M8, respectively.

All models are used eight concrete stiffeners with $t_i = 1.5m$ and $t_e = 0.5m$. These parameters are considered the same for all models because changing of these parameters does not affect natural frequency of the structure.

Changes in the tank geometry and water elevation affect the natural frequencies, some of these frequencies moves close to the predominant frequencies of translational and rotational components of ground motion. This problem can obviously affect the dynamic response of water storage tanks due to the resonance phenomena.

Table 2: The first natural frequencies of water storage tanks

Model	M1	M2	M3	M4	M5	M6	M7	M8
Natural frequency(Hz)	13.35	11.22	9.55	4.98	4.30	1.62	0.75	0.57

Table 3: El Centro (24 January 1951) characteristics

Earthquake	Station	Epicentral distance (km)	Record Component	PGA (g)	Predominant frequency(Hz)
Imperial Valley 1951/01/24	117 El Centro Array #9	28.24	Up-Down	0.013	4.5
			North-South	0.029	2.5
			East-West	0.030	2.0

The linear constitutive properties of tank material at ambient temperature are assumed to be as follows: Young modulus of concrete E_c = 33GPa, the steel Young modulus of reinforcement E_s = 200GPa, the Poison's ratio is 0.3, the mass density of concrete is 2400kg/m^3. The water density is 1000kg/m^3. The sound speed in water is assumed to be 1483 m/s, which is equivalent to the Bulk modulus of elasticity of 2.2 GPa. The uniaxial tensile and compressive strength of concrete are considered 3.5 and 30MPa, respectively.

To evaluate the rotational components of ground motion, the propagation velocities of P and S waves for the medium type of soil are considered to be 6 and 3.675 km/s, respectively [29].

The reinforcement is defined as a percentage of the volume ratio in *x, y* and *z* direction, which is equal to 2%. The damping coefficient in the structure domain is maintained at 5% and the viscosity of fluid is also considered 1 % [30]. The modal analysis of considered models M1 to M8 is carried out to obtain their corresponding natural frequencies and results are summarized in Table 2.

The full transient analysis is performed to calculate the dynamic responses of water tanks subjected to three and six components of ground motion. For this purpose, the three translational components of El Centro (24 January 1951) have been used to derive the time histories of the corresponding rotational components. The characteristics of this earthquake are listed in Table 3.

Fast Fourier transform is applied to translation motion time histories with 4096 discrete frequencies to obtain their relative rotational components. It is assumed that the recorded motions are primarily generated by shear waves [9]. Therefore, Eqs. 14 and 15 are used to calculate the frequency dependent angle of incidence for each harmonic component. Knowing the angle of incidence, the rotational components at each discrete frequency are obtained from Eqs. 9 and 13 for the rocking and torsional components, respectively.

This process is used to calculate the Fourier spectra of the rotational components at all discrete frequencies. Then, the rotational time histories are obtained from inverse Fourier transform of these spectra.

These rotational power spectrums and rotational time histories of El Centro, calculated from the proposed methodology, are shown in Figures 4 and 5, respectively. According to Figure 4, the predominant rocking component frequencies are 9.5 and 12.5 Hz; while the torsional component predominant frequency range is within 2-2.5 Hz [11].

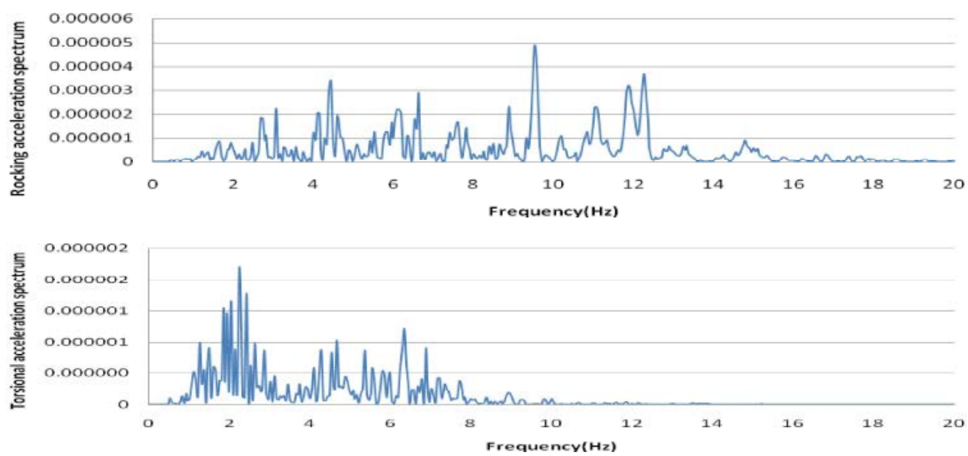
Seismic Response of Water Storage Tank: From Tables 2 and 3, it is clear that the natural frequency of models M1 and M3 are approximately the same range as the predominant frequency of rocking component; therefore, resonance phenomena is expected for these models.

Results of the nonlinear dynamic analyses of elevated water storage tanks with and without considering rotational components of earthquake are presented in Table 4. In this table, variables $(\tilde{F})$, $(\tilde{D})$ and $(\tilde{R})$ are denote the normalized structure responses where $(\tilde{F})$ is the ratio of maximum base shear force for the model subjected to six components of ground motion to the same the result obtained when the model is subjected to the three translational components. In addition, $(\tilde{D})$ and $(\tilde{R})$ are ratios regarding the maximum displacement and vertical reaction force respectively. Normalized response larger than unity implies that the rotational components of the ground motion increase the tank's response and vice versa. Table 4 is also listed the vertical reaction forces under three and six components of ground motion, their normalized response and the relative time of failure.

As shown in Tables 4, it can be justified that the rotational components of ground motion can decrease or increase some of the responses of structure depend on structure frequency and also frequency content of earthquake. It is necessary to mention that all calculation

Table 4: Results summary of nonlinear dynamic analysis (in X direction)

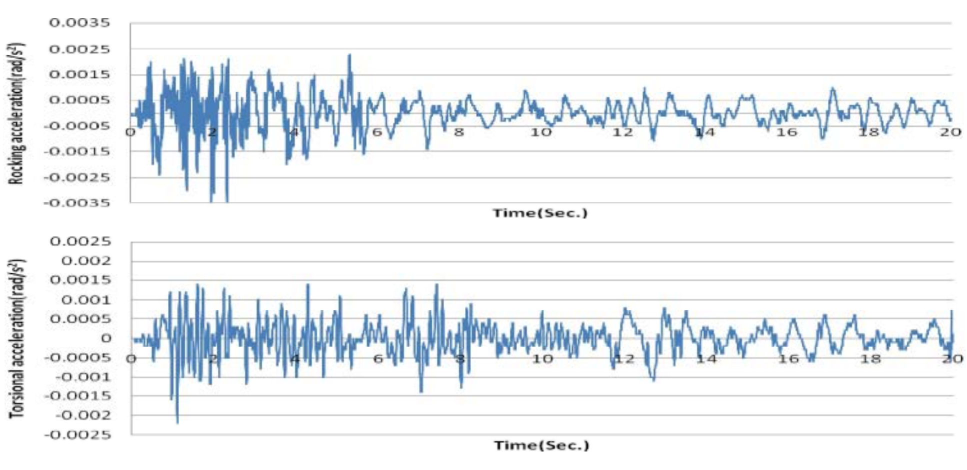
Model No.	No. of Earthquake Component	Max. Base Shear F(kN)	Max. Displacement D(mm)	Normalized response $(\tilde{F})$	Normalized response $(\tilde{D})$	Max. Vertical Reaction R(kN)	Failure Time (Sec)	Normalized response $(\tilde{R})$
M1	3CT	655	1	1.004	1.000	1689	20	1.370
	6C	658	1			2314	20	
M2	3CT	755	1.700	0.980	0.977	1806	20	1.000
	6C	740	1.662			1806	20	
M3	3CT	880	2.770	1.028	0.998	1856	1.72	1.051
	6C	905	2.764			1950	1.665	
M4	3CT	1029	10.300	0.862	0.831	2843	1.66	1.003
	6C	888	8.560			2852	1.625	
M5	3CT	769	2.080	0.997	1.025	873	2.41	0.993
	6C	767	2.131			867	2.41	
M6	3CT	2776	51.700	1.061	1.030	17523	1.245	1.000
	6C	2945	53.200			17535	1.245	
M7	3CT	456	31.500	1.055	0.965	24453	1.13	1.001
	6C	481	30.400			24464	1.125	
M8	3CT	941	29.930	0.984	0.964	25087	0.92	0.999
	6C	926	28.850			25077	0.92	



(a)

(b)

Fig. 4: El Centro rotational accelerations power spectrum, a) rocking, b) torsional component (s/rad).



(a)

(b)

Fig. 5: El Centro rotational accelerations time history, a) Rocking, b) Torsional component.

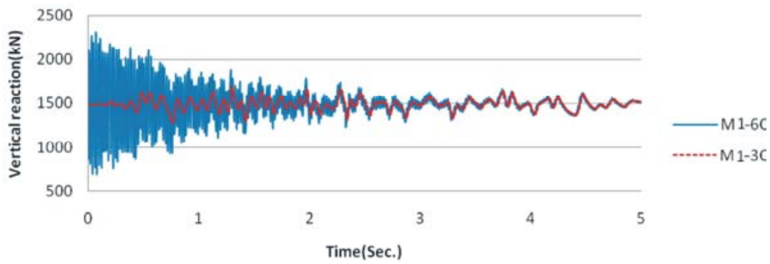


Fig. 6: Vertical reaction force time history for model M1.

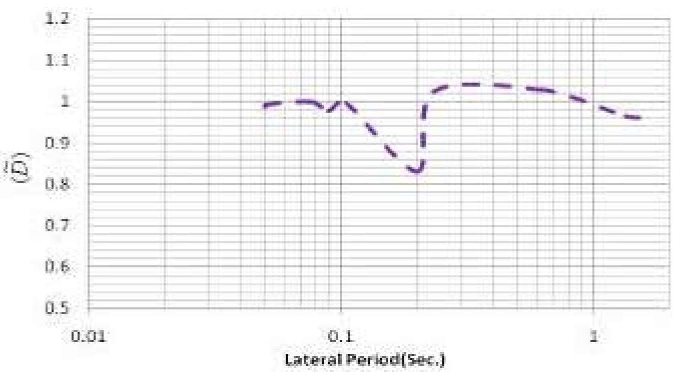


Fig. 7: Normalized response $(\tilde{D})$ as a function of lateral period of tank

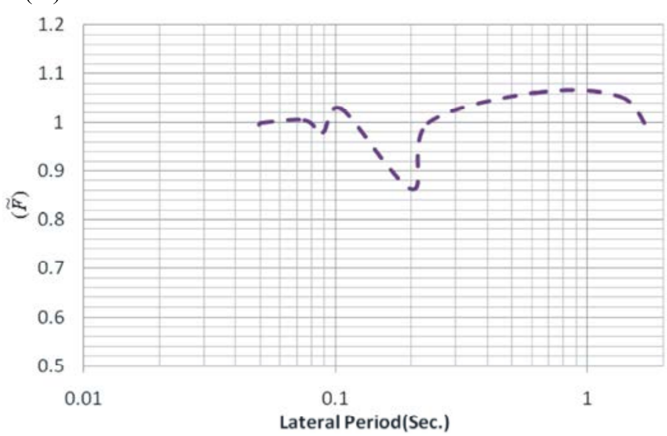


Fig. 8: Normalized response $(\tilde{F})$ as a function of natural frequency of tank.

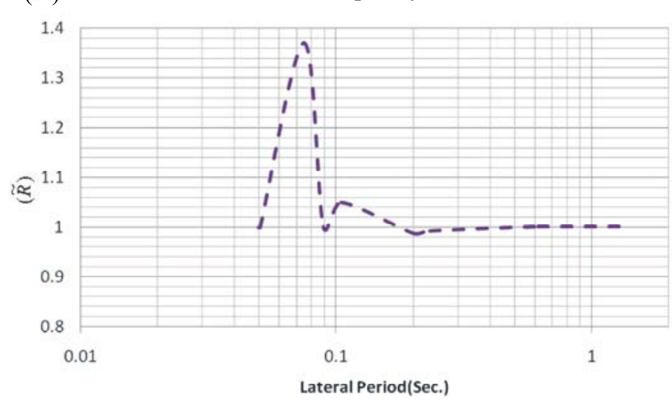


Fig. 9: Normalized response $(\tilde{R})$ as a function of natural frequency of tank.

have continued up to when in the Newton-Raphson schema iteration conversion is performed. Otherwise, it is supposed that the structure is failed and calculations are stopped. For model M1, the analysis showed that the tank did not lose its stability and was able to withstand the whole 20 seconds earthquake. The time history of the vertical reaction force for this model during the first 5 seconds is schematically illustrated in Figure 6. As shown, the rotational components during the first 3 seconds of earthquake generated a high frequency response and the timing of the maximum forces has changed drastically.

Models M7 and M8 are the same as M6 filled with 1.3 (0.2full) and 3.9 meters (0.6full) of water, respectively. As shown in Table 4, when the water elevation is increased, all responses of structure due to six components of ground motion near those due to three components and more increase of water elevation, results in lower responses due to six components of ground motion compared to three components. These results is valid for M3 and M5 models where the first one model is empty and the second one is filled with 40 percent of full reservoir.

The values of the normalize responses for models M1 to M8 are computed and results are shown in Figures 7, 8 and 9.

It is concluded that the normalized response for models with natural period of 0.075 and 0.105 second, is larger than other models and for model with lateral period of 0.2 second is the least.

CONCLUSIONS

In this study, effect of six correlated components of ground motion is investigated for the nonlinear dynamic responses of water storage tanks using finite element method considering fluid-structure interaction base on Lagrangian-Lagrangian approach.

For this purpose, rotational components of ground motion are obtained from translational components and the reliability of the method is confirmed by other references. Several types of storage tanks are modeled changing tank's geometry and water elevation. Nonlinear dynamic analysis of these structures under El Centro earthquake, the following specific conclusions are made.

- The increase in the base shears and vertical reaction forces of tanks due to rotational excitations of ground motion is the largest for elevated tank with short height (about 6 meter). This structure is laterally stiff and rotationally flexible and the accidental torsion could be larger than those proposed by the design codes.
- The effect of rotational components can be more considerable in tanks with less elevation of water, due to their natural frequencies are changed close to predominant frequency of rotational components. In this study, the increase of water elevation increased the rotational stiffness of water storage tanks and decreased the response of structures.
- In some cases, which structure is laterally stiff and rotationally flexible, the rotational components of ground motion can increase the response of structure. This result can be inversed for rotationally stiff structures.
- It is found that the accidental torsion in elevated tanks depends on the structural characteristics and torsional eccentricities of these structures need to be considered especially for tanks with short height.
- The analyses showed structure responses are changed by change of peak acceleration, frequency content of earthquake and its rotational components, soil type, water elevation and tank characteristics. Therefore, six-component-ground motion analysis of these structures can be necessary for design control.

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