DYNAMIC ANALYSIS OF WATER TANKS WITH INTERACTION BETWEEN FLUID AND STRUCTURE

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ABSTRACT :

Due to growing population and expansion of cities, the number of elevated water tanks supplying the demand urban water system is on the rise. As it has been mentioned in the Iranian code of practice for Earthquake /2800 because of the importance of sanitation and hygiene water tanks have been considered as important structures during the unexpected events such as earthquake. There is a great expectation not to see any phase out for their serviceability after the earthquake. Because of the presence of fluid with different behavioral properties of structures containing it and the most part of mass of tanks are located in a considerable distance from its foundation, the behavior of these types of structures in compare with conventional structures are more complicated. In this research, cylindrical concrete water tanks, which have a central shaft, have been evaluated with considering the effect of the structure's interaction with water through precise implementation of boundary conditions on the interface between fluid and structure. Also considering the level of water in the tank and their behavior under recorded acceleration of different earthquakes using finite element method. The results were then compared with suggested methods by Iranian code /2800, which the results show a relatively considerable difference between mentioned methods.

KEYWORDS: Elevated water tank, Fluid Structure interaction, Dynamic analysis

1. INTRODUCTION

Liquid storage tanks are essential structures in water, oil and gas industrials and the behavior of them during earthquake is more important than the economic value of the tanks and their contents. It is important that utility facilities remain operational following an earthquake to meet the emergency requirements such as firefighting water or meet the public demands as a source of water supply. For these reasons, serviceability becomes the prime design consideration in most of these structures. A good understanding of the seismic behavior of these structures is necessary in order to meet safety objectives while containing construction and maintenance costs.

One of the problems that are important in analysis and designing of these structures is the interaction between fluid and structure.

Prediction of analytical response of coupled field systems is very complex and approximately no available. So most of investigations are concerned about numerical methods such as finite element method.

In this paper Numerical analysis of elevated concrete water tanks with central shaft is performed by using of finite element software which fluid- structure interaction is considered.

2.THEORY

Methods of considering interaction between fluid and structure are variety. These methods are basically divided to three groups, such as:

a)Added mass method, b)The Eulerian- Lagrangian method , c)The Lagrangian- Lagrangian method.

In the first method, some of the fluid mass is added to structure at interface of them and structure is subjected to dynamic analysis. In this method the structure is considered flexible and the compressibility and stiffness of fluid are neglected in most cases. This method is relatively simple and used for 2-D and 3-D structures but results will be often with considerable errors.

In the second method the main purpose is the solution of governing equation for fluid and structure domain. The governing equation of fluid domain for an ideal, homogenous, inviscid, compressible and irrotational flow in term of velocity potential variable, ϕ, is:

$$\nabla^2 \phi = \frac{1}{C^2} \frac{\partial^2 \phi}{\partial t^2} \tag{2.1}$$

where C is the velocity of acoustic waves.
By this assumption that fluid is incompressible, the Eqn.1 is conformed to Laplace Eqn.2.

$$\nabla^2 \phi = 0 \tag{2.2}$$

With solving Eqn.1 or Eqn.2 for fluid domain in terms of variables P or ϕ , that p is pressure variable , behavior of fluid is modeled in term of time for nodes with constant coordinates.
Because the requisite variable for structure domain is nodal displacement, equations for coupled field system of fluid and structure will be unsymmetrical and their solution is complicated.
In the third method a particle has been considered in term of time and variable for fluid and structure domain is nodal displacement in finite element method. The most important advantage of this method is the use of same equation for fluid and structure domain and by solving just this motion equation, displacement, pressure and stress for fluid and structure domain have been determined.
In this research, the Langrage-Lagrange method is used to modeling interaction between fluid and structure. Elements that are used for Fluid and structure in ANSYS software are Fluid80 and Shell63 where Fluid80 element has eight nodes with three degrees of freedoms in each node and Shell63 element has four nodes with six degrees of freedom in each node.
The following assumption is considered in this research:
1-The foundation of structure is assumed to be rigid, 2-The tank and the water are assumed to have a linear and elastic behavior. Material properties of concrete and water are listed in Table.1 and the finite element characteristics of reservoir geometry as shown in figure.1 are listed in Table.2. In this Table the number of fluid and structure elements is obtained by using of sensitivity analysis of displacement for static and dynamic analysis.

Table 1 Material properties

water			Concrete		
Kinematics viscosity (m^2/s)	Specific mass (kg/m^3)	Bulk modulus (N/m^2)	Poison ratio	Specific mass (kg/m^3)	Modulus of Elasticity (N/m^2)
0.005	1000	2.2e9	0.27	2400	2e10

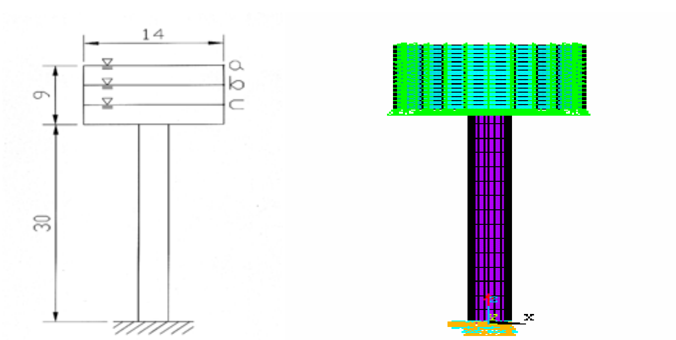

Figure 1 Finite element model of elevated water tanks.

Table 2 Geometric characteristic of tank

Reservoir of tank			shaft			Number of elements		Number of nodes	
thickness of wall (m)	diameter of wall (m)	height of wall	thickness of wall	diameter of wall	height of wall	Fluid	tank	Fluid	tank
0.3	14	9	0.5	3	30	3135	929	25080	3716

3. STATIC RESULT AND DISCUSSION

In order to study of modeling proportion, displacement and hydrostatic pressure are compared by using of theoretical and finite element methods. Eqn.3 and Eqn.4 are used to calculate the result of fluid weight as shown in Figure .2.

To compare of this result with finite element one, the wall of tank are assumed to be rigid. The results are shown in Figures 3 and 4, which show a relatively compatibility between numerical and theoretical methods.

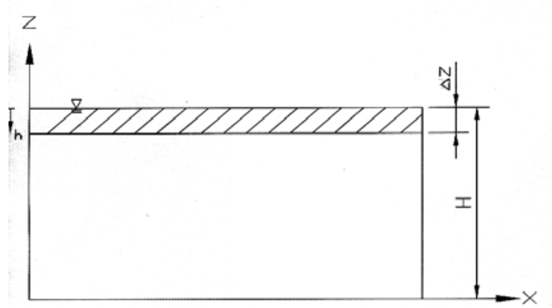

Figure 2 Tank with water

$$U_z = \frac{1}{k}\int_H^h \gamma z dz = \frac{\gamma}{k}\left[\frac{z^2}{2}\right]_H^h = \frac{-\rho g}{2k}\left[H^2 - h^2\right] \quad (3.1)$$

$$P = \gamma h \quad (3.2)$$

where K is the bulk modulus, γ, ρ are specific weight and specific mass, P is the hydrostatic pressure in depth of h from free surface, u_z is the displacement in Z-direction and g is the gravity acceleration.

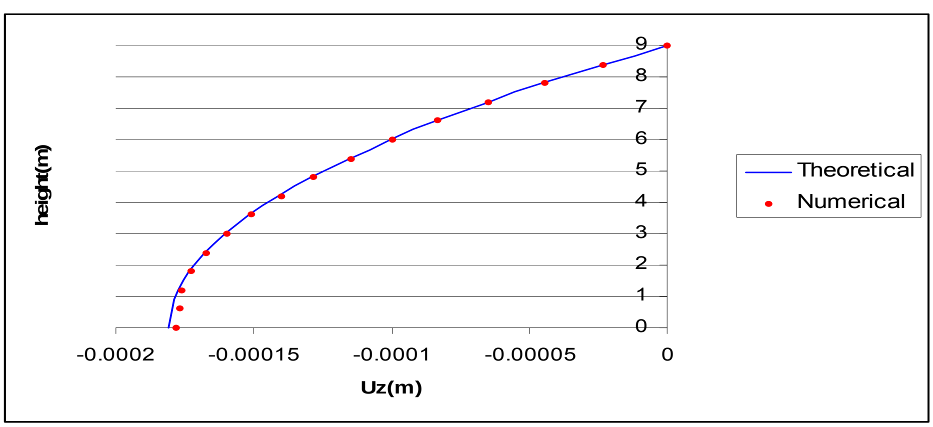

Figure3 Displacement variation along the height of water for theoretical and numerical methods

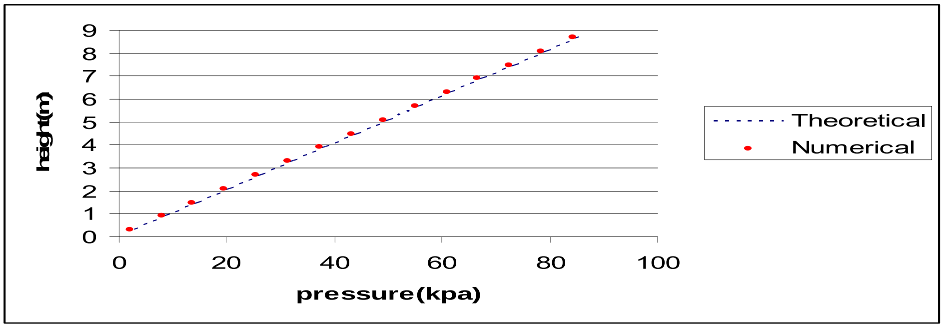

Figure4 Hydrostatic pressure variation along the height of water from theoretical and numerical methods

4. PERIOD AND DAMPING COFFICIENTS IN SOFTWARE

By solving eigen-value Eqn.5 for tank with different elevation of water (Empty, $\frac{1}{3}$ Full, $\frac{2}{3}$ Full, Full), the natural periods of system are obtained. A summary of the calculation results is listed in Table 3. While the mode shapes are shown in Figure.5.

$$[k][\phi] = [M][\phi][\Omega^2] \qquad (4.1)$$

where *[k]*, *[M]* are stiffness and Global mass matrices. And $[\phi]$ is the eigen-vector.

Table 3 periods of system with different elevation of water

Mode number	Period (sec)			
	Empty	$\frac{1}{3}$ Full	$\frac{2}{3}$ Full	Full
1	1.608	2.42	2.95	3.175
2	1.608	2.42	2.95	3.175
3	0.626	0.669	0.67	0.466
4	0.626	0.669	0.67	0.2
5	0.491	0.491	0.49	0.2
6	0.336	0.36	0.48	0.05

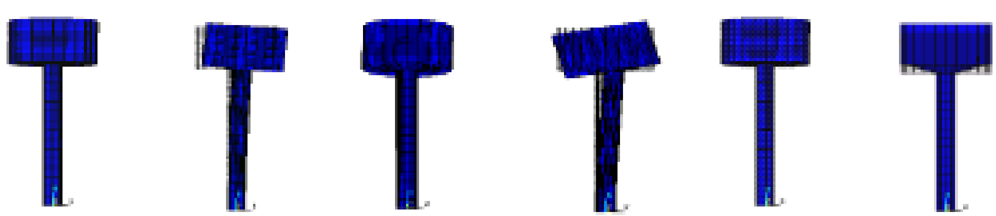

Figure5 Mode shapes (left to right)

Eqn.6 are used to obtaining damping matrix related to dynamic analysis, which α and β are obtained by using of Eqn.7 and Eqn.8 with this assumption that damping ratio is considered 0.05 for tow first modes. These results are summarized in Table.4

$$[c] = \alpha[M] + \beta[k] \tag{4.2}$$

$$\beta = \frac{2(\xi_i w_i - \xi_j w_j)}{(w_i^2 - w_j^2)} \tag{4.3}$$

$$\alpha + \beta w_i^2 = 2 w_i \xi_i \tag{4.4}$$

Where α, β are coefficients related to mass and stiffness matrices w_i, w_j are periods of i and j modes. ξ_i, ξ_j are damping ratio of i and j nodes.

Table.4 Data for α and β with $(\xi = 0.05)$

water elevation	Empty	$\frac{1}{3}$ Full	$\frac{2}{3}$ Full	Full
α	0.281	0.203	0.177	0.152
β	0.0072	0.0086	0.009	0.0093

5. PERIOD OF SYSTEM RELATED TO IRANIAN CODE/2800

In Iranian code/2800, elevated water tanks are modeled with lumped mass in the end of slender cantilever. These results are summarized in Table.5.

Table 5 periods of elevated water tank by using of Iranian code/2800 relations.

Empty	$\frac{1}{3}$ Full	$\frac{2}{3}$ Full	Full
1.25	1.75	2.138	2.466

From Table.5, It is observed that periods calculated by Iranian code/2800 for elevated storage tank are less than those by using of finite element method.

6. RESULT OF HARMONIC ANALYSIS

To study the behavior of structure subjected to seismic loads, these forces must be known in first step. Because the acceleration of ground motion is arbitrary and containing of different frequencies, can not observe the behavior of structure subjected to seismic excitations in terms of specific parameters such as period, vibration amplitude and etc. but these acceleration are capable to be converted harmonic functions by using of Fourier Integration. With this method we can study behavior of structure subjected to harmonic excitation and effect of different parameters instead of earthquake excitation. In this investigation the harmonic analysis are done for tank with different elevation of water and result are represented for an elevation for example $\frac{1}{3}$ full.

6.1. Harmonic analysis with variation of excitation period

Figure.6 presents a variation of base shear force due to sinusoidal excitation of the tank in X-direction (Eqn.9). The amplitude of the excitation is 0.3 m/s with varying period and the period of excitation is variety.

$$a_x = 0.3g \ \sin(\frac{2\pi}{T})t \tag{6.1}$$

From these result, it is observed that structure responses are not increase with period increasing some times.

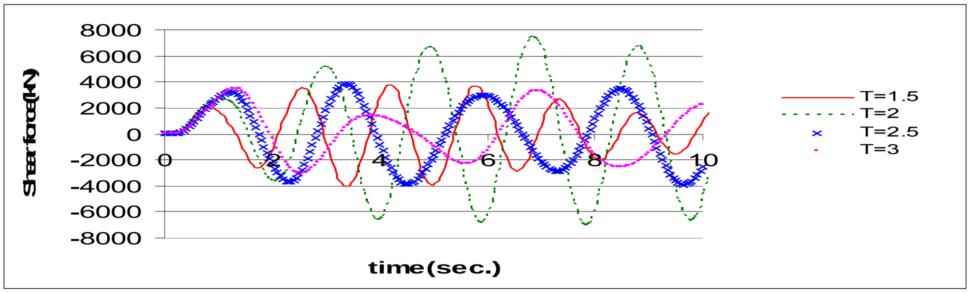

Figure 6 Shear force response due to harmonic base excitation with varying period for an elevation ($\frac{1}{3}$*Full*)

6.2. Harmonic analysis for X-Y-Z direction acceleration

To study the effect of ground excitation components on the structure response, a cylindrical tank is analyzed under X-direction, X-Y direction and X-Y-Z direction of sinusoidal acceleration (Eqn.9) and results showed that effects of vertical component of earthquake acceleration on the base shear force response are very small and maximum value of them in this analysis is 0.1 percent and effects of them are neglected in calculating at this time.

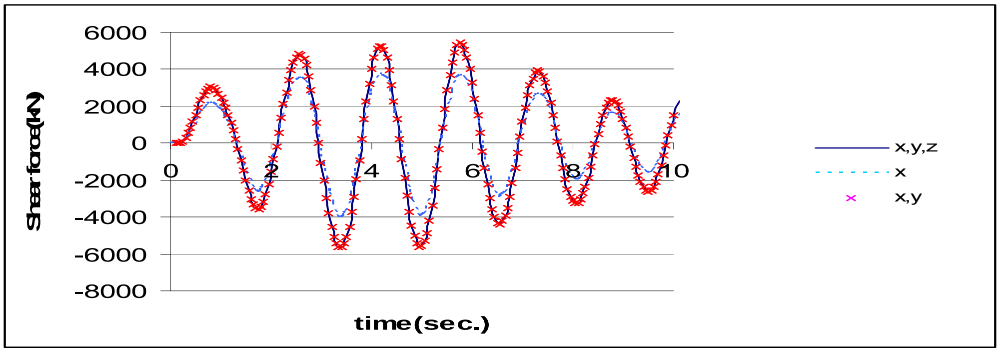

Figure7 Base shear force response due to X, X-Y and X-Y-Z direction for an elevation ($\frac{1}{3}$ Full)

7. RESULT OF DYNAMIC, PSEUDO STATIC AND PSEUDO DYNAMIC ANALYSIS

In this investigation by using of seismic characteristic of available accelerogram, velocity of shear wave in soil condition of accelerogram site and compatibility between it and soil condition of structure, distance of accelerogram with fault and also accelerogram frequency content, is used from three couple accelerogram concerned about Tabas, Manjil and Northridge earthquakes. These accelerogram are scaled to 0.26g by using of Iranian code/2800 suggestion so that peak ground acceleration (PGA) in these accelerogram becomes 0.26g.

7.1. Result of dynamic analysis

In this section by using of scaled accelerogram, Dynamic analysis are performed on a storage tank for longitudinal component of earthquake one time and for both components of earthquake in the form of 100 percent of longitudinal component and 30 percent of lateral component following of Iranian code/2800 suggestion another time. A summary of these results is listed in Table.6.

In some cases, effects of vertical component are also considered. Results show that this component is not effective on the response accurate, so it is negligible.

Table 6 Base shear force of storage tank for Tabas, Manjil and Northridge earthquakes

Tank	Longitudinal Component			%100 Longitudinal+%30 Lateral Component		
	Northridge	Manjil	Tabas	Northridge	Manjil	Tabas
Empty	449	1508	1519	479	1528	1550
$\frac{1}{3}$ Full	403	1351	1394	427	1376	1495
$\frac{2}{3}$ Full	412	876	1475	422	1306	1500
Full	389	1120	1639	489	1247	1690

From obtained result for each accelerogram. It is observed that lateral component of earthquake have not important effect on structure response. This problem are resulted primary from this fact that lateral peak ground acceleration is 30 percent of longitudinal peak ground acceleration and secondary storage tank is symmetric in tow normal direction. Also the comparing of obtained results from different accelerogram demonstrated that effect of frequency content on structure response is important.
In order to comparing the effect of frequency content on structure response, base shear force time history and maximum displacement of structure for these three earthquakes are obtained for different elevation of water and for example result of elevation $\frac{1}{3}$ Full with period, T=2.42sec, are demonstrated in Figure.8 and 9.
This difference is described by frequency content of Tabas, Manjil and Northridge earthquake accelerogram.

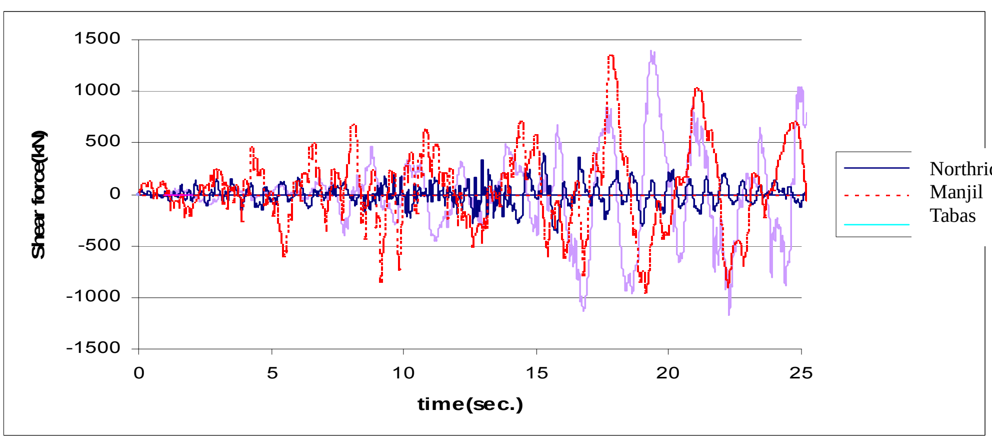

Figure 8 Base shear force time history for Tabas, Manjil and Northridge earthquakes for elevation $\frac{1}{3}$ Full

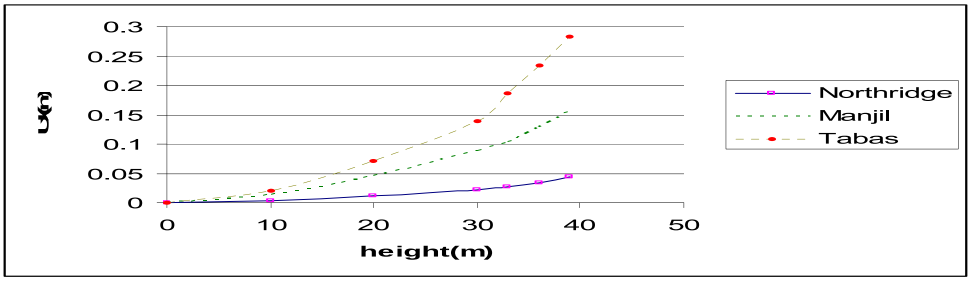

Figure 9 Maximum horizontal displacement of tank along height for elevation $\frac{1}{3}$ Full

7.2. Result of pseudo static analysis

In this section base shear force is calculated by using of pseudo static analysis and Iranian code/2800 relations , Eqn.9 and Eqn.10, and a summery of the calculation results is listed in Table. 7.

$$C = \frac{ABI}{R} \tag{7.1}$$

$$V = C * W \tag{7.2}$$

where W, V, C are Structure Weight, base shear force and earthquake coefficient respectively. Parameters concerned about C, in Eqn.9, are listed at bellow.
I is this Importance coefficient of structure and for water storage tank is equivalent 1.4, R is response modification factor of tank that by following of Iranian code/2800 is considered 3, A is the base design acceleration and by this assumption that soil type is III, is considered 0.3 following Iranian code/2800, B is the structure reflection coefficient that is obtained by using of soil condition and design spectrum.
By comparing the results from Tables 6 and 7, it is observed that results of pseudo static analysis for base shear is much higher than those of dynamic analysis in all cases.

Table 7 result of pseudo static analysis

Tank	Period (T) (sec)	B	I	R	C	W (kN)	V (kN)
Empty	1.25	1.868	1.4	3	0.261	7211	1882
$\frac{1}{3}$ Full	1.75	1.493	1.4	3	0.209	11742	2454
$\frac{2}{3}$ Full	2.138	1.306	1.4	3	0.183	16272	2977
Full	2.466	1.188	1.4	3	0.166	20803	3453

7.3. Result of pseudo dynamic analysis of water storage tank

By using of Iranian code/2800, pseudo dynamic analysis of structure can be used for structure analysis. A summary of results is listed in Table.8 based on pseudo dynamic analysis for period higher than 0.4sec according to the Iranian code/2800.From this table, it is observed that results in pseudo dynamic analysis are much higher than those in pseudo static and dynamic analysis.

Table 8 result of pseudo dynamic analysis by using of Iranian spectrum

Tank	Shear Force (kN)					
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	CQC
Empty	1140	1140	956	956	8.7	2107
$\frac{1}{3}$ Full	1600	1600	2680	2680	399	4412
$\frac{2}{3}$ Full	2050	2050	2750	2750	4030	7100
Full	2620	2620	118	-	-	3714

8. CONCLUSIONS

From analytical results of cylindrical elevated water storage tank with central shaft and considering linear behavior of material subjected to different harmonic and earthquake excitation, it was concluded that:

1. The base shear force resulted of structure in pseudo static analysis according to the Iranian code/2800 for Empty tank is four times and for tank with water is seven times as much as those from linear dynamic analysis that these difference are resulted from response modification factor, R.
2. Vibration periods according to the Iranian code/2800 are less than those from dynamic analysis with finite element method that these differences in this investigation reach to 27 percent for empty tank, 22 percent for tank with $\frac{1}{3}$ water, 22 percent for tank with $\frac{2}{3}$ water and 27 percent for Full tank.
3. From analysis results for three earthquakes, Tabas, Manjil and Northridge, It is observed that base shear force and maximum displacement are sharply dependent on frequency content of earthquake accelerogram and major difference between static and dynamic analysis is resulted from this problem.
4. Base shear force in pseudo dynamic analysis is much higher than that in static analysis. So that it is more than the result of dynamic analysis surely.
5. The effect of vertical component of three accelerograms for base shear force and maximum displacement of storage tank was not significant and we can neglect it in calculation.

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