SHAKE TABLE TESTS ON THE STEEL FLUİD STORAGE TANK MODELS

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ABSTRACT

Dynamic behaviors of storage tanks under seismic loads are generally complex, which has been studied by many researchers. This issue was first introduced by Housner for cylindrical rigid Tanks. He assumed that the answer to Seismic rigid containers is divided into two impulsive and convective components. Impulsive pressure according to the coordinated movement is part of the generated rigid tanks walls. Convective pressure is also the other part of created fluid at the free surface of the tank contents. In this paper, dynamic behavior of steel cylindrical tank model withdiameter of 1.2 meter and height of 1.25 meters and with fixed roof condition have been tested on the international institute of Earthquake Engineering and Seismology (IIEES) shaking table.In this research, experimental tank model with three different level of liquid height subjected to three different earthquake records.Experimental results including frequency contents, damping values, and sloshing amplitudes have been compared with API650-2008 and ASCE regulations.

INTRODUCTION

Cylindrical steel tanks are the most commonly used Structures in Refineries, Petrochemical facilities, Oil warehouse's , Industrial factory's etc. Past earthquakes indicate extreme vulnerability of these kinds of Tanks. The dynamical Behavior of the tanks was first modeled by Housner which has been the basis of the regulations. He showed the free surface of a liquid tank when subjected to dynamic lateral acceleration, that the Fluid has two effects through the walls which includes; 1) impulsive pressure 2) convective pressure. The convective Pressure appears at the top of the tank because of the Sloshing and the impulsive pressure appears at the bottom of the tank and the fluid motion is created to coordinate with the walls. In fact, the frequency of the Sloshing is significantly lower than the frequency of the impulsive motion; this means that these modes can be amplify in specific frequency conent of an earthquake. (ASCE,2003)

Alaska earthquake in 1964 imported intense damages to the fluid tanks. The result of this earthquake indicated that the flexibility of the tank walls was one of the main reason extensive tank damages. Therefore,Housner, G, W, (1954), Housner, G,W, (1957a), Housner, G,W, (1957b) and Haroun, M, A. (1980), Haroun, M, A, and Housner, G,W, (1982a), Haroun, M, A, and Housner, G,W, (1982b), and other researchers started to extensive investigations and analyzing the interaction of fluid and structure issues using numerical and experimental methods Based on these investigations, a simplified model was presented to indicate the effects of flexibility of the tank walls. The results of extensive investigation regarding seismic behavior and seismic design of fluid tank presented in the API standard 650 (2008), and ASCE regulations (2003).

In this paper, dynamic behavior of a steel cylindrical tank model with fixed roof condition have been tested on the International Institute of Earthquake Engineering and Seismology (IIEES) shaking table. Due to the experimental limitations, including the size of the shaking table and the capacity of the hydraulic system it is necessary to use scaled models for the experimental test of the desired tank. By considering all the constraints, the geometric scale factor λ_L=16 is intended for the tank model and finally the diameter of 1.2m and higher of 1.25 meters is considered for the test model.

PREVIOUS STUDIES ON THE SEISMIC PERFORMANCE OF TANKS

Whenever a liquid is in a state of stasis the Hydrostatic pressure of the liquid at each point of the liquid volume equals the weight of the liquid column above that point. Therefor the pressure created on the walls linearly distributed with the height and the bottom of the tank has a higher amount of pressure value on it. Also, the hydrostatic pressure exerted on the bottom of the tank is constant. In situation where the tank is subjected under strong ground motion, the liquid inside the tank behave differently.

Therefore, the changing of fluid pressure on the walls and floor of the tank is nonlinear and hydrodynamic in any moment.

Hydrodynamic pressure distributed on the floor and walls of the tank cause damage or collapse of the tank roof which can cause extensive surrounding pollution. Therefore, horizontal forces generated from an earthquake on the tank itself and on the fluid inside. The mass of the convective and impulsive modes creates such damages and losses.

Fluid wave (sloshing) is a phenomenon that the movement of the liquid on a free surface in the tank is under the effect of vibration. Recognition of this phenomenon is really important in designing a tank. Strongsloshinggeneratesbig forces to the ceiling and walls of the tank and it can cause serious damage to them. Initial estimates of the phenomenon of sloshing have been done with very low tilt.

Jacobsen (1949) discovered the Hydrodynamic pressure exerted on cylindrical tanks. The most practical and most ideal to estimate the response of fluid rectangular or cylindrical tank under seismic stimulation was presented by Haousner (1954 a,b). He divided the hydrodynamic pressure in tank into two categories including: 1) impulsive mode of pressure from the vibration of some parts of the fluid along with the body of the tank and 2) convective pressure caused by the sloshing part of the fluid. Sloshing fluid component is modeled by a single free degree oscillator. The Specifications of this mechanical model is calculated by the geometry of the tank and the fluid properties inside it. To obtain maximum response of the tanks from the spectrum design Housner(1957 a,b) model have extensively been used. In this model, the tank's wall has been assumed rigid and therefore the acceleration is equal to accelerated stimulation moves, but, in a real tank with flexible walls, Acceleration exerted on the rigid part of the fluid could be more, equal or less than the stimulation accelerated. As a result the hydrodynamic pressure obtained from this mode is a movement towards assumption of the difference of rigid wall.

The first computer analysis of the tanks with fluid content using finite element method was performed by Edwards (1969). This analysis was conducted on a cylindrical tank containing a fluid with controlled height ratio less than one. In this analysis the interaction of the fluid and the elastic walls of the tank shell were considered.

The Tanks have been considered as linear elastic and totally anchored in the researches. Therefore the fluid inside the tanks are formed as an ideal homogeneous incompressible and the fluid motion are considered as non-rotational excitation force.

PLANNING A TEST FOR TANK ON A SHAKING TABLE

GEOMETRIC AND MECHANICAL PROPERTIES

Scale models can be used to simulate complex systems such as fluid storage tanks and they can be beneficial to understanding the main mechanisms of their performance under controlled conditions. Scaled models are very economical compared to the actual scale samples in many static and dynamical experiments. In addition the scaled model experiment results often serve as basis of calibration for analytical methods or evaluating the quality of experimental data that are scattered and incomplete also used to complete answers for real examples.

Due to experimental limitations, including the size of the shaking table and the capacity of the hydraulic jack it is necessary to use scaled models for the experiment of the desired tank. But providing all scaled geometrical and mechanical conditions is not possible for various reasons. For example, the wall thickness of the tank cannot be chosen smaller than a certain size due to welding problems and lateral instability. Furthermore, no other liquid can be used due to the high volume of fluid tank because it would be expensive. Therefore, considering all the constraints the geometric scale factor($\lambda_L=16$) is intended for the height and diameter of the tank.

Vibrational frequency of the model is one of the basic parameters for scaling. Tank Natural period of sloshing mode and impulsive mode are obtained in order from the relations 1 and 3. These relationships indicate that the use of similar materials, for both pulsatile walls and sloshing mode is not proportional to the geometric scale factor. Therefore, the equivalence between actual mode and scale model is not possible by geometric scaling. In fact, this goal can be achieved by taking variable modulus of elasticity of the walls of the tank or the fluid density. However in the model of study, it is considered that only the frequency of the convective mode is proportional to the geometric scale factor. Regarding the rest of the parameters it has been assumed that the dynamical model in condition of acceleration 1g and with the density is constant. The built scaling model for experiment is shown in Table 1.

$$T_c = 1.8\, K_s \sqrt{D} \tag{1}$$

In which K_s is a coefficient that is obtained from equation 2.

$$K_s = \frac{0.578}{\sqrt{Tanh(\frac{3.68H}{D})}} \tag{2}$$

$$T_i = \frac{1}{\sqrt{2000}} \frac{C_i H \frac{\sqrt{\rho}}{\sqrt{E}}}{\sqrt{\frac{t_u}{D}}} \tag{3}$$

Which in the above equations, D diameter of the tank in terms of meters, H the height of the fluid in terms of meters, C_i pulse in terms of the ratio to $\frac{H}{D}$ coefficients for the specified period mode, E the modulus of elasticity of the tank walls by MPa, ρ fluid density in terms of $\frac{kg}{m^{۳}}$ and t_u the tank wall thickness is in terms of millimeters.

Table 1.Scaled Geometric and mechanical Specifications of a tank

ROW	VALUE	PARAMETER	DESCRIPTION OF PARAMETERS
1	1.2	D	TANK DIAMETER (m)
2	2	T_U	TANK WALL THIKNESS (mm)
3	10	B	THIKNESS OF THE FLOOR COVER(mm)
4	1.25	H_W	HEIGHT OF TANK WALL, (m)
5	0.6,0.8,1	H	HEIGHT OF THE FLUID FILLING (m)
6	1000	P	FLUID DENSITY($\frac{kg}{m^{۳}}$)
7	1131,905,678	M	MASS FLOW (Kg)
8	210000	E	STORAGE MODULUS OF ELASTICITY(MPA)

PREPARATION OF LABORATORY MODELS AND SHAKING TABLE

Three different tank models with fluid heights of 60, 80 and 100 cm was chosen for experimental tests (Figure 1). The structural system of the tank is assumed to be anchored. The objective of dynamic experiments is evaluating the tank models response subjected to different earthquakes records.

Figure 1. A view of the installation of tank model on the shaking table

Therefore, between the registration records of past earthquakes, the horizontal component of 3 earthquakes longitudinal was chosen for the shaking table test, includes:Elcentro USA, Irpinia Italy, and Tabas Iranrecords. Characteristics of these earthquakes are presented in Table 2. The Maximum horizontal acceleration (PGA) of these earthquakes is scaled to 0.4g. The earthquake acceleration response spectrum for 5% damping is shown in Figure 2. It is worth noting that due to the geometric scale factor of the tank (λ_L=16) coefficient time scale for the scaled tank is considered (λ_t=4).

Table 2. Characteristics of earthquakes used in dynamic testing

Earthquake	Magnitude	PGA(g)	Duration of earthquake (seconds)
Tabas،Iran،1978	7.4	0.852	32.78
Elcentro,USA 1940	7.2	0.31881	16.31
Irpinia ،Italy،1980	6.5	0.313	40

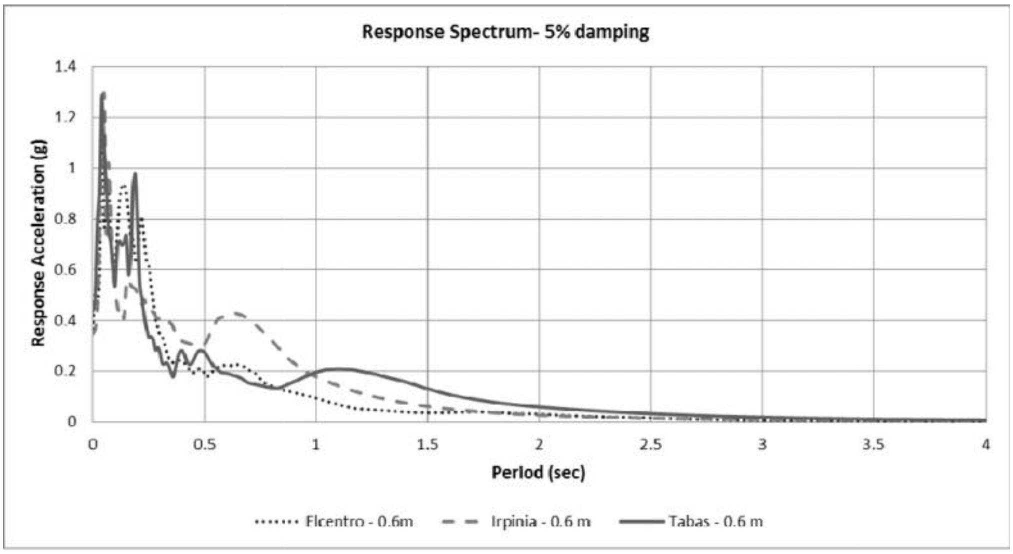

Figure 2.response spectra of Tabas, elcentro and irpinia earthquakes for 5% damping coordinated to 0.4g

Vibration recorder of DMCPLUS with 8 channels was used which 4 channel were devoted to accelerometer, 2 channels were devoted to displacement gauge and 2 channels to the strain gauge. To obtain a sloshing, visual screening was used by A Digital Camcorder with HD quality. Sample results of the sensors and the camcorder that records the vibrations are shown in Figures 3 and 4.It is worth noting that two of the accelerometers have been placed vertically on the shaking table and they have been placed on the two sides of the tank so that the unwanted vertical vibrations of the table can be examined.

Figure 3. The position of the digital camcorder to capture the sloshing

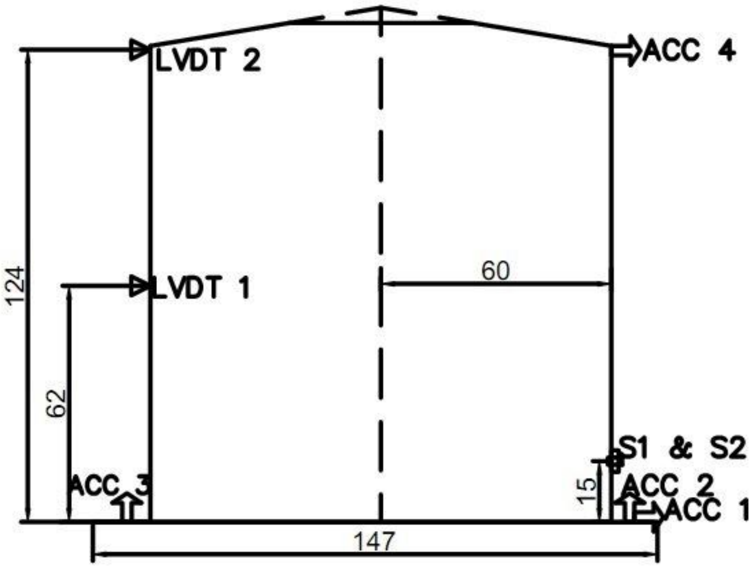

Figure 4. location of the data vector for the tank Dynamic test on the shaking table.

VIBRATION CHARACTERISTICS OF STUDIED TANK

Before assessing the effects of seismic in the testing tank, will discuss the dynamic features of the tank including frequency and damping of the various modes of the original vibration. To determine the vibrational impulsive frequency of the walls, the Fourier spectrum of acceleration recorded at the top and bottom of the tank and its transfer function is used. The wall damping ratio can be achieved by using half-power bandwidth. The results of all tests of information processing impulsive frequency response are presented in Table 3.

Table3. Results of pulse-mode frequency and damping for the various models of the tank tests on shaking table

fluid height(cm**)**	earthquake	main impulsive frequency(Hz**)**	damping ratio (%ζ)
60	tabas	108	1.11
	elcentro	101.5	1.18
80	Tabas	103.55	1.11
	elcentro	103.2	1.07
100	tabas	103.4	1.06
	elcentro	104.2	1.15

To obtain the vibrational mode frequencies of the fluid, the Sloshing Fourier spectrum results are used in both forced and free vibration mode. Vibrations recorded during the earthquake indicate forced vibration and the fluid vibration after the earthquake records are considered as free vibration. Vibration frequencies of the convective fluid tank modes are presented in Table 4.In this table, the results obtained from the forced and free vibrations is presented for comparison.

Table 4.Results of frequency and damping of the tested tank in convective mode.

Earthquake		Experimental		Analytical	
		Convective Frequency – Force Vibration(Hz)	Convective Frequency – Free Vibration(Hz)	Convective Frequency – Force Vibration(Hz)	Convective Frequency – Free Vibration(Hz)
60	tabas	0.8202961	0.84373	0.84313	0.80647
	elcentro	0.843731	0.84373	0.84313	0.84313
	irpinia	0.84373	0.84373	0.84313	0.84313
80	tabas	0.84373	0.84373	0.84313	0.87979
	elcentro	0.86717	0.84373	0.84313	0.84313
	irpinia	0.86717	0.84373	0.86146	0.84313
100	tabas	0.84373	0.84373	0.84313	0.87979
	elcentro	0.86717	0.89061	0.86146	0.84313
	irpinia	0.86717	0.84373	0.86146	0.84313

THE MAXIMUM HEIGHT OF WITH FLUID SLOSHING

The maximum height of the sloshing in the following tank under Tabas Earthquake at heights of 60, 80 and 100 cm are equal to 23.2, 24.3, and is 23 cm. Similar values are obtained from the analytical modeling results which is equal to 19.173, 815.87and 18.97. Based on API 650 regulations the maximum height of sloshing can obtain from equation 4:

$$\delta_s = 0.5 \times D \times A_f \tag{4}$$

Which in this regard: D the nominal diameter of tank (inner diameter cylindrical tank); andA_f acceleration coefficient to calculate the height of the sloshing. A summary of the results obtained from the model of sloshing height, Lab model, analytical model and relatingAPI650 regulations are compared in Table 5.It is worth noting that in this study the regulation based on spectrum ASCE design regulations are different from the result of the earthquakes range. The results presented in this table show that the experimental values are generally higher than the analytical values and the values of the regulations.

Table 5. Comparison of sloshing height in the tank and compared with results obtained from experimental model and API650 regulations.

Fluid height(cm)	earthquake	maximum sloshing height(cm)	
		Experimental	API650
60	Tabas	23.2	12.51
	Elcentro	8	
	Irpinia	10.2	
80	Tabas	24.3	12.74
	Elcentro	4.85	
	Irpinia	11.5	
100	Tabas	23	12.80
	Elcentro	5	
	Irpinia	11.5	

CONVECTIVE MODE DAMPING

To determine the convective mode damping of the free vibration fluid, the logarithmic decrement method (Logarithmic Decay) is used. Vibrations recorded after the earthquake is considered as the region of free vibration,as previously noted.The damping rate of convective mode is negligible therefore after the end of the earthquakes the free vibrations continues. However, the area that is studied in this research is free vibrations immediately after the end of the earthquake. The results of convective mode damping obtained from experimentaltests are summarized in the Table 6.

Table 6.Convective mode damping of the tested tank.

Fluid height(cm)	earthquake	Convective mode damping ratio (%)
		experimental
60	tabas	
	elcentro	0.4
	irpinia	0.5
80	tabas	0.3
	elcentro	0.4
	irpinia	0.3
100	tabas	0.5
	elcentro	-----
	irpinia	0.4

According to API650 Regulations damping value of the 0.5%is considered for convective mode. Therefore, the experimentalresults are generally below of the code recommendation.

CONCLUSIONS

By examining frequency values and damping values of impulsive modes and convective modes and also check the height of the sloshing of the tested tank model on the shaking table subjected to various earthquakes and comparing test results with values of API650 regulations the follow concluding remakes have been obtained:

1. Convective and impulsive frequencies of the tested tank obtained from experimental results are in good agreement with the results of API650 regulation. This agreement in the convective mode is more than in the impulsive mode.
2. Experimental damping values for the convective modes are in the range of 0.3% to 0.5%. This value according to the API650 regulations is 0.5%. Therefore, experimental results indicate lower values between 10%to 20% percent.
3. The maximum height of the fluid sloshing in the tank subjected to the Tabas earthquake is about 2 times the API650 regulations. Therefore more investigation of code requirements it necessary.

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