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Shake Table Study of Impulsive and Convective Damping Coefficients for Steel Cylindrical Tanks and Comparison with API 650

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ABSTRACT

Dynamic behavior of Tanks under seismic loads is generally nonlinear and has been widely studied by numerous researchers. This was first introduced by Jacobsen and after that, the new method was introduced by Housner for the rigid cylindrical tanks. Fluid vibration induces hydrodynamic pressure on the wall and hence, Housner assumed and classified the seismic response of the rigid tanks into two impulsive and convective components. The Impulsive pressure is caused by the coordinated motions of a fluid part in the tank with the rigid wall of the tank, and the convective pressure is caused by the motion of the other part of the fluid on the tank's free surface. In this paper, a cylindrical steel tank model with a diameter of 120 cm, wall height of 125 cm and fluid depths of 60, 80, 100 and 120 cm has been tested under Tabas, El Centro and Irpinia Earthquakes on the shaking table in the International Institute of Earthquake Engineering and Seismology. The purpose of the experiments was to determine the damping of the impulsive and convective modes of the mentioned tank and to compare the experimental results with the proposed values by API650 Code.

Keywords:
Steel tanks; Seismic stimulation; Convective mode; Impulsive mode; Damping

1. Introduction

Storage tanks in refineries and petrochemical plants contain large volumes of flammable and hazardous liquids. A small accident may lead to million-dollar property loss and a few days of production interruption [1]. Regarding the importance of these systems, especially their seismic safety for avoiding the adverse consequences such as fires, explosions and environmental pollution, better understanding of their seismic behavior still seems necessary. In this research, the tank shell assumed to be rigid and only the dynamic response of the tank's liquid content is highlighted. After some strong earthquakes in the United States and Japan (Niigata, 1964; Alaska, 1964; and Parkfield, 1966), which caused heavy damage to liquid storage tanks, the rigid tank concept could not be retained for the modeling of tanks since real tanks deform significantly under earthquake loads. Numerous analytical and numerical studies have been conducted, focusing on the interaction between a flexible wall and a liquid. An analytical approach to the analysis of flexible containers was developed by Veletsos [2]. He presented a simple procedure for evaluating hydrodynamic forces induced in flexible liquid-filled tanks. The tank was assumed to behave as a single degree of freedom system, to vibrate according to a prescribed mode, and to remain circular during vibrations. Later, Veletsos and Yang [3] estimated the maximum base overturning moment induced by a horizontal motion by modifying Housner's model to consider the first cantilever mode of the tank. The first numerical analysis was completed by Edwards [4]. He employed the finite element method and a refined shell theory to predict seismic stresses and displacements in a vertical cylindrical tank. This investigation treated the coupled interaction between the elastic wall of the tank and its liquid content. Fenves et al. [5] used a mixed displacement-fluid pressure formulation for the liquid. The finite element method is a powerful numerical technique for analyzing liquid storage tanks. However, this method requires a lot of computer storage space because a liquid region must be subdivided into a large number of meshes, and such a tendency becomes more marked in 3-D problems.

A mechanical model [6-7], which takes into account the deformability of the tank wall, was derived and was widely applied because the previous models were either too complicated to be used in the design or too simple to yield accurate results. The finite element method combined with the boundary element method was used by several investigators. Hwang et al. [8], Lay [9], and Kim et al. [10] employed the boundary element method to determine the hydrodynamic pressures associated with small-amplitude excitations and negligible surface wave effects in the liquid domain. Czygan and Estorff [11] and Cho et al. [12] concentrated on the coupling of the finite elements used to model the structure and the boundary elements that represented the fluid [13].

In last decades, trade organizations and engineering societies such as the American Petroleum Institute (API), American Institute of Chemical Engineers (AICHE), American Society of Mechanical Engineers (ASME), and National Fire Protection Association (NFPA) have published strict engineering guidelines and standards for construction, material selection, seismic design and safe management of storage tanks and their accessories. Most companies follow these standards and guidelines in design, construction and operation, but tank accidents still occur [14].

Several damages to industrial facilities happened due to strong earthquakes in Iran (Bam, 2003; Silakhor, 2006) including steel storage tanks, etc. [14-15]. Therefore, engineering and construction departments of the oil ministry of Iran decided to adjust seismic design requirements for structural systems and facilities. Then, the seismic hazard zones of Iran have been used to develop code requirements to utilize in future industrial facilities.

Fluid mass inside the tank can be divided into a rigid fluid mass and a convective fluid mass for ease of analysis. The rigid fluid mass is the part of the fluid that is supposed to move with the tank structure. Convective fluid mass is the part of the fluid that causes a wave motion in the upper part. In most cases, the major part of the base shear and overturning moment is caused by the rigid fluid. Free surface motion of the fluid in the tank is determined using the convective fluid mass properties [16].

Housner investigated the fluid dynamic effects in both rigid cylindrical and rectangular tanks under horizontal earthquake motion in 1957 by using a model shown in Figure (1). He classified the hydrodynamic pressure into impulsive and convective parts. Impulsive pressure is generated by the coordinated motion of the fluid and the rigid wall of the tank. Convective pressure is generated from the part of the fluid located at the free surface. Impulsive pressure effect is modeled as a fraction of the total fluid mass (M_0) at H_0 height that is connected to the tank's wall rigidly. The effect of convective pressure is also modeled as a fraction of the total mass (M_1) at H_1 height using springs to have a stiffness of $K/2$ attached to the tank wall. Thus an equivalent two-mass mechanical model will be obtained [17].

API650 American Regulations [18] and Guidelines for Seismic Evaluation of Oil Industry Facilities (Pub. No 041-11) have used Houser's mechanical model. In Guidelines for Seismic Evaluation of Oil Industry Facilities (Pub. No 041-11), a damping value

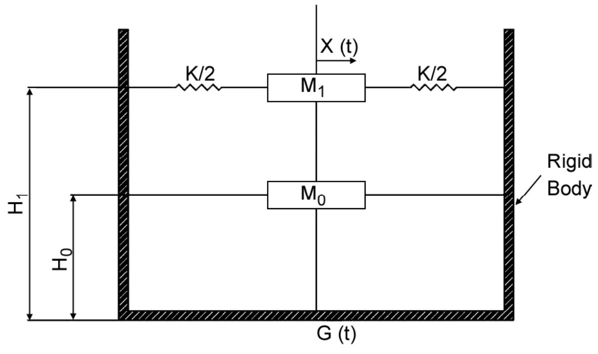

Figure 1. Equivalent mechanical model by Housner [3].

of 5% is used for the rigid fluid (impulsive mode) and tank structure, and a damping value of 0.5% is used for the convective fluid (convective mode) [19].

2. Experimental Setup

2.1. Model Characteristics

To determine damping of the impulsive and convective modes of the tank, an actual tank with a height of 20 m and a diameter of 19.2 m was considered as an example of typical existing tanks, for which a 1/16 scaled model was tested on the shaking table of the International Institute of Earthquake Engineering and Seismology. Due to experimental limitations, including shaking table dimensions and the hydraulic actuator capacity, scaled tank model was considered using a geometric scale factor of 16 with 125 cm height and 120 cm diameter. Due to operational conditions and the available materials, tank wall thickness of 2 mm was considered. The geometry of the tank with a cone-shaped roof with a slope of 1:6 and thickness of 2 mm is shown in Figure (2).

2.2. Selected Input Earthquakes for Dynamic Tests

The long-duration earthquakes were assumed to occur in soil type II of 2800 Standard. Based on this assumption, three earthquakes were selected as input for the shaking table test from the recorded earthquakes that exist in the Earthquake Engineering Research site (PEER), as shown in Table (1) [20].

Table 1. Characteristic of input earthquakes.

Earthquake Name	Location	Magnitude	PGA
Elcentro - 1940	USA	7.2	0.319 g
Irpinia - 1980	Italy	7.5	0.2898 g
Tabas - 1981	Iran	7.5	0.8128 g

Acceleration histories of the three earthquakes are shown in Figure (3). Three earthquakes were scaled to a maximum equivalent acceleration of $PGA = 0.40$ g.

Vibrations were recorded with a time interval of 0.02 second for Tabas and El Centro earthquakes and 0.0024 second for Irpinia earthquake. Considering the equivalent time scale factor, time intervals of the earthquakes were reduced into 0.005 and 0.0006 seconds, respectively.

2.3. Extracting Data from Experiments

A horizontal accelerometer to evaluate the input records (ACC 1), and a horizontal accelerometer to extract the tank response (ACC 4) were installed on the wall as shown in Figure (4).

To obtain the fluid turbulence, cameras with HD quality were used. A view of the installed camera for filming is shown in Figure (5). After filming the fluid sloshing amplitude, data were taken frame by frame from videos, and fluid turbulence amplitude was converted to digital form.

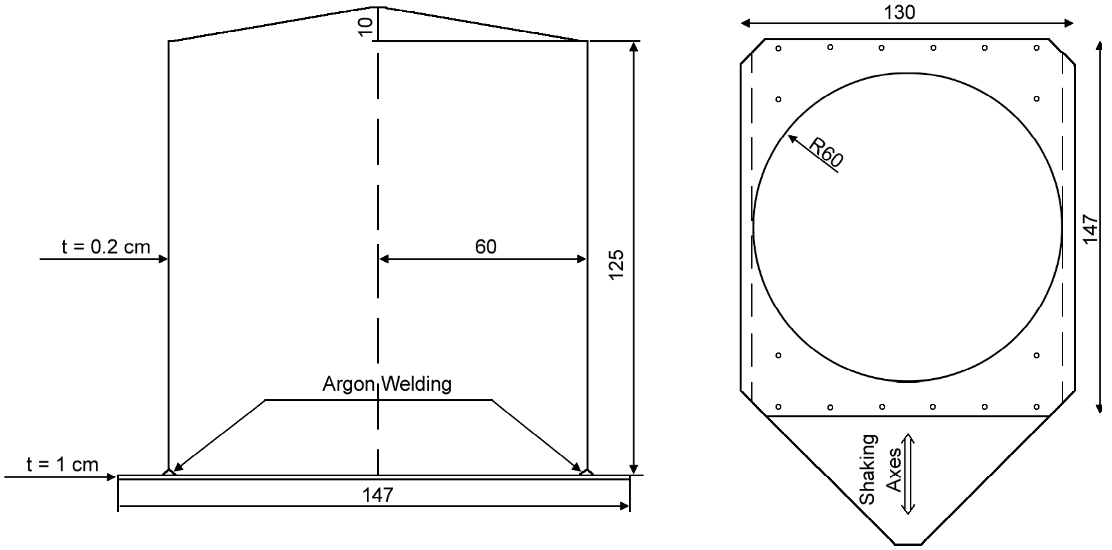

Figure 2. Experimental tank characteristics tested on the shaking table.

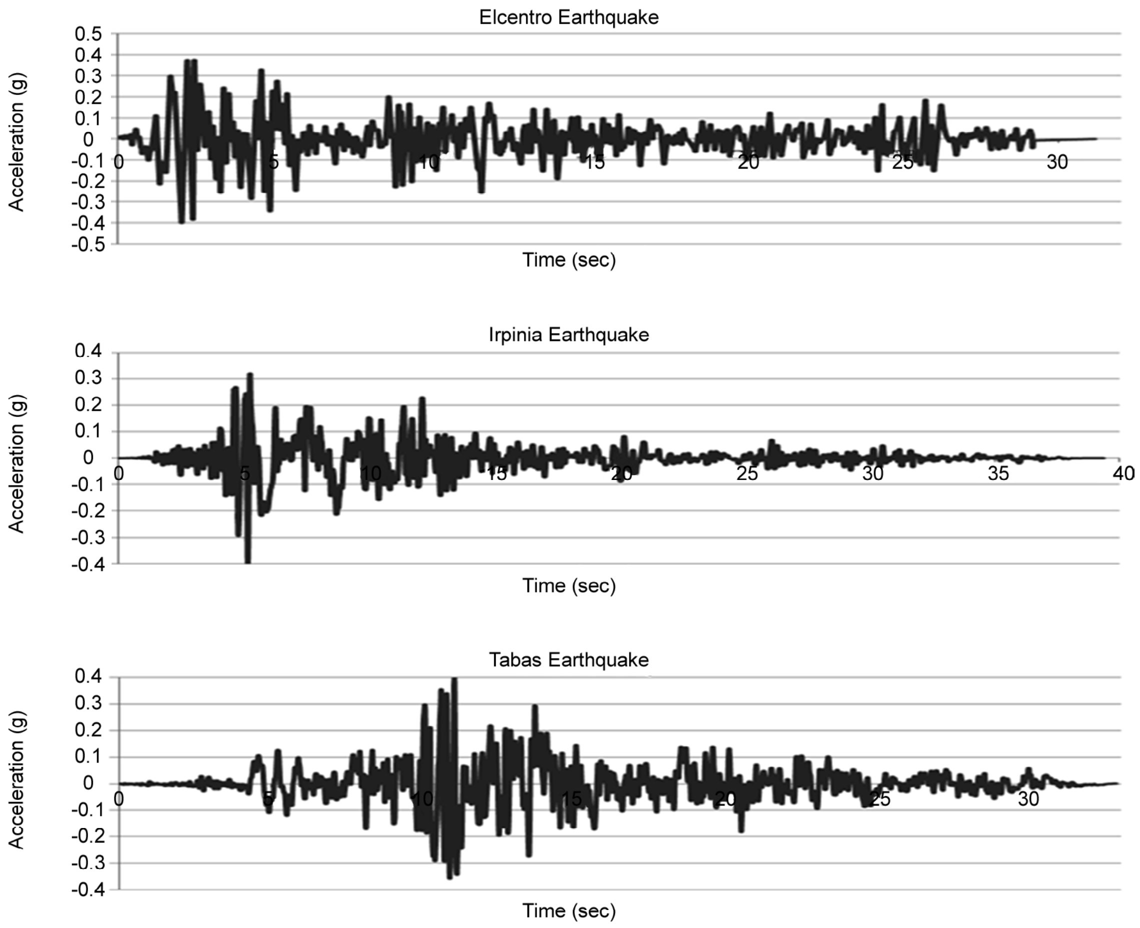

Figure 3. Real accelerogram of the three earthquakes of El Centro, Irpinia and Tabas.

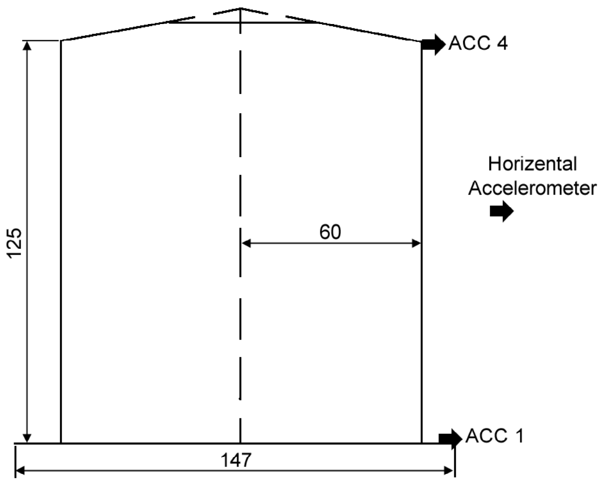

Figure 4. Location of the accelerometer on the tank wall.

Figure 5. Location of the camera for filming the fluid Sloshing.

3. Impulsive and Convective Frequency Results

In earthquake engineering and strong motion seismology, Fourier techniques present an important tool in understanding and interpreting the frequency content of various time signals. Ambient vibration tests [21], source mechanism studies [22], response spectrum analyses [23], and instruments correction techniques [24] are only some of the examples in which Fourier representations are widely used.

To obtain the impulsive mode frequency, Fourier Amplitude of ACC4 was divided by Fourier Amplitude of ACC 1 to obtain the Transfer Function. Then the graph of this function in terms of the frequency was plotted to determine the dominant frequency of the impulsive mode. As an example, the time history response of the tested tank under Tabas earthquake with a fluid height of 60 cm of the impulsive vibrations of the ACC 1 and ACC 4 as well as the Fourier Amplitude of these vibrations and their transfer functions are drawn in Figure (6).

To obtain the frequency of the convective mode from the recorded turbulence, Fourier Amplitude of the turbulence results were obtained. An example of the time history and Fourier Amplitude of the fluid turbulence results in the studied tank under Tabas earthquake with a fluid height of 60 cm is plotted in Figure (7). Moreover, experimental and analytical fluid sloshing time histories compared in this figure.

The above calculations were repeated for different tested tank models with fluid heights of 60, 80, 100 and 120 cm. Frequency results of the

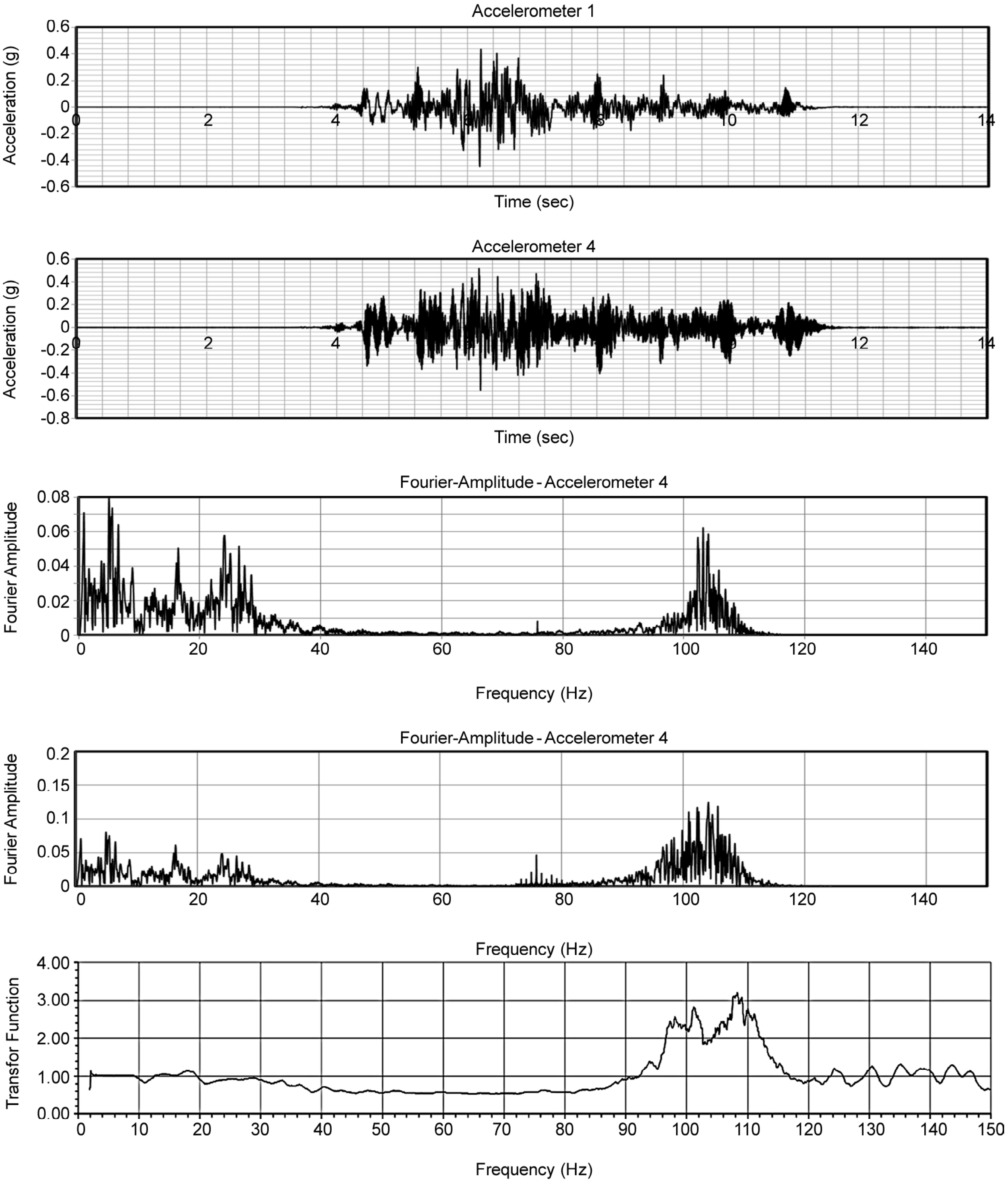

Figure 6. Time history of the ACC 1 and ACC 4 and fourier amplitude of the accelerometers and transfer functions.

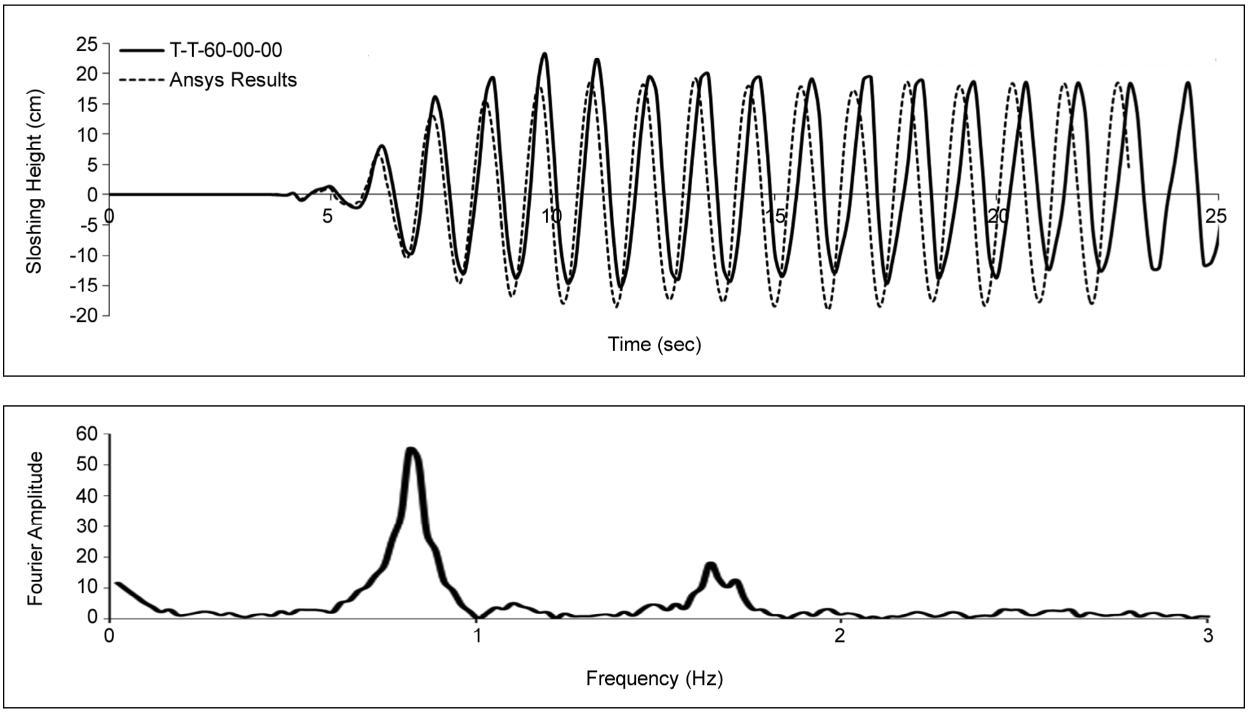

Figure 7. Time history and Fourier Amplitude of the fluid turbulence under Tabas earthquake with a fluid height of 60 cm.

convective and impulsive modes from different tests are listed in Table (2). As it can be seen, the dominant frequency of the impulsive mode ranges about 100 Hz, while the dominant frequency of the convective mode ranges about 0.8 Hz. Furthermore, the results of the test and analytical frequencies of convective mode indicated in this table have good agreement.

4. Damping Results of the Impulsive and Convective Modes

Frequency and damping are then key parameters for earthquake design and seismic vulnerability assessment, since, as mentioned by Spence et al. [25], the adjustment of structural models must assume a large set of unknown parameters influencing the response of existing structures. Knowing frequency and damping can reduce the range of errors and epistemic uncertainties for representing the vulnerability as fragility curves [26].

To obtain the damping of the convective mode, variations of the fluid oscillation amplitude in the free vibration domain is obtained by applying the logarithmic decrement method according to Eq. (1).

Table 2. Values of the dominant frequency of the convective and impulsive modes.

Test Description		Dominant Frequency of the Convective Mode (Hz)	Analytical Convective Mode Frequency (Hz)	Dominant Frequency of the Impulsive Mode (Hz)
Fluid Height (cm)	Input Earthquake			
60	Tabas	0.8203	0.8029	108
	El Centro	0.8437		101.5
	Irpinia	0.8437		----
80	Tabas	0.8437	0.8153	103.55
	El Centro	0.8671		103.2
	Irpinia	0.8671		----
100	Tabas	0.8437	0.8214	103.4
	El Centro	0.8671		104.2
	Irpinia	0.8671		----
120	Tabas	0.8671	0.8258	103.7
	El Centro	0.8671		102
	Irpinia	0.8671		----

Besides, to obtain the amplification of the impulsive mode, the half-power method is used according to Eq. (2).

$$\zeta = \frac{1}{2\times\pi\times j} ln \frac{u_i}{u_i + j} \qquad (1)$$

$$\zeta = \frac{f_b - f_a}{2 f_n} \qquad (2)$$

U_i in Eq. (1) is the amplitude of the i^{th} oscillation and j is the number of complete oscillation cycle. Parameters of Eq. (2) are explained in Figure (8).

Damping calculation was repeated for different tested tank models with fluid height of 60, 80, 100 and 120 cm. Damping values of the impulsive and convective modes are shown in Table (3).

Based on the test results, the minimum and maximum damping factors of the impulsive mode are 1.06% and 1.18%, respectively. Moreover, the minimum and maximum damping factors of the convective mode are 0.3% and 0.5%, respectively.

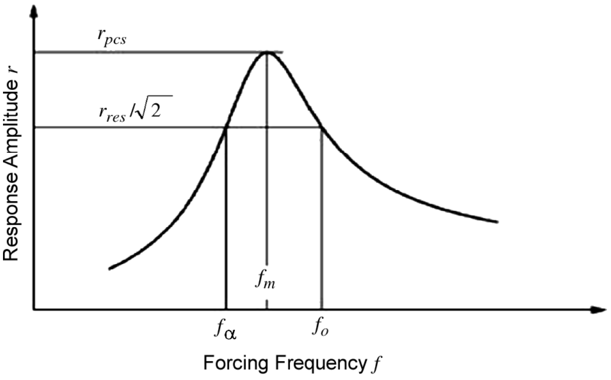

Figure 8. Damping calculation from response-frequency curve using half-power method [28].

Table 3. Damping values of the convective and impulsive modes.

Test Description		Damping of the Convective Mode (%)	Damping of the Impulsive Mode (%)
Fluid Height (cm)	Input Earthquake		
60	Tabas	0.3	1.11
	El Centro	0.4	1.18
	Irpinia	0.5	----
80	Tabas	0.3	1.11
	El Centro	0.4	1.07
	Irpinia	0.3	----
100	Tabas	0.5	1.06
	El Centro	------	1.15
	Irpinia	0.4	----
120	Tabas	0.3	1.06
	El Centro	0.4	1.08
	Irpinia	0.4	----

As mentioned before, Guidelines for Seismic Evaluation of Oil Industry Facilities (Pub. No 041-11) and API650 Regulations recommend a 5% damping for the impulsive mode that is higher than the obtained experimental result (1.18%). But it must be noted that the values proposed by the regulations consider tank-soil interactions as well as the effects of nonlinear behavior of the tank during severe earthquakes. Furthermore, a 0.5% damping for the convective mode is recommended by the regulations that seems appropriate compared with the experimental results (0.3% to 0.5%).

5. Conclusions

By investigating the frequency and damping of the impulsive and convective modes in the tested tank on the shaking table under various earthquakes and by comparing the results with the recommended values by the Guidelines for Seismic Evaluation of Oil Industry Facilities (Pub. No 041-11) and API650 Regulations, the following concluding remarks may be made:

- Proposed damping of the convective mode by Guidelines for Seismic Evaluation of Oil Industry Facilities (Pub. No 041-11) and API650 Regulations is 0.5%. This parameter was obtained in the range of 0.3% to 0.5% in the present experiments. Thus, the proposed values by the regulations are not in safe side.
- Proposed damping of the impulsive mode by Guidelines for Seismic Evaluation of Oil Industry Facilities (Pub. No 041-11) and API650 Regulations is 5%. This parameter was obtained in the average value of 1.1% in the present experiments that is considerably lower than the proposed value by the regulations. To obtain the real damping of the impulsive mode, soil-structure interaction, soil plastic behavior, etc. are considered by the regulations. However, these effects were not considered in the dynamic tests of the studied tank. Therefore, more investigations are needed on the damping of the impulsive mode.
- Impulsive and convective vibration frequencies obtained from the shaking table tests show that the two vibration modes are independent.
- Experimental results show that the damping

factors of the impulsive and convective modes are different under various input earthquake motions. This observation indicates that the dynamic frequency content and vibration amplitude of the earthquake records can have an effect on damping values and dynamic responses of the studied tank model.

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