EXPERIMENTAL EVALUATION OF CODE PROVISIONS FOR HYDRODYNAMIC WALL PRESSURE OF A RECTANGULAR STORAGE TANK

Pouya NOURAEI DANESH
Master student, IIEES, Tehran, Iran
p.nouraeidanesh@iiees.ac.ir

Mohammad KABIRI
Master student, IIEES, Tehran, Iran
m.kabiri@iiees.ac.ir

Mohammad Ali GOUDARZI
Assistant Professor, IIEES, Tehran, Iran
m.a.goodarzi@iiees.ac.ir

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ABSTRACT

One of the most important key factors in designing liquid storage tanks is the design of wall thickness to provide sufficient resistance and rigidity against critical loads. The hydrodynamic pressure on tank wall shells is considerable in determination of a tank wall thickness. The motivation for this study is to carry out a wall pressure comparison between experimental tests results and values suggested by the ACI-350 code. This comparison could lead to a better understanding of ACI code provisions. In this regard, a series of experimental tests are conducted using a rectangular liquid tank excited by different earthquake oscillations. The experimental results agree well with those calculated by the code in most cases. The reason of minor deviation in some cases will be discussed and justified.

INTRODUCTION

Liquid sloshing in tanks is one of the key issues of tank design.With continuous increase of tank volume due to the industry demand, liquid sloshing becomes more important in engineering.

Extensive analytical, numerical and experimental studies have been performed in the past decades. Early studies of sloshing focused on linear problems in two dimensional simple geometrical containers, which can be solved by analytical methods (Ibrahim RA, 2005). Linear potential-flow theory does not account for damping, so that the response near the lowest natural frequency is infinite, which is not consistent with the physical phenomenon (Zhijun Wei, 2012). Then based on potential-flow theory, nonlinear models with viscous damping were developed to describe the sloshing in both 2D and 3D containers well. Faltinsen (1974) developed third-order perturbation method to study 2D sloshing.

There are a number of numerical approaches for modeling the sloshing effects, too (e.g. Wu *et al.* 1998, Faltinsen and Rognebakke 2000). Kim *et al.* (2001, 2004) developed a numerical scheme based on the finite difference method and extended the investigation to geometries that are more complicated (e.g. three-dimensional prismatic tanks). The method concentrates on the global motion of sloshing flows, adopting the concept of a buffer zone (Fabrizio Pistani, 2012). Other numerical techniques that have been widely used for modeling the sloshing problems are known as Smoothed-Particle-Hydrodynamics (SPH) and consistent particle method (CPM). The SPH method has been applied to various free-surface problems, especially for strongly nonlinear wave modeling. The CPM method is recently developed by Gao Mimi (2011), in which the discretization of the equations is based on derivatives consistent with a Taylor series expansion. This method is less suffered from pressure fluctuations especially in fluid problems with long time simulation in comparison with other related methods.

Due to the complexity of sloshing, there has been a considerable amount of work carried out to understand the complex sloshing behavior and to design appropriate devices to suppress it. One of the earlier experimental investigations of nonlinear, free-surface standing waves was reported by Taylor (1953) who focused on the wave crest in the center of a rectangular tank. Wang *et al.* (1996) experimentally studied the waves in a water-filled circular tank excited by two shakers at opposite sides of the tank. The excitation frequency used was near one of the natural frequencies of sloshing waves. Tveitnes *et al.* (2004) carried out a series of experiments and proposed a simplified load formula for estimation of sloshing load in preliminary design. La Rocca *et al*. (2005) empirically and theoretically investigated the problem of sloshing waves of a two-liquid system. Rognebakke *et al.* (2005) conducted a series of tests on a scaled tank. They investigated the high filling impacts by using pressure sensors and analyzing the pressure data statistically. Akyildiz and Unal (2005) investigated the pressure distributions at different locations and three-dimensional (3D) effects on liquid sloshing experimentally. Shuo Huang, Wen-yang Duan (2010) carried out experiments using partially filled rectangular tank with forced sway motion to validate time-domain simulation of tank sloshing pressure. Recently, Mei-rong JIANG, Bing REN (2014) conducted a Laboratory investigation of the hydroelastic effect on liquid sloshing in rectangular tanks. Their analyses indicate that, in the non- resonant cases, the elastic results, the rigid experimental results and the theoretical values are in a good agreement.

EXPERIMENTS

In order to compare the seismic wall pressure obtained from test results and ACI-350 code, a series of shaking table tests have been conducted at International Institute of Earthquake Engineering and Seismology.

The dimensions of rectangular tank are $100\times 100\ \times 30$(height $\times$length $\times$width). The tank is comprised of plexiglass with thickness of 1cm. A 10cm high lateral support with 14 bolts is used to fix the tank to shaking table (figure. 1). The pressure transducer is placed at 13 cm from the base (figure. 1). The tank is excited in three different height levels of 20cm, 50cm, and 70cm.

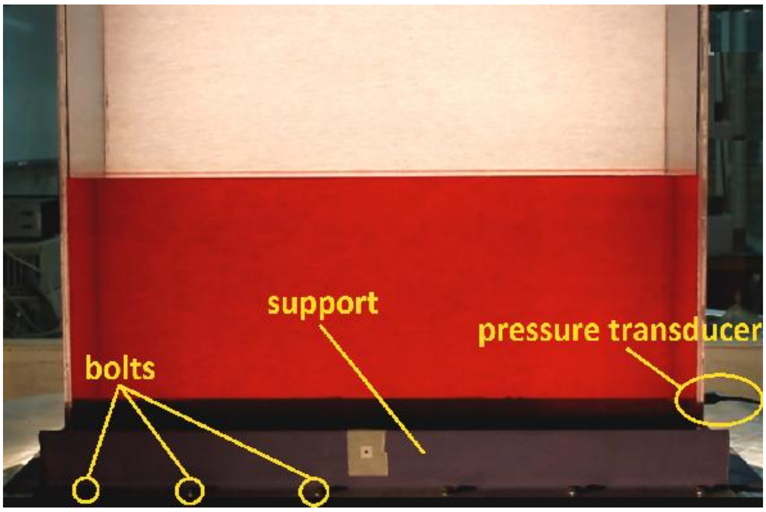
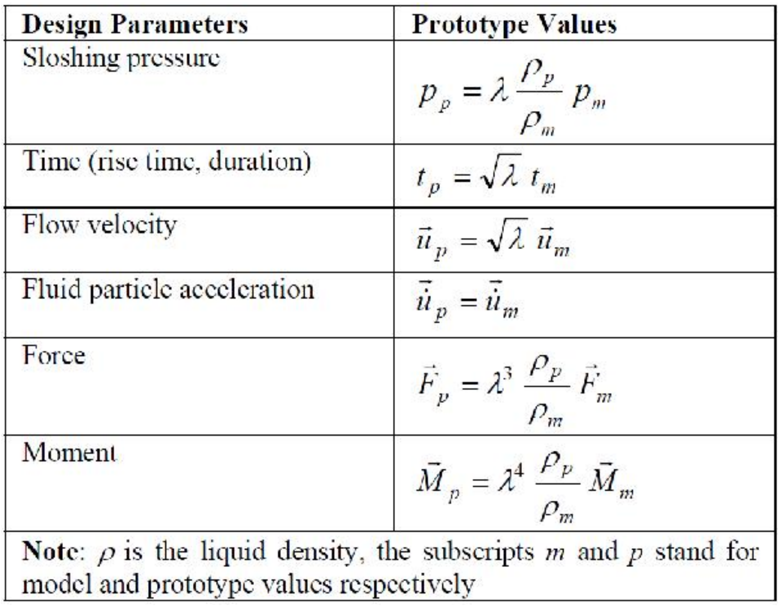


Figure 1. Tank support and the location of pressure transducer

The earthquake records that have been selected for this study are Tabas (PGA=0.66g), Chichi (PGA=0.34g) and Kobe (PGA=0.6g). These records should be scaled according to the prototype size of tanks. As such, conditions for dynamic similitude at model and prototype scales must be identified and corresponding scaling laws established. A traditional procedure such as the Buckingham Π theorem for finding these parameters is available. Table 1 shows the scaling laws in sloshing which have geometrically similar bodies. Note that ^{a} is the ratio of prototype length to model.

Table 1. Scaling laws in sloshing



Design Parameters	Prototype Values
Sloshing pressure	$p_p = \lambda \dfrac{\rho_p}{\rho_m} p_m$
Time (rise time, duration)	$t_p = \sqrt{\lambda}\, t_m$
Flow velocity	$\vec{u}_p = \sqrt{\lambda}\, \vec{u}_m$
Fluid particle acceleration	$\ddot{u}_p = \ddot{u}_m$
Force	$\vec{F}_p = \lambda^3 \dfrac{\rho_p}{\rho_m} \vec{F}_m$
Moment	$\vec{M}_p = \lambda^4 \dfrac{\rho_p}{\rho_m} \vec{M}_m$
Note: ρ is the liquid density, the subscripts m and p stand for model and prototype values respectively	

The existing shaking table test runs with the displacement time histories of records which are given in figure. 2.

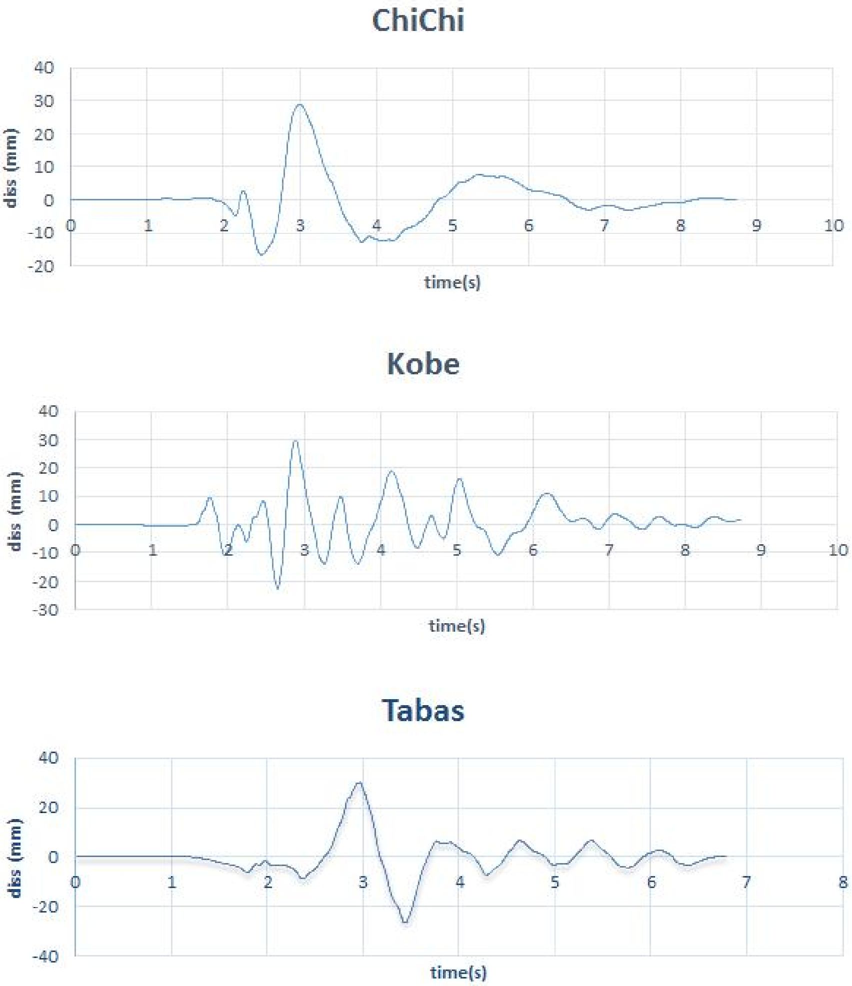


figure 2. Displacement time histories of earthquake records

Figure. 3 shows the tank where it is excited by Kobe earthquake.

Figure 3. Rectangular storage tank under seismic excitation

ACI CODE MEASUREMENTS

In order to calculate hydrodynamic pressures, ACI code generally divides the contained liquid in to two separate parts: a) Hydrodynamic impulsive pressure P_i from the contained liquid and b) Hydrodynamic convective pressure P_c from the contained liquid. The dynamic lateral forces above the base shall be determined as follows:

$$P_i = ZSIC_i \times \frac{W_i}{R_{wi}} \tag{1}$$

$$P_c = ZSIC_c \times \frac{W_c}{R_{wc}} \tag{2}$$

W_i and W_c are the impulsive and convective component of the liquid mass, respectively. Factor Z represents the maximum effective peak ground acceleration for the site, while C is a period-dependant spectral-amplification factor. In equations 1 and 2 factor C is represented by C_i and C_c , corresponding to the responses of the impulsive and convective, respectively. R_{wi} and R_{wc} are response modification factors which reduce the elastic response spectrum to account for the structure's ductility, energy-dissipating properties and redundancy.

P_{iy} is the lateral impulsive force due to equivalent mass of the impulsive component and P_{cy} is lateral convective force due to equivalent mass of the convective componant of the stored liquid, which are represented as follows:

$$P_{iy} = \frac{\frac{P_i}{2}(4H_L - 6h_i - (6H_L - 12h_i) \times (\frac{y}{H_L}))}{H_L^2} \tag{3}$$

$$P_{cy} = \frac{\frac{P_c}{2}(4H_L - 6h_c - (6H_L - 12h_c) \times (\frac{y}{H_L}))}{H_L^2} \tag{4}$$

The vertical force distribution for impulsive and convective component of a rectangular tank which are suggested by ACI code is shown in figure. 4.

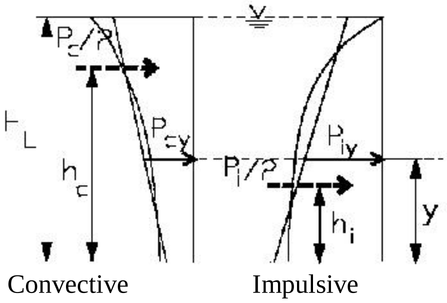


Figure 4. Vertical force distribution in a rectangular tank suggested by ACI code

The factor H_L is design depth of stored liquid. H_i and h_c are heights above the base of the wall to the center of gravity of the impulsive and convective lateral force, respectively (figure 4) which are calculated from the equations 5 and 6:

$$\text{For tanks with } \frac{L}{H_L} \prec 1.333 \rightarrow h_i = (0.5 - 0.09375(\frac{L}{H_L})) \times H_L \tag{5-1}$$

$$\text{For tanks with } \frac{L}{H_L} \succ 1.333 \rightarrow h_i = 0.375 \times H_L \tag{5-2}$$

$$\text{For all tanks } h_c = (1 - \frac{\cosh(3.16(H_L/L)) - 1}{3.16(H_L/L)\sinh(3.16(H_L/L))}) \times H_L \tag{6}$$

Therefore, the horizontal distribution of the dynamic pressures across the wall width B is:

$$p_{iy} = \frac{P_{iy}}{B} \text{ and } p_{cy} = \frac{P_{cy}}{B} \tag{7}$$

The hydrodynamic pressure at any given heights y from the base shall be determined by the following equation:

$$p_y = \sqrt{p_{iy}^2 + p_{cy}^2} \tag{8}$$

Comparison of maximum wall pressure obtained from the above equations and experimental test results are given in figures 5 to 7.

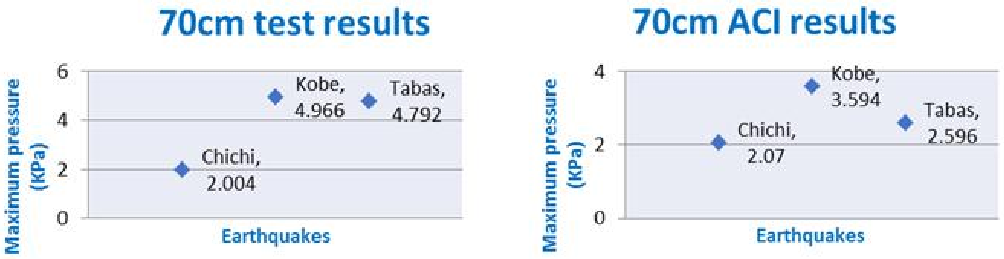


Figure 5. Comparison of maximum wall pressure between test results and ACI code for H_w=70cm

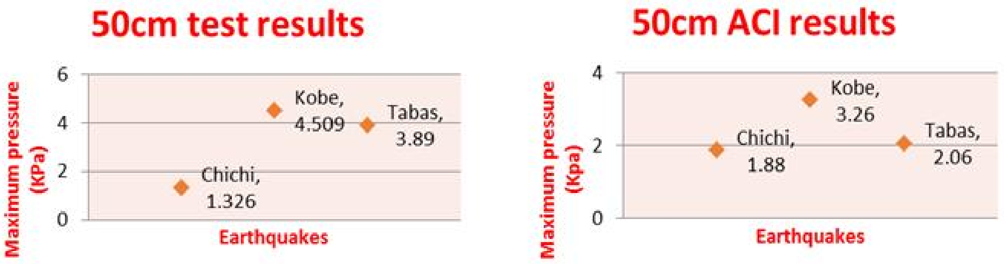


Figure 6. Comparison of maximum wall pressure between test results and ACI code for H_w=50cm

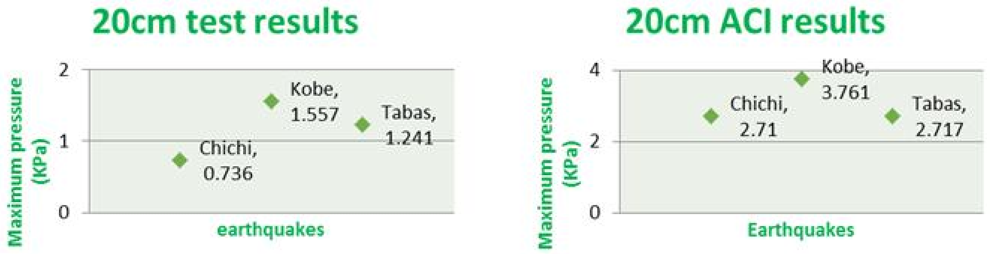


Figure 7. Comparison of maximum wall pressure between test results and ACI code for H_w=20cm

CONCLUSIONS

In this work, 9 experiments were conducted on a rigid rectangular tank by a shaking table at International Institute of Earthquake Engineering and Seismology. The tank was subjected to three different seismic oscillations and the time histories of wall pressure were obtained.

In this study, the maximum wall pressure of a rectangular tank due to horizontal excitation was experimentally investigated, and then, the results were compared with the calculated hydrodynamic wall pressure of ACI code.

As it’s shown in figures 5 through 7, we could deduce the ACI code in case of lesser h/a (a=Length/2) have closer wall pressure response versus the experimental results, however, according to the fact that higher liquid level leads to more pressure in convective part, pressure distribution will vary and deviate from the code values. It also has to be noticed that if the earthquakes have been set due to ACI code spectrum, the response will probably have more equality to the ones in experimental results.

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