AN EXPERIMENTAL INVESTIGATION OF A RECTANGULAR TANK FREEBOARD ON THE IMPACT ROOF PRESSURE

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

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

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

Keywords: Experimental Investigation, Liquid Storage Tanks, Roof Pressure, Roof Total Force

ABSTRACT

Large amplitude liquid sloshing and applied loads caused by hydrodynamic pressure of this phenomenon are always one of the most important factors in designing liquid storage tank roofs, especially in LNG (Liquefied Natural Gas) tanks. Codes approach in dealing with this matter is to provide sufficient freeboard in order to prevent liquid collision to the tanks roof. However, due to the technical reasons, providing a proper freeboard is not always an optimum solution. Therefore, the impact forces should be reasonably evaluated based on the experimental measurements and analytical solutions. In this paper, an investigation has been implemented in order to clarify the influence of various geometrical parameters on the impact roof pressure and force values of a rectangular tank. In this regard, a series of shaking table tests are conducted at International Institute of Earthquake Engineering and Seismology. The results have shown a reasonable relationship between roof pressure and freeboards.

INTRODUCTION

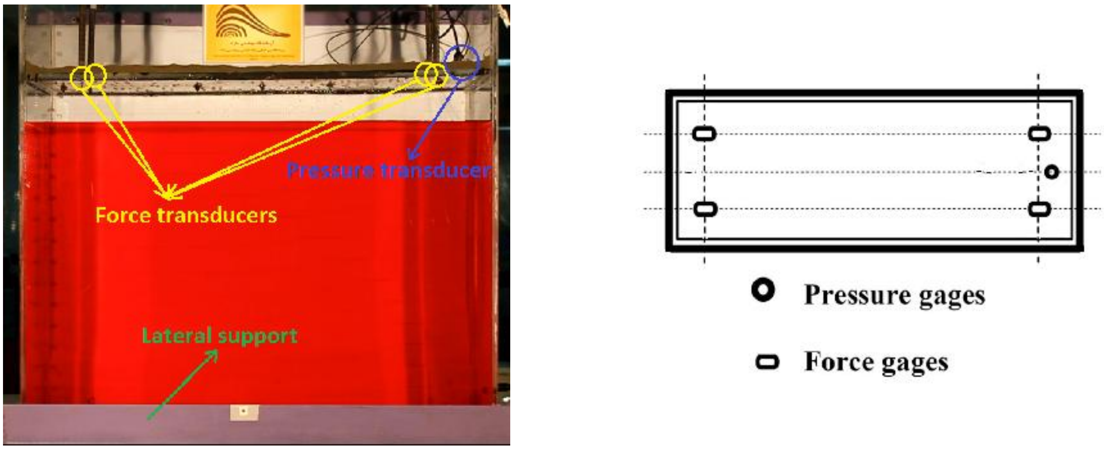
Fluid sloshing in tanks with a free surface is of interest in a variety of engineering fields. It is known that partially filled tanks with fluids are prone to violent sloshing under certain dynamic conditions. For example, when the frequency of the tank motion is close to the natural frequency of the interaction between sloshing fluid and structure, the enhanced fluid motion creates localized high impact loads on the tank walls and ceiling which can cause structural damage (Y. Chen, 2008). The convective part of liquid (the upper part which is subjected to the sloshing effects) is the main source of the sloshing wave and needs to slosh freely in the upper part of tanks. Hence, a sufficient freeboard is usually provided to prevent the impaction of liquid wave to tank roofs during earthquakes. However, defining the maximum sloshing wave height and the required freeboard is somehow challenging. On the other hand, providing a large freeboard is not economical, particularly for broad tanks and elevated tanks. Therefore, large-amplitude sloshing in case of insufficient freeboard may result in significant damage to tank roofs.

As the tank oscillates, the free surface profile can be considered as the composition of several different wave modes such as standing, travelling and hydraulic jump, (Kim, 2001 and Lee, 2002) whose superposition depends on liquid depth, tank geometry, frequency and amplitude of external excitation and position of the centre of rotation. The motion of fluid in a tank is governed by the Navier–Stokes (NS) equations or Euler equations depending on assumptions introduced relating to the fluid. Since analytical solutions available for this kind of real nonlinear fluid problem are non-existent, computational techniques are therefore of great importance to support experimental evidence. Several mathematical models have been employed to predict the liquid sloshing problem. For example, linear potential flow theory provides a simplified means of evaluating sloshing induced loads and offers physical insights into sloshing mechanisms but its use is of a limited nature (Ahramson, 1996).

Malhotra(2005) proposed a simple method of estimating sloshing loads when the freeboard is insufficient. The method only considers the hydrostatic pressure which occurs on the contacting area between the tank roof and the liquid. However, sloshing may result in both hydrodynamic and hydrostatic impact forces on the roof tanks.

EXPERIMENTS

This study aims to investigate the sloshing phenomenon using a series of experiments on a rectangular tank. The dimensions of rectangular tank are $100 \times 100 \times 30$ (height $\times$ length $\times$ width). The tank comprises of plexiglass with thickness of 1cm. Tank model, four force transducers and one pressure transducer which are mounted on the roof are shown in figure. 1.



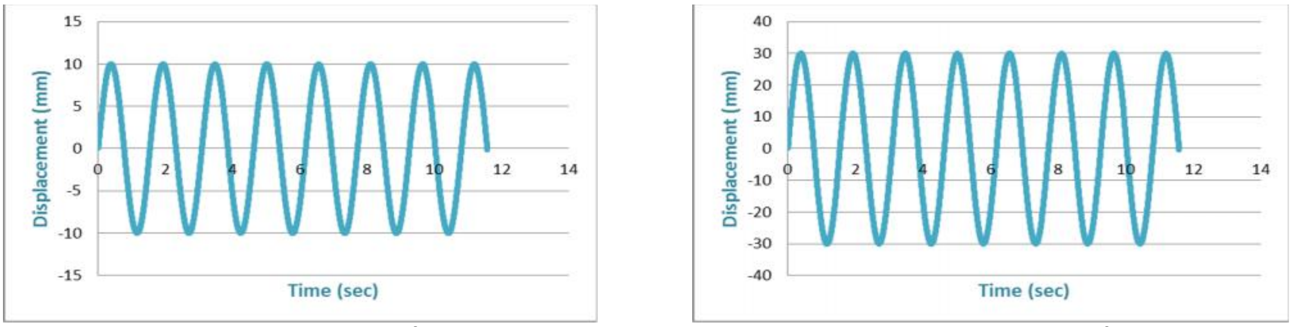
1-a) Force and pressure transducers' positions 1-b) Plan of the roof

Figure 1. Tank model and the position of force and pressure transducers

The tank is excited at the primary natural frequency of sloshing. These frequencies are calculated from equation 1. Primary variables are the freeboard height, free surface level and excitation amplitude. Various experiments are carried out for partially filled tanks with water height of 20cm, 50cm, and 70cm.

$$\mu_n = \sqrt{\Pi g / L \times \tanh(\frac{\Pi \times H_W}{L})} \quad (1)$$

μ_n is the natural frequency of tank model with the liquid height of H_W and the tank length of L. Sample displacement time histories of records are shown in figure. 2.



2-a) displacement time history of 10mm amlitude 2-b) displacement time history of 30mm amlitude

Figure 2. Displcement time histories of harmonic oscillation for $H_W = 20cm \rightarrow \mu_n = 4.07\, rad/\sec$

Figure. 3 shows the tank model while it is excited by harmonic oscillation of 1cm amplitude.

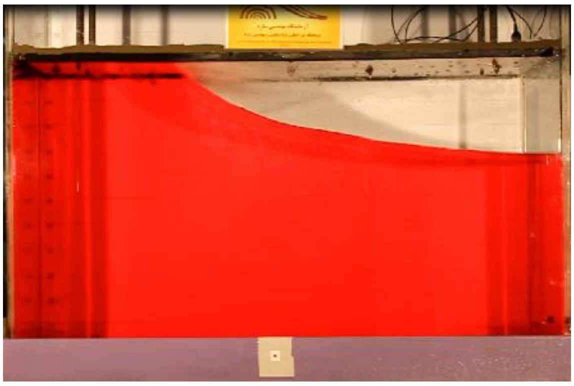


Figure 3. Tank model excited by harmonic oscillation

As an example, the time histories of total roof force and roof pressures at a specific point placed on the roof are shown in figures 4 and 5.

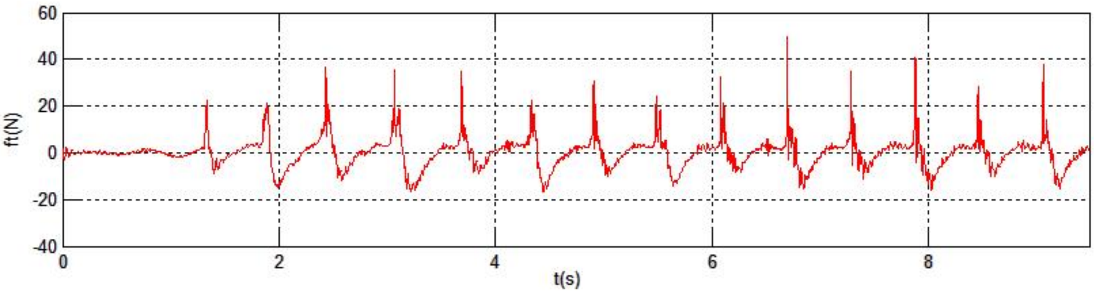


Figure 4. Time history of total roof force for harmonic oscillation with the amplitude of 1cm

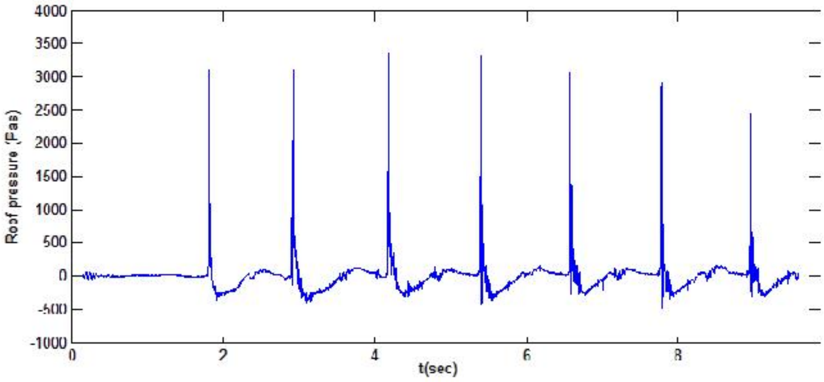


Figure 5. Time history of roof pressure for harmonic oscillation with the amplitude of 1cm

The maximum roof pressure and force values of different freeboard with different water levels are shown in figure 6 through 8.

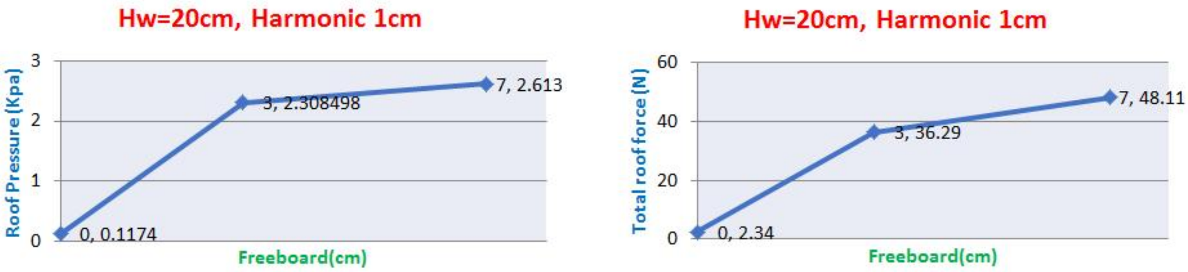


Figure 6. Roof pressure and force values of different freeboard heights for H_w=20 cm

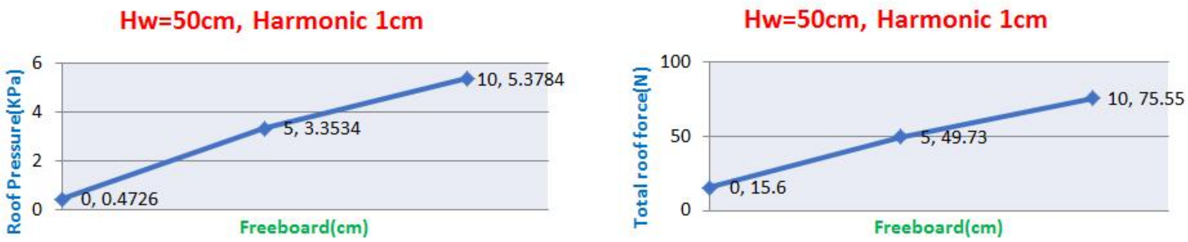


Figure 7. Roof pressure and force values of different freeboard heights for H_w=50 cm

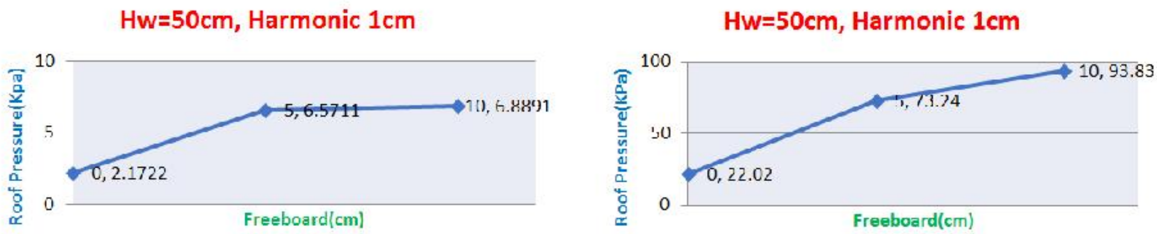


Figure 8. Roof pressure and force values of different freeboard heights for H_w=70 cm

CONCLUSIONS

In this work, a series of 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 harmonic oscillations with the amplitude of 1cm and 3cm. Time histories of roof pressure and force values were obtained and the maximum values in different freeboards were reported.

The maximum values of impact pressure and related forces were presented in figures 6 through 8. As can be seen, increase in the freeboard heights results in enhancement of impact pressure and force values of tank roof. It should be noted that force enhancement continues up to a specific freeboard height and then the line slope becomes negative. Therefore, It can be concluded that there is an optimum freeboard height in tanks for different liquid height levels. The reason of this issue would be justified by the fact that the higher freeboard lets the liquid to increase the wave velocity. However, due to the increment of liquid inertia, this trend does not continuous after a certain freeboard height. The optimum value of freeboard height directly affects the roof resistance designing system.

REFERENCES

Ahramson HN (1996) The dynamic behaviour of liquids in moving containers with applications to space vehicle technology, Report NASA Sp-106, Washington

American Concrete Institute (ACI) Committee 350(2006) Seismic design of liquid-containing concrete structures (ACI 350.3-06) and commentary (350.3R-06). ACI 350.3-06, Environmental Engineering Concrete Structures, Farmington Hills, Mich

Kim Y (2001) Numerical simulation of sloshing flows with impact load. Appl Ocean Res 2001;23:53–6

Lee T, Zhou Z and Cao Y (2002) Numerical simulations of hydraulic jumps in water sloshing and water impacting. *ASME J Fluids Eng*;124:215–26

Malhotra PK (2005) Sloshing loads in liquid-storage tanks with insufficient freeboard. *Earthquake Spectra*, 21(4), 1185-1192

Chen YG, Djidjeli K and Price WG (2008) Numerical simulation of liquid sloshing phenomena in partially filled containers. School of Engineering Sciences, Ship Science, University of Southampton, Southampton, UK