16th World Conference on Earthquake Engineering, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 4019
Registration Code: S-O1464658298

AN EXPERIMENTAL STUDY ON REDUCTION OF SEISMIC SLOSHING IN FLOATING ROOF TANKS BY USING A SUSPENDED ANNULAR BAFFLE (SAB)

M. Hosseini(1), M. A. Goudarzi(2), A. Soroor(3), Z. Bayat(4)

(1) Associate Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, Email: hosseini@iiees.ac.ir
(2) Assistant Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, Email: m.a.goodarzi@iiees.ac.ir
(3) PhD Student, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, Email: amihossein.soroor@gmail.com
(4) MSc Student, Rasam Higher Education Institute, Karaj, Iran, Email: zohrehbayat20@yahoo.com

Abstract

Floating roof tanks, with capacity as large as one million barrel, because of their advantages are among very common tanks in oil industry, and only in Kharg Island of Iran there are more than 45 ones of these tanks. However, these tanks have shown their vulnerability against large earthquake happened in recent decades, such as Kobe, Izmit and Tokachi-oki earthquakes. The main cause of damage has been reported to be the sloshing of liquid, resulting in sinking of the floating roof and also escaping of flammable gases leading into fire. In this research the possibility of reduction of seismic sloshing in floating roof cylindrical tanks by using a suspended annular baffle (SAB) has been investigated experimentally. The tests were conducted by using the shake table of the Structural Laboratory of the International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, and included a set of harmonic excitations and also a set of simulated earthquake motions. The annular baffle was hanging from the roof by some ropes, connecting to the roof near its perimeter, so that the baffle was located inside the impulsive section of the liquid in the tank. During the dynamic excitation, which causes sloshing of the liquid as well as tilting of the floating roof, the SAB resists against the upward motion of the floating roof, and can reduce its fluctuations remarkably. To do the test, small model of the real tanks with 100 cm diameter and 120 cm height, made of transparent condensed plastic (Plexiglas), was used. Transparency of the tank wall gives the possibility of observing the motion of the liquid, the floating roof as well as the SAB. Two SABs were used, one with 7 cm width and the other with 11 cm. Three values of 70, 50, and 20 cm were considered for the depth of the impounded liquid in the tank. Tests were done once without the SAB and once again with it to find out how the SAB can reduce the seismic response. Results show that using the SAB reduces the maximum fluctuation amplitude of the liquid around 80% and 40% in average respectively, for harmonic and seismic excitations.

Keywords: Shake table, Impulsive section of the liquid, Maximum fluctuation amplitude, Harmonic and seismic excitations

1. Introduction

Oil storage tanks are used mostly with floating roofs, basically for elimination of breathing losses and reduction of the evaporative loss of the stored oil. This is while past earthquakes have shown that vertical cylindrical oil storage tanks with floating roof are seismically vulnerable, mainly due to sloshing phenomenon, leading to consequences such as roof sinking as well as devastating fires. Samples of these disaster cases have been observed in Anchorage earthquake of 1964, reported by Cooper (1997) [1], Niigata earthquake of 1964 and Nihonkai-chubu (Japan sea) Earthquake of 1983, reported by Nishi (2008) [2]; Yamauchi and colleagues (2006) [3], Izmit earthquake of 1999, reported by Sezen and colleague (2000) [4], Tokachi-oki Earthquake of 2003 and Tohoku earthquake of 2011, reported by Hatayama (2013) [5]. Sloshing-related damages in floating-roof tanks due to the aforementioned earthquakes include sinking of the floating roof, buckling of the pontoon, and also sloshing-induced fires either open top fire or ring fire. It is noticeable that based on Cooper's report all damaged floating-roof tanks in Anchorage earthquake of 1964 were full or nearly full, and that tanks less than half-full did not suffer damage. As reported by Nishi (2008) sloshing in floating-roof tanks in Niigata earthquake of 1964 and Nihonkai-chubu (Japan sea) earthquake of 1983 induced devastating fires as shown in Fig. 1.

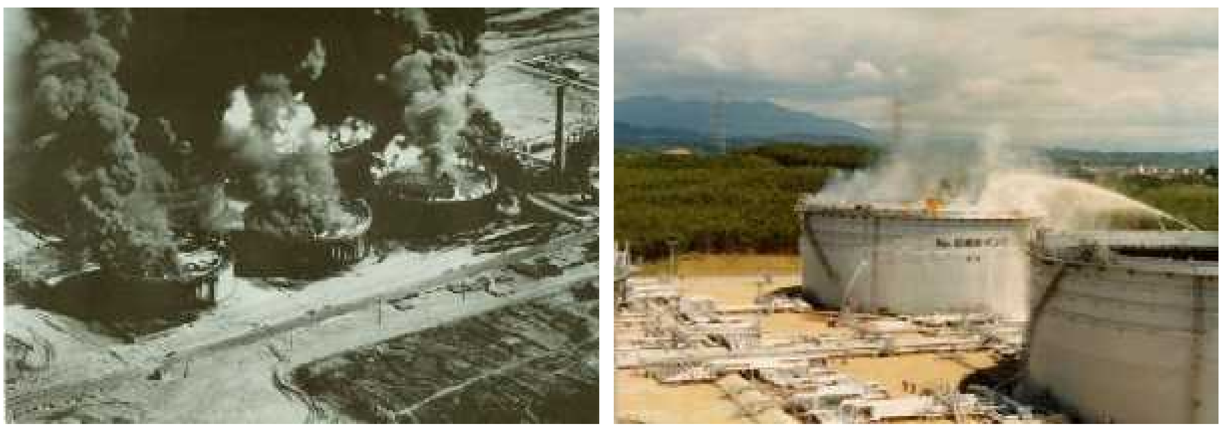
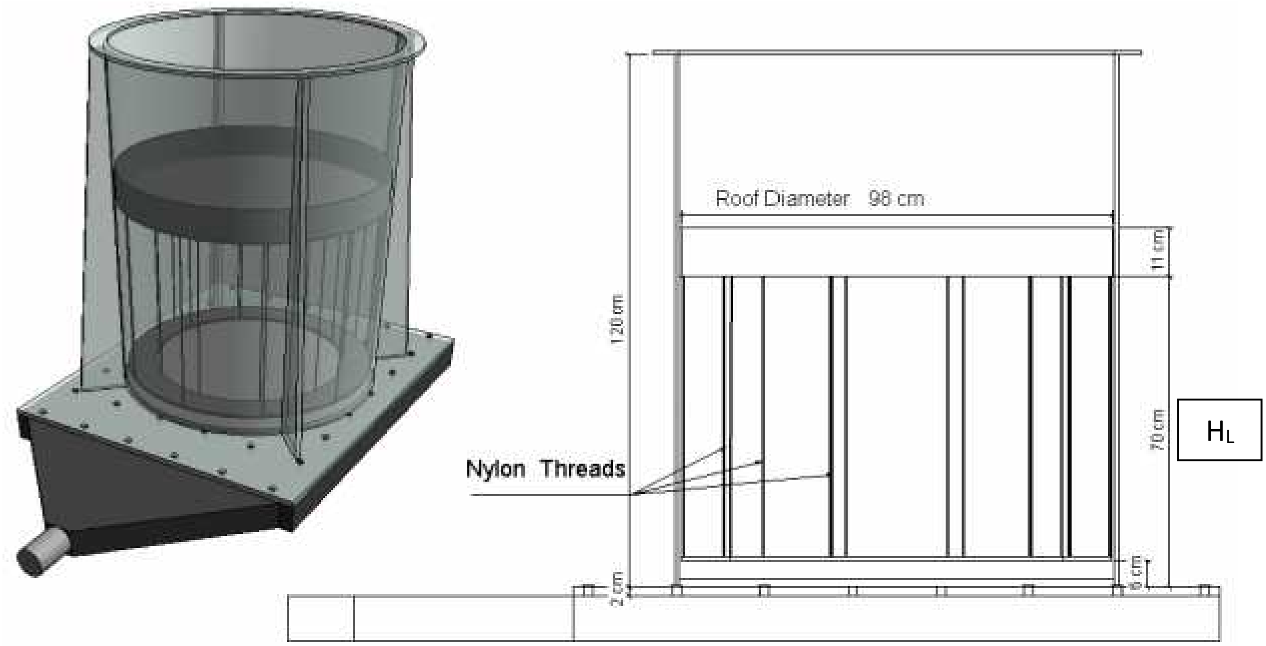


Fig. 1- Sloshing-induced fire in floating-roof tanks of Showa oil refinery in Niigata earthquake of1964 (left) and Akita power plant in Nihonkai-chubu (Japan sea) earthquake of 1983 (right) reported by Nishi (2008) [2]

Although some countermeasures have been proposed for reducing the sloshing response or its effects in floating-roof tanks so far by researchers such as Yumoto (1968) [6], Matsui and Muto (2005 & 2007) [7], Sakai and Inoue (2005 & 2008) [8-9], Jafarieh (2012) [10] and Yuezhou (2013) [11], they are more concentrated on preventing the floating roof from damage. The very few cases, which discuss directly the reduction of sloshing height, either have difficulties in practice or have not been studied thoroughly and need more research work. In this study the effectiveness of a passive control technique for reducing the maximum sloshing height in a small model tank by using a suspended annular baffle (SAB), has been investigated experimentally based on shake table tests. The SAB is hanging from the floating-roof by some threads of adjusted length, so that it is located inside the impulsive part of the fluid. The set-up, the process, and the results of shake table tests, conducted once without the SAB and once with it, by applying sine sweeps as well as seismic excitations, are presented briefly in the following sections.

2. The Test Set-up

The test tank was a cylindrical tank with 99 cm and 101 cm internal and external diameters, respectively (100 cm in average), and 120 cm height. The tank was made of Plexiglas to benefit from its transparency, which facilitated visual observation and inspection of the fluid sloshing and roof movements. Fig. 2 shows a perspective and a 2-D view of the tank and the geometric features of the annular baffles as well as a side view of the test tank installed on the used shake table in case that the distance of the floating roof is 50 cm from the tank bottom tank, in which the floating roof and the height measuring gauges are seen as well, along with a bird view of the whole test environment.



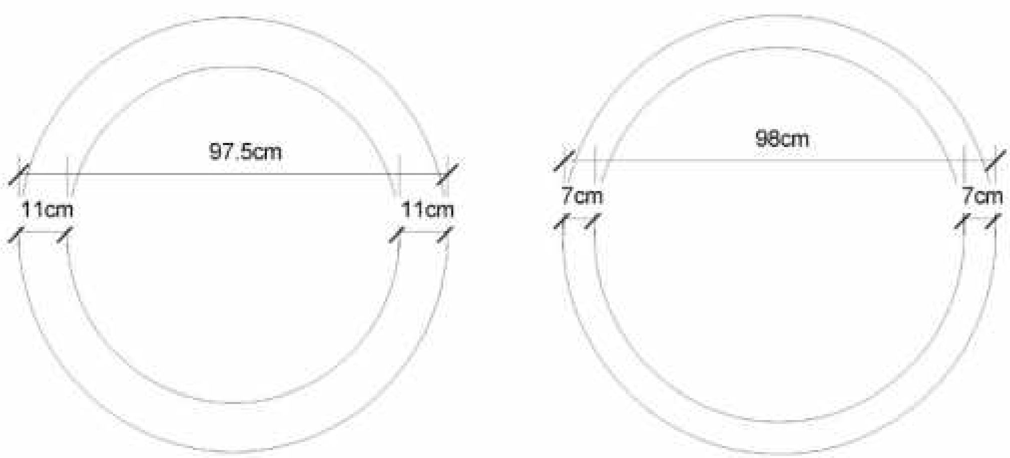


Fig. 2- A side view of the test tank with floating roof installed on the shake table (left) and a bird-view of the test environment (right) in which cameras 1, 2, and 4 as well as the four used gauges can be seen

Around the edge of the floating roof a ring wall of 11 cm height was considered, which can be seen in Fig. 2 (lower part in black and upper part in white). This relatively large height was considered for two reasons: a) preventing the floating roof from sinking, and b) creating enough stiffness in the floating roof to keep its stability.

3. The Input Excitations

The input excitations included sine sweeps as well as simulated earthquakes. The harmonic base excitations were applied by using three values of 2, 4, and 8 mm for the amplitude of the input motion, with the corresponding frequency for each value of H_L. The seismic base excitations considered for the tests were selected based on their dominant frequencies to be close to the first sloshing mode frequency of the tank in each case. The selected earthquakes included the main components of Loma Prieta earthquake of 1989 (Emeryville Station), Kocaeli, Turkey earthquake of 1999, and Chi-Chi, Taiwan earthquake of 1999. The time step size of these records were modified so that their dominant frequencies get close to the average sloshing frequencies, given in **Error! Reference source not found.**. Also their amplitude were scaled down to match with the maximum oscillation amplitude of the shake table (3 cm). The displacement histories of the modified scaled records of the selected earthquakes, used in the shake table tests, are shown in Fig. 3, and their Fourier Amplitude spectra in Fig 4.

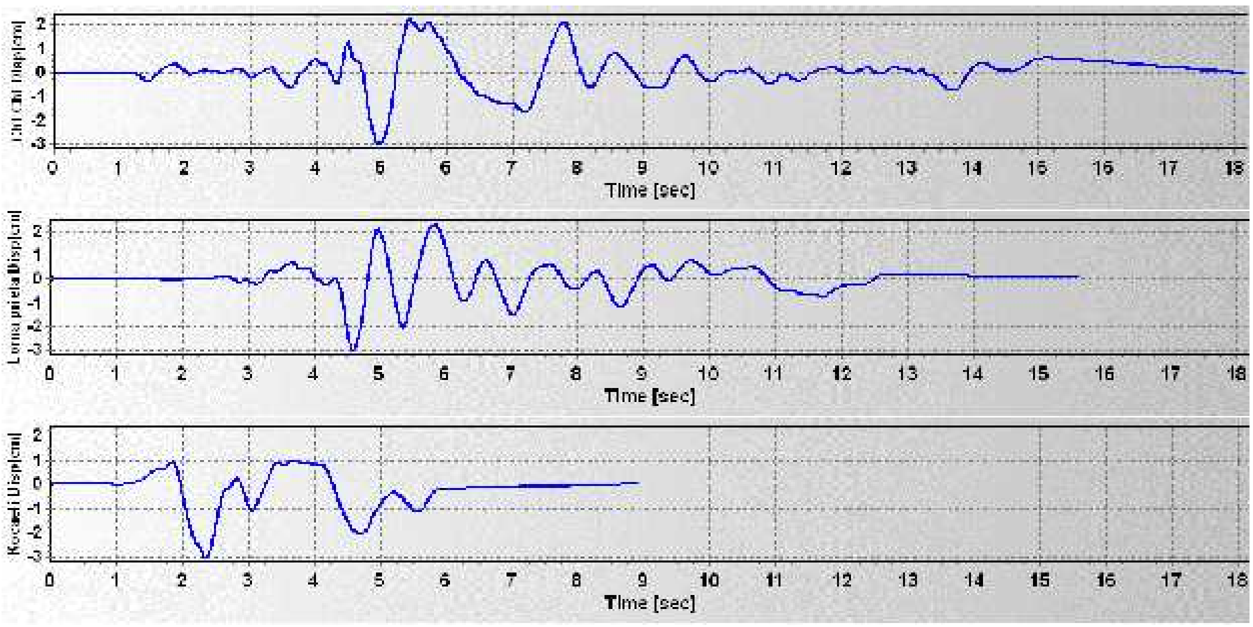


Fig. 3- Displacement histories of the scalded records of the selected earthquakes used in the shake table tests

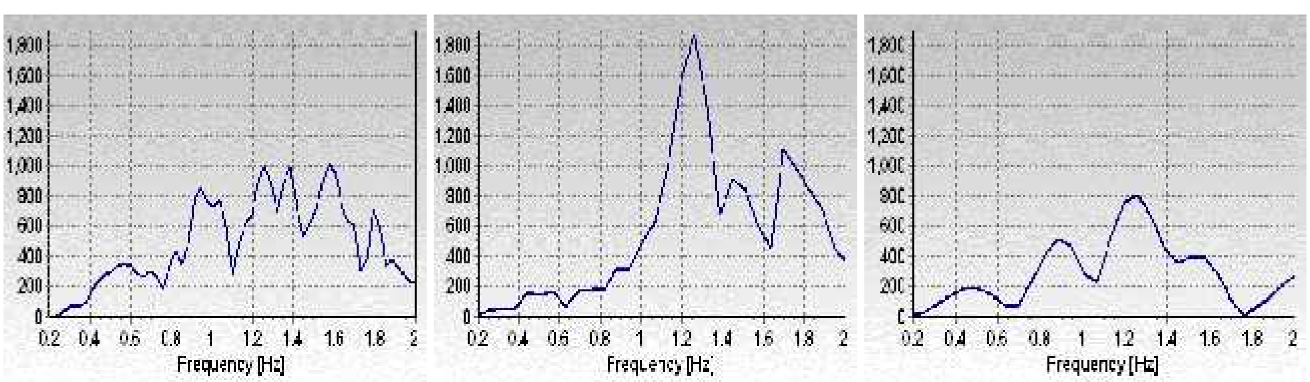


Fig. 4- Fourier Amplitude spectra (in cm/s^2) of the scalded records of the Chi-Chi (left), Loma Prieta (middle) and Kocaeli (right) earthquakes

It is seen in Fig. 3 that the amplitude of all displacement records in their first seconds of the time history is zero. This is a condition imposed to the tests due to the operation mechanism of the shake table. Also it is seen in this figure that in the last three seconds of the time histories in all cases the amplitude gradually decreases to zero, which is again an operation requirement of the shake table. Looking at Fig. 4 one can realize that Chi-Chi earthquake record has the highest Fourier Amplitude in the frequency range of 0.75 to 0.95 Hz, which is the range of the frequencies of the first sloshing mode for the three liquid height of H_L=70, 50, and 20 cm [12].

4. Tests Results

Time histories of the floating roof fluctuations, particularly the maximum vertical roof displacements, were considered as the main output of the tests. These displacements were obtained by measuring the vertical movements of the top surface of the floating roof in four locations close to the roof edge with a distance of 10 cm form the edge, by the four downward-looking gauges installed at the top ring of the tank as shown in Fig. 5Fig. 5-.

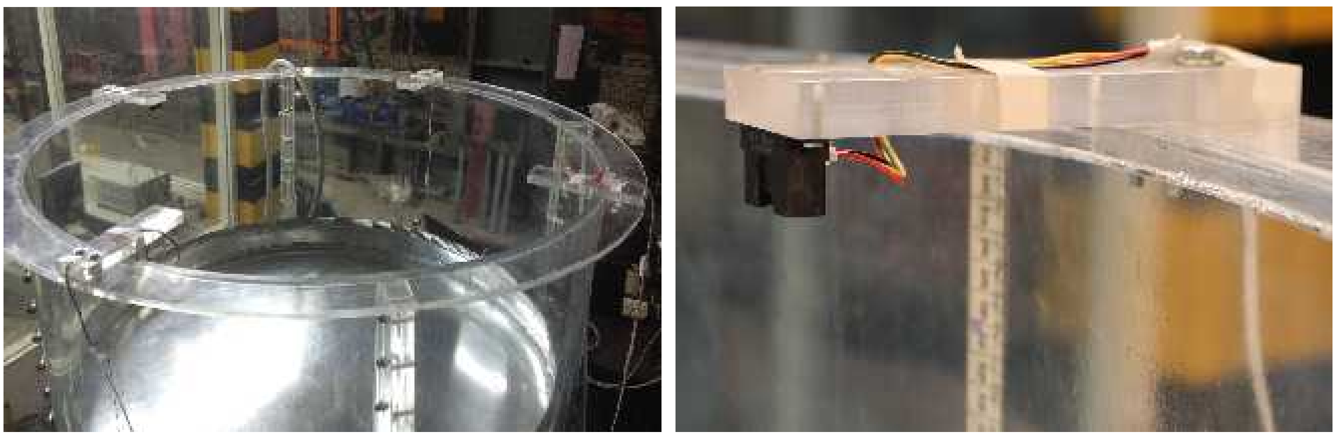


Fig. 5- Four installed gauges on the tank top ring for measuring the sloshing height (left), and the close-up of one of the gauges (right)

Fig. 6 shows the side view of the tank form the position of camera 1 for H_L=70 cm, both at rest and at the instant of maximum sloshing height due to harmonic excitation with amplitude of 4 mm and frequency of 0.95 Hz in both non-baffled (NB) and baffled cases with baffle width of 7 cm (BW7).

Fig. 6- The side view of the tank from the position of camera 1 for H_L=70 cm, at the instant of maximum sloshing height due to harmonic excitation with amplitude of 4 mm and frequency of 0.95 Hz in both non-baffled (NB) (left) and baffled (right) cases with baffle width of 7 cm (BW7)

Looking at Fig. 6 one can realize the effect of the SAB in reducing the sloshing height. Samples of the test outputs, related to the vertical fluctuation time histories of the floating roof in non-baffled and baffled cases, due to harmonic excitations with amplitude of 4 mm and frequency of 0.95 Hz for H_L=70 cm obtained by gauge 2 are shown in Figs. 7 and 8 respectively.

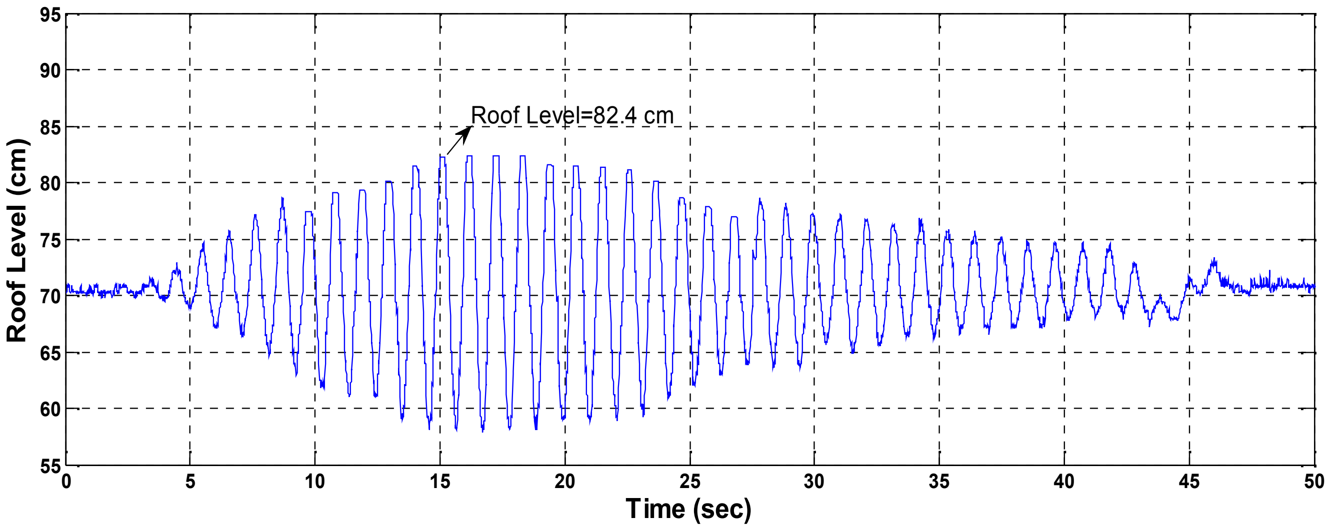


Fig. 7- A sample of the vertical fluctuation time histories of the floating roof in non-baffled case, due to harmonic excitations with amplitude of 4 mm and frequency of 0.95 Hz for H_L=70 cm obtained by gauge 2

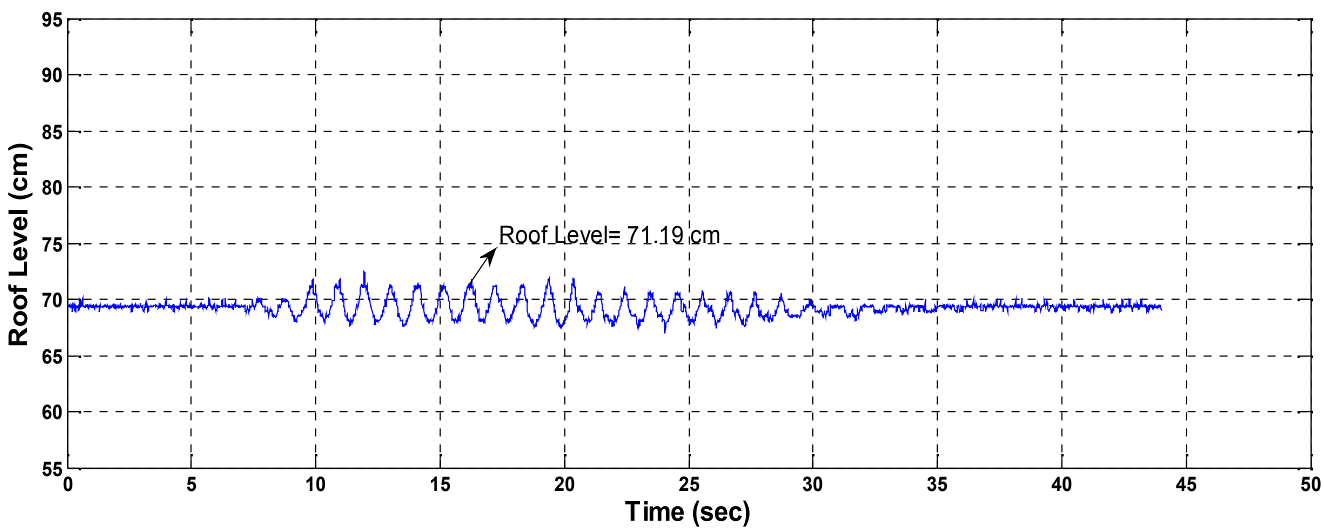


Fig. 8- A sample of the vertical fluctuation time histories of the floating roof in baffled case, due to harmonic excitations with amplitude of 4 mm and frequency of 0.95 Hz for H_L=70 cm obtained by gauge 2

More samples of response histories similar to those shown in Figs. 7 and 8 **Error! Reference source not found.**can be found in the main reports of the study which us under preparation by Hosseini and colleagues (2016) [13]. It is seen in **Error! Reference source not found.**that the maximum levels of the roof at the location captured by gauge 2, due to sloshing in NB and BW7 cases, are respectively 82.40-70.30=12.10 cm and 71.19-69.40=1.79 cm (70.3 and 69.4 are the baseline levels) of meaning 15.22 cm and 2.25 cm at the roof edge, which are in good agreement with the data captured by Camera 2. Based on the maximum roof levels in baffled and non-baffled cases it can be seen that the presence of the SAB with 7 cm width has resulted in almost 85%

reduction in the sloshing height for H_L=70 cm. The complete set of tests' results of the maximum sloshing height in each one of test cases, including cases without SAB as well as cases with SAB with two different widths of 7 and 11 cm, considered for comparison to show how much the use of SAB is effective in reducing the sloshing response, are presented in 1 to 3, respectively for H_L=70, 50 and 20 cm.

Table 1- Max sloshing heights (cm) in the floating-roof tank, subjected to harmonic and scaled seismic excitations in non-baffled (NB) and baffled cases with baffle width of 7 cm (BW7) and 11 cm (BW11), and their corresponding reduction percentages for H_L=70 cm

H_L=70 cm	NB	BW7	Reduction Percent	BW11	Reduction Percent
Harmonic F=0.95Hz, A=8 mm	17.75	4.50	74.65	2.75	84.51
Harmonic F=0.95Hz, A=4 mm	14.50	2.25	84.48	1.25	91.38
Harmonic F=0.95Hz, A=2 mm	8.50	1.50	82.35	0.75	91.18
Kocaeli	12.50	6.50	48.00	5.00	60.00
Loma Prieta	16.00	11.67	27.08	10.50	34.38
Chi-Chi	17.50	7.33	58.10	6.67	61.90

Table 2- Max sloshing heights (cm) in the floating-roof tank, subjected to harmonic and scaled seismic excitations in non-baffled (NB) and baffled cases with baffle width of 7 cm (BW7) and 11 cm (BW11), and their corresponding reduction percentages for H_L=50 cm

H_L=50 cm	NB	BW7	Reduction Percent	BW11	Reduction Percent
Harmonic F=0.93Hz, A=8 mm	19.75	4.75	75.95	3.00	84.81
Harmonic F=0.93Hz, A=4 mm	15.00	2.50	83.33	1.75	88.33
Harmonic F=0.93Hz, A=2 mm	10.00	1.50	85.00	1.00	90.00
Kocaeli	12.50	6.00	52.00	5.00	60.00
Loma Prieta	15.33	10.33	32.61	10.17	33.70
Chi-Chi	16.00	7.00	56.25	6.00	62.50

Table 3- Max sloshing heights (cm) in the floating-roof tank, subjected to harmonic and scaled seismic excitations in non-baffled (NB) and baffled cases with baffle width of 7 cm (BW7) and 11 cm (BW11), and their corresponding reduction percentages for H_L=20 cm

H_L=20 cm	NB	BW7	Reduction Percent	BW11	Reduction Percent
Harmonic F=0.73 Hz, A=8 mm	12.50	5.50	56.00	3.50	72.00
Harmonic F=0.73 Hz, A=4 mm	10.00	3.50	65.00	1.75	82.50
Harmonic F=0.73 Hz, A=2 mm	5.75	2.00	65.22	0.63	89.13
Kocaeli	6.50	5.50	15.38	4.75	26.92
Loma Prieta	8.00	7.67	4.17	6.42	19.79
Chi-Chi	8.00	6.50	18.75	5.67	29.17

The maximum sloshing heights, given in Table 1 to 3, were obtained based on the visual measurements through video capturing by using the four cameras installed around the tank. In cases of harmonic excitations the average of the maximum sloshing heights at two opposite sides of the tank during the steady state phase of the response, read on the installed gauges were considered. In cases of seismic excitations tests by using the simulated records of the three selected and scaled earthquakes, which were repeated three times for each earthquake to get more assured results, the average value of the absolute maximum sloshing heights in the three repetitions, read at either sides of the tank wall, were considered for comparison of non-baffled and baffled cases. One can see in Table 1 to Table 3 that in case of harmonic excitations the use of SABs has resulted in around 74 to almost 91 percent reduction in the maximum sloshing height for the case of H_L=70. This reduction percent is around 75 to 90 for the case of H_L=50, and 56 to around 89 for the case of H_L=20. For seismic excitations the amount of sloshing height reduction because of using SABs are around 27 to almost 62 percent for the case of H_L=70, around 33 to almost 63 percent for the case of H_L=50 cm, and around 4 to almost 29 percent for the case of H_L=20 cm, depending on the input earthquake and the SAB geometry.

5. Conclusions

Based on the results obtained from shake table tests conducted on a floating roof cylindrical tank model with various heights of the impounded liquid, subjected to both harmonic and seismic excitation, in two states of non-baffled and baffled (by using a suspended annular baffle hanging from the roof), the following conclusions can be made:

- The presence of the suspended annular baffle in the impulsive part of the impounded liquid is very effective in reducing the maximum sloshing height. The amount of this sloshing height reduction is in average around 80% and 40% in case of, respectively, harmonic and seismic excitations.
- In case of harmonic excitations the amount of sloshing height reduction slightly decreases with increase of the excitation amplitude.
- The amount of sloshing height reduction in case of seismic excitations is dependent, to a great extent, on the earthquake characteristics, and may vary from below 5% to over 60%.
- The amount of sloshing height reduction increases with increase of the height of impounded liquid in the tank. This implies that the use of suspended annular baffle is more effective in case of full tanks.
- The width of the annular baffle is very effective in sloshing height reduction, so that by increasing the baffle width from 7 cm to 11 cm the amount of reduction increases in average from around 12% to over 25% in case of seismic excitation, for the smallest height of the impounded liquid, which is the case with lowest efficiency of the annular baffle.

Other width, weight and stiffness values for the annular baffles as well as other weight and stiffness values for the floating roof can be considered to give more depth to the investigation. The numerical modeling for these considerations is now at hand as the second stage of the research.

6. Acknowledgement

This research was granted by the International Institute of Earthquake Engineering and Seismology (IIEES) as Research Project 593. The IIEES support is highly appreciated. Furthermore, the authors would like to express their genuine thanks to: a) Mr. Peyman Razavi, Mr. Reza Tayefi and Mr. Amirreza Soroor for their sincere helps, b) The Water Research Institute ("Water Research Institute,"), and particularly Mr. Sahand Akbarian Poorsalmasi, for their supports in manufacturing the Plexiglas sample tank used in the study, c) The personnel of the Structural Laboratory of the IIEES for all their efforts in conducting the tests.

7. References

[1] Cooper, T. (1997). A Study of the Performance of Petroleum Storage Tanks during Earthquakes, 1933–1995, NIST No. GCR 97-720. *US Dept. of Commerce, National Institute of Standards and Technology*.

[2] Nishi, H. (2008, Oct, 8). *Experimental Study of Floating Roof Integrity for Seismic Sloshing.* Paper presented at the API Storage Tank Conference 2008.

[3] Yamauchi, Y., Kamei, A., Zama, S. and Uchida, Y. (2006). *Seismic design of floating roof of oil storage tanks under liquid sloshing.* Paper presented at the ASME 2006 Pressure Vessels and Piping/ICPVT-11 Conference.

[4] Sezen, H., Elwood, K. J., Whittaker, A. S., Mosalam, K. M., Wallace, J. W. and Stanton, J. F. (2000). Structural Engineering Reconnaissance of the August 17, 1999 Earthquake: Kocaeli (Izmit), Turkey. Retrieved from http://peer.berkeley.edu/publications/peer_reports/reports_2000/0009.pdf

[5] Hatayama, K. (2013, September 25). *Sloshing Damage to Oil Storage Tanks due to Long-Period Strong Ground Motions during the 2011 Tohoku, Japan Earthquake.* Paper presented at the 10th International Workshop on Seismic Microzoning and Risk Reduction, at Sokairo Hall, GRIPS, Tokyo, Japan.

[6] Yumoto, G. (1968). Vibrations of Fluid and Floating Roof of a Tank during an Earthquake and Its Prevention Equipment. *Journal of Japan Society for Safety Engineering, 7*(3).

[7] Matsui, T. and Muto, A. (2005-2007). *浮屋根との連成を考慮した大型液体貯槽の地震時スロッシング応答とその抑止策,* Retrieved from https://kaken.nii.ac.jp/d/p/17360278.en.html

[8] Sakai, F. and Inoue, R. (2005). *Proposals of an earthquake-resistant floating-roof and an isolation system for larg-sized oil tanks.* Paper presented at the Proc. Mini-symp on earthquake-resistance, vibration control and isolation against sloshing of large-sized tank, JSCE, Tokyo.

[9] Sakai, F. and Inoue, R. (2008). Some considerations on seismic design and controls of sloshing in floating-roofed oil tanks, Proceedings of the 14th World Conference on Earthquake Engineering, October 12-17, Beijing, China.

[10] Jafarieh, F. (2012). *A Technique for Upgrading the Seismic Performance of Floating Roof Tanks.* (M.Sc.), Islamic Azad University, Tehran South Branch.

[11] Yuezhou, M. H. S. (2013). Passive control vibration reducing analysis of large elevated liquid-storage tank with outside floating roof under bidirectional earthquake. *Industrial Construction,* S1.

[12] Soroor, A. (2016). *Reducing the seismic sloshing in cylindrical storage single-deck floating roof tanks by using energy dissipaters.* (Dissertation), IIEES, Tehran, Iran., International Institute of Earthquake Engineering and Seismology (IIEES).

[13] Hosseini, M., Goodarzi, M. and Soroor, A. (2016). Reducing the seismic response of cylindrical storage single-deck floating roof tanks based on decreasing the sloshing height, Technical Research Report (under preparation), IIEES, Tehran, Iran.