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Reduction of seismic sloshing in floating roof liquid storage tanks by using a Suspended Annular Baffle (SAB)

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ABSTRACT

Sloshing in floating-roof cylindrical oil storage tanks subjected to earthquake has been known as a damaging phenomenon, resulting in devastating consequences such as sinking of the roof and/or vast destructive fires. Most of the previous studies have focused on clarifying the mechanism of the dynamic failure of floating roofs subjected to seismic loads. However, applicable remedies have been rarely suggested. In this paper, an innovative and practical method is proposed to reduce the floating roof motion during earthquakes, and an experimental study, conducted by shaking table to show the efficiency of this technique is presented. This new proposed passive control technique reduces the maximum sloshing height by using a Suspended Annular Baffle (SAB), hanging from the floating-roof by some strings with adjusted length, so that the baffle is located as much likely as possible inside the impulsive part of the fluid. The tests, conducted by using various baffle widths, included both sine sweeps and seismic excitations. The experimental results prove that using SAB reduces the maximum seismic sloshing height, in average, to almost 80% and 40% of its values of non-baffled case, respectively, for harmonic and seismic excitations, in a small model tank. Results also show that the presence of SAB reduces the swirling of the floating roof to a great extent. With regard to damping of the convective mode, the results of harmonic tests related to the highest depth of liquid in the tank show that the presence of floating roof increases the damping ratio almost 2.5 times, and the presence of SAB increases it more than 6 times comparing to the case with no floating roof. It is notable that the benefits of the SAB are not limited to only floating roof tanks, and in all cases in which sloshing may have adverse effects, such as elevated tanks, and other types of roofed and even open top tanks employing the SAB can be recommended as a sloshing reduction remedy.

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, and also for creating more pressure to increase the flow rate during the tank discharging. 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, which have been called Natech in recent decade (Girgin, 2011), have been observed in Anchorage earthquake of 1964 (Cooper, 1997),Niigata earthquake of 1964, Nihonkai-chubu (Japan sea) Earthquake of 1983 (Nishi, 2008); Yamauchi et al., 2006), Izmit earthquake of 1999 (Sezen et al., 2000), Tokachi-oki Earthquake of 2003 and Tohoku earthquake of 2011 (Hatayama, 2008; Hatayama, 2013). 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.

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Even in cases of minor damage to tanks due to earthquake, most of them have been related to floating-roof tanks (Cooper, 1997). As Cooper has reported, in Long Beach earthquake of 1933 sloshing in floating-roof tanks caused damage to seals. In Kern County earthquake of 1952 out of 9 damaged tanks 7 were floating-roof tanks. In the time period of 1951–2003 in total 480 fires have been identified, related to floating-roof tanks, almost with a growing trend (Persson and Lonnermark, 2004).

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. Sloshing in floating-roof tanks in Niigata earthquake of 1964 and Nihonkai-chubu (Japan sea) earthquake of 1983 induced devastating fires (Nishi, 2008). This was also the case in the Tokachi-oki earthquake of 2003 (Hatayama, 2008).

Sezen et al. (2000) have expressed that because fires burned out of control for several days in the tank farms, international attention was focused on the Tüpras refinery immediately following the earthquake. According to refinery staff the first major fire ignited in a floating-roof tank that contained naphtha, which is a highly volatile flammable liquid mixture distilled from petroleum. Many of the 100+ tanks in the Tüpras refinery farm were constructed with floating roofs. Sloshing of the fluid in the tank likely damaged the perimeter seal, which permitted the fluid to escape from the containment.

The inability of perimeter seals to retain the sloshing fluid in the tanks resulted in failure or sinking of these floating roofs. Each of the damaged floating roofs required repair or replacement before the tanks could be returned to service. Repair of the damaged or sunken roofs would have involved draining the tanks, decontamination of the roof, and replacement of the perimeter seals. Approximately 20 tanks in the Tüpras refinery farm were damaged or destroyed by fire.

In a study on the damages to liquid storage tanks occurred during the 1999 Kocaeli earthquake, (Yazici and Cili, 2008), it has been reported that more than 30 of the floating-roof Naphta tanks failed due to fires at the Tüpras refinery. In that study Yazici and Cili first have outlined the mechanical analogue systems to be used for calculating the overturning moment and the base shear in tank wall as well as the free surface displacements for cylindrical tanks subjected to horizontal base excitation. They have concluded that the frequency content of the base acceleration has a significant influence on the seismic response. Furthermore, they have pointed out that there is a need to check the reliability of existing tank farms, especially those built before the 70 s, with the current codes of design.

Yamauchi et al. (2006) have reported that the 2003 Tokachi-oki earthquake caused the severe damage to oil storage tanks by liquid sloshing. They have expressed that especially at Tomakomai in Hokkaido, the ground motions at the periods of 3–8 s predominated, which were harmonized with the natural period of liquid sloshing of oil storage tanks, causing damage to and sinking of seven single-deck-type floating roofs. In the 30,000 m^3 tank (42.7 m diameter), with about 7 s of fundamental sloshing period, maximum sloshing wave height was estimated 3 m and over. On the other hand, for the 100,000 m^3 tank (78.2 m diameter) with about 12 s of fundamental sloshing period, maximum sloshing wave height was estimated about 1.5 m and the excitation of 2nd sloshing mode was considered to be significant. Several cases of roof sinking and fires due to sloshing were observed in floating-roof tanks in Tokachi-oki earthquake of 2003 (Nishi, 2008).

With regard to Tokachi-oki earthquake of 2003 (Koketsu et al., 2005) have reported that several cases of severe damage were observed in floating-roof tanks in Tomakomai city. Also in Tohoku earthquake of 2011 several cases of sloshing related damages were observed in floating-roof tanks (Hatayama, 2013). As Hatayama has described, the main cause of fire in floating roof oil tanks subjected to earthquake is the spark created by collision of the floating roof edge with the top angle of the tank. Hatayama has claimed that lowering the oil level at tanks should prevent fires and spill-out of oil.

In dense tank farms like in Kharg, Iran, and special the farms containing LPGs, the fire is more crucial. This is while due to the fluid-roof interaction and the varying stiffness throughout the floating roof, the mechanism of dynamic motion of a floating roof is a complicated phenomenon. This is why the famous codes for storage tank design ignores the seismic stress inside the floating roof tanks. (As an example, API states in Annex E of the API Standard 650, the seismic design of floating roof is beyond the scope of this standard (API 650, 2013)).

Many researchers have attempted to clarify various aspects of floating roofs dynamic behavior and the consequences of its troublesome response to earthquake excitations. Some prevention techniques have been also proposed in this regard, among which reducing the maximum sloshing response seems to be a good solution. Based on the published literature the endeavors of researchers for reducing the sloshing amplitude in tanks goes back to late 60 s (Yumoto, 1968). (Matsui (2005–2007) studied on sloshing and dynamic interaction between liquid and floating roof in a storage tank under seismic excitation, they considered a cylindrical liquid storage tank with a uniform isotropic floating roof and single deck type floating roof. He has expressed that in order to prevent the damages of the floating roof, as experienced during the 2003 Tokachi-oki earthquake, the single-deck type roof is replaced by the double-deck type roof or the rib-stiffened roof.

Sakai and Inoue (2005) have suggested two opposite countermeasures for reducing the sloshing-related damages in floating-roof tanks, which include: a) increasing the rigidity of the floating roof, to prevent it from buckling, by adding some stiffeners or using double deck instead of single deck, and b) reducing the overall rigidity of the floating roof by putting rubber-like materials with very low rigidity and high capability of deformation intermittently in the radial and circumferential directions between double-deck or stiffening members, so that the floating-roof can be able to deform along the wave motion of sloshing, but be free from large stresses, and consequently keep the function. However, they have not mentioned to what extent these two countermeasures are effective.

The use of tuned liquid column damper (TLCD) has been also proposed and studied as a vibration control of floating-roof sloshing (Sakai and Inoue, 2008). They have shown that the maximum sloshing height at resonance can be decreased up to almost 50% by using an appropriate TLCD, however, they have expressed that to actualize this countermeasure more research is needed.

Seismic isolation has also been used as a remedy for reducing the sloshing response of floating roof tanks (De Angelis et al., 2010). In that experimental study on a steel liquid storage tank the effectiveness of the base isolation on the tank has been

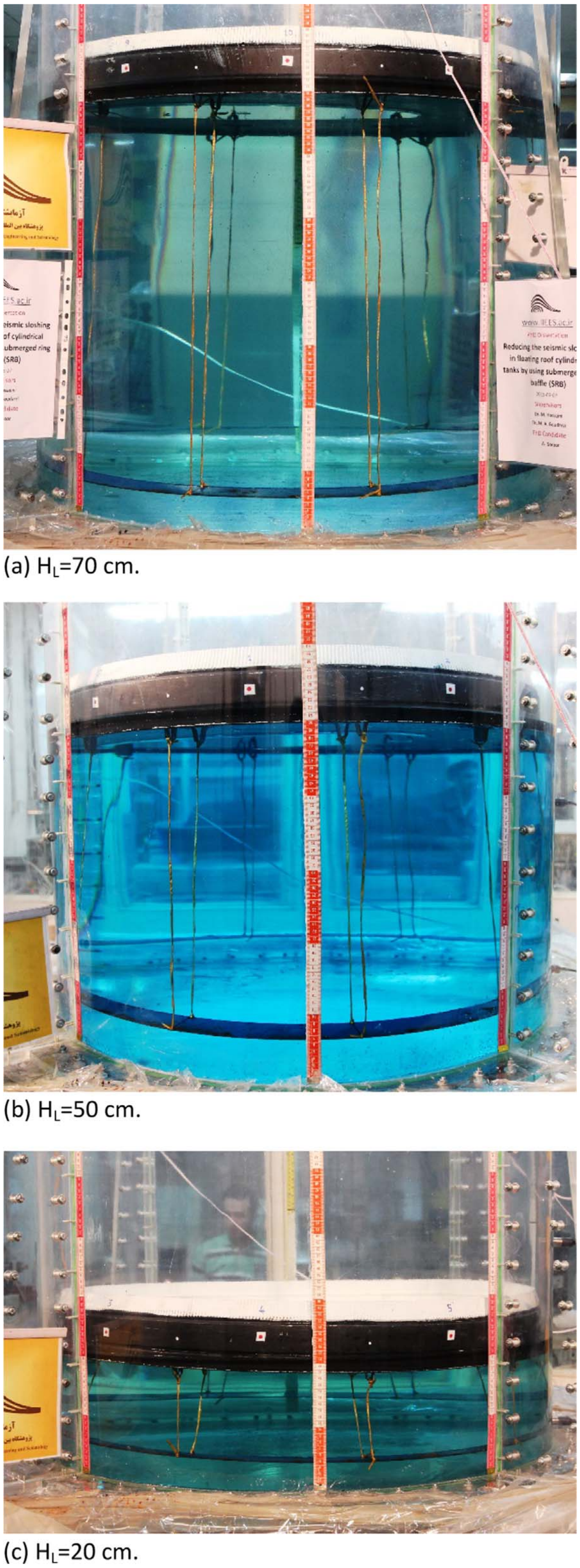


Fig. 1. Side views of the test tank with floating roof and SAB installed on the shake table in the three cases of roof-to-bottom distance of a) 70, b) 50 and c) 20 cm (the vertical meters with 10-cm red and white segments are also seen in the pictures).

investigated through numerical models and then checked by shaking table tests on a reduced scale (1:14) model of a real steel tank, typically used in petrochemical plants. The tests have been performed on the physical model both in fixed and isolated base configurations; in particular, two alternative base isolation systems have been used: 1) high-damping rubber bearings devices, and 2) sliding isolators with elasto-plastic dampers. Their results show the effectiveness of both isolator typologies in reducing the total pressure generated by the earthquake on the tank wall. On the contrary, a low increase of the oscillation amplitude of the liquid surface, consequently of the floating roof, has been observed.

A technique similar to the second countermeasure proposed by Sakai and Inoue (2005) has also been suggested based on reducing the overall rigidity of the floating roof by dividing the floating roof to several parts in the radial and circumferential directions and using soft material with high capability of deformation between those parts, so that the floating-roof can be able to deform consistent with the liquid surface motion during sloshing, but be free from large stresses (Jafarieh, 2012). It should be noted that although this countermeasure is very effective in reducing the stress values in the roof, it is not much effective in reducing the sloshing height.

As another countermeasure for reducing the sloshing effect, installing either viscous or frictional damper between the floating roof and rigid wall of the tank, as a passive control tool has been studied (Haiyan and Yuezhou, 2013). It has been shown that the amplitude of fluid sloshing, the vertical compressive stress, the hoop tensile stress and the height of the bottom tank uplift are all reduced by installing dampers. The results have also illustrated that the seismic response of the large elevated liquid-storage tank can be effectively reduced by erecting different types of dampers, however, the specifications of viscous and frictional dampers and the details their installation have not been given in that study.

In the previous studies it has also been tried to analytically formulate the various aspects of a floating roof dynamic behavior. Those studies mostly have been focused on determining the seismic stress in various parts of a floating roof. Evaluating these stresses is a key factor to seismically strengthen and rehabilitate this type of floating roofs. In this regard, comprehensive studies have been recently accomplished by Goudarzi (2013, 2014, 2015a, 2015b).

It is seen that the previous studies mostly have focused on clarifying the mechanism of seismic behavior of floating roofs and their consequent damages. In fact, they have rarely addressed the applicable methods for preventing those damages. In the present study, a new passive control technique for reducing the Maximum Sloshing Height (MSH) by using a Suspended Annular Baffle (SAB) is proposed. The effectiveness of the proposed method is examined in a small model tank by various shaking table tests. The details of the conducted experiments as well as discussion about the measurements are presented in the following sections.

2. Methodology

To evaluate the effectiveness of proposed method based on using SAB, a series of shake table tests on a tank model, were considered. The tests were conducted in the structural laboratory of the International Institute of Earthquake Engineering and Seismology (IIEES).

2.1. The test set-up

The test tank, made in the Water Research Institute, Tehran, Iran, was a cylindrical tank with 99 cm and 101 cm internal and external diameters, respectively (100 cm in average). The shell of the tank was made of Plexiglas (with 1 cm thickness) to benefit from its transparency, which facilitated visual observation and inspection of the fluid sloshing and roof movements. Fig. 1 shows side views of the test tank, with floating roof and SAB, installed on the used shake table in the three cases of roof-to-bottom distance of 70, 50 and 20 cm.

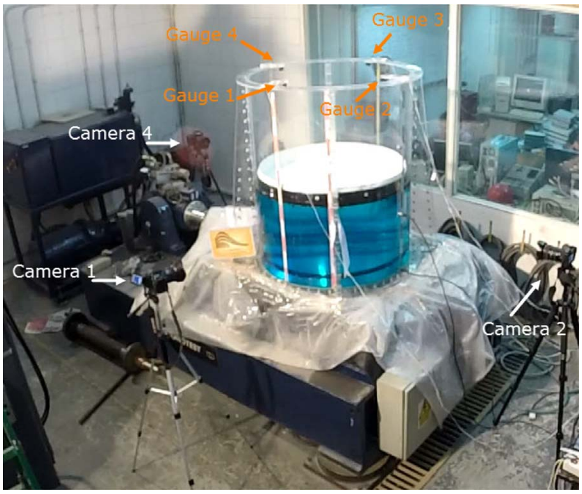


Fig. 2. A bird's-eye view of the test tank on the shake table (cameras 1, 2, and 4 as well as the four used gauges are can also be seen in the picture).

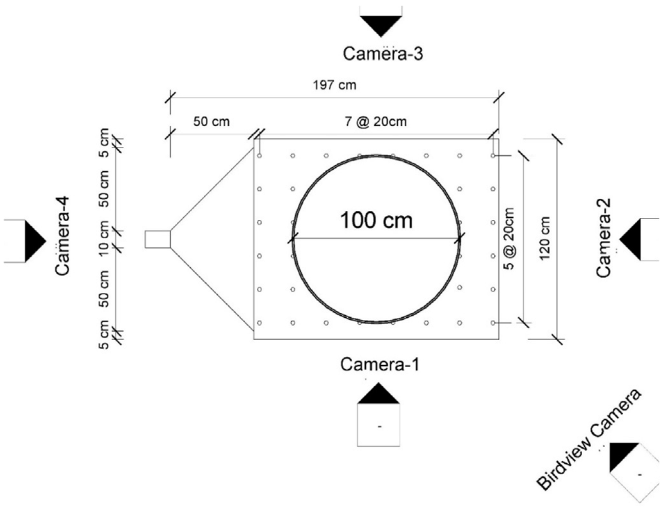


Fig. 3. Geometric details of the shake table along with the location of cameras used in the tests.

The floating roof was made of steel plate with a thickness of 0.5 mm and its weight was 5.05 kg. In order to increase the stability of the floating roof, its edge was vertically folded, as shown in Fig. 1, creating a ring wall of 11 cm height (lower part in black and upper part in white). This relatively large height in addition to increasing the stiffness of the floating roof, was helpful in preventing the roof from sinking. Fig. 2 depicts a bird's-eye view of the tank installed on the shake table, in which the used cameras as well as the used gauges for measuring the floating roof fluctuations are also seen.

Fig. 3 shows the geometric details of the shake table along with the location of cameras used in the tests, and Fig. 4 depicts the schematic view and details of the test tank and its floating roof as well as the used SABs.

Two different width values of 7 and 11 cm were considered for the SAB to investigate the effect of this parameter on the sloshing

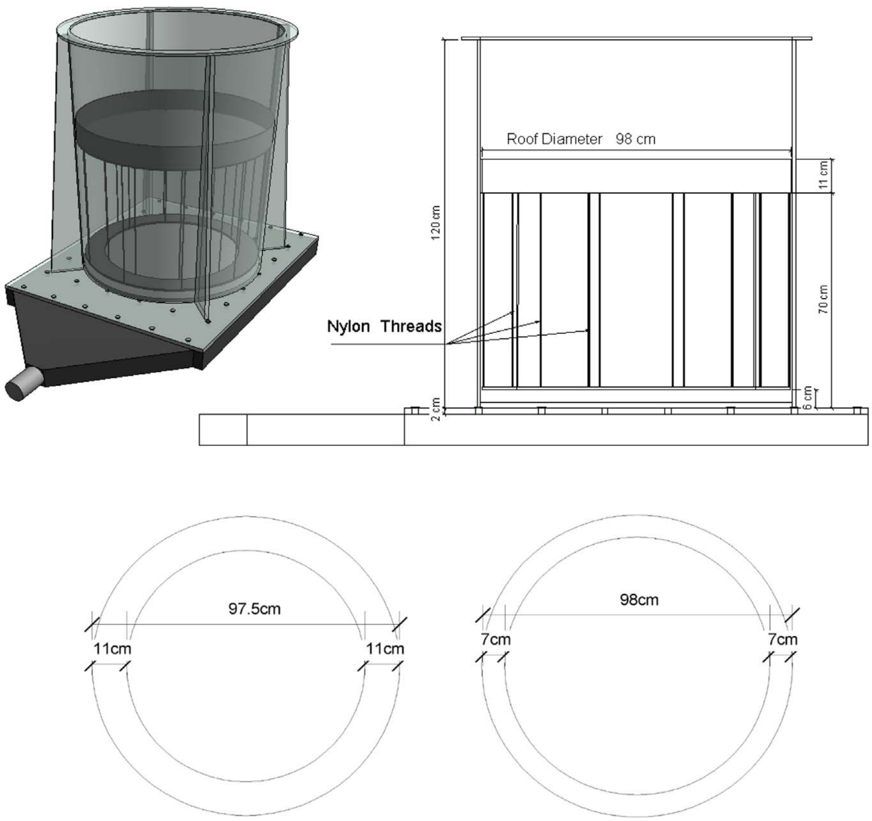


Fig. 4. The perspective and details of the floating roof as well as the used SABs with 7 and 11 cm width (the nylon threads used for hanging the SAB from the floating roof are also shown).

(a)

(b)

Fig. 5. Connecting the annular baffle to the roof by using nylon threads in case of a) BW7 adjusted 20 cm below the roof, and b) BW11, adjusted 70 cm below the roof.

height. The SAB (made of steel plate) with Baffle Width of 7 cm (BW7) had a thickness of 2 mm and a weight of 3.03 kg, and the one with Baffle Width of 11 cm (BW11) was 1.5 mm thick with a weight of 3.33 kg (there was almost 10% difference in the weight of the two SABs). To connect the annular baffle to the floating roof some nylon threads with adjusted length were used as shown in Fig. 5.

The length of nylon threads was adjusted in all cases so that the annular baffle is placed almost 6 cm above the tank bottom. This distance was considered, based on experience, to prevent the annular baffle from collision to the tank bottom. As shown in the Fig. 5, at each location in radial direction two threads were used to make the baffle more stable.

The used shake table was unidirectional with 6 cm stroke capable of producing harmonic sine motions with various frequencies and amplitude up to 3 cm, as well as simulated single-component earthquake motions. The base excitations considered for the tests included a series of harmonic excitation with frequency of the first mode of sloshing in each case, as well as three selected seismic excitations.

2.2. Natural frequencies

The frequency of the first sloshing or convective mode (F_C), used for harmonic excitations, was calculated by using the relationships given in (ACI-350) code, which results in formula (1) for the angular frequency of sloshing as a function of the liquid height (H_L) and diameter in the tank:

Table 1
The angular frequencies of first mode of sloshing for various considered liquid depth values.

H_L (cm)	ω_c (rad/sec)	f_c (Hz)
20	4.8	0.76
50	5.9	0.93
70	6	0.95

$$F_c = \frac{\sqrt{3.68 g \tanh[3.68 \ (\frac{H_L}{D})]}}{2\pi\sqrt{D}} \tag{1}$$

Where g is acceleration due to gravity (32.17 ft/s^2), H_L (in feet) is the design depth of stored liquid or the height of the liquid surface above the tank bottom, and D (in feet) is the inside diameter of tank. It should be mentioned that the value of $\boldsymbol{\omega_c}$, given by formula (1) in rad/sec, is related to the case of free-surface liquid. However, in a study on sloshing behavior of floating-roof oil storage tanks through theoretical analysis and model testing (Sakai et al., 1984), it has been shown that the existence of floating roofs hardly affects the first natural mode of sloshing. On this basis the frequency values, given by formula (1) for the free-surface cases, were used in this study for the cases of the presence of floating roof as well. These values are given in Table 1 for the three considered liquid depth values of 20, 50, and 70 cm.

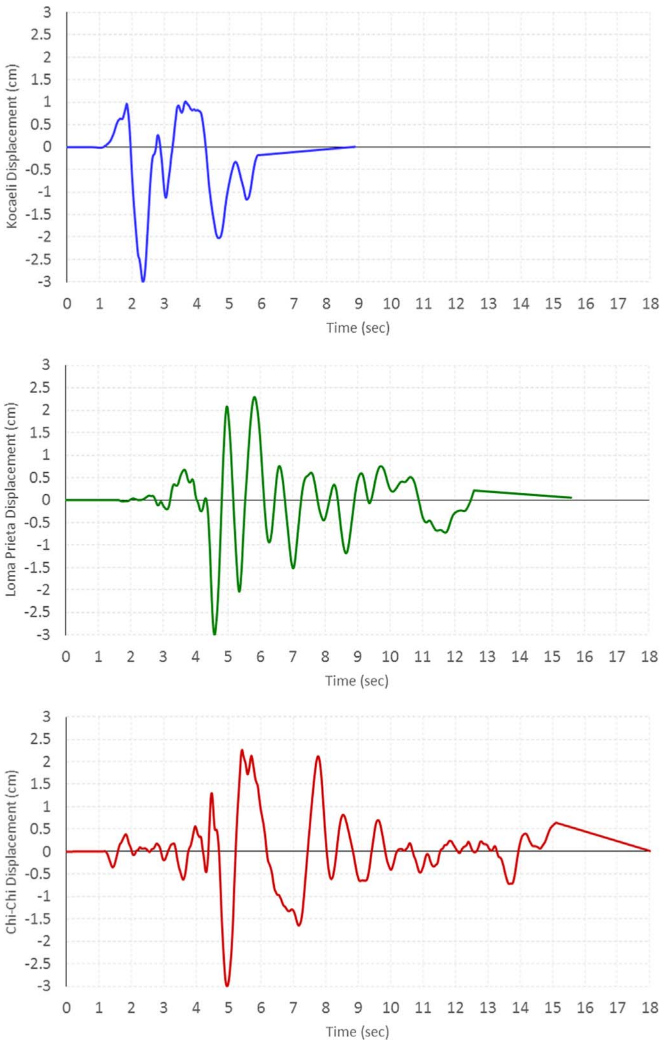


Fig. 6. Displacement histories of the scalded records of the selected earthquakes used in the shake table tests.

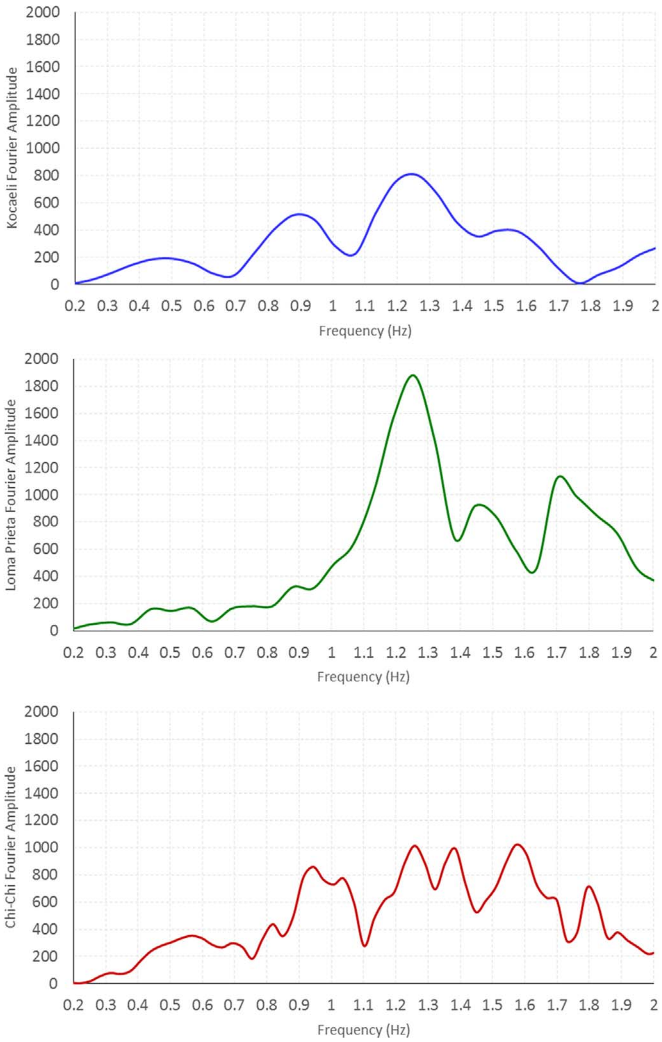


Fig. 7. Fourier Amplitude spectra for acceleration of the scalded records of the selected earthquakes used in the shake table tests.

2.3. The applied excitations

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

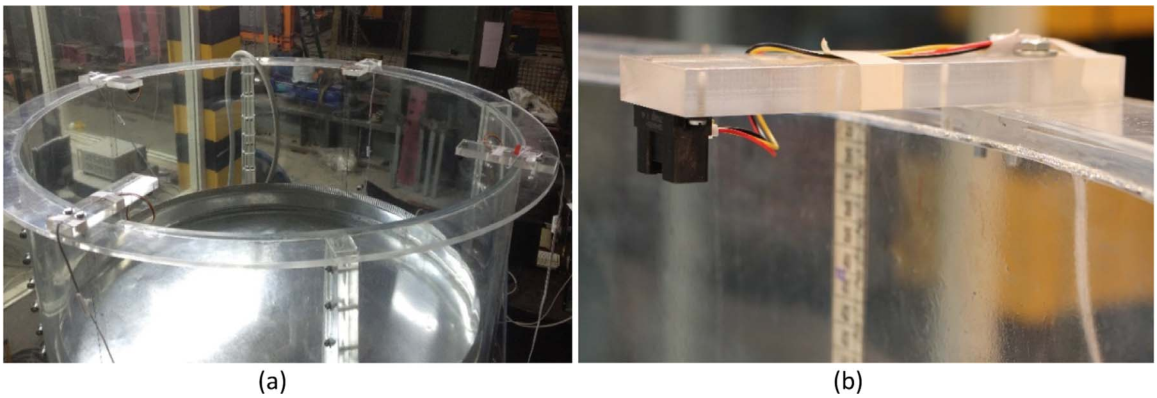


Fig. 8. a) Four installed gauges (Sharp-GP2Y0A02YK sensors) on the tank top ring for measuring the sloshing height, and b) close-up of one of the gauges.

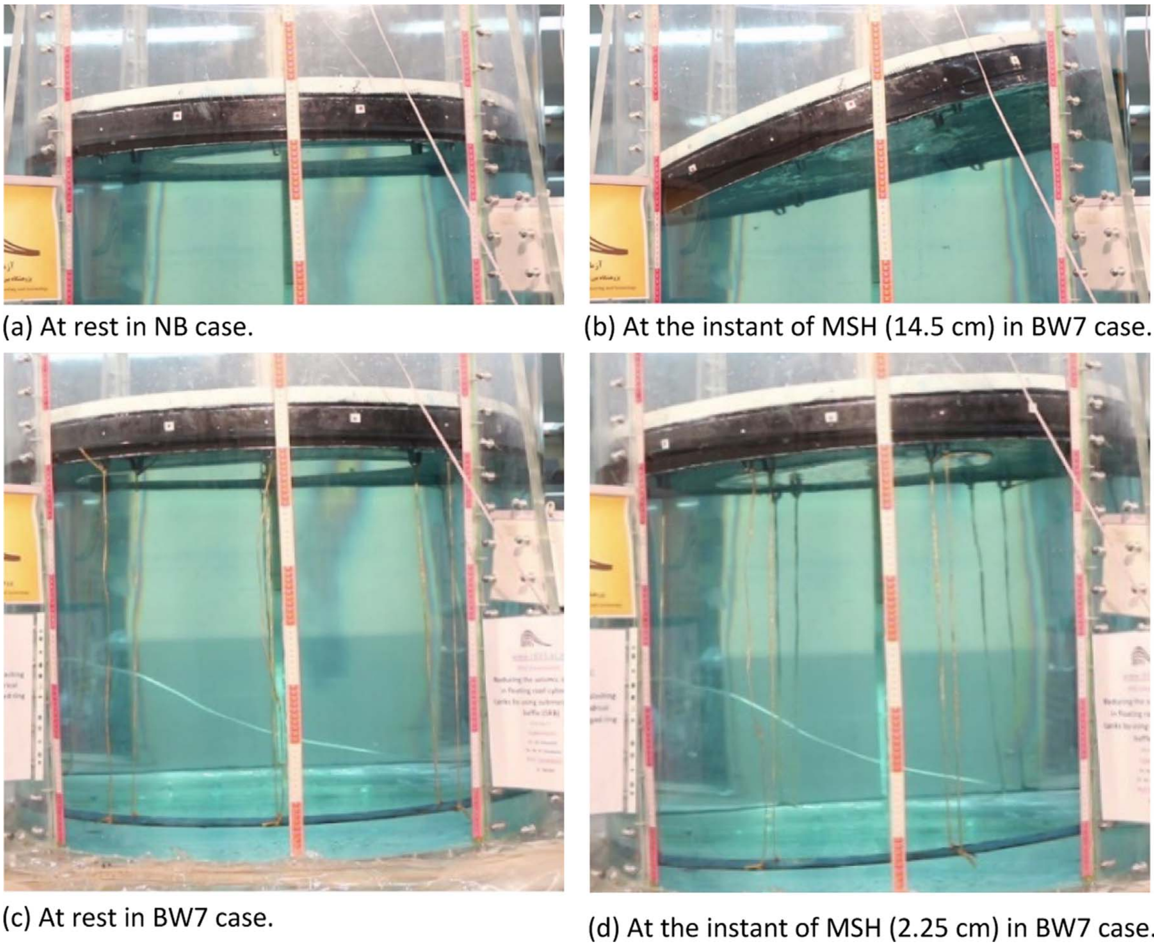


Fig. 9. The side view of the tank forms the position of camera 1 for H_L=70 cm, both at rest and at the instant of MSH due to harmonic excitation with amplitude of 4 mm and frequency of 0.95 Hz in both NB and BW7 cases.

main components of Kocaeli, Turkey earthquake of 1999, Loma Prieta earthquake of 1989 (Emeryville Station) and Chi-Chi, Taiwan earthquake of 1999 (all records were selected from the set of accelerograms of Seismosignal software, version 5.0.0). The time step size of these records were modified so that their dominant frequencies get close to the considered sloshing frequencies, given in Table 1. Also their amplitudes 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. 6, along with their corresponding acceleration Fourier amplitude spectra in Fig. 7, developed by using version 5.1.0 2016 Seismosignal software.

It is seen in Fig. 6 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. 7, one can realize that the scaled Chi-Chi earthquake record has the highest Fourier Amplitude in the frequency range of 0.75–0.95 Hz, which is the range of the frequencies of the first sloshing mode of the liquid for the three considered depths as shown in Table 1.

2.4. The used displacement-meter sensors

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 (Sharp-GP2Y0A02YK sensors) installed at the top ring of the tank as shown in Fig. 8.

(a) Bird view at the instant of MSH (14.5 cm) in NB case.

(b) Bird view at the instant of MSH (2.25 cm) in BW7 case.

Fig. 10. The bird's-eye view of the tank for H_L=70 cm at the instant of MSH due to harmonic excitation with amplitude of 4 mm and frequency of 0.95 Hz in both NB and BW7 cases.

3. The tests' results

Fig. 9 shows the side view of the tank from the position of camera 1 for H_L=70 cm, both at rest and at the instant of MSH due to harmonic excitation with amplitude of 4 mm and frequency of 0.95 Hz in both Non-Baffled (NB) and BW7 cases.

The bird's-eye view of the tank and the corresponding side views from Cameras 1, 2 and 4 for H_L=70 cm at the instant of MSH due to harmonic excitation with amplitude of 4 mm and frequency of 0.95 Hz in both NB and BW7 cases are shown respectively in Figs. 10 and 11.

It should be noted that the suspending threads are kept taut when they are in tension during the oscillation, as expected. However, when the threads are not in tension they cannot be kept taut, and of course this does not have much adverse effect on the performance of the SAB. Two samples of the test outputs, related to the vertical fluctuation time histories of the floating roof in non-baffled and baffled cases are presented here. These samples, which are related to harmonic excitations with amplitude of 4 mm and frequency of 0.95 Hz for liquid depth of 70 cm, obtained by gauge 2 (Sharp-GP2Y0A02YK sensors – see Fig. 8), and filtered by Butterworth Filter of MATLAB software, version R2016a, are shown in Fig. 12.

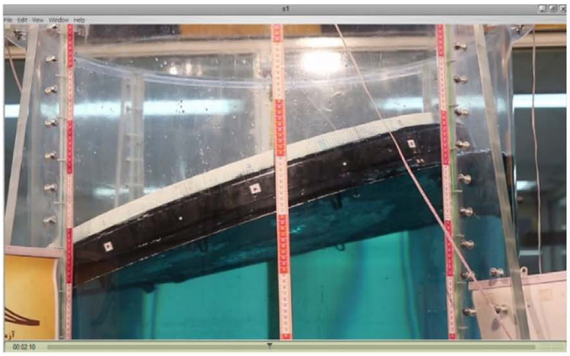
It is seen in Fig. 12 that using SAB decreases the MSH to a great extent, however, as it is observed in this figure, the effect of baffle on the sloshing period is negligible. In the test of which the results are shown in Fig. 12 the harmonic excitation was stopped at the 24th sec of the test, and from this instant the free vibration took place. The exponential reduction of the free vibration amplitude was used for calculating the damping ratio of the sloshing oscillations in both non-baffled and baffled cases. For this purpose, the peak values of the responses were obtained from Fig. 12 and then an exponential trendline was found as shown in Fig. 13, and finally by using the found trendline function the damping ratios were calculated by using Formula (2), which is valid for small values of damping ratio (Clough and Penzien, 2003).

$$\xi = \frac{\ln\left(\frac{\upsilon_n}{\upsilon_{n+m}}\right)}{2m\pi} \tag{2}$$

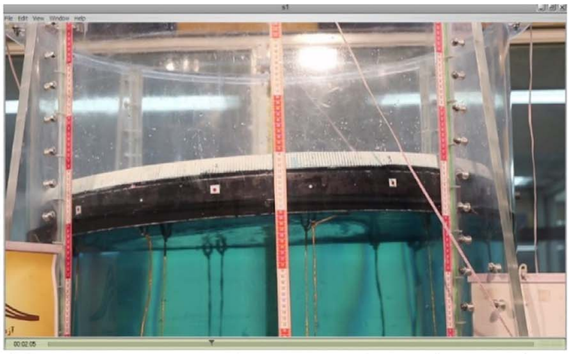
In Formula (2) ξ is damping ratio, υ_n is the sloshing height at the instant of the first peak after the start of free vibration based on trendline function, υ_{n+m} is the sloshing height at the last peak was considered based on trendline function, m is the number of cycles after the first peak up to last peak considered. On this basis the values of damping ratio for non-baffled and baffled cases are obtained, respectively, as:

$$\xi_{NB} = \frac{\ln\left(\frac{9.680}{3.244}\right)}{2*13*\pi} = 0.013$$

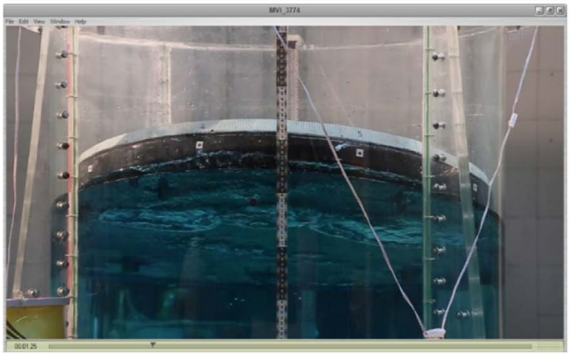
and



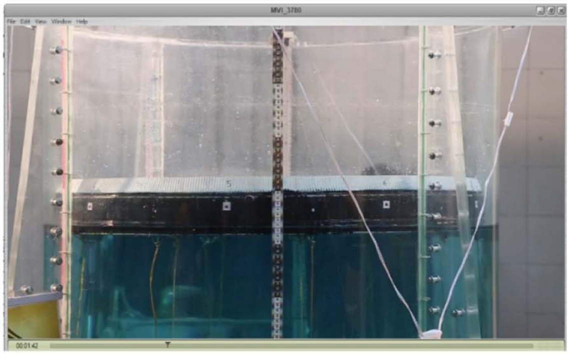
(a) Camera 1 view at the instant of MSH (14.5 cm) in NB case



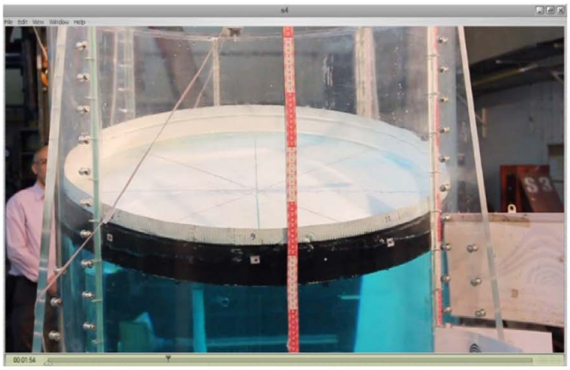
(b) Camera 1 view at the instant of MSH (2.25 cm) in BW7 case



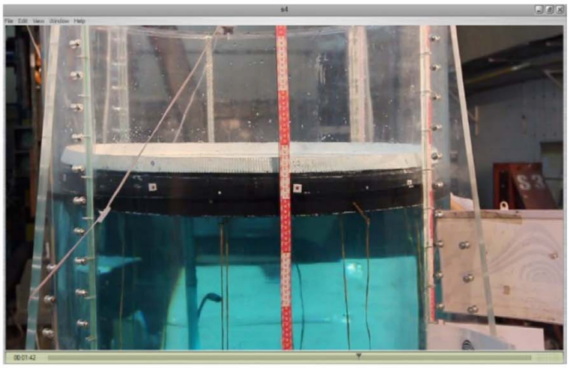
(c) Camera 2 view at the instant of MSH (+14.5 cm) in NB case



(d) Camera 2 view at the instant of MSH (+2.25 cm) in BW7case



(e) Camera 4 view at the instant of maximum sloshing height (-14.5 cm) in NB case



(f) Camera 4 view at the instant of maximum sloshing height (-2.25 cm) in BW7case

Fig. 11. Side view of the tank from Cameras 1, 2 and 4 for H_L=70 cm at the instant of MSH due to harmonic excitation with amplitude of 4 mm and frequency of 0.95 Hz in both NB and BW7 cases.

$$\xi_{BW7}= \frac{\ln\left(\frac{1.584}{.096}\right)}{2*13*\pi}=0.034$$

Looking at these two values one can realize that firstly The presence of the floating roof results in almost 2.5 times increase in the damping ratio (the API 650 recommended values 0.005 for the convective mode (API 650, 2013)), and secondly the presence of the SAB makes this increased damping almost 2.5 times again.

Based on the two cases of the tests, of which the results are shown in Fig. 12, a short video clip has been prepared which compares NB case with BW7 case (the video can be watched in the corresponding website of the journal). More samples of response histories similar to those shown in Fig. 12 can be found in the main reports of the study (Soroor, 2017; Hosseini et al., 2017).

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.jfluidstructs.2017.02.008.

The complete set of tests' results of the MSH in each one of test cases, including cases without SAB as well as cases with SAB with

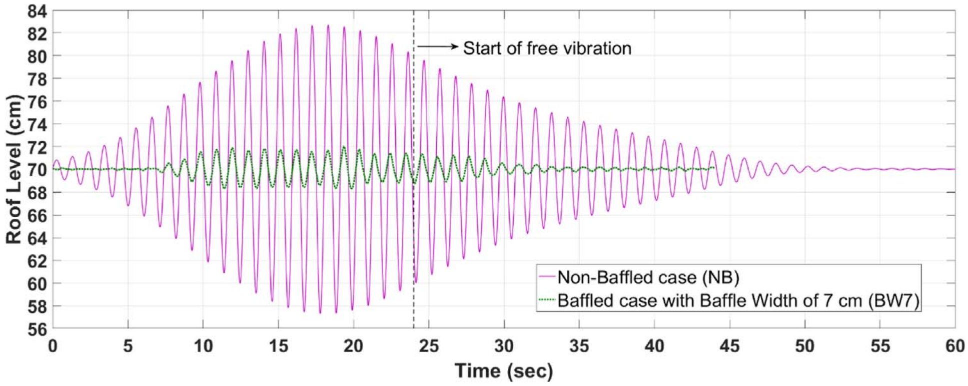


Fig. 12. The vertical displacement histories of the floating roof, obtained by gauge 2 in NB and BW7 cases, filtered by Butterworth Filter of MATLAB software, related to harmonic excitations amplitude of 4 mm and frequency of 0.95 Hz in case of liquid depth of 70 cm.

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 Table 2, respectively for H_L=70, 50 and 20 cm.

The MSHs, given in Table 2, were obtained based on the visual measurements through video capturing by using the four cameras installed around the tank as shown in Figs. 2 and 3. In cases of harmonic excitations, the average of the MSHs at two opposite sides of the tank during the steady state phase of the response. 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 MSHs in the three repetitions, were considered for comparison of non-baffled and baffled cases. One can see in Table 2 that in case of harmonic excitations the use of SABs has resulted in around 74 to almost 91% reduction in the MSH for the case of H_L=70. This reduction percent is around 75–90 for the case of H_L=50, and 56 to around 89 for the case of H_L=20. It is observed that for higher tank aspect ratio (H_L/D), the effectiveness of the proposed SABs is more. This can be mainly due to the fact that the depth of impulsive portion of liquid, is more for these tanks. Therefore, using SABs is more effective for slender tanks.

It can also be realized form the presented results that the amount of sloshing height reduction slightly decreases with increase of the excitation amplitude. To suggest a reason for this observation it can be said that the sloshing height is naturally more for higher excitation amplitude, meaning that the SAB also is pulled up higher with the roof, and therefore it takes more time for it to return back to its original level, but before it reaches its original level and while the connecting threads are still slack, the roof moves upward again, and naturally some portion of its upward movement is required for compensation of the thread's slackness. Therefore, the baffle cannot work effectively for some instants.

It should be mentioned that no prevention was made against swirling of the floating roof in the tests. By thorough investigation of the test videos (getting help from the white squares with red spots stuck on the black colored ring wall of the floating roof, which can be seen in the tank pictures - see Fig. 1 for example) related to harmonic excitations with amplitude of 4 mm and frequency of 0.95 Hz in case of liquid depth of 70 cm, it was realized that in non-baffled case the floating roof did around 78° swirling counterclockwise (looking downward at the roof) and then returned back (clockwise) around 87°. This is while in baffled case the roof did only 31° counterclockwise swirling. This observation show that the presence of SAB can significantly decrease the roof swirling.

For scaled seismic excitations the amount of sloshing height reduction because of using SABs are around 28 to almost 62% for the case of H_L=70, around 32 to almost 62% for the case of H_L=50 cm, and around 4 to almost 29% for the case of H_L=20 cm, depending on the input earthquake and the SAB geometry. For harmonic excitations the amount of sloshing height reduction

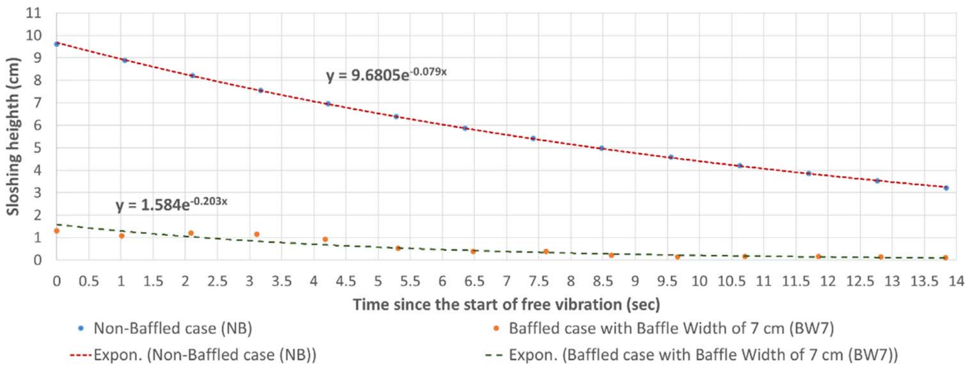


Fig. 13. The exponential reduction of free vibration amplitudes of sloshing liquid in tank, extracted from Fig. 12 in both non-baffled and baffled cases.

Table 2
MSHs (cm) in the floating-roof tank (obtained by video capturing), subjected to harmonic and scaled seismic excitations in NB and BW7 and BW11 cases, and their corresponding reduction percentages for three values of H_L=70, 50, and 20 cm.

H (cm)	Excitation	MSH (cm)		Reduction Percent (%)	MSH (cm)	Reduction Percent (%)
		NB	BW7		BW11	
70	**Harmonic F=0.95 Hz, A=8 mm**	20.00	4.50	77.50	2.75	86.25
	Harmonic F=0.95 Hz, A=4 mm	14.50	2.25	84.48	1.25	91.38
	Harmonic F=0.95 Hz, A=2 mm	8.50	1.50	82.35	0.75	91.18
	Kocaeli	12.67	6.50	48.68	5.00	60.53
	Loma Prieta	16.33	11.67	28.57	10.50	35.71
	Chi-Chi	17.67	7.33	58.49	6.67	62.26
50	**Harmonic F=0.93 Hz, A=8 mm**	19.75	4.75	75.95	3.00	84.81
	Harmonic F=0.93 Hz, A=4 mm	15.00	2.50	83.33	1.75	88.33
	Harmonic F=0.93 Hz, 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
20	**Harmonic F=0.76 Hz, A=8 mm**	12.50	5.50	56.00	3.50	72.00
	Harmonic F=0.76 Hz, A=4 mm	10.00	3.50	65.00	1.75	82.50
	Harmonic F=0.76 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

because of using SABs are around 74 to almost 91% for the case of H_L=70, around 75 to almost 90% for the case of H_L=50 cm, and around 56 to almost 89% for the case of H_L=20 cm, depending on the input amplitude and the SAB geometry. For better comparison of the MSH in various cases, presented in Table 2 they are shown graphically in Fig. 14.

It is observed in Fig. 14 that in cases of harmonic excitations the MSH is almost proportional to the excitation amplitude, and that the SAB of 11 cm width is more effective in reducing the sloshing height than the SAB of 7 cm width, as expected, because of more drag forces. In cases of seismic inputs, all earthquake displacement records were scaled to have 3.0 cm maximum amplitude (due to the shake table limitations), as shown in Fig. 6, however, the MSHs are different for the three earthquakes. These maximum heights are not even proportional to the maximum spectral Fourier amplitude of the scaled records, shown in Fig. 7. It is seen in this figure that the Fourier amplitudes of Chi-Chi, Loma Prieta and Kocaeli scaled earthquakes are respectively 600, 300, and 400 cm/s^2 in average in frequency range of 0.7–1 Hz, implying that the sloshing height due to Chi-Chi and Loma Prieta records should be respectively the highest and the lowest. But, as it is seen in Fig. 14, Loma Prieta record, which has the Fourier amplitude lower than Kocaeli, has resulted in larger sloshing response than Kocaeli record. The reason behind this fact is the nearly two complete cycles of harmonic motion of the ground surface in Loma Prieta earthquake during the strong motion phase happening between time instants of 4.5 and 6.5 s, as seen in Fig. 6. As this figure shows, this is not the case for Kocalei earthquake record.

It should be noted that in this research the SAB was located in a distance of almost 6 cm above the tank bottom (to prevent it from collision to the tank bottom during sloshing) regardless of the height of the impounded liquid in the tank. This means that in case of larger heights of the impounded liquid a big portion of the impulsive part of the liquid was above the annular baffle, while in case of smaller heights of the impounded liquid a little portion of the impulsive part was above the baffle, or the baffle was actually in the lower portion of the convective part of the liquid, resulting in its lower efficiency in sloshing height reduction. To resolve this limitation of the study employing a larger tank seems necessary. Also it should be notified that to apply the SAB in real liquid storage tanks, it seems that the length of the linking strings (cables or chains) need to be controlled to respond to the liquid depth changing frequently during the periods of operation and inspection. For this purpose, an engineering solutions, such as use of multi-level baffles, or some fixing-and-releasing mechanism or device can be thought of. However, based on the results of this study it can be said that, since the cases of fire and roof sinking have been reported mostly for tanks which have been over half-full (Hatayama, 2008), by fixing the length of the linking strings to hold the SAB at the tank bottom when the tank is half-full (to make the maximum benefit from the impulsive portion of the liquid), in full case the SAB will be located in the lower one third of the convective portion of the liquid, which can still reduce the sloshing height (as it was observed in case of H_L=20 cm, approximately).

Moreover, by numerical and/or analytical modeling of the tanks with larger sizes and validation and verification based on the results of this study the abovementioned limitation can be better resolved. Using other width, weight and stiffness values for the annular baffles, and even other shapes or forms (for example perforated circular baffle) as well as other weight and stiffness values for the floating roof can be considered to give more depth to the investigation. The analytical modeling for these considerations is now at hand as the second stage of the research.

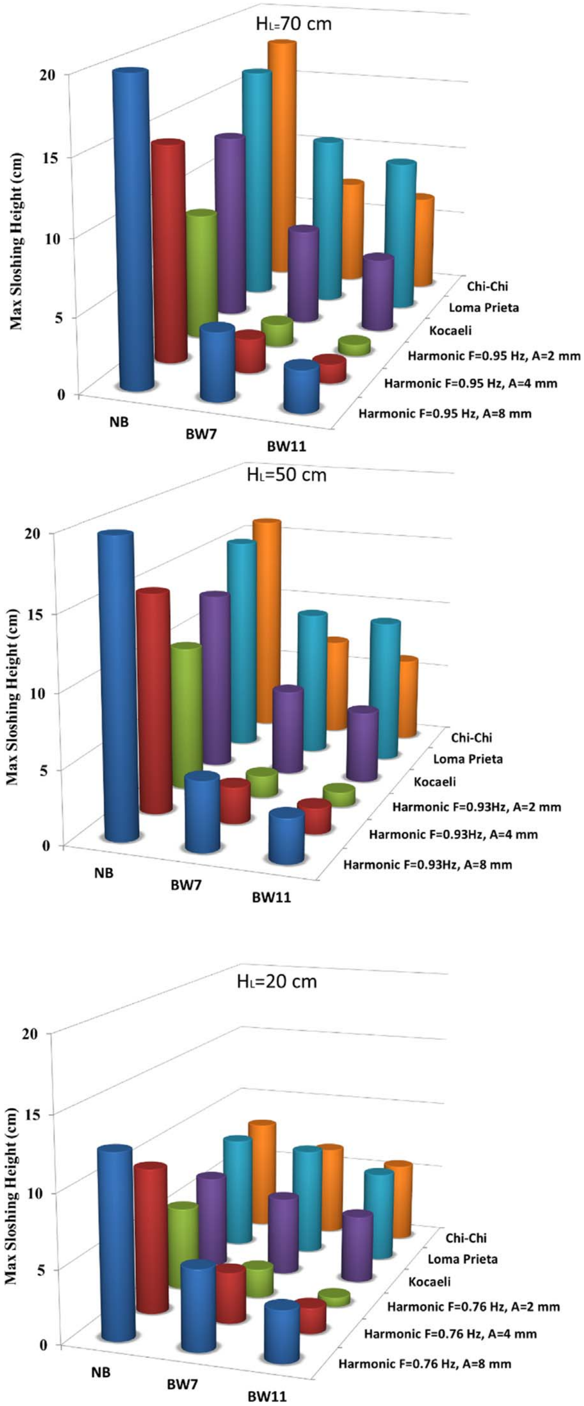


Fig. 14. MSH (cm) in the floating-roof tank (obtained by video capturing), subjected to harmonic and scaled seismic excitations in NB, BW7 and BW11 cases for H_L=20 cm.

4. Conclusions and future prospects

In this study, an innovative technique based on using Suspended Annular Baffle (SAB), which is in fact a movable baffle hanging from the floating roof of the tank has been proposed. The effectiveness of the proposed technique was experimentally investigated and the results confirms the validity of the suggested method to prevent the large sloshing displacement of the floating roof. Shaking table tests were conducted on a floating roof cylindrical tank model with various heights of the impounded liquid, subjected to both harmonic and seismic excitation, in non-baffled and baffled cases. From the results of the experiments, the following conclusions can be made:

1) The presence of the SAB in the impulsive part of the impounded liquid is very effective in reducing the Maximum Sloshing Height (MSH). The amount of reduction is 85% and 50% in average (H_L=70 and H_L=50), for harmonic and seismic excitations, respectively.
2) The presence of the SAB in the lower portion of the convective part of the impounded liquid is also effective in sloshing height reduction. In this case the reduction percent is around 70% and 20% (H_L=20), for harmonic and seismic excitations, respectively.
3) In case of harmonic excitations, the amount of MSH reduction slightly decreases with increase of the excitation amplitude.
4) The presence of the SAB does not have any significant effect on the sloshing period of the liquid-floating roof system.
5) The presence of the floating roof results in almost 2.5 times increase in the damping ratio of fluid-roof system, and the presence of the SAB makes this increased damping almost 2.5 times again.
6) In case of seismic excitations, the MSH reduction depends, to a great extent, on the earthquake characteristics.
7) For higher tank aspect ratio (H/D), the use of the SAB is more effective, since the depth of impulsive portion of liquid is more for these tanks.
8) The width of the annular baffle has a reasonable effect on the amount of MSH reduction, so that by increasing the baffle width from 7 cm to 11 cm, the amount of reduction increases in average from around 35% to over 43% in case of seismic excitations and from around 75% to over 86% in case of harmonic excitations.
9) The presence of the SAB is also effective in reducing the swirling of the floating roof to a great extent.

It is notable that the benefits of the SAB are not limited to only floating roof tanks. In fact, in all cases in which sloshing may have adverse effects, such as elevated tanks, and other types of roofed and even open top tanks employing the SAB can be recommended as a sloshing reduction remedy. Finally, it should be noted that this research was limited to a small tank sample. To get more generalized conclusions, further experimental, analytical and numerical researches are required.

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