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Seismic behavior of submerged spent fuel trays stack with and without base isolators

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ABSTRACT

Seismic isolation systems are widely used between the base and foundation of structure to reduce the peak response acceleration of the structure. No detailed studies are available on effect of isolators on stability of submerged spent fuel trays stack in spent fuel pools/tanks. For the safety requirements, the trays stack should not collide with neighboring stacks and fuel bundles should not fall from trays during design basis seismic event. Nonlinear dynamic behavior of spent fuel trays stack submerged in water contained in Spent Fuel Storage Tank (SFST) with and without base isolators has been investigated. Lead Rubber Bearings (LRBs) have been used as base isolation system. Behavior of the system is highly non-linear due to presence of gap, friction among trays and pool floor and hydrodynamic pressure on stack and side walls of the pool. A shake table testing of full scale 30 trays stacks submerged in SFST is carried out with and without base isolators. Response parameters like acceleration, displacement, fundamental frequencies of stacked trays and tank were recorded, analyzed and discussed in the paper.

INTRODUCTION

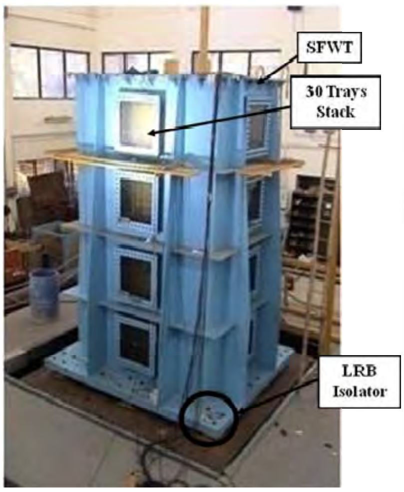
In recent years, seismic base isolation systems are extensively used between the base and foundation of structure to reduce the peak response acceleration of the structure. There have been several studies and research to investigate the effectiveness of seismic isolation for buildings and water tank. Kim and Lee (1995) experimentally studied seismic performance of liquid storage tanks isolated by elastomeric bearings and found that the isolators are useful in reducing the peak acceleration of tank. Chalhob and Kelly (1990), Shrimali and Jangid (2004) studied seismic performance of liquid storage tanks isolated by elastomeric bearings and found that the isolators are useful in reducing the dynamic response of the liquid storage tank. Also according to Koh et al. (1998) and Park (1997), for use of a seismic base isolation system, the spent fuel pool can enhance the required safety functions effectively. However, no detailed studies are reported for effect on stability of trays stack submerged in spent fuel pools/tanks supported on seismic base isolators. For the safety requirements, the trays stack should not collide with neighboring stacks and fuel bundles should not fall from trays during design basis seismic event.

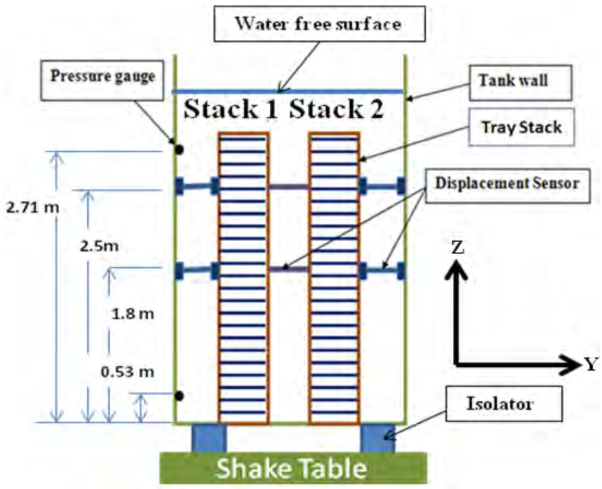
In this paper, nonlinear dynamic behavior of spent fuel trays stack submerged in Spent Fuel Storage Tank (SFST) with and without base isolators is investigated. Lead Rubber Bearings (LRBs) are used as base isolation system. The behavior of the system is highly non-linear due to presence of gap, friction between trays and hydrodynamic pressure on trays stack. Hence, a Shake table experiment of full-scale model of two stacks of 30 trays containing dummy fuel bundles with and without base isolators has been carried out. Simplified finite element model developed in Binu et al. (2011) is used for numerical analysis of trays stack with and without base isolators. Gap, contact and friction elements were modeled to simulate sliding, uplifting and impacting of trays during earthquake (Singh et al. (2009)). Response parameters like acceleration, displacement and frequency of stacked trays and spent fuel tank wall were recorded and analyzed.

SHAKE TABLE TEST SET UP

Shake table testing of Full scale of two stacks of trays containing dummy fuel bundles submerged in SFST mounted on servo controlled shake table as shown in Figure 2.1 is carried out at CSIR-SERC. The size of shake table is of 4mX 4m with payload capacity of 50 tons. Experiments have been carried out with two stacks, each having 30 trays with and without LRB isolators. The Spent Fuel Storage Tank (SFST) has a maximum capacity of 22,500 litre.

SFST along with trays stack and water is supported on four LRB base isolators as shown in Figure 2.1. Each LRB type isolator has load capacity of 12 ton. If these four isolators support a structure of 48 ton, the natural frequency of the base isolated structure will be 0.5 Hz. However, in the tests the total load supported on the base isolators is 45 ton, for 30 trays stack configuration. Hence the frequency of the isolated tank system will be around 0.52 Hz respectively for 30 trays stack system.





(a) Experimental Setup (b) Schematic arrangement for 30 trays stack

Figure 2.1. Spent Fuel Storage tank on Shake table at SERC, Chennai

Figure 2.2 shows a typical lead-rubber bearings considered in the shake table test. It consists of alternative layers of rubber and steel plates with a central lead core. The bearing has isotropic property, which signifies the same dynamic characteristics in all directions. The vertical stiffness provides a conventional support condition in the vertical direction and the high horizontal flexibility causes the structure to move like a rigid body at a low frequency. The vertical stiffness is derived from combination of rubber and steel plates while parallel layers of rubber bearings provide horizontal flexibility. The lead core yields relatively at very low shearing stress leading to dissipation of seismic energy and reduction of earthquake response (Robinson (1982)).

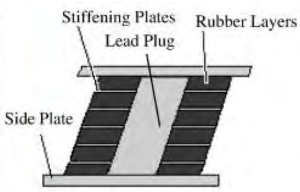


Figure 2.2. A Typical lead-rubber isolation bearing

INSTRUMENTATION DETAILS

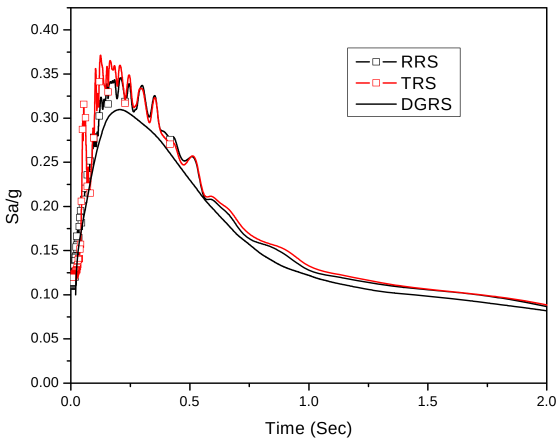
Instrumentations like displacement sensor and underwater accelerometer have been mounted at different elevation as shown in to capture response parameters like displacement and acceleration. Displacement sensors are specially fabricated and calibrated to capture the dynamic displacements of SFST and stack of trays at different elevation. This strain gauge based sensor is calibrated using standard calibration rig. The sensor is used to measure displacement of trays. Dynamic strain meter SDA-810C/-830C is used for signal conditionings.

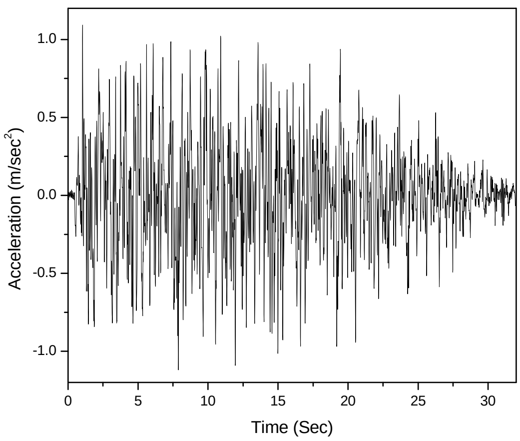
Dynamic pressure transducer of PW-500 KPA type were used to measure hydrodynamic pressure typically at top location. Pressure transducer is strain gauge based pressure sensor. The Capacity of pressure transducer is 500 KPa and its sensitivity is 1501 uV/V. Dynamic strain meter SDA-810C/-830C used for signal conditionings.

Two ICP type accelerometer having 941mv/g Sensitivity are kept on the SFST to record the response of the tank in X and Y-direction. These accelerometers are of 4507B005 type. The frequency ranges from 0.4 kHz to 6 kHz. Figure 2.1(b) shows front view of SFST and indicates the location of different gauges/sensor used in test setup.

INPUT TIME HISTORY

The compatible displacement time history for 5% damping design ground response spectra (DGRS) was obtained and given to shake table controller directly. Figure 2.3 (a) shows the comparison among Test Response Spectra (TRS), Required Response Spectra (RRS) and Design Ground Response Spectra (DGRS) of 0.1g PGA. Figure 2.3 (b) shows response spectrum compatible acceleration time history of 0.1g PGA applied along Y-axis. Similar time histories were generated for X and Z axis. However along Z direction the PGA is 2/3rd of X and Y direction PGA (ASCE 4-98 and IEEE 344-2004).





(a) Response spectra compability (b) Input time history along X direction

Figure 2.3. Comparison of TRS and RRS with DGRS and Input Time history for 0.1g PGA

EXPERIMENTAL AND NUMERICAL ANALYSIS

The shake table experiment of 30 trays stacks submerged in SFST with and without base isolators have been performed for Design Ground Time Histories (DGTH) of 0.05g and 0.1g Peak Ground Acceleration (PGA). The shake table test results like response frequency, maximum displacement, acceleration, hydrodynamic pressure etc. have been analyzed and compared with numerical results computed using simplified finite element model developed in Binu et al. (2011 and 2012). Contained water is modelled using in-house Finite Element Acoustic Field Analysis Code (FEAFAC). Figure 2.4 represents the finite element model of SFST with submerged trays stack used in numerical analysis. Table1 shows the maximum displacement and acceleration of trays stack, acceleration of tank and hydrodynamic pressure at different elevations for 30 trays stack submerged in water with and without base isolators in shake table experiment.

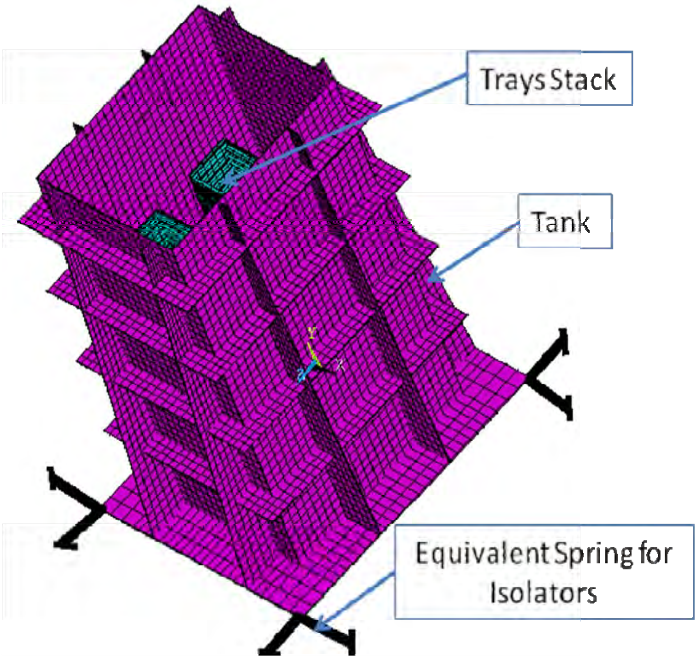


Figure 2.4. Finite element model of SFST with submerged trays stacks

Table 1: Response of 30 trays stack and tank in shake table test at different elevation

Sr.no.	Response		Without isolators		With isolators	
			0.05g PGA	**0.1g PGA**	**0.05g PGA**	**0.1g PGA**
1	**Displacement at 30th tray (mm)**					
a	Along Y-Direction	Stack 1	31.06	49.21	46.54	83.45
		Stack 2	21.68	40.92	38.26	53.45
2	**Acceleration at 30th tray (m/sec^2)**					
a	Along Y-Direction	Stack 1	1.71	3.36	1.23	2.26
		Stack 2	----	3.35	1.12	2.01
3	**Hydrodynamic Pressure (Pa)**					
a	At top along Y axis		4354.45	6365.33	----	----
b	At top along X axis		3250.08	4850.56	----	----
4	**SFST Top Acceleration (m/sec^2)**					
a	Along Y axis		0.54	1.234	0.75	1.44
b	Along X axis		0.76	1.63	0.91	2.11

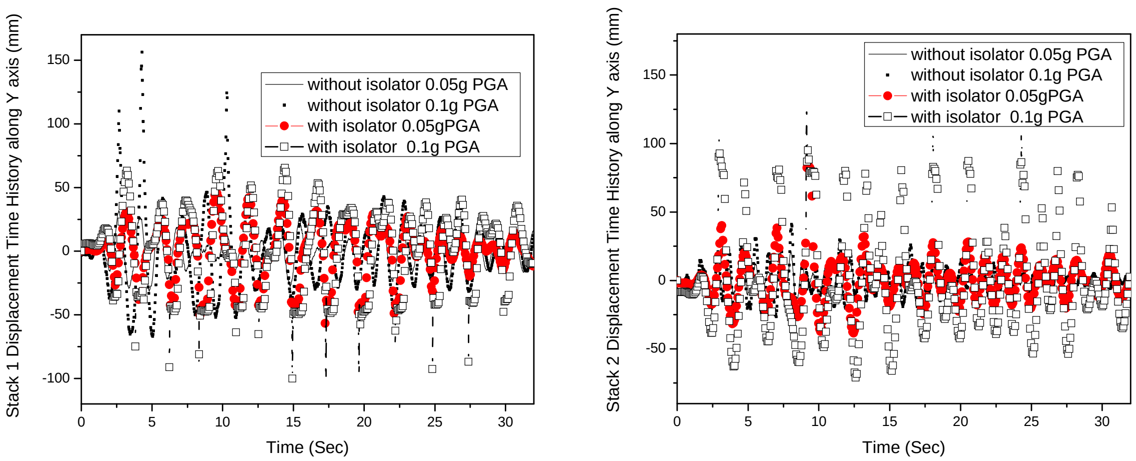
It can be seen in Table1 that in the case of base isolators maximum of 83.45 mm (at 30^{th} tray location) displacement along Y axis is recorded for 30 trays stack at seismic excitation of 0.1g PGA. This may be due to increase in hydrodynamic effects. This may be because of resonance among sloshing vibration modes of SFST with isolator and trays. The tank top has maximum 1.44 m/sec^2 acceleration along Y axis direction for 30 trays stack system with isolator. Maximum 6365.33 Pa and 4850.56 Pa hydrodynamic pressures are recorded at top location along Y and X axis respectively for 30 trays stack submerged in SFST without base isolator.

Table 2: Comparison of frequency of trays and tank in experimental and numerical analysis

Sr.no.	Frequency response (Hz)	Without isolators		With isolators	
		Experimental	Numerical	Experimental	Numerical
1	Trays stack	1.32	1.49	0.80	0.96
2	SFST wall	9.34	10.11	0.53	0.50
3	Convective water	0.53	0.56	0.50	0.48
4	Impulsive water	9.34	10.86	0.53	0.50

Table 2 compares the response frequency of trays, tank and sloshing/impulsive water obtained in the shake table test and numerical analysis. It is found that natural frequency of the tank and trays stack is reduced due to base isolator. The natural frequency of the SFST has reduced to 0.53 Hz from 9.34 Hz. It can also be seen found that results obtained from numerical analysis are in good agreement with results recorded during the shake table test.

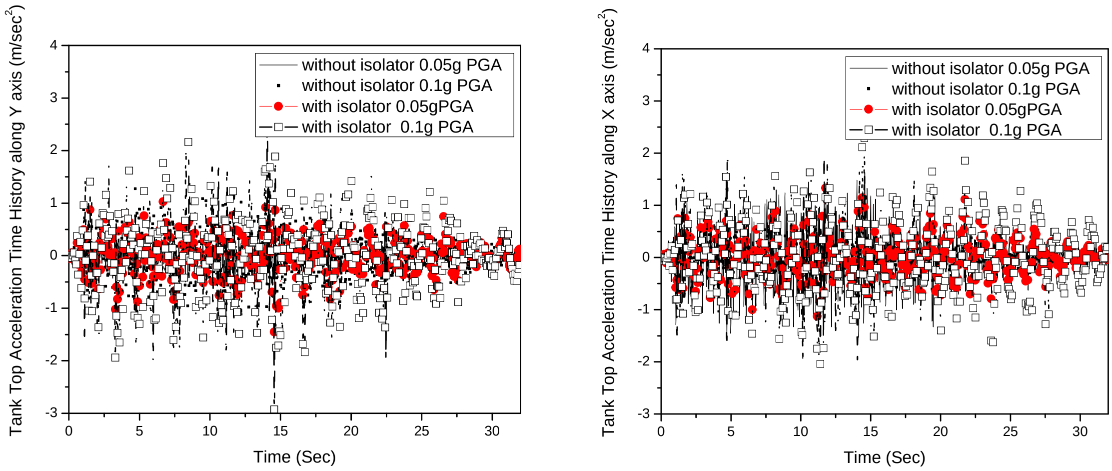
Figure 2.5 compares top 30^{th} tray experimental for 0.05g and 0.1g PGA excitation. It is observed that both stacks move in same phase. Peaks are observed in displacement time histories which may be due to noise in the signal and are of higher frequency contain.



(a) Displacement of top Tray for Stack 1 (b) Displacement of top Tray for Stack 2

Figure 2.5. Comparison of top tray displacement with and without isolator in shake table test

Figure 2.6 shows the acceleration time histories of tank wall along X and Y direction at top location. It is shown in the Figure 2.6 that response of tank will increase with increase in Peak Ground Acceleration (PGA).



(a) Top tank acceleration along Y axis (b) Top tank acceleration along X axis

Figure 2.6. Comparison of acceleration of tank at top location with and without isolator in shake table test

Fig 2.7 and Fig 2.8 compares the FFT of displacement time histories of 30th tray and acceleration time histories of tank top location with and without base isolators respectively. It can be inferred that resonance frequency of stacked trays has been decreased to 0.80 Hz which is comparable to slosh frequency of 0.53 Hz. Therefore, stack will displace more in the SFST with isolator than SFST without isolator.

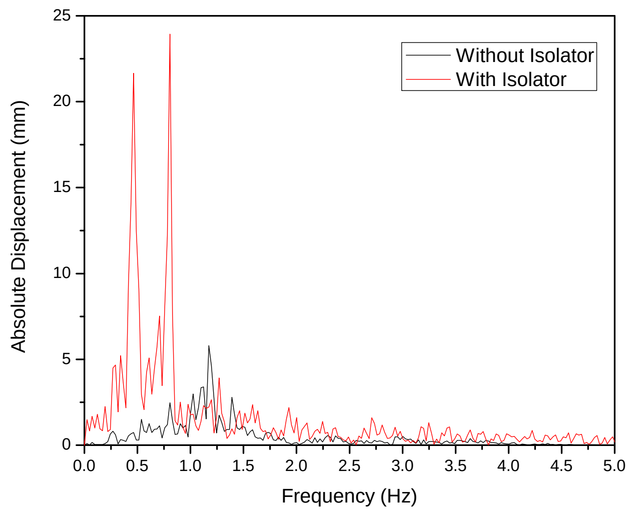


Fig 2.7. FFT of trays stack displacement with and without isolator along Y axis

Figure 2.9 (a) and (b) shows the hydrodynamic pressure time history at top tank location along Y axis for trays stack submerged in water without isolator.

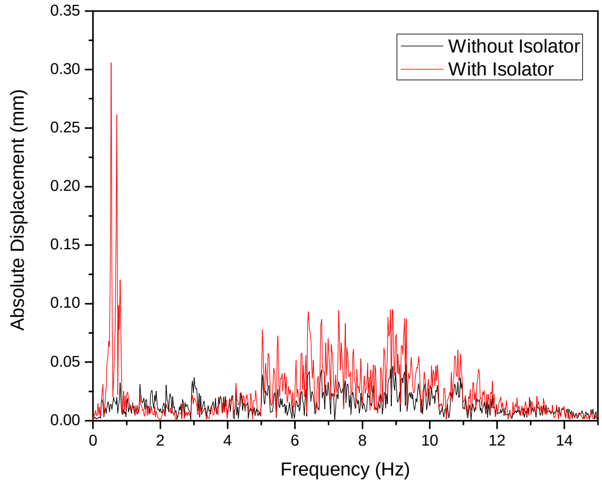
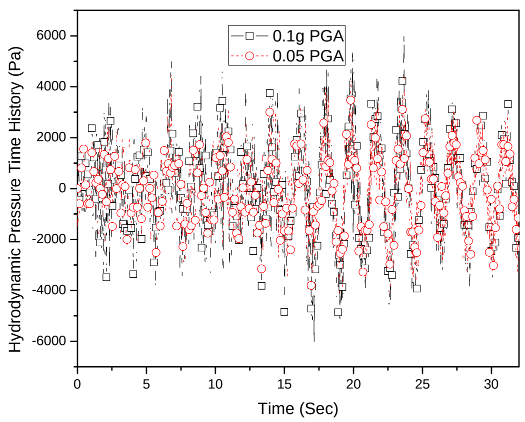
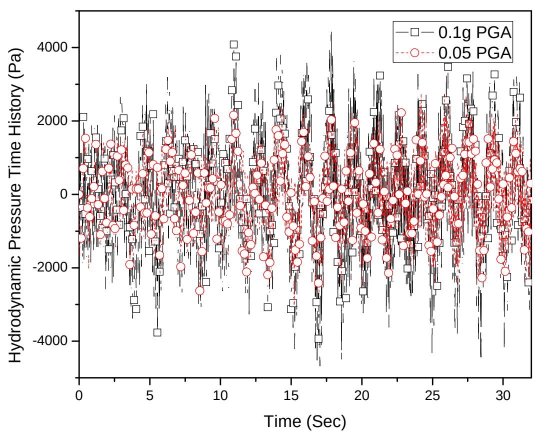


Figure 2.8. FFT of top tank acceleration for with/without isolator along Y axis





(a) Hydrodynamic Pressure along Y axis (b)Hydrodynamic Pressure along X axis

Fig.2.9 Hydrodynamic pressure time history on tank wall without isolator in shake table test

CONCLUSION AND DISCUSSION

The test was conducted for 30 trays containing dummy spent fuel bundles in each stack. The spent fuel trays column is found stable up to tested height of 30 trays and subjected to a maximum PGA level of 0.1g with base isolators. Impact of adjacent tray stack was not observed upto 0.1g PGA seismic excitation. Also no slipping or permanent movement of the trays stack at the bottom was observed during the test. Maximum 83.45 mm displacement is obtained for 30 trays stack for 0.1g PGA with isolator . It is observed that both stacks move in phase with each other.

It is observed that trays stack frequency has reduced to 0.80 Hz from 1.32 Hz due to base isolator. The acceleration of tank has increased due to increase in convective responses of sloshing. In both cases with and without base isolators displacement of trays stack is generally more along the Y axis than X axis.

The fundamental natural frequencies of the SFST alone are 13 Hz and 16 Hz (Binu et al. (2011)) respectively along X and Y axis direction. The natural frequency of SFST with submerged trays stack is equal to 0.56 Hz along X and Y axis with base isolators. Experimentally evaluated sloshing frequency of water is around 0.53 Hz for 30 trays stack submerged in water. It is observed that the response of stacked trays submerged in water increases significantly with use of base isolator than without base isolators. The impulsive frequency of the coupled system is 9.34 Hz for without isolator which it reduces to 0.53 Hz for SFST submerged stacked trays with isolator.

Thus, if the isolation system is chosen such that it is not in resonance with the first mode of the contained liquid, the effects on the free-surface displacement would be small. The present experimental results do not represent the behavior of such tank as the isolated structural model had a fundamental period very close to first sloshing mode.

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