

## Tuned Liquid Sloshing Water Damper: A Robust Device for Seismic Retrofitting

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### ABSTRACT

The medium height, RC framed, masonry infilled, existing structures (ES) houses a substantial proportion of population and economic activities world-wide. These structures may be retrofitted against vibratory forces by restricting their displacement response through energy dissipation with tuned sloshing water damper (TSWD). The parameters of TSWD are dependent on structural displacement and its performance is sensitive to its tuning with ES. For well-defined structures and excitations the single frequency TSWD (STSWD) retrofitting system is a very efficient device. For approximately assessed structures subjected to broad band excitations the STSWD system may be replaced by multiple frequency TSWD (MTSWD) system and more robust performance is achieved. The concept has been explained with example of retrofitting proposal of an existing four story building (ES). The TSWD parameters and retrofitting system has been designed theoretically and subsequently verified through shake table simulated experiments. An experimental study has been conducted with a reduced scale model (SM) having dynamic similitude with ES mounted with three acrylic boxes exactly similar to that to be used as TSWD. The simulated testing has been conducted on ES in coupling with TSWD for three discrete frequencies representing the first mode frequency of the ES for three different structural conditions. The performances of the STSWD and MTSWD system, with mass ratio equivalence, have been observed and compared against resonant frequency harmonic excitation and earthquake excitation. An execution scheme of MTSWD retrofitting system for ES has also been proposed.

*Keywords-* Tuned sloshing water damper, Tuning ratio, Frequency ratio, Mass ratio

### 1. INTRODUCTION

The medium height, RC framed structures, constructed before 1970 were not designed for seismic forces due to lack of provisions in the then prevailing building codes. These structures are of 4 to 8 story height and made of ordinary moment resisting concrete frames with masonry in-filled walls. These structures exhibit sound structural performance during static load conditions but have got relatively low lateral strength against dynamic loading. These structures house a large proportion of the human activities in the form of residential and institutional buildings of urban world. Strengthening and re-qualification of these existing structures (ES) against earthquakes is of vital importance for sustenance of developmental process. The seismic retrofitting of such structures can be accomplished by displacement response control method with tuned sloshing water dampers.

The tuned sloshing water damper (TSWD) is the simplest form of passive device of structural response control belonging to TLD family. The TSWD is essentially a tank rigidly attached with structure; the water of the tank is tuned with the prime frequency of the host structure. The water in tank resonates with vibrating host structure, causing sloshing and thereby dissipation of some part of the seismic energy imparted on the structure, resulting in reduced structural response. The real life applications of TSWDs in tall structures have exhibited the response reductions up to 70% against wind loads (Tamura et al. 1995).

For structural systems, with major mass participation in first mode of vibration, the single frequency TSWDs tuned with first mode frequency, named as STSWD system may be provisioned. For structures of multiple degrees of freedom, TSWDs tuned with each mode of vibration may be provided. These systems are named as multiple frequency TSWD (MTSWD) system. The STSWD and MTSWD systems have performed very efficiently in tall buildings, against wind loads. The MTSWDs are more robust and effective in mitigating earthquake excitation (Kline, S and Kareem A, 1995).

The MTSWD system may also be used for the ES with approximately assessed dynamic properties. The TSWD frequencies are distributed around the assessed first mode frequency of the ES. This paper explores the possibility of seismic retrofitting of a four story residential building with MTSWD systems, wherein the overhead tank of ES is modified to behave as cluster of TSWDs. Additional tanks as TSWDs have been provided on the roof of the ES for further response reduction. The retrofitting regime will effectively perform as MTSWD system as the frequencies of the TSWDs are distributed among the estimated first mode frequencies of the ES.

## 2 STRUCTURAL RESPONSE CONTROL WITH TSWD

### 2.1 Concept development

The ES with substantial mass participation in first mode of vibration is considered as single degree of freedom system. By incorporating a TSWD in structural system, the ES becomes a two degree of freedom system. The dynamic magnification factor ( $DMF_r$ ) of a linear two degree of freedom system subjected harmonic excitation is given as:

$$DMF_r = 1/(RE^2 + IM^2)^{0.5} \quad (1)$$

Here

$$RE = 1 - \beta^2 - \mu\beta^2 \{ [f^2 (f^2 - \beta^2 + 4 \zeta_d^2 \beta^2)] / [(f^2 - \beta^2)^2 + 4 f^2 \zeta_d^2 \beta^2] \} \quad (2)$$

$$IM = 2 \zeta_s \beta + \{ (2\mu f \zeta_d \beta^5) / [(f^2 - \beta^2)^2 + 4 f^2 \zeta_d^2 \beta^2] \} \quad (3)$$

With excitation frequency ' $\omega_e$ ', frequency of ES ' $\omega_s$ ' and damper frequency ' $\omega_d$ ' the  $DMF_r$  of retrofitted ES depends on frequency ratio ' $\beta = \omega_e / \omega_s$ ', tuning ratio ' $f = \omega_d / \omega_s$ ', mass ratio ' $\mu = m_d / m_s$ ', damping ratio of ES ' $\zeta_s$ ' and damping ratio of damper ' $\zeta_d$ '. Increase in damper mass and thereby mass ratio reduces the  $DMF_r$ , resulting in higher structural response control. The dynamic properties of ES are considered beyond scope of alteration. The response control can be accomplished by controlling the properties of TSWD i.e.  $\omega_d$ ,  $m_d$ , and  $\zeta_d$ .

### 2.2 Properties of TSWD

The frequency of sloshing liquid ' $\omega_n$ ' in a TSWD, on the basis of linear wave theory (Abramson, 1966) is as follows:

$$\omega_n = [(\pi g / a) \{ \tanh(\pi h / a) \}]^{0.5} \quad (4)$$

Here, ' $g$ ' is gravitational acceleration, ' $h$ ' is depth of water in tank and ' $a$ ' is dimension in direction of vibration of TSWD. The Eq. (4) is valid for small excitation amplitudes. At larger excitations the equivalent nonlinear frequency ' $\omega_d$ ' and damping ratio ' $\zeta_d$ ' of TSWD may be derived by empirical relations (Yu, 1999) as function of excitation amplitude ' $A_e$ ' which is equal to displacement of ES at TSWD location:

$$\omega_d = \omega_n (1.037 (A_e / a)^{0.0035}) \quad \text{for } A_e < 3\% \text{ of tank dimensions } a. \quad (5)$$

$$\omega_d = \omega_n (1.59 (A_e / a)^{0.125}) \quad \text{for } A_e > 3\% \text{ of tank dimensions } a. \quad (6)$$

$$\zeta_d = 0.5 (A_e / a)^{0.35} \quad (7)$$

Mass of sloshing water  $m_d$  in TSWD is given by (Graham and Rodriguez, 1952):

$$m_d = M \{ \{ 8 \tanh(\pi h / a) \} / (\pi^3 h / a) \} \quad (8)$$

Here,  $M$  is total mass of water contained in the tank.

The design of the TSWD retrofitted ES coupling is governed by Eq. (1). Mutual tuning of ES and TSWD with respect to frequency and damping ratio is vital for efficient performance but difficult to achieve in real life applications due to uncertainties involved in assessment of dynamic properties of ES, which are dependent on many factors such as material quality, execution methodology and excitation type. This problem may be addressed by providing multiple frequency TSWDs designated as MTSWD system. The MTSWD system can be applied conveniently as the total sloshing water mass required for desired response control has to be accommodated in multiple TSWDs. The natural frequencies of these TSWDs are tuned with the assessed first mode frequencies of the ES. This can be achieved by varying the length ' $a$ ' of the TSWD. The MTSWD system ensures that some part sloshing mass is always tuned with the ES and major part of sloshing mass is slightly detuned.

## 3 RETROFITTING OF EXISTING STRUCTURE

### 3.1 Details of Structure

Existing structure considered for seismic retrofitting is a four story RC framed, masonry infilled structure situated in Mumbai, with no visible signs of distress. The performance of ES against earthquake is dependent on its frequency  $\omega_s$  and damping ratio  $\zeta_s$ . The structural contribution of infilled masonry is considered as compressive diagonal strut. The frequency of the ES may lie between  $\omega_f$  (all walls participating designated as Case-1) and  $\omega_n$  (no wall participating designated as Case-2) depending on the structural condition. The salient analysed features of the ES are given in TABLE 1. The structural RC skeleton and typical floor plan of the ES is shown in Fig. 1.

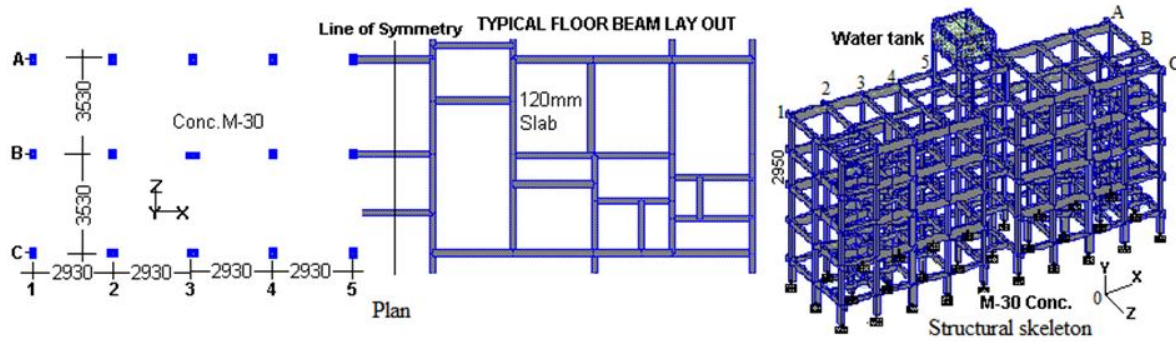


Figure 1. Typical floor plan and structural skeleton of ES

Table 1. Salient Features of ES

Feature		Description
Total weight of structure		1164000 kg with water tank full.
Mass participation in first mode $m_s$		76% (885000 kg).
Damping ratio		3%
Seismic zone		III as per IS 1893 part-1
First mode frequency	With all masonry infill as compressive strut ( $\omega_f$ ) (Case-1)	1.766 Hz along Z and 1.803 Hz along X
	Bare RC frame ( $\omega_n$ , no structural contribution from masonry walls) (Case-2)	1.195 Hz along Z and 1.135 Hz along X
Intermediate state of structure ( $\omega_s = \text{mean of } \omega_f \text{ and } \omega_n$ ) (Case-3)		1.48 Hz along Z and 1.47 Hz along X
Max. displacement at roof level ( $D_0$ ) considered		14.74 mm along Z and 15.11 mm along X

### 3.2 Design of TSWD Retrofitting System

Deformed shape and idealised retrofitting scheme of the ES are shown in Fig. 2. It is proposed to reduce the maximum displacement response of ES by 25%, so that crack in masonry is avoided while resisting earthquake forces. The reduced displacement shall result in reduction of stresses in RC members. The un-cracked masonry shall contribute as diagonal strut leading to further reduced stresses in the RC members.

The parameters of the TSWDs have been determined for amplitude of excitation of 12 mm and for a water depth of 80 mm. After some iteration 0.75% mass ratio has been found to be adequate for 25% response reduction. Thus the total 6638 kg of sloshing mass is required for retrofitting. Two retrofitting schemes, one as STSWD of 1.48 Hz frequency and another as MTSWD, with total sloshing mass distributed between  $\omega_f$ ,  $\omega_s$  and  $\omega_n$  have been proposed. The details of both the systems are given in TABLE-2.

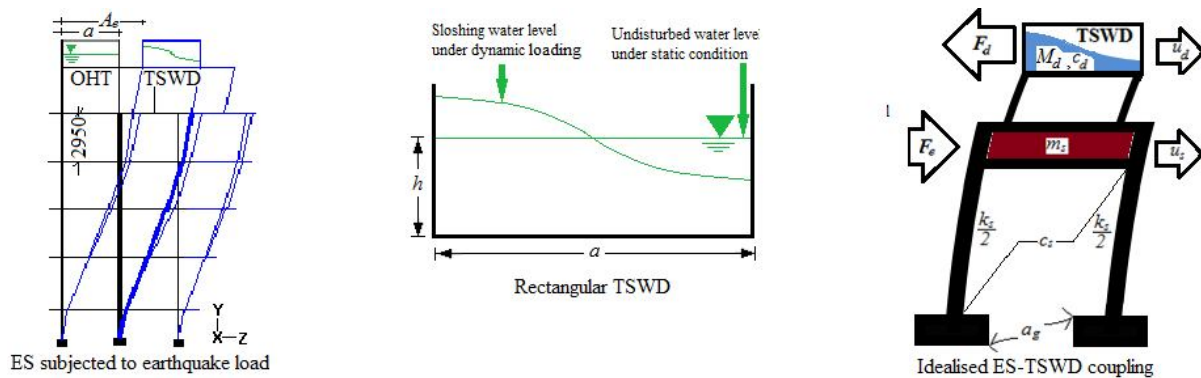


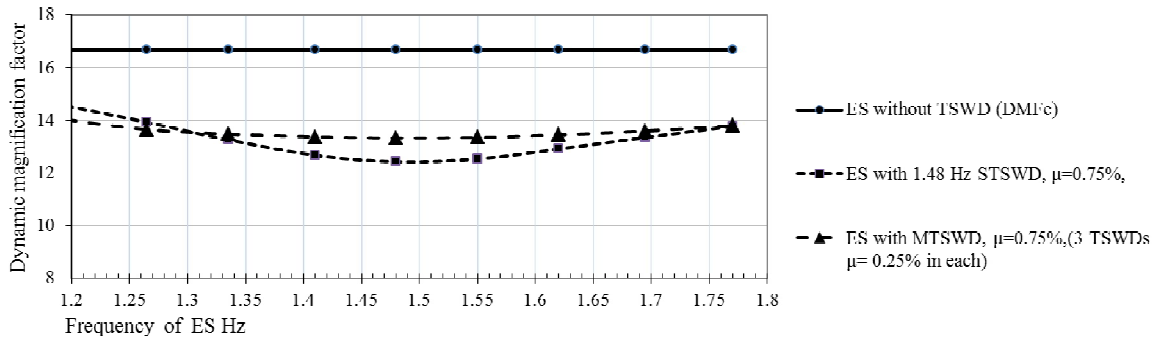
Figure 2. Seismic retrofitting scheme for ES

Table 2. Details of TSWD Based Retrofitting Systems

TSWD ID	Frequency (Hz)		Plan dimensions (mm)		Damping ratio (%)		Sloshing mass (kg)	No. of TSWDs
	Along Z	Along X	Along Z	Along X	Along Z	Along X		
STSWD system								
TSWD <sub>285</sub>	1.48	1.47	285	285	16.5	16.5	4.22	1573
MTSWD system with 4570 kg of sloshing mass allocated to each probable structural frequency								
TSWD <sub>235</sub>	1.766	1.803	235	230	17.65	17.65	3.04	728
TSWD <sub>285</sub>	1.48	1.47	285	285	16.5	16.5	4.22	525
TSWD <sub>350</sub>	1.195	1.135	350	375	15.36	14.99	5.59	396

**3.3 Performance check of Retrofitting System**

The DMF<sub>r</sub> of the ES subjected to resonant harmonic excitation ( $\beta=1$ ), with STSWD and MTSWD systems has been calculated by Eq. (1). The effectiveness of the retrofitting systems has been evaluated in with respect to DMF<sub>e</sub> of ES without TSWD as shown in Fig. 3. It can be seen that response reduction of 25% is achieved with STSWD system for an ES of frequency range of 1.45 Hz to 1.52 Hz. With MTSWD system response reduction in access of 20% is achievable over a wider range of structural frequencies exhibiting comparative robustness.



**Figure 3. Performance comparison of STSWD system and MTSWD system**

**4 SIMULATED EXPERIMENTS WITH SCALED MODEL AND TSWD**

**4.1 Scaled model of ES and simulated test setup with TSWDs**

The simulated experimental study has been conducted to visualise the effectiveness of the TSWD based retrofitting system. A 1:20 reduced scaled model (SM) of ES has been constructed with mild steel wires, rods and plates. The geometrical similarity in terms of proportionality of plan dimensions, elevations and floor height between ES and SM is maintained. The experimental observations along Z axis are being described.

The dynamic properties of the SM have been controlled by symmetrical placement of imposed loads applied in the form of rigidly attached different sized blocks of lead and MS. The fine tuning of the dynamic properties are accomplished by manipulating the distribution of floor loads, such that frequency of ES = frequency of SM. The inherent damping ratio of 3% has been achieved by adjusting the tightness of the lead blocks with SM. The load combination on SM for three discreet structural conditions of masonry as full contribution, no contribution and intermediate state has been obtained by free vibration tests. The load combination and corresponding frequency of SM obtained from free vibration tests are tabulated in TABLE 3. The SM1 is representative of Case-1, SM2 is representative of Case-3 and SM3 is representative of Case-2.

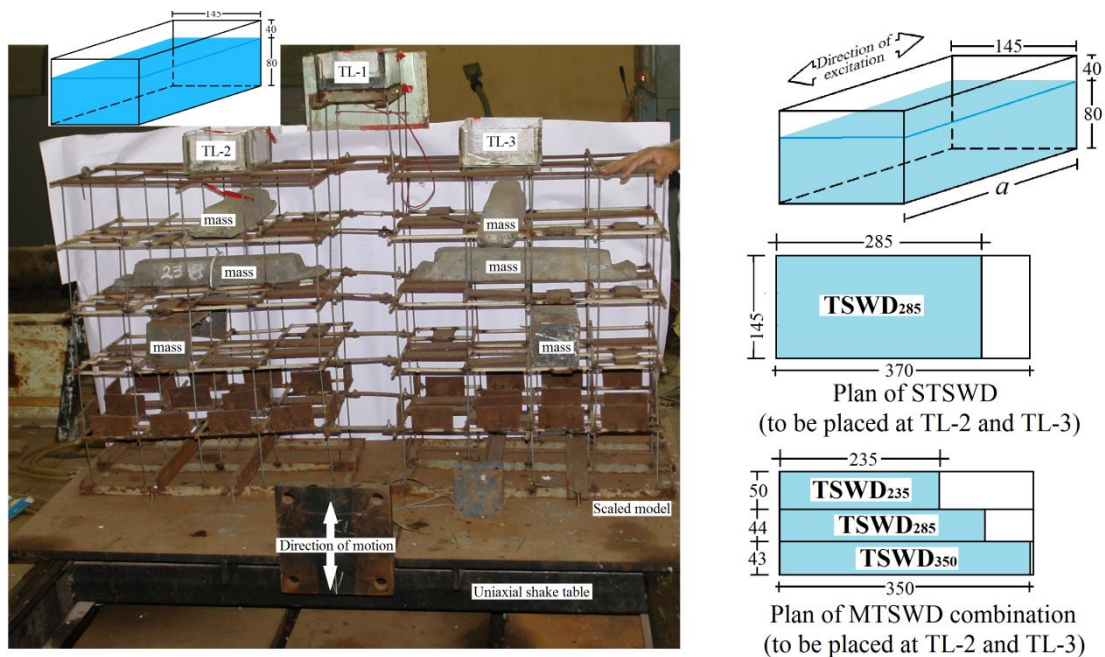
**Table 3. Load Distribution on Scaled Models for Different Frequencies**

SM ID	Corresponding structural condition	Loading description kg					Total	Frequency of SM Hz
		Gr lvl	1 <sup>st</sup> Flr.	2 <sup>nd</sup> Flr.	3 <sup>rd</sup> Flr.	Roof		
SM1	All masonry walls acting as diagonal strut	13	108	108	108	37	413	1.76
SM2	Intermediate state	13	152	134	118	86	542	1.48
SM3	No structural contribution of masonry walls	13	100	152	152	152	608	1.2

Three acrylic boxes, of internal dimensions 145 mm x 370 mm in plan and 120mm depth, have been rigidly attached, with the SM to simulate the coupling of ES and TSWD. One box (TL-1) is fixed on the four central columns extended from main frame to simulate overhead tank in existing buildings. The remaining two boxes (TL-2 and TL-3) are placed on the roof, one on each side of axis of symmetry. The sizes of TSWDs matching with different frequencies are achieved by inserting acrylic sheet at desired location inside the acrylic boxes. The scaled model and laboratory test setup is shown in Fig. 4. Two combinations of TSWDs have been devised to achieve the STSWD and MTSWD systems as shown in Fig. 4 and given in TABLE 4.

**Table 4. Details of TSWD Systems for Simulated Testing**

TSWD ID	Frequency	Plan dimensions (mm)		Damping ratio (%)	Slushing mass (kg)	Number of TSWDs and location
		Along Z	Along X			
<b>STSWD system</b>						
TSWD <sub>285</sub>	1.48	285	145	16.5	4.29	2 at TL-2 and TL-3
<b>MTSWD system with 4570 kg of slushing mass allocated to each probable structural frequency</b>						
TSWD <sub>235</sub>	1.766	235	50	17.65	1.29	2 at TL-2 and TL-3
TSWD <sub>285</sub>	1.48	285	44	16.5	1.3	2 at TL-2 and TL-3
TSWD <sub>350</sub>	1.195	350	43	15.36	1.28	2 at TL-2 and TL-3



**Figure 4.** Scaled model and test setup with STSWD and MTSWD system

#### 4.2 Forced vibration tests on SM-TSWD couplings

The forced vibration tests have been conducted with harmonic excitation of resonant frequencies ( $\beta=1$ ), recorded ground motion of El Centro and a synthetic broad band excitation compatible with BIS 1893 response curve.

The magnitudes of the forced excitations have been scaled down to the extent that maximum displacement of SM at roof level, without water in TSWDs, is of the order of 15mm which is equivalent to the displacement of ES due to earthquake forces. These tests have been designated as bare SM tests.

The forced vibration tests with same magnitude of excitation, as for bare tests, have been repeated with water in two TSWD<sub>285</sub> as proposed in STSWD system, one each at location TL-2 and TL-3. The maximum displacements have been recorded.

The tests have been repeated again with water in TSWDs as proposed in MTSWD system and maximum displacements have been recorded. The reductions in displacement response of each SM, caused due to both retrofitting systems have been compared for each excitation. The observations are tabulated in TABLE 5.

**Table 5.** Maximum Displacement of SM-TSWD coupling Subjected to Forced Vibration

Excitation definition	Maximum Displacement			Response reduction	
	Bare SM	STSWD	MTSWD	STSWD	MTSWD
	mm	mm	mm	%	%
<b>SM1, frequency 1.76 Hz, mass ratio of STSWD 1.02%, mass ratio of MTSWD 0.92%</b>					
1.76 Hz sinusoidal, 075mm at base	12.66	10.23	10.11	19.19	20.14
El Centro (N-S), 0.064g	16.84	15.36	14.54	8.79	13.66
El Centro (E-W), 0.07g	15.89	14.96	13.76	5.85	13.40
BIS 1893 compatible, 0.1g	14.64	13.8	13.41	5.74	8.40
<b>SM2, frequency 1.48 Hz, mass ratio of STSWD 0.78%, mass ratio of MTSWD 0.71%</b>					
1.76 Hz sinusoidal, 075mm at base	12.24	8.62	9.98	29.58	18.46
El Centro (N-S), 0.064g	14.65	13.19	13.27	9.97	9.42
El Centro (E-W), 0.07g	16.23	14.74	14.91	9.18	8.13
BIS 1893 compatible, 0.075g	14.54	12.20	12.45	16.09	14.37
<b>SM2, frequency 1.2 Hz, mass ratio of STSWD 0.70%, mass ratio of MTSWD 0.63%</b>					
1.76 Hz sinusoidal, 075mm at base	12.06	10.62	10.35	11.94	14.18
El Centro (N-S), 0.037g	14.92	14.12	13.55	5.36	9.18
El Centro (E-W), 0.044g	16.08	14.55	13.84	9.51	13.93
BIS 1893 compatible, 0.06g	13.39	12.51	12.01	6.57	10.31

#### 4.3 Discussion on experimental observations

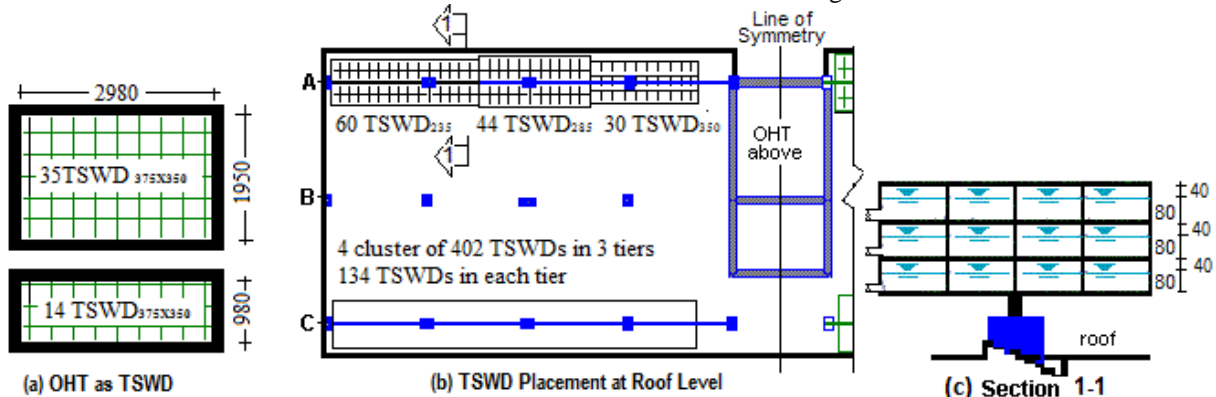
It can be seen from TABLE 5 that for SM1 subjected to sinusoidal excitation of 1.76 Hz effectiveness of the MTSWD is marginally high. Since the STSWD system has been devised with reference to 1.48 Hz frequency, its

tuning with SM2 is optimum. The performance of STSWD is at best under resonant sinusoidal excitation of 1.48 Hz, as is evident that the STSWD is 14% more effective than the MTSWD system. For SM3 the MTSWD system is more effective than STSWD system. Further the experimental observations with SM2 subjected to resonant harmonic excitations have followed very closely theoretically determined values.

It is noted that effectiveness of TSWDs has reduced considerably under earthquake excitations. For such broad band excitations the MTSWD system is more efficient for SM1 and SM3. Although the STSWD system is designed for optimum tuning with SM2, but its effectiveness under earthquake excitations is reduced considerably and is comparable with that of MTSWD system. This substantiates the comparative robustness of MTSWD system.

## 5 EXECUTION SCHEME OF TSWD RETROFITTING SYSTEM

Execution scheme with 80 mm deep MTSWD system, as proposed in TABLE 2 is being described. The required sloshing mass of 6638 kg is proposed to be provided by attaching 1649 TSWDs. These TSWDs shall be accommodated in the overhead tank and on the roof of the ES as shown in Fig.5.



**Figure 5.** Execution scheme of MTSWD system for ES

The existing water tank may be converted in to 49 TSWD<sub>350</sub> of 375 mm X 350 mm plan size by inserting 1 mm thick GI partitions (Fig. 5-a). Balance 1600 TSWDs of different sizes may be fabricated with GI sheets, as multi-layered cluster of TSWDs. The overall depth of all the fabricated TSWDs is fixed as 120 mm. A typical scheme of the proposed cluster fabricated from GI sheet is shown in Fig. 5. Each cluster contains 402 TSWD in three tiers. The scheme proposed is similar to that of adopted in Shin Yokohama Prince Hotel in Yokohama, Japan (Tamura et al, 1995).

## CONCLUSION

For well-defined structures subjected to resonant harmonic excitations TSWD based retrofitting systems are efficient and STSWD systems are more suitable. For well-defined structures subjected to broad band earthquake excitations the performance of STSWD and MTSWD system are comparable. For approximately assessed ES subjected to any random excitation the MTSWD systems are more suited and give robust performance.

The TSWD based retrofitting systems can be incorporated in the ESs in multi-layered clustered configuration without interfering with the architectural, structural features and occupancy, hence conveniently adoptable.

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