SEISMIC RETROFITTING OF EXISTING STRUCTURES BY TUNED SLOSHING WATER DAMPER: AN EXPERIMENTAL STUDY

Nishant Kishore Rai[1], Dr. G.R.Reddy[2], V.Venkatraj[1], P.N. Dubey[2],
[1] DCSEM, DAE, Mumbai, India -400094
[2] BARC, DAE, Mumbai, India -400094

ABSTRACT

The existing medium height structures (ES) may be retrofitted with tuned sloshing water dampers (TSWD), for mitigating increased seismic demands. The performance of the TSWD as response reducing device against vibratory loads has been investigated through shake table tests, in coupling with scaled model(SM) of ES. The optimum coupling parameters of the TSWD with respect to SM have been obtained through free vibration tests. Subsequently the optimally tuned SM-TSWD coupling has been subjected to forced sinusoidal vibration of the resonant frequency. The effectiveness of the retrofitting regime has also been tested against ground motion time histories. The experimental data have been analytically extrapolated for application to the real life existing structure (ES). A response reduction of the order of 25% has been predicted for the ES with 1.5% mass ratio. A seismic retrofitting design methodology of ‘hardware interactive soft path’ for assured displacement response reduction has been devised.

Keywords: Effective Damping Ratio, Effectiveness Ratio, Frequency Ratio, Tuned Sloshing Water Damper

INTRODUCTION

The existing medium height non-seismically detailed, RC framed structures, are likely to fail due to excessive deformation under seismic loads. The seismic resistance of such structures may be improved by restricting their displacements under dynamic loads within safe limit. This can be achieved by incorporating energy dissipaters, such as TLDs, in structural load resisting mechanism. The common passive dampers such as hysteretic, viscous, viscoelastic and self-centering systems are usually designed to control structural displacement and end up amplifying the acceleration response of the structure. Whereas well designed TLDs are able to reduce both displacements and accelerations for lightly damped structures (Malekghasemi and Mercan, 2011). The shake table tests, conducted on a scaled model of a RC framed structure retrofitted with TLDs, have observed more than 20% acceleration response reduction under simulated seismic loads (Sharma et al., 2012).

The initial application of TLD was conceptualised and proposed by W. Froude in 1862, to reduce the rolling motion of the ship. The application was standardised by Frahm in 1911 (Frahm, 1911). The application of TLD for ground structures were first proposed by Modi and Sato (Modi and Welt, 1987; Sato, 1987).

Water is the most economical and commonly used liquid for the TLDs. Further TLDs are classified based on their physical characteristics as tuned liquid column damper (TLCD) and tuned sloshing water dampers (TSWD).

A TLCD depends on the inertia of a liquid column in a U-shaped tube to neutralise the dynamic forces acting on the structure. The damping in the TLCD is introduced as a result of head loss experienced by the liquid column moving through an orifice. A TLCD is unidirectional by design and well suited for negotiating wind loads in tall buildings where the characteristics of anticipated excitation (direction and amplitude) can be estimated more accurately (Sakai et al., 1989).

TSWD has got better applicability potential for seismic retrofitting of existing structures (ES). The water tanks of designed geometry as TSWD may be provided to reduce the dynamic response of the structure. The TSWDs may be constructed in alignment with the principal axes of the ES offering functionality in all possible directions in horizontal plane (Rai et al., 2011).

A TSWD dissipates energy through the liquid boundary layer friction, the free surface contamination, and wave breaking. Initially the TSWD parameters have been derived through potential flow theory for small excitation amplitude. Under large excitation amplitudes, TSWDs dissipate a large amount of energy due to its nonlinear behaviour corresponding to wave breaking. Kareem and Sun developed and validated equations that model the TLD as an equivalent linear Tuned mass damper (TMD), where the damper mass is in the form of liquid (Kareem and Sun, 1987). The nonlinearity of TSWDs has been addressed by adding empirical amplitude dependant parameters on well-established TMD linear equations (Sun et al. 1995). An equivalent mass damper system with amplitude dependant non-linear stiffness and damping have been proposed with stiffness hardening ratio derived from experimental data (Yu, 1997). A sloshing–slamming model for TSWD was proposed capturing physics of mass momentum transfer involved in sloshing phenomenon at high amplitudes (Yalla, 2001). Like the potential flow theory, in all these studies TSWD characteristics under large amplitudes were not captured accurately. However, TSWD–structure interaction was predicted with reasonable accuracy (Hassan, 2010).

The non-linearity of sloshing water in TSWD, under large excitation amplitudes, has been physically eliminated by incorporating screens normal to movement direction. This has resulted in increased damping ratio of TSWD without wave breaking. Expressions for equivalent linearized damping ratio has been developed and substantiated through shake table experimental observations for structural response of a single degree of freedom (SDOF) structure in coupling with the TSWD (Tait, 2008).

For achieving an effective performance of a vibration absorber it is crucial that the fundamental frequency of the absorber should be tuned to the natural frequency of structure, and the damping ratio of its motion should be set to an optimal value (Warburton, 1981). But the damping induced in TSWD, by the liquid motion, is dependent on vibration amplitude which is same as displacement of the structure. Therefore, for the optimum damping ratio and tuning condition, an accurate assessment of the structural displacement and excitation amplitude is required.

Against wind excitations, TSWDs has been installed and their functional usefulness has been established in tall structures (Tamura et al., 1995). But for TSWD retrofitting systems real life data of seismic events are not available for functionality assurance.

A simple structural model in coupling with cylindrical TSWDs has been experimented to substantiate the formulations of earlier researchers. The same formulae have been proposed for seismic retrofitting of an existing structure (Savyanavar et al., 2006).

This paper proposes to use the laboratory data, generated through simulated verification testing, on the scaled model (SM), having dynamic similitude with the ES (Langhar, 1951), for assured functionality of the TSWD system at the required instance of time.

The similitude in terms of frequency, damping ratio, geometry, aspect ratios, number of structural elements and joints has been established between ES and SM. The bare SM is representative of un-retrofitted ES and SM-TSWD coupling represents retrofitted ES. The TSWD actually proposed to be installed on the ES has been experimented, in coupling with SM, on shake table under dynamic excitations.

Unlike previous studies wherein parameters of the TSWD alone have been studied, this paper focusses on the coupled behaviour of TSWD and structure. This paper is an attempt to bridge the gap between theoretical studies and real life data. The main objectives of this paper are the following:

1. Study of the dynamic characteristics of a coupled SM-TSWD system through shake table experiments and compare the TSWD parameters thus determined, with those obtained by previous researchers by experimentation on TSWDs alone (Yu, 1997 and Yalla, 2001).
2. Experimental verification of effectiveness of TSWD based retrofitting system on scaled model SM for displacement response reduction.
3. Develop and illustrate a retrofitting methodology with TSWDs for real life ES and substantiate its suitability with respect to assured performance at required instance of time. The methodology has been explained with example of an existing four story building (ES), for achieving a predetermined displacement response reduction by installing TSWDs.

The methodology proposed in this paper may be applied to most of the, medium height, 4 to 10 story, existing structures. The TSWDs may be integrated with the plumbing system of the ES to serve for thermal storage and fire fighting requirements. This retrofitting system has the advantages of minimal interference with occupancy and all time performance assurance at almost zero maintenance cost (Rai et al., 2010).

STATE OF EXISTING STRUCTURES AND RETROFITTING STRATEGY

The existing medium height structures are of RC frame with masonry infill. The quality of masonry is generally poor by structural considerations, which may give way at very small deformation under dynamic load. The failure of masonry leads to stiffness loss and catastrophic effects for structure during earthquake. Thus the retrofitting strategy is governed by the purpose of restricting the structural displacement within safety limits in a seismic eventuality. The structures, designed with working stress method, possess damping ratio in the range of 2% to 3%. The retrofitting approach of coupling damped damper (TSWD) with damped structure (ES) is appropriate and has been adopted.

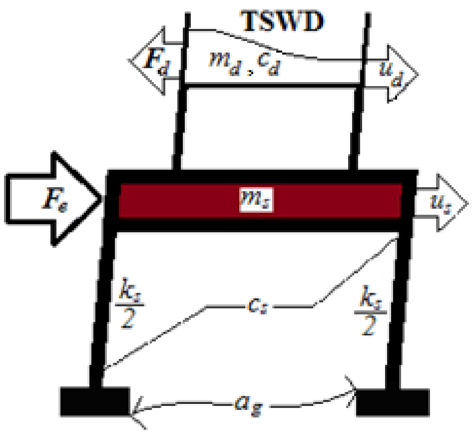


Fig. 1 Structure with TSWD

The dynamic structural response of ES is dependent on frequency ω_s and damping ratio ξ_s. The ES is assumed as single degree of freedom system (SDOF) of its first mode frequency ω_s, where major part of its mass participates in the vibration. The structural deformation of this SDOF is governed by its dynamic magnification factor (DMF_o), given as:

$$DMF_o = \frac{1}{2\xi_s} \tag{1}$$

The ES is retrofitted by rigidly attaching a TSWD of mass m_d, frequency ω_d and damping ratio ξ_d, with it.

ES as a single degree of freedom system retrofitted with TSWD may be modelled as linear two degree of freedom system (Fig.1). The dynamic magnification factor (DMF_r) for undamped structure coupled with damper was given by Den Hartog (Den Hartog, 1962). The concept has subsequently been extended to real life structures with damping. Considering ES-TSWD coupling as a linear two degree of freedom system, its dynamic magnification factor (DMF_r) under harmonic excitation is derived as (Yu, 1997):

$$DMF_r = \frac{1}{\sqrt{RE^2 + IM^2}} \tag{2-a}$$

Here:

$$RE = 1 - \beta^2 - \mu\beta^2 \frac{f^2\left\{f^2 - \beta^2 + (2\xi_d\beta)^2\right\}}{(f^2 - \beta^2)^2 + (2f\xi_d\beta)^2} \tag{2-aa}$$

$$IM = 2\xi_s\beta + \frac{2\mu f\xi_d\beta^5}{(f^2 - \beta^2)^2 + (2f\xi_d\beta)^2} \tag{2-ab}$$

β = ω_e / ω_s, Frequency ratio,
μ = m_d / m_s, Mass ratio,
f = ω_d / ω_s, Tuning ratio,
ω_e = Frequency of excitation,
The equivalent damping ratio 'ξ_e' of ES-TSWD coupled structure may be given as:

$$\xi_e = \frac{1}{2(DMF_r)} \tag{2-b}$$

For a condition of *f=1 and β=1* Equation (2-a) leads to (Connor, 2003):

$$\xi_e = \frac{\mu}{2}\sqrt{1 + \left(\frac{2\xi_s}{\mu} + \frac{1}{2\xi_d}\right)^2} \tag{2-bb}$$

As evident from above mentioned equations the ξ_e of retrofitted structure depends on f, μ, β, ξ_s and ξ_d. Modification of dynamic properties of ES is tedious, inconvenient and obstructive, hence considered beyond scope. The only controllable tuning parameters are ω_d, ξ_d, and μ. The ES-TSWD coupling is considered to be tuned if $\omega_d \approx \omega_s$. In tuned conditions, under dynamic loading, the sloshing mass of water in TSWD will resonate with the motion of ES and a part of the seismic energy imparted on ES will be dissipated. The energy dissipation results in reduced response of the coupled structure as two degree of freedom system.

The required damping mass M_d for effective retrofitting may be large enough to be accommodated in a single TSWD. Thus N number of TSWDs are required such that

$$M_d = N\, m_d \tag{2-c}$$

The DMF_o of bare ES is maximum when frequency content of ground motion is same as that of ES i.e at $\beta = 1$ (ω_e=ω_s). The ES-TSWD coupling has to be retrofitted for such eventuality.

TUNED SLOSHING WATER DAMPERS

A TSWD consists of a rigid vessel holding a given mass of water, rigidly attached with the structure (Figure 2).

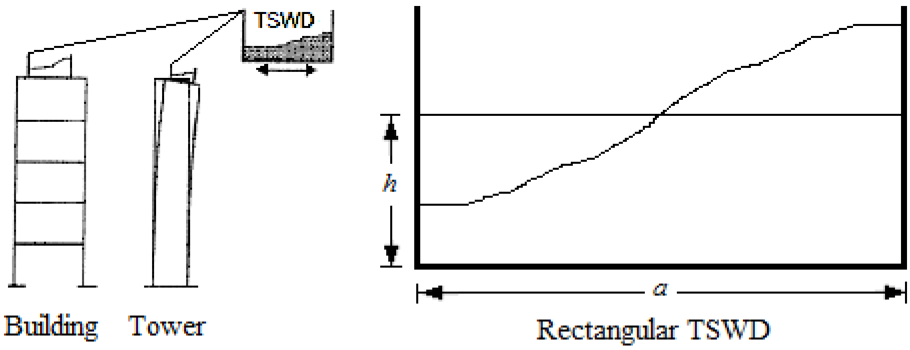


Fig. 2 TSWD on a structure

The water in the tank is tuned with the prime frequency of the host structure. The sloshing mass of water resonates with the host structural motion. The energy dissipation is caused by sloshing of water contained in the vessel. A part of the seismic energy imparted on the structure is dissipated by sloshing motion of water, thereby modifying the resultant structural response within acceptable limits.

The linear sloshing frequency of liquid ω_n (radian/sec), in a TSWD, on the basis of linear wave theory, (Abramson, 1966) is given as:

$$\omega_n^2 = \frac{g(2n-1)\pi \tanh(2n-1)\pi r}{a} \qquad \text{(3-a)}$$

The nonlinearity of the sloshing liquid frequency has been captured by empirical relations (Yu, 1997) as:

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

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

The mass of sloshing water m_d is given by potential flow theory (Graham and Rodriguez, 1952):

$$m_d = M \frac{8 \tanh\{(2n-1)\pi r\}}{r\pi^3 (2n-1)^3} \qquad \text{(4)}$$

For seismic design of rectangular water tanks the sloshing mass is designated as convective mass and the above-mentioned equation is simplified for fundamental mode of vibration (Housner, 1963) as:

$$m_d = M \frac{(0.83) \tanh 3.2r}{3.2r} \qquad \text{(4-a)}$$

Here:

n = sloshing mode equals to 1 for natural frequency,

M	= total mass of liquid in the tank,
g	= gravitational acceleration,
h	= depth of liquid in tank,
a	= tank dimension in direction of vibration,
r	= h/a
A_e	=Vibration amplitude of TSWD, equals to structural displacement at TSWD location.

The damping ratio 'ξ_d' of TSWD is a function of amplitude of excitation and tank dimension (A_e/a). The empirical relationships for TSWD damping ratio have been proposed as:

$$\xi_d = 1.78\,(A_e/a)^{0.68} \tag{5-a}$$

$$\xi_d = 0.5\,(A_e/a)^{0.35} \tag{5-b}$$

Equation (5-a) has been proposed by Yalla (Yalla, 2001) and Equation (5-b) has been proposed by Yu (Yu, 1997).

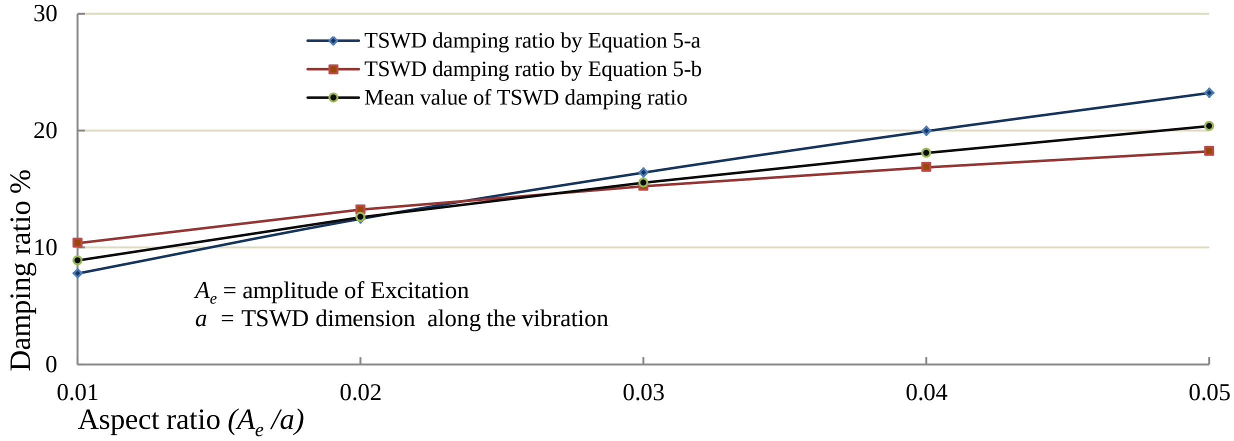


Figure 3 Damping ratio of TSWD w.r.t. amplitude of excitation

The mean value of the damping ratios obtained from Equations (5-a) and (5-b) has been plotted in Fig. 3 and considered in the present study for initial calculations.

EFFECTIVENESS OF RETROFITTING SYSTEM

The effectiveness of the TSWD retrofitting system is expressed, by a non-dimensional parameter effectiveness ratio 'E', as percentage reduction in structural displacement (from $D_{maximum}$ to $D_{permissible}$) due to application of retrofitting measure (Rai et al., 2011):

$$E = \{1 - (D_p/D_m)\} \times 100$$

or

$$E = [1 - \{DMF_r/DMF_o\}] \times 100 \tag{6}$$

For an ES and TSWD combination the effectiveness of TSWD depends on mutual tuning and it increases with increase in mass ratio 'μ'.

RETROFITTING METHODOLOGY

The above described concept of response control may be applied directly to the existing structures with all the advantages of TSWDs. A ‘hardware interactive soft path’ methodology is being proposed for the assured retrofitting performance. The reduced scaled model (SM) of ES with full size proposed TSWD is the hardware processed through the analytical path for the design of the ES-TSWD retrofitting regime. The step by step methodology is as follows:

1. **Step 1**

The ES is idealised for theoretical analysis. The damping ratio of ES is assumed with due engineering justification. The reference values of dynamic properties such as first mode frequency (ω_s), damping ratio (ξ_s) and maximum displacement (D_m) under particular dynamic excitation is determined analytically. Depending on structural assessment, value of maximum permissible displacement (D_p) and targeted effectiveness (E) is fixed.

2. **Step 2**

Based on the analysis of ES the TSWD dimensions are obtained for frequency $\omega_d = \omega_s$ and amplitude of excitation A_e=D_p through equations (3-a, b and c). The damping ratio (ξ_d) of TSWD is obtained from Fig.3.

3. **Step 3**

A physical scaled model (SM) of ES matching with the experimental resources available is constructed. The SM should have:
Dimensional aspect ratios with respect to plan, elevation and floor height of SM ≡ ES,
Number of structural members and joints in SM ≡ ES

4. **Step 4**

The SM is subjected to free vibration for determining its fundamental frequency. The floor wise distribution of loads should be fine-tuned in such a way that $\omega_{es} = \omega_{sm}$. The load distribution on SM should be similar to that of ES and fixed rigidly on all the floors. Symmetry of loading about axis of symmetry is maintained.

5. **Step 5**

A virtual model of SM, designated as VSM, is developed such that SM≡VSM. The VSM is analysed and its frequency is determined. The first mode frequency of the VSM should be equal to the fundamental frequency of the SM. In case of discrepancy, the material and sectional properties of members are adjusted globally in such a manner that concurrence in terms of frequency is achieved. Thus first mode frequency of ES is equal to fundamental frequency of SM and that in turn equal to first mode frequency of VSM, may be presented as follows:

$\omega_s = \omega_{es} = \omega_{sm} = \omega_{vsm}$.

6. **Step 6**

The TSWDs are constructed as proposed in step 2 and coupled with SM by mounting rigidly at the location of D_p=A_e. The dimensions of TSWD are experimentally fine-tuned for pre-determined depth (as proposed in step 2) of water, under free vibration test, by varying the length of

TSWD along the direction of vibration. The length of TSWD at which fastest decay of SM-TSWD coupling vibration occurs is considered optimum for mutual tuning of SM and TSWD.

7. Step 7

The SM without water in TSWDs, designated as bare SM, is subjected to forced sinusoidal excitation of resonant frequency through shake table. The bare SM is subjected to a range of excitation amplitudes at its base and displacements at the base of TSWD (location of D_p=A_e) are recorded through laser displacement sensor. The damping ratio of bare SM (ξ_s) is determined by equation (1). The VSM is also analysed with experimentally obtained values of ξ_s for the sinusoidal excitations of similar magnitude. The analytically obtained displacements for VSM should match the experimental observation on SM. In case of major discrepancy steps 3, 4 and 5 are to be repeated with modifications in load distribution of SM and input parameters in VSM.

Once concurrence in terms of maximum displacement, between experimental observations for SM and analytical values for VSM is achieved then it may be perceived that SM ≡ VSM.

The amplitudes of excitation at base (A_{be}) for which $A_e \approx D_m$ shall be selected and considered for further investigation on performance of SM-TSWD coupling.

8. Step 8

The optimised SM-TSWD coupling (with water in TSWDs) obtained from free vibration tests (step 6) is subjected to forced vibrations of magnitude selected from step 7 through shake table tests. The sloshing mass of water is varied by increasing the number of TSWDs. The reduced response of the SM due to TSWD coupling, under dynamic loading, is used to arrive at the ξ_e of SM-TSWD coupling by Equation 2-b. The effectiveness (E) of the retrofitting system is determined from Equation 6. Test specific relations between ξ_e, E and μ are developed.

The VSM is analysed with revised damping ratio as ξ_e for the same loadings as have been applied to the ES. The analytically determined displacement response reduction is compared with that target response reduction. In case of major discrepancy between both the displacement values, the input value of ξ_e for the VSM is revised to achieve the concurrence.

9. Step 9

The dynamic similitude between SM, VSM and ES is established and verified through steps 1 to 8. The test observations may be extrapolated analytically for real life application to the ES. The SM represents ES and SM-TSWD coupling represents retrofitted ES. It is considered that damping ratio of ES has increased from ξ_s to ξ_e after retrofitting. The mass ratio required for desired E and ξ_e are determined from the test specific relationship obtained in step 8. The required sloshing mass for desired mass ratio is applied on ES in the form of multiple numbers of TSWDs, obtained by arithmetical multiplication.

The above described methodology bridges the gap between analytical models and real life experienced data for existing structures as explained with the example of an existing structure (ES).

DESCRIPTION OF EXISTING STRUCTURE (ES)

The existing structure (ES), considered in present study, is situated in Mumbai, India. The ES is designed and executed in accordance of prevalent code provisions (BIS 456, 2000). It is a residential building with a centrally located staircase; over which overhead tank (OHT) is placed. All the columns are of 250 mm x 350 mm cross section except column no. B3, which is of 250 mm x

500 mm cross section. Typical beam cross section is 230mm x 400mm along X axis and 230mm x 450mm along Z axis. The external and internal walls are, of 230 mm and 115 mm thickness respectively, constructed in burnt clay bricks with 1: 4 cement sand mortar. The RC frame skeleton and structural floor plan of the building are shown in Fig. 4 and Fig. 5.

The structure is in sound structural condition, without any visible signs of distress or structural cracks hence a structural damping of 3% (Newmark and Hall, 1978) has been assumed for analysis. The structure is modelled and analysed by software STAADPRO, with structural damping of 3% for seismic conditions of zone III (BIS 1893, 2002). The salient analytically determined features of ES are given in Table-1.

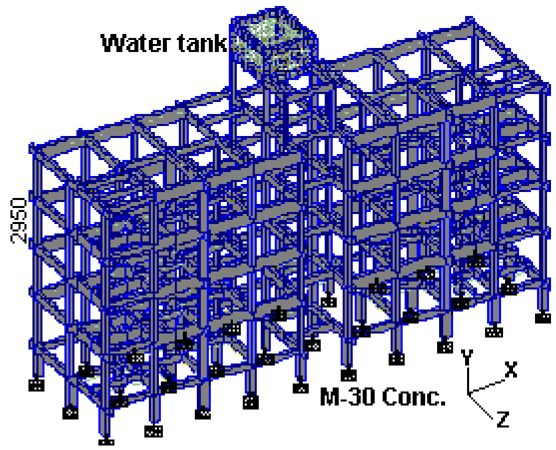


Fig. 4 RC Frame of existing structure (ES)

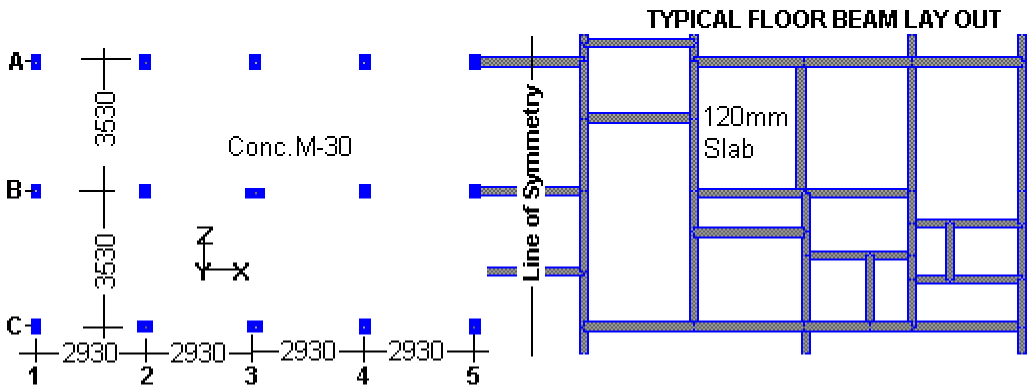


Fig.5 Structural floor plan

Table -1 Salient Features of Existing Structure (ES)

Sl.no.		Feature	Description
1		Mass of structure and mass participation in first mode m_s	1164000 kg. Mass participation in first mode 76% (885000 kg).
2		Structural damping ξ_s	3% (Newmark and Hall 1978)
3		Seismic zone	III as per IS 1893 part-1
4	a	First mode frequency of structure ω_s along Z	1.766 Hz (With masonry as diagonal strut). 1.195 Hz (Without structural contribution of masonry).
	b	First mode frequency of structure ω_s along X	1.803 Hz (With masonry as diagonal strut). 1.135 Hz (Without structural contribution of masonry).
6	a	Maximum displacement D_m	14.74 mm at roof level along Z axis.
	b		15.11 mm at roof level along X axis.
7	a	Permissible displacement D_p	11.05 mm at roof level along Z axis.
	b		11.33 mm at roof level along X axis.
8		Targeted effectiveness ratio 'E'	25%

The frequency of the ES shall have some intermediate value between the two extreme conditions of full structural contribution and no structural contribution from masonry. For the present study the average value has been considered as 1.48 Hz along Z and 1.47 Hz along X axis. The retrofitting methodology is being described in detail with respect to axis of symmetry along Z.

TSWDs FOR EXISTING STRUCTURE

For ω_d =1.48 Hz and A_e = 11.05 mm the TSWD parameters obtained from Equations 3, 4 5 and Fig. 3 are given in Table-2.

Table -2 Parameters of Tuned Sloshing Water Damper (TSWD)

Size mm			**Frequency along motion ω_d**	**Damping ratio ξ_d**	**Sloshing mass m_d**	
Length *a*	Depth *h*	Width *b*			Eq. 4	Eq. 4-a
mm	mm	mm	Hz	%	kg	kg
284	80	145	1.479	18.13%	2.1391	2.1749
220	40	145	1.481	20.77%	0.9348	0.9538
182	25	145	1.479	23.00%	0.5039	0.5149

Equation (4-a) gives slightly higher values of sloshing mass, for the present study equation (4) has been considered.

SCALED MODEL (SM) OF EXISTING STRUCTURE, TSWD AND TEST SET UP (HARDWARE)

A 1:20 reduced scaled model (SM) of ES has been constructed with mild steel wires, rods and plates (Fig. 6). The geometrical similarity in terms of proportionality of plan dimensions, elevations and floor height between ES and SM is maintained.

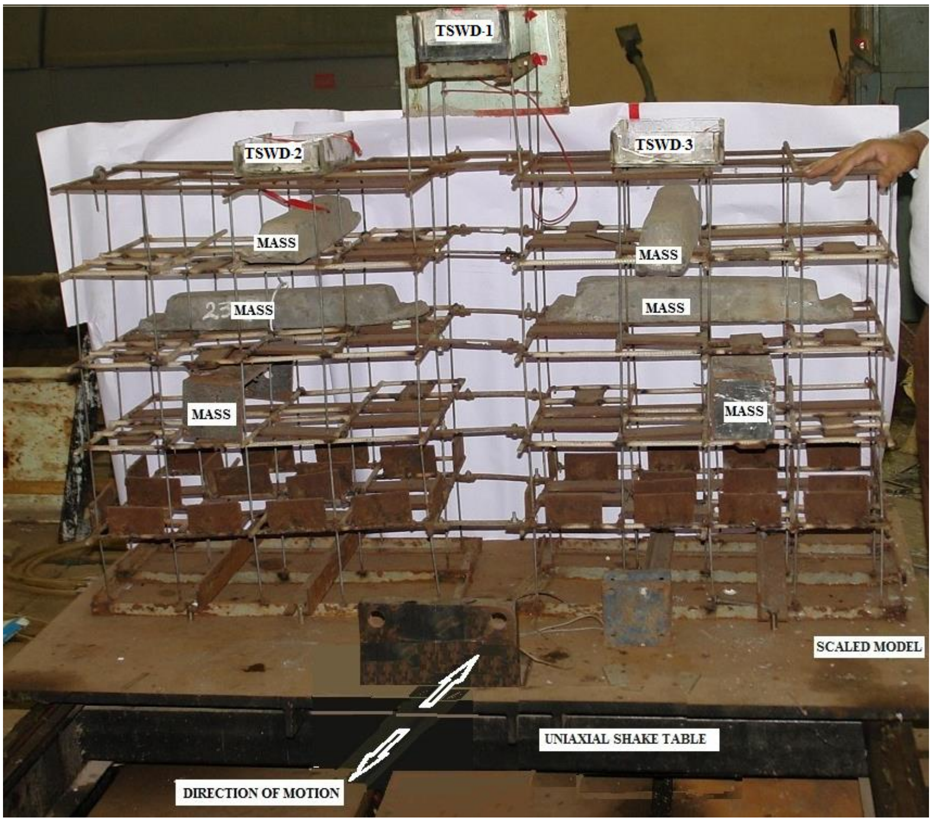


Fig. 6 Experimental setup with TSWD mounted scaled model (SM) on shake table

Self-weight of the SM is 39 kg. The imposed loads have been applied in the form of rigidly attached lead blocks of 25 kg and MS blocks of different sizes. Symmetry of loading about axis of symmetry has been ensured in all tests. The fine tuning of the dynamic properties are accomplished by manipulating floor loads and their distribution. The displacement profile of the SM should also be maintained comparable to that of the ES for 3% inherent damping under similar loading.

Three acrylic boxes, of internal dimensions 145mm x 350 mm in plan and 100mm depth, have been rigidly attached, with the SM to simulate the coupling of ES and TSWD. One box (TSWD-1) is fixed on the four central columns extended from main frame to simulate overhead tank in existing buildings. The remaining boxes (TSWD-2 and TSWD-3) are placed on the roof, one on each side of axis of symmetry. The boxes have been oriented in such a way that 145mm side is normal to the direction of vibration. Dimension of the TSWD along the axis of vibration has been varied by inserting a 145mm acrylic sheet partition normal to axis of vibration. The laser displacement sensor is fixed at the base of TSWD-1, to record the displacements during all tests. The scaled model and laboratory test setup is shown in Fig. 6.

VIRTUAL SCALED MODEL (VSM) OF EXISTING STRUCTURE

A virtual scaled model (VSM) of ES exactly similar to SM has been developed in STAADPRO.

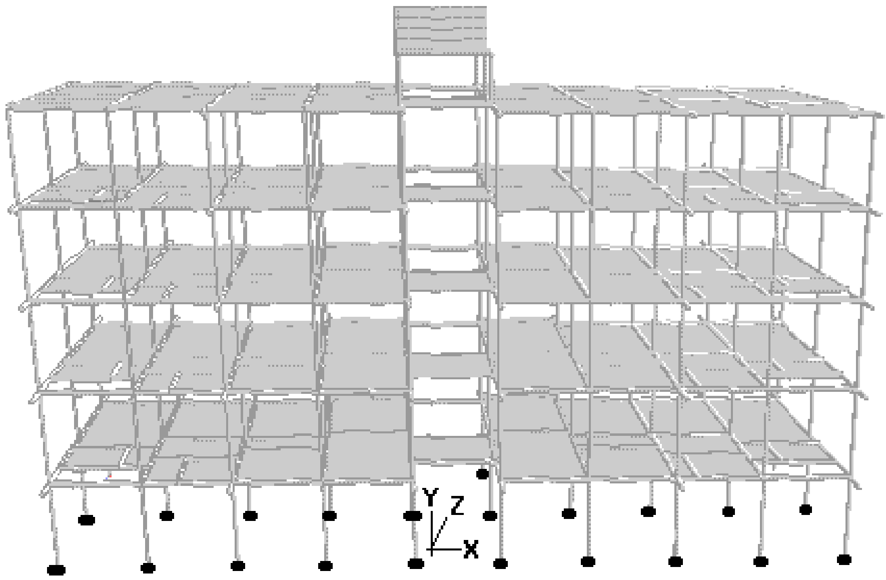


Fig.7 Structural Skeleton of Virtual Scaled Model (VSM)

The virtual model thus created is shown in Fig. 7. The analytical values of dynamic properties of VSM are tabulated in Table-4 and Table -7.

EXPERIMENTAL VERIFICATION

The performance of the retrofitting regime has been visualised by laboratory simulations for assured performance of the retrofitted structure at during real earthquake. The test schedule is planned in four stages with free and forced vibrations as given in Table-3. The free vibration tests have been conducted for, verifying the consistency of SM and TSWD with respect to analytical approach, and assessment of dynamic properties of the SM and TSWD for selecting the suitable test regime of experimental verification. The forced vibration tests have been planned and conducted for simulating coupled SM-TSWD performance under externally applied dynamic load of resonant frequency and ground motion time histories.

Table-3 Experimental Test Matrix

Sl. no.	Excitation type	Purpose
1	Free vibration	On bare SM, for verification of consistency of SM and determination of frequency.
2	Free vibration	On SM-TSWD coupling, for determination of optimum TSWD parameters.
3	Forced vibration (harmonic)	On bare SM, for obtaining suitable test regime and range of base excitation (A_{be}).
		On SM-TSWD coupling, for visualisation of response reduction due to TSWD and effect of mass ratio.
4	Ground motion time histories	Performance observation.

FREE VIBRATION TESTS

1. Verification and Behavioural Evaluation of Structural Model (SM):

The Bare SM (scaled model without water in TSWDs) is subjected to initial displacement of the order of 11mm at roof level and allowed to vibrate. The vibration amplitudes have been continuously recorded by laser displacement sensor. The test is repeated, with different weight combinations at floors, for verification of consistent behaviour of SM and respective similitudes with VSM. The SM under free vibration has been observed for 25 cycles, for the amplitude decay. The observed behaviour is compared with analytical results for VSM, as mentioned in Table-4.

Table-4 Free Vibration Tests on Scaled Model (SM) of Structure

Test model	Loading description						Observed frequency for SM	Analytical frequency for VSM	
	Gr. flr. UDL	1st flr.	2nd flr.	3rd flr.	Roof	Total		Initial	Modified
	kg/m	kg	kg	kg	kg	kg	Hz	Hz	Hz
SM-1	1.2	50	50	50	0	202	2.56	2.968	2.563
SM-2	1.2	50	50	50	50	252	2.41	2.881	2.390
SM-3	1.2	0	100	100	50	302	1.88	2.213	1.895
SM-4	1.2	118	118	118	7	413	1.76	2.047	1.759
SM-5	1.2	134	134	134	88	542	1.48	1.73	1.479

The free vibration tests on bare SM are primarily aimed to ascertain the consistency of structural behaviour of the model under dynamic loading. The observed frequencies of SMs are less than the analytical frequencies of VSM. This variance may be attributed to non-uniformity in sectional properties of the structural elements, imperfect fixity of beam-column joints and the fixity of the model with shake table. The VSM has been modified by 7.5% global reduction in cross-sectional area of all the structural elements and modulus of elasticity of the material of VSM. After these modifications the analytical values show good concurrence with observed values. The analytical values obtained after modification in the VSM are mentioned in the last column of the Table-4. As the convergence of observed values and analytical values are similar for all the floor loading combinations and frequencies hence the modification rule has been considered adequate for the present model and test regime. The frequency of SM-5 is equal to that of ES hence the same has been considered and designated as SM for further study.

The amplitude of vibration of SM, during free vibration tests, decays from 10.45mm to 3.21mm in 25 cycles. The damping ratio of the SM, evaluated by logarithmic decrement method, is 0.75% (Fig. 8). This value is consistent with the damping ratios adopted for metal structures in elastic range (Adams and Askenazi, 1999).

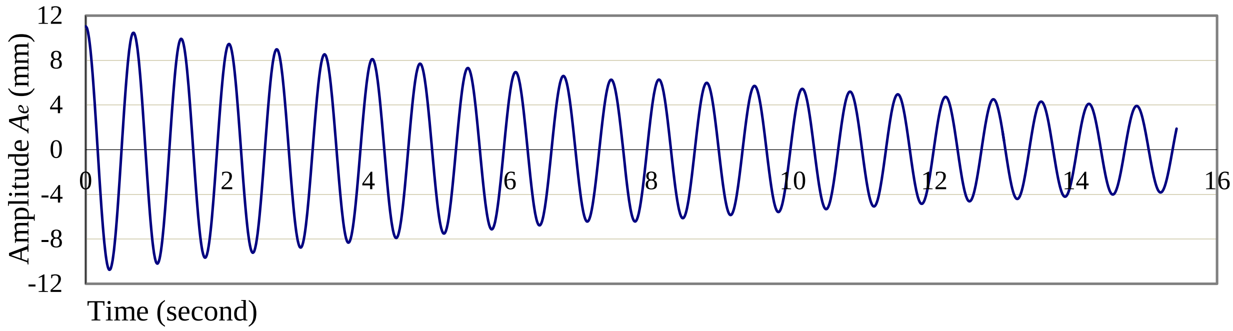


Fig. 8 Free vibration test on Bare SM

The damping ratio of SM for first 10 cycles is 0.79% and for last 10 cycles is 0.72%. The damping ratio of 0.75% is observed during the vibration amplitude of 8.5 mm to 7 mm. As the damping ratio is amplitude dependent phenomenon the representative amplitude considered in present study is 70% of the maximum amplitude of vibration imparted.

2. Determination of Optimum TSWD Parameters in Coupling with SM:

The coupling of SM and TSWD with water in only TSWD-1 location has been subjected to free vibration by giving an initial displacement of approximately 11mm. The optimum length '*a*' of TSWD has been searched for three, analytically pre-determined, depths of 80mm, 40mm and 25mm. The length variation has been affected by inserting a 145mm wide acrylic sheet partition, normal to direction of vibration at different locations, with constant depth of water.

The displacement of SM at the base of TSWD-1 is the amplitude of excitation 'A_e' for TSWD-1. The first set of the observations have been recorded with 80mm of water in TSWD-1. For every free vibration observation effective damping ratio 'ξ_e' of SM-TSWD coupling is determined by logarithmic decrement method (Table-5). The length of the TSWD, at which maximum value of 'ξ_e' is obtained, has been considered to be as optimum size of the TSWD, implying perfect tuning with SM, i.e. $\omega_s \approx \omega_d$.

Table-5 Optimum Size Search of TSWD in Coupled Conditions with SM

Size mm			Effective damping ratio 'ξ_d' %	Sloshing mass 'm_d' equation (4) kg
Length *a*	Depth *h*	Width *b*		
350	80	145	1.14	2.822
320	80	145	1.30	2.512
290	80	145	1.46	2.201
260	80	145	1.40	1.890
280	80	145	1.50	2.098
270	80	145	1.47	1.994

For the SM-TSWD coupling, with 80mm water depth 280mm is the optimum length of TSWD in direction of vibration. The significance of the mutual tuning of structure and TSWD has been substantiated. In tuned condition, 2.098 kg of water mass, has affected an increase in effective damping from 0.75% to 1.5%. In detuned conditions with 350 mm length of TSWD, 2.82 kg of water mass has been able to achieve an effective damping ratio of 1.14% only (Table-5, Fig.9-a).

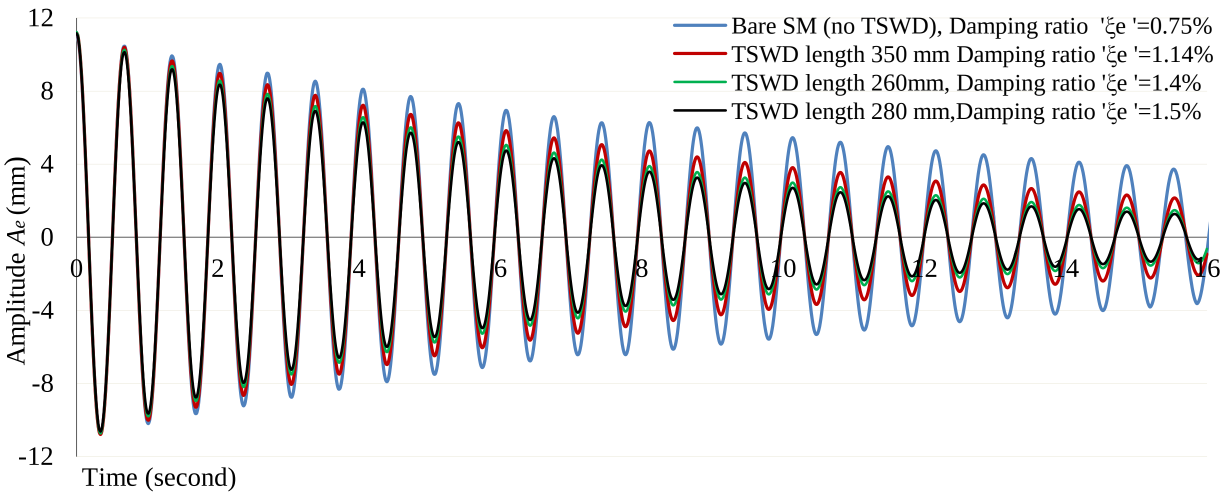


Fig. 9-a Effective damping ratio 'ξ_e' of SM-TSWD with 80 mm water depth

Similarly optimum lengths of TSWDs have been searched for 40 mm and 25 mm of water depths (Fig. 9-b and Fig. 9-c).

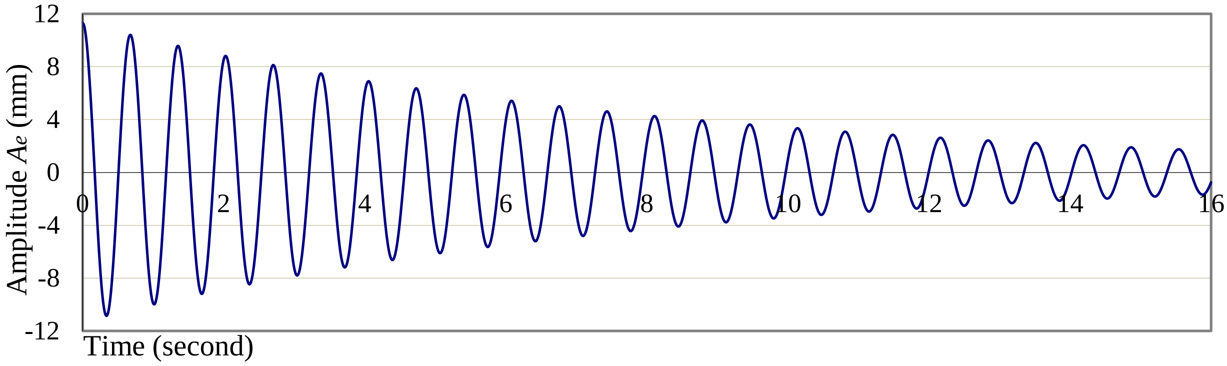


Fig. 9-b Optimum effective damping 'ξ_e'=1.29% of SM-TSWD with 40 mm water depth

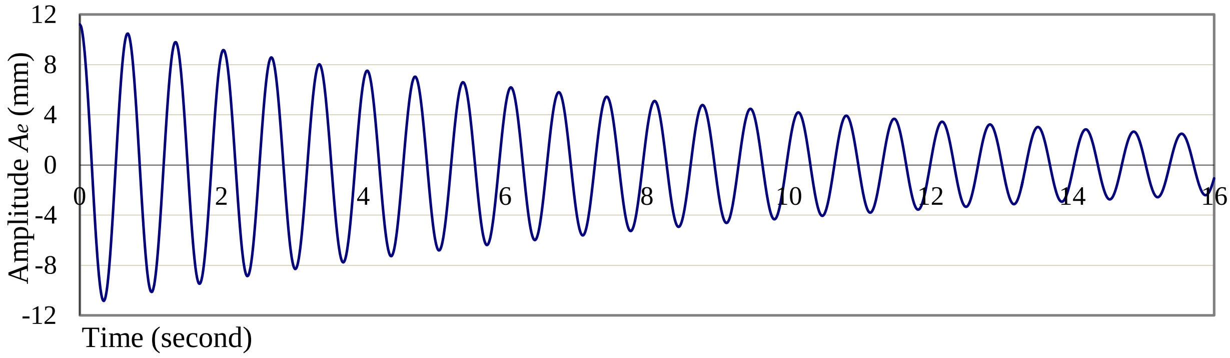


Fig. 9-c Optimum effective damping 'ξ_e'=1.02% of SM-TSWD with 25 mm water depth

The free vibration tests exhibited the effectiveness of the TSWD system, as there has been increase in effective damping ratio of the SM-TSWD coupling for all sizes of TSWD. The dimensions of TSWD and effective damping ratio of TSWD, obtained experimentally, have been tabulated in Table-6. The effective damping ratio 'ξ_e'of SM-TSWD coupling is sensitive to tuning ratio 'f' = ω_d / ω_s. In turn ω_d is sensitive to amplitude of excitation A_{emax}. Thus amplitude of excitation of TSWD is an important parameter for design of retrofitting system.

Two additional set of data for relevant TSWD parameters are generated analytically (by Equations 2, 3, 4 and Fig. 3) for A_{emax} and for 70% of A_{emax} respectively for each TSWD. The analytical values are compared with the experimentally obtained values (Table-6).

Table -6 Parameters of TSWD (Experimental and Analytical)

Sl. no.	TSWD Id	Experimental values			Analytically derived parametric values						
		Length 'a'	Depth 'h'	Eff. damping ratio ξ_e	Sloshing mass m_d (Eq. 4)	At A_{emax}			At 70% of A_{emax}		
						ω_d (Eq. 3)	ξ_d (Fig. 3)	ξ_e (Eq. 2)	ω_d (Eq. 3)	ξ_d (Fig.3)	ξ_e (Eq. 2)
		mm	mm	%	kg	Hz	%	%	Hz	%	%
1	$TSWD_{80}$	350	80	1.14	2.822	1.210	16.25	1.14	1.199	13.51	1.13
2	$TSWD_{80}$	280	80	1.50	2.098	1.500	18.27	1.33	1.446	15.16	1.44
3	$TSWD_{40}$	210	40	1.29	1.388	1.553	21.29	1.06	1.485	17.62	1.12
4	$TSWD_{25}$	174	25	1.02	0.952	1.552	23.57	0.93	1.484	19.46	0.98

It is seen that analytical values of 'ξ_e' obtained with 70% of A_{emax} are in good concurrence with observed values.

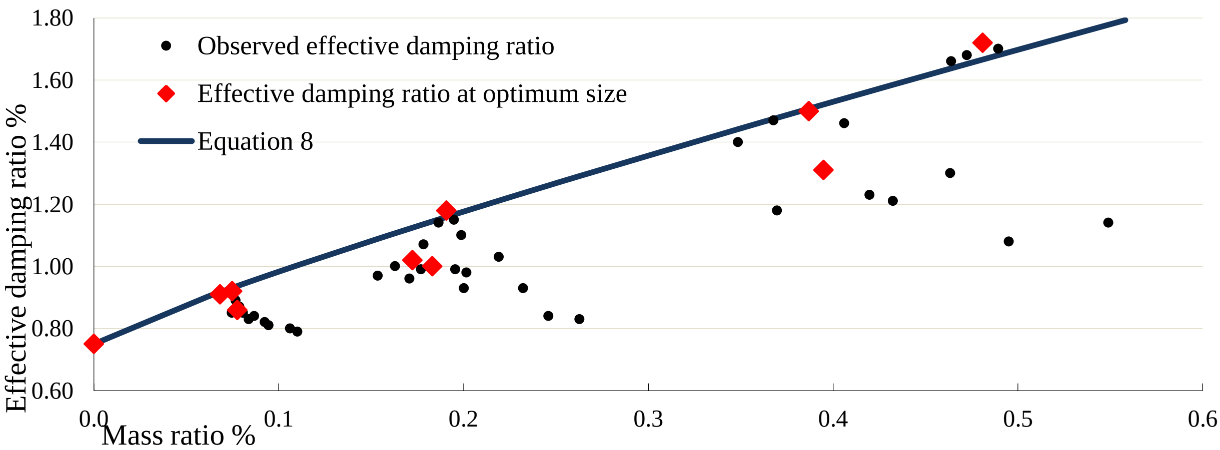


Fig. 10 Experimentally determined effective damping ratio w.r.t. mass ratio under free vibration

The spread of experimentally obtained values of 'ξ_e' with respect mass ratio suggests an almost linear relationship between them in perfectly tuned condition (Fig. 10).

FORCED VIBRATION TEST

1. SM Subjected to Harmonic Excitations (Bare Test):

The dynamic properties of the SM have already been assessed by free vibration tests. The SM with no water in TSWDs has been subjected to sinusoidal excitation of 1.48 Hz, the resonant frequency. These tests have been designated as bare tests.

Five sets of forced vibration tests with varying amplitudes of sinusoidal excitation at base 'A_{be}' have been conducted. The 'A_{be}' has been increased from 0.25 mm to 1.25 mm in incremental steps of 0.25mm. The performance of the bare SM has been observed and recoded for 50 cycles in each set. The observed displacements at TSWD-1 level and evaluated damping ratios of SM are mentioned in Table-7.

Table-7 Comparison of SM Performance Subjected Forced Vibration with That of VSM

Sl. no.	**Amplitude of excitation at base A_{be}**	**Experimental observations for SM**		**Analytical values for VSM**	
		Displacement	Damping ratio	Initial	Modified
	mm	mm	%	mm	mm
1	0.25	4.94	2.53	4.42	4.901
2	0.5	9.23	2.71	8.51	9.358
3	0.75	12.24	3.06	11.46	12.56
4	1	15.75	3.17	14.39	15.862
5	1.25	17.75	3.52	16.21	17.979

The VSM has also been analysed, with the observed structural damping ratios, for same excitations as applied to SM. The displacements thus obtained are tabulated (Column 4 and 5 of Table-7). The modification rules, applied to VSM for free vibration tests have been substantiated.

2. SM-TSWD Coupling Subjected to Harmonic Excitations:

The TSWD parameters are amplitude dependent, meaning different value for different vibration amplitude. Maximum vibration amplitude (A_{emax}) of the TSWD is same as the maximum structural displacement (D_m) at the TSWD location. The maximum displacement of ES under study is 14.74 mm. The maximum displacement of similar order in bare SM has been observed with amplitude of excitation at base 'A_{be}' of 0.75mm and 1.0mm. The effect of retrofitting performance of TSWD on SM has been studied for these sinusoidal base excitations only.

Each acrylic box is converted into a TSWD of width 145mm ('b' normal to excitation). The length of TSWD is fixed by inserting a 4mm thick acrylic sheet. The experimental observations have been taken with combination of $TSWD_{80}$ and $TSWD_{25}$, with 9 mass ratios varying from 0.177% to 2.34%. The observations thus obtained are tabulated in Table-8. The effectiveness of the TSWD on the SM performance is evident.

Table-8 Performance of SM-TSWD Coupling Under Forced Sinusoidal Excitation

Test no.	**Mass ratio μ%**	**Maximum displacement mm**	**Effective damping ratio %**			**Maximum displacement mm**	**Effective damping ratio %**		
			Observed	Analytical			Observed	Analytical	
				At A_{emax}	At 70% of A_{emax}			At A_{emax}	At 70% of A_{emax}
		Amplitude of excitation at base 'A_{be}' =0.75 mm				**Amplitude of excitation at base 'A_{be}' =1.0 mm**			
1	0	12.24	3.06	Bare test		15.75	3.17	Bare test	
2	0.177	11.2	3.35	3.22	3.27	14.25	3.51	3.3	3.34
3	0.354	10.26	3.66	3.38	3.51	13.23	3.78	3.43	3.52
4	0.53	9.38	4.00	3.55	3.77	12.2	4.1	3.57	3.7
5	0.757	8.67	4.33	3.98	4.28	11.39	4.39	3.9	4.18
6	0.991	8.02	4.68	4.31	4.67	10.57	4.73	4.18	4.54
7	1.228	7.55	4.97	4.54	4.86	9.98	5.01	4.3	4.65
8	1.56	6.47	5.58	4.99	5.36	9.26	5.4	4.82	5.16
9	2.34	6.05	6.42	5.97	6.51	8.06	6.42	5.71	6.22

As has been done for free vibration tests, analytically two additional sets of data for effective damping ratio 'ξ_e' are generated for A_{emax} and for 70% of A_{emax} respectively for each mass ratio and tabulated in Table-8. The inference of free vibration test has been substantiated, that analytical values for 70% of A_{emax} are closer to experimental values of ξ_e. Thus, analytically, the TSWD characteristic parameters should be evaluated for 70% of A_{emax}.

The experimentally observed effective damping ratio exhibits a relationship with mass ratio as shown in Fig.11. This empirical relationship from present study may be expressed as follows:

$$\xi_e = \xi_s + (5/\xi_s)\mu^{0.9} \tag{7}$$

The unique number 5 in second terms of RHS of Equation (7) is derived from the fact that 5% structural damping ratio is standard reference point in all the code treatments (Nawrotzki, 2005).

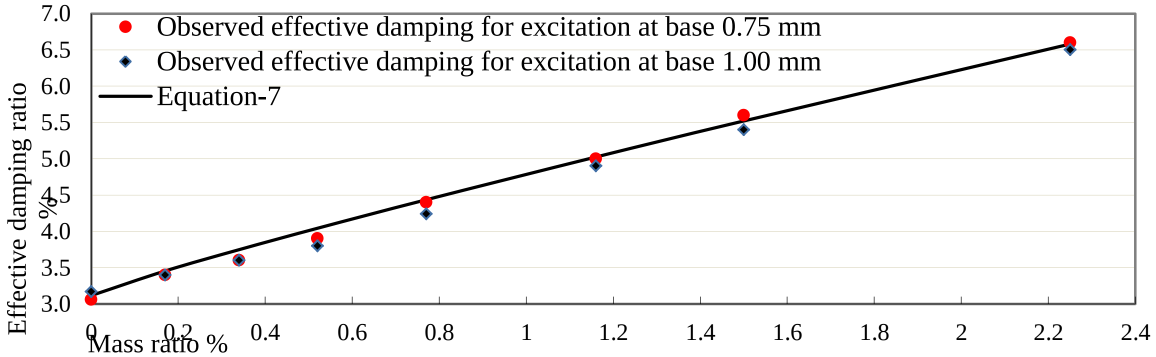
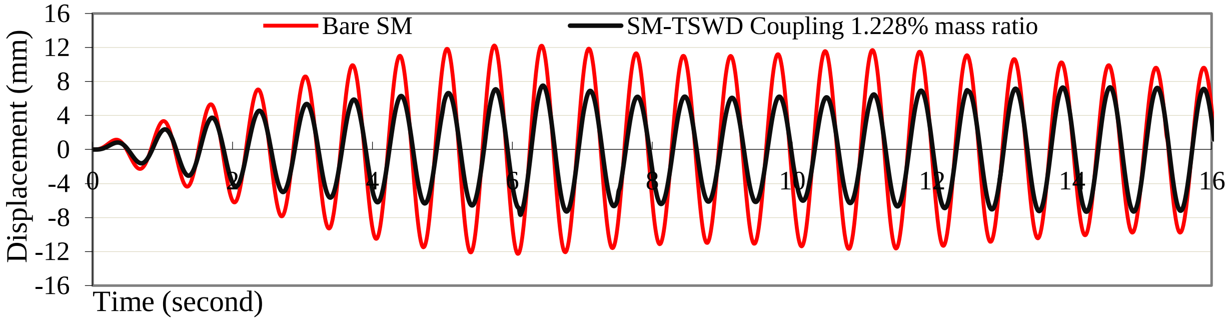
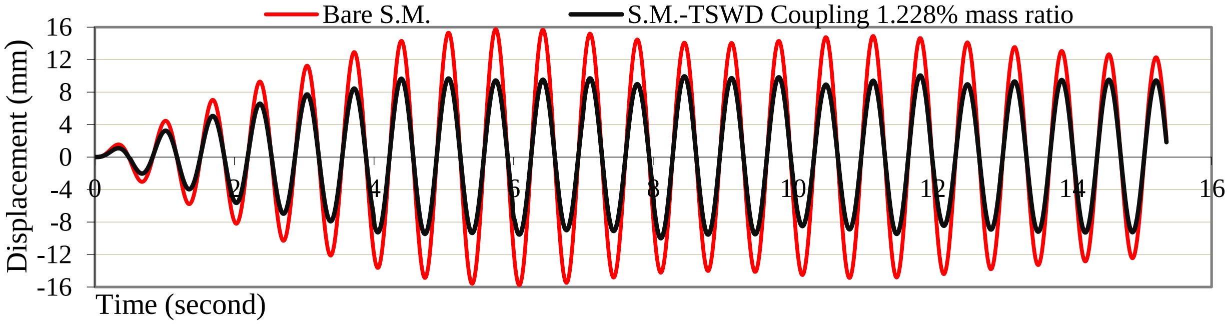


Fig. 11 Experimentally observed effective damping ratio with respect to mass ratio

For input base excitation amplitude (A_{be}) of 0.75mm and 1.0mm, the behaviour of SM with and without TSWD has been plotted for 1.228% mass ratio.



(a) Response reduction of 38.7% for an excitation amplitude at base A_{be} =0.75 mm



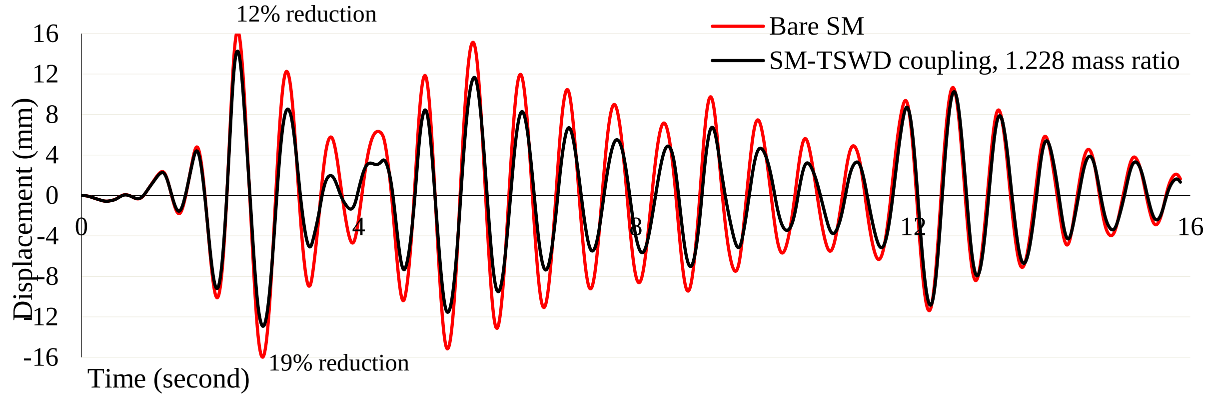
(b) Response reduction of 36.5% for an excitation amplitude at base A_{be} =1.0 mm

Fig. 12 Performance of SM -TSWD coupling under forced sinusoidal excitation

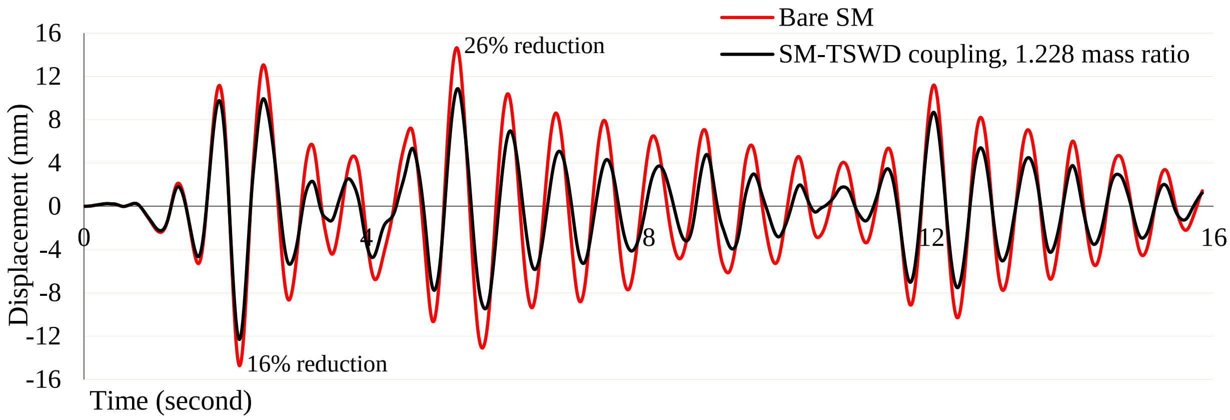
More than 35% reduction in maximum cyclic displacement of SM is observed as shown in Fig. 12-a and Fig. 12-b.

3. SM-TSWD Coupling Subjected to Ground Motion Time History:

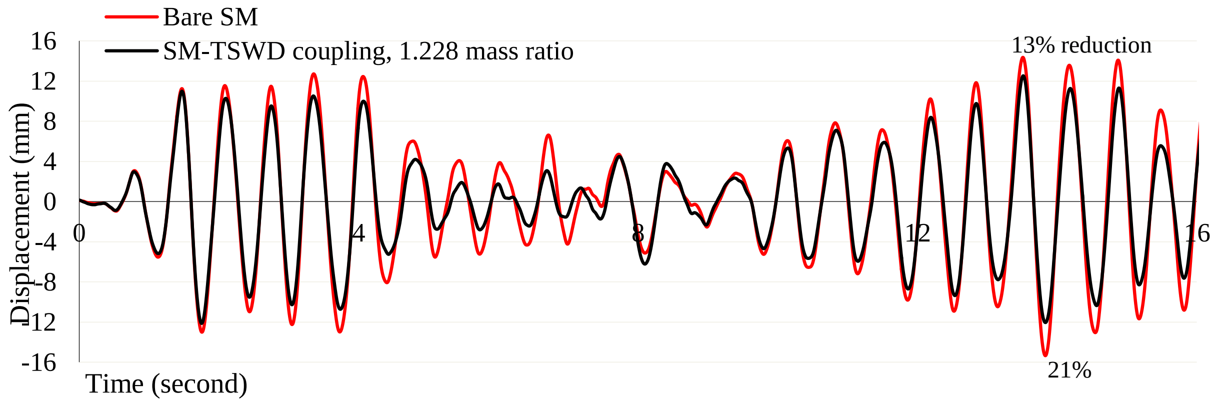
The performance of retrofitting system has further been substantiated with respect ground motion time histories. The SM has been subjected to ground motion of El Centro 1940 earthquake (Chopra, 1995) and IS1893 compatible time history. The maximum displacement observations of bare SM and with three $TSWD_{80}$ (1.228% mass ratio) have been recorded. The corresponding vibration profiles are plotted in Fig.13-a, Fig.13-b and Fig.13-c.



(a) SM-TSWD coupling against El Centro ground motion (EW component)



(b) SM-TSWD coupling against El Centro ground motion (NS component)



(c) SM-TSWD coupling against IS-1893compatible time history

Fig. 13 Performance of TSWD retrofitting system against ground motions

The effectiveness of the TSWD system is less as compared to that under sinusoidal excitation. This may be attributed to the fact that the TSWDs have been designed for excitation amplitude of 11.05 mm which may not be the same as has been experienced by the TSWD under ground motion histories chosen for experimentation.

4. SM and TSWD Parameters Along Axis X:

The above described test matrix and analytical procedures have been repeated with the SM oriented by 90^o such that axis X of the SM is parallel to direction of vibration. The acrylic box used as TSWD is of 280mm x350mm plan and 100mm depth, with 280mm side fixed normal to axis of vibration. The experimental observations substantiate the concept and various modification rules. The properties of SM and TSWD thus obtained are as follows:

Mass of SM	502 kg.
Frequency	1.47Hz (Obtained from free vibration test, modification rule of 7.5% global reduction in cross sectional area and modulus of elasticity have also been verified with VSM).
Damping ratio	3.25% (Under forced vibration with sinusoidal excitation amplitude at base A_{be}=1.0mm)
Length 'a' of $TSWD_{80}$	280 mm.
Sloshing mass in $TSWD_{80}$	4.05kg

In effect the $TSWD_{80}$ with 280mm x280mm plan size with 80 mm have effectiveness along the both principle axes of the SM. The total mass of water contained in the $TSWD_{80}$ is 6.27 kg.

EFFECTIVENESS OF SM-TSWD COUPLING

The relationship between mass ratio and effectiveness is nonlinear and depends on all the parameters (f, μ, β, ξ_s and ξ_d.) already included in Equation (2). From the experimental data tabulated in Table-8, a plot has been developed between E and μ (Fig.14).

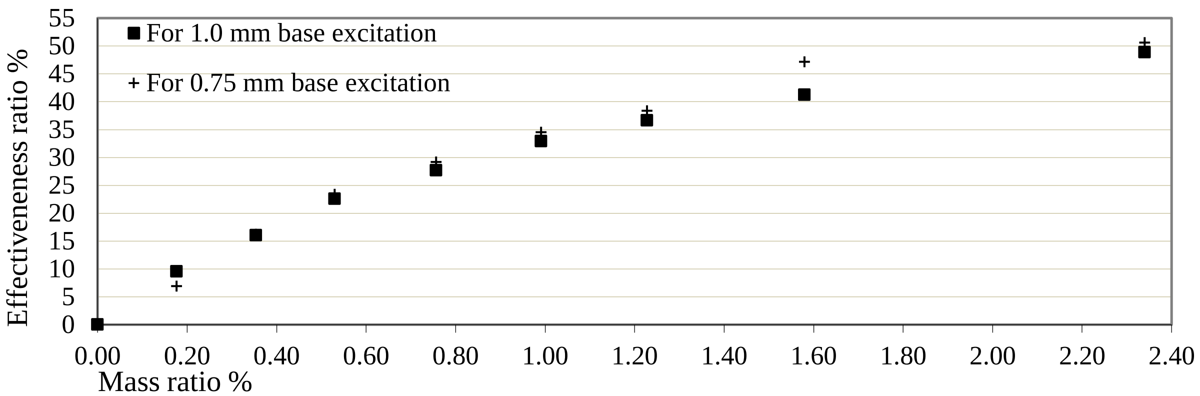


Fig. 14 Effectiveness of retrofitting system (observed values) with respect to mass ratio

The effectiveness of retrofitting system increases with increase in mass ratio. For the present SM-TSWD coupling, the E and μ relationship may be approximated by a linear equation as:

$$E = K\mu \tag{8}$$

Equation (8) is a model specific approximate expression for nonlinear relation between effectiveness and mass ratio. The factor *'K'* represents a gross value for cumulative effect of all the mutually interactive parameters of structure and TSWD. It may vary for different systems and structure-TSWD combinations. Equation (8) gives a quick preliminary estimate of mass ratio for desired effectiveness. The estimated mass ratio leads to effective damping ratio of retrofitted structure through Equation-7. The value of effective damping is subsequently checked analytically for desired response reduction.

APPLICATION OF THE TSWD RETROFITTING SYSTEM TO ES:

The above discussed retrofitting concept with TSWD is directly applicable to the existing structure for improving their seismic performance (Savyanayar et al, 2006). The ES has already been analysed (Table-1) and a scaled model of dynamic similitude has already been tested and visualised in the laboratory. The design of retrofitting system becomes a simple arithmetical iterative exercise for a desired effectiveness ratio of 25% as given below:

1. 1st Iteration

For the experimented SM-TSWD coupling the value of *'K'*, as obtained from Fig. 14, is 25. The Equation (8) may be written as:

$$E_{SM} = 25\mu \qquad \text{(8-a)}$$

The required mass ratio μ for 25% effectiveness ratio E (Equation 8-a) = 1.0%
For a mass ratio of 1.0% effective damping ratio ξ_e (Equation 7) = 4.72%

It is considered that after adopting the retrofitting scheme the effective damping ratio of the structure has increased to 4.72% as against initial 3% for un-retrofitted state. The VSM is analysed for increased damping ratio of 4.72% and the resultant maximum displacement is obtained as 10.48 mm along Z. Thus the effectiveness ratio achieved is 28.9%. The ES is also analysed with increased damping ratio of 4.72%. The maximum displacement obtained is 12.28 mm along Z. Thus the effectiveness ratio achieved is only 16.7% as against targeted 25%. This may be attributed to the fact that total mass of ES is not participating in the first mode of vibration.

It may be inferred the value of factor *'K'*, as determined for SM-TSWD coupling and used in Equation (8-a) is not applicable to ES-TSWD coupling and has to be revised, leading to 2nd iteration.

2. 2nd Iteration

The retrofitting regime is redesigned with increased damping mass to achieve the desired effectiveness. The value of factor *'K'*, of Equation (8) for ES-TSWD coupling is determined on the basis of approximate linear relationship between mass ratio and effectiveness as:

For 16.7% effectiveness ratio 'E' the value of factor *'K'* = 25
For 25% effectiveness ratio 'E' the value of factor *'K'* = 25 x16.7/25
= 16.7

The Equation (8) for ES-TSWD coupling may be written as:

$$E_{ES} = 16.7\mu \qquad \text{(8-b)}$$

The required mass ratio μ for 25% Effectiveness ratio (Equation 8-b) = 1.5%
For a mass ratio of 1.5% Effective damping ratio ξ_e (Equation 7) = 5.4%

After adopting the modified retrofitting mass ratio through Equation (8-b), the effective damping ratio of the ES has been increased to 5.4%. With this increased damping ratio the analytically determined maximum displacement for ES is 11.03 mm along Z and 11.28 mm along X, which is less than the targeted reduced response.

Corresponding total sloshing mass M_d to be contained in TSWDs is $= m_s\,\mu$

$= 13275$ kg.

The number of TSWDs required 'N' (from Equation 2-c) $= 3278$ units

The seismic response of the ES may further be reduced by increasing the sloshing mass.

3. Execution Scheme:

The total mass of water contained in one unit of $TSWD_{80}$ is 6.27 kg and sloshing mass of water in each unit is 4.05 kg. A total of 3278 $TSWD_{80}$ are to be provided for achieving required mass ratio.

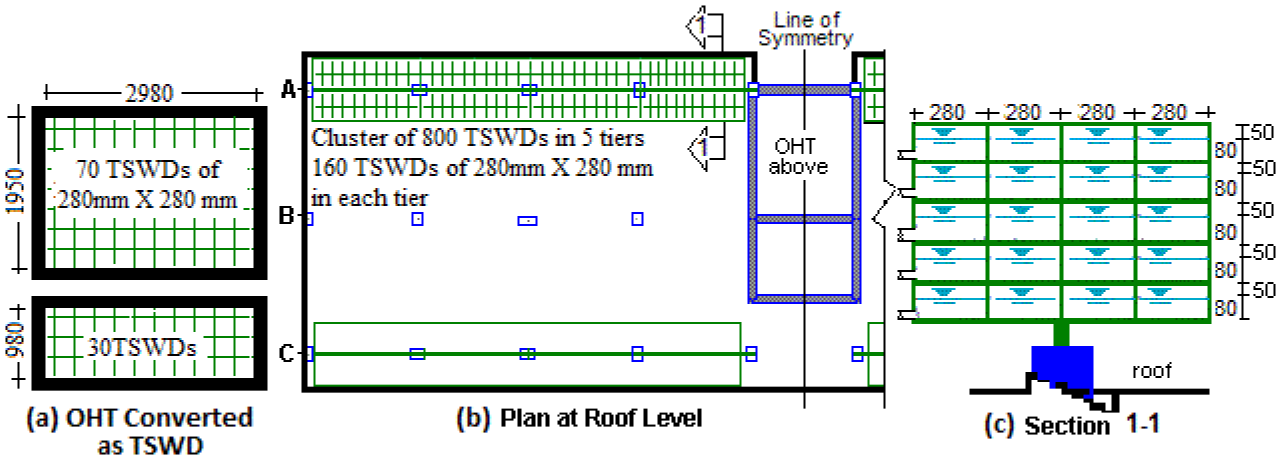


Fig. 15 Execution scheme of TSWD retrofitting system on ES

The existing water tank may be converted in to 100 TSWDs of 280 mm X 280 mm plan size by inserting 1 mm thick GI partitions (Fig. 15-a). Balance 3178 TSWDs of 280 mm X 280 mm X 130 mm size may be provided in four clusters at the roof of the ES. Each cluster contains 800 $TSWD_{80}$ in five tiers. Each tier contains 4 rows of 40 $TSWD_{80}$. These TSWD clusters may be fabricated in GI sheet as shown in Fig. 15-b and Fig. 15-c.

Increase in structural mass due to provision of additional 3200 units of TSWDs will be approximately 20070 kg. The mass of 150 mm thick and 1050 mm high parapet wall on the roof is 22600 kg. The increase in structural mass due to provision of TSWDs may be compensated by replacing the masonry parapet by MS piped railing. Thus a sloshing mass of 13365 kg contained in 3300 TSWDs, is accommodated on the roof which will act as $TSWD_{80}$ under seismic excitation, without causing any architectural, structural and occupancy interference with the ES.

Similar multi-layered TSWDs are already installed and are performing well against wind excitation in tall structures such as Nagasaki airport tower, Yokohoma marine tower, Shin-Yokohoma prince hotel and Tokio international airport tower (Tamura et al, 1995). The effectiveness of the retrofitting scheme for earthquake loading has been established through experimental simulations with different sizes of TSWDs having same natural frequency. It has been substantiated that for a given tuning ratio retrofitting performance is dependent on mass ratio. Thus the performance of the retrofitting regime under earthquake loading is assured by provisioning adequate sloshing mass in cluster of multi-layered TSWDs.

4. Comparison with TLCD Proposition

As evident from Fig. 15 even after incorporation of TSWD retrofitting regime in the ES, its roof is available for other utilities also. For comparable performance with TLCDs, based on the available design methods (Fahim et al, 1996), the U shape TLCD proposed will be of 40 mm internal diameter, 188 mm horizontal length and 40 mm vertical arm with orifice opening ratio of 0.75. The number of TLCDs required is 44640 along each principal axis. The provision 89280 TLCDs on roof will be highly cumbersome, more over in the non-designed directions TLCDs will be ineffective.

CONCLUDING REMARKS

This study focuses on the coupled behaviour of the TSWD with ES for best performance under various dynamic excitations. The ES- TSWD interaction was investigated by employing a 'hardware interactive soft path' method. The method involves intermittent use of theoretical formulations, their experimental verification and arriving on a case specific application rule. This method compensates for real life field data by simulated experimental investigations.

The Experiments have been conducted to investigate the performance of SM-TSWD coupling. The accuracy of empirical relations proposed by previous researchers has been checked in tuned conditions by varying other parameters (i.e., different types of loading, levels of excitation frequency, amplitude of excitation and mass ratios). For excitation amplitudes equivalent to 70% of maximum amplitude, the convergences of the experimental results are very good with empirical relations proposed by previous researchers. The modification rule of 70% vibration amplitude has been observed in free vibration tests and validated through forced vibration tests.

A structure specific relationship exists between mass ratio and effectiveness of retrofitting regime. For proposed SM-TSWD coupling it is represented by Equation (8-a), which may be modified for other combinations (e.g. Equation (8-b) for ES-TSWD coupling).

It has been observed that the TSWD is more effective for structures with low damping ratios. The phenomenon has been encapsulated in Equation (7). The effective damping ratio ξ_e is derived from the decreased structural displacements due to incorporation of TSWD. The TSWDs are effective from the start of the dynamic motion (Figure 12 and 13) without any time lag ensuring real time structural response control.

The equations and plots developed through shake table tests have been applied for developing a retrofitting regime of an ES. It is seen that the effective damping of ES increases from 3% to 5.4% without any stiffness loss. A seismic response reduction of 25% with 1.5% sloshing mass is achievable for the ES.

The TSWDs to be applied to the ES is tested, for the retrofitting effect on a reduced scale model (SM) having dynamic similitude of ES, for all types of dynamic excitations. The observed effectiveness of TSWD in reducing the response of SM against forced vibration is also valid for real life structures with comparable dynamic similitude. In effect a retrofitting system tested in the laboratory has been multiplied manifold for its effectiveness on a real life structure, providing a very high degree of performance assurance. The ES considered in the study is representative of existing building stock. Most of the medium height existing structures designed and constructed with working stress principles may be retrofitted with TSWD to safety against earthquake forces.

This method of seismic retrofitting of existing structures with TSWDs addresses the serviceability, safety and durability concerns. The method is easy to execute, environmentally sustainable, cost effective and ensures all time preparedness against earthquake without any post retrofitting maintenance.

REFERENCES

1. Abramson, H.N. (1966), “The Dynamic Behaviour of Liquids in Moving Container” NASA SP-106.
2. Adams, V. and Askenazi, A. (1999), “Building Better Products with Finite Element Analysis”, On Word Press, Santa Fe, N.M.
3. BIS (2000), “IS 456-2000 Indian Standard Code of Practice for Plain and Reinforced Concrete”, Bureau of Indian Standards.
4. BIS (2002), “IS 1893(Part 1)-2002 Criteria for Earthquake Resistant Design of Structures: Part1 General Provisions and Buildings (Fifth Revision)”, Bureau of Indian Standards.
5. Chopra, A.K. (1995), “Dynamics of Structures: Theory and Applications to Earthquake Engineering”, Prentice Hall, USA.
6. Connor, J.J. (2003), “Introduction to Structural Motion Control**”,** Prentice Hall, USA.
7. Den Hartog, J.P. (1962), “Mechanical Vibrations”, 4th edition, McGraw-Hill.
8. Fahim, S., Bijan, M. and Lew, H.S. (1996), “Single and Multiple Tuned Liquid Column Damper for Seismic applications”, NISTIR 5920.
9. Frahm Herr II (1911) “Results of Trials of Anti-rolling Tanks At Sea”, Read at Spring Meeting of 52nd Session of Institution of Naval Architects.
10. Graham, E.W. and Rodriguez, A.M. (1952), “The Characteristics of Fuel Motion Which Affect Airplane Dynamics”, Journal of Applied Mechanics, Vol.19, No.3, pp381-388.
11. Hassan, M. (2010), “A Numerical Study of the Performance of Tuned Liquid Dampers”, Open Access Dissertations and Thesis, Paper 4253.
12. Housner, G.W. (1963), “The Dynamic Behaviour of Water Tanks”, Bulletin of Seismological Society of America, Vol.53, No.2, pp 381-387.
13. Kareem, A. and Sun, W.J. (1987), “Stochastic Response of Structures With Fluid Containing Appendages”, Journal of Sound & Vibration, Vol. 119, pp. 389 - 408.
14. Langhar, H.L. (1951), “Dimensional Analysis and Theory of Models”, John Wiley and Sons Inc., New York.
15. Malekghasemi, H. and Mercan, O. (2011), “Experimental and Analytical Investigations of Rectangular Tuned Liquid Dampers (TLDs)”, RCI Report No. 2011-02.
16. Modi, V.J. and Welt F. (1987), “Vibration Control Using Nutation Dampers”, Proc. International Conference Flow Induced Vibration, England, pp 369-376.
17. Newmark, N.M. and Hall, W.J. (1978), “Development of Criteria for Seismic Review of Nuclear Power Plants”, NUREG/CR-0098.
18. Nawrotzki, P. (2005), “Visco-elastic Devices for the Seismic Control of Machinery Equipment and Buildings”, Pro. of 9th World Seminar On Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures, Kobe, Japan.
19. Rai, N.K., Reddy, G.R., Venkatraj,V., Agrawal, P. and Ramanujam, S. (2009), “Seismic Response Control Systems for Structures”, Defence Science Journal, Vol.59, pp 239-251.
20. Rai, N.K., Reddy, G.R. and Venkatraj, V. (2010), “Seismic Retrofitting of Existing Structures: Over Head Tank as TSWD”, Proceedings of the 14th Symposium on Earthquake Engineering, December 17-19, Roorkee.

21. Rai, N.K., Reddy, G.R. and Venkatraj, V. (2011), "Effectiveness of Multiple TSWD for Seismic Response Control of Masonry In-filled RC Framed Structure", ISET Journal of Earthquake Technology, Vol.48, 2-4.
22. Sakai, F., Takeda, S. and Tamaki, T. (1989). "Tuned Liquid Column Damper- New Type Device for Suppression of Building Vibrations", Proceedings of the International Conference on High Rise Buildings, pp 926-931, March 25-27, Nanjing, China.
23. Sato, T. (1987), "Tuned Sloshing Damper", Japan Journal of Wind Engineering, Vol.32, pp 67-68.
24. Savyanayar, R.C., Reddy, G.R., Parulekar, Y.M., Kumar, P., Rama Rao, A., Chavan, S.P., Vaze, K.K., Ghosh, A.K. and Kushwaha, H.S. (2006), " Experimental Evaluation and Retrofitting of Structure Subjected to Earthquake Loading with Circular Tuned Liquid Damper (TLD)", Journal of Structural Engineering, SERC, Vol. 33, No. 6, pp 479-486.
25. Sharma, A., Reddy, G.R. and Vaze, K.K. (2012), "Shake Table Tests on A Non-seismically Detailed RC Frame Structure", Structural Engineering and Mechanics, Vol. 41, No.1, pp 1-24.
26. Sun, L. M., Fujino, Y., Chaiseri, P. and Pacheco, M. (1995), "The Properties of Tuned Liquid Dampers Using A TMD Analogy", Earthquake Engineering and Structural Dynamics, Vol. 24, pp. 967-976.
27. Tait, M.J., (2008), "Modelling and Preliminary Design of A Structure-TLD system", Engineering Structures, Vol. 30, Issue 10, pp 2644-2655.
28. Tamura, Y., Fujii, K., Ohtuski, T., Wakahara, T. and Kohsaka, R. (1995), "Effectiveness of Tuned liquid Dampers under Wind excitation", Engineering Structures, Vol.17, No.9, pp. 609-621.
29. Warburton, G.B. (1981), "Optimum Absorber Parameters for Minimizing Vibration Response", Earthquake Engineering and Structural Dynamics Vol. 9, pp 251-262.
30. Yalla, S. K. (2001), "Liquid Dampers for Mitigation of Structural Response: Theoretical Development and Experimental Validation", Ph.D. Dissertation, University of Notre Dame.
31. Yu, J. K. (1997), "Non-linear Characteristics of Tuned Liquid damper", Ph.D. Dissertation, University of Washington.