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EFFECTIVENESS OF MULTIPLE TSWDs FOR SEISMIC RESPONSE CONTROL OF MASONRY-INFILLED RC FRAMED STRUCTURES

Nishant Kishore Rai[*], G.R. Reddy** and V. Venkatraj[*]

*Directorate of Construction, Services & Estate Management
Department of Atomic Energy, Mumbai-400094
**Bhabha Atomic Research Centre
Department of Atomic Energy, Mumbai-400094

ABSTRACT

An existing masonry-infilled RC framed structure can be retrofitted for improved performance under earthquake loading by the structural response control methodology using tuned sloshing water dampers (TSWDs). The retrofitting may be accomplished by modifying the existing overhead tank, and by installing additional tanks of tuned geometry, for the required response reduction. The required water mass is provided in multiple TSWDs, with their frequencies distributed around the natural frequency of the existing structure. The system as a whole behaves as a multiple-TSWDs retrofitting regime with robustness and reliability. This system takes care of the assessment approximations in the dynamic properties of the existing structure. The proposed retrofitting method aims for reduced displacements during an earthquake. The efficiency of the proposed system may be quantified by its effectiveness ratio. Design charts are developed for reducing the iterative computational efforts. The simplicity of the design and execution of the proposed retrofitting regime is illustrated by the example of an existing four-story structure.

KEYWORDS: Dynamic Magnification Factor (DMF), Mass Ratio, Frequency Ratio, Tuning Ratio, Effectiveness Ratio

INTRODUCTION

Conventional structures have been built to support loads due to gravity only, thus having very little resistance to the lateral forces caused due to earthquakes. The destruction caused in Ahmedabad during the Bhuj 2001 earthquake (EERI, 2001) has exposed the vulnerability of such buildings against earthquakes.

The strengthening and re-qualification of the existing structures against earthquakes is a major area of concern. Most of the existing structures (ES) with ordinary moment-resisting RC frame and masonry-infilled walls have not been designed for earthquake loads. Therefore, these structures are required to be retrofitted. The conventional method of retrofitting an RC framed structure involves the strengthening of its structural components by jacketing and grouting, which may be cumbersome and inconvenient for the occupants of the structure. At the same time the architecture and utility of the building may also be adversely affected.

Another method of retrofitting gaining acceptance lately is of structural response control by incorporating damping devices in the existing structure. As shown in Figure 1, the active, semi-active, hybrid and passive types of damping devices are being used all over the world for structural control (Rai et al., 2009).

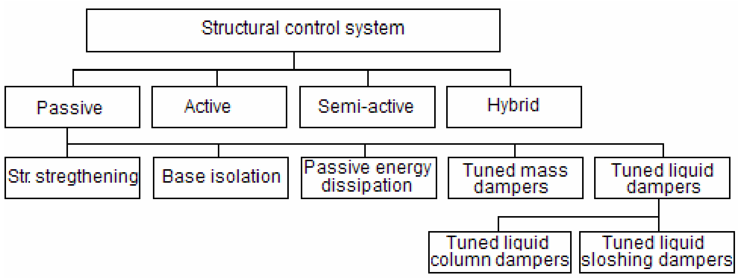


Fig. 1 Structural control systems

The active, semi-active and hybrid types of structural control systems are technology intensive. Further, these systems require an external source of energy for their operation, which may not be available at the required instant of time. In view of these limitations the passive devices are considered more suitable and reliable. Among these, tuned mass dampers (TMDs) and tuned liquid dampers (TLDs) perform by utilizing the damper inertia for energy dissipation. The frequency of the dampers is tuned with the natural frequency of the structure such that the damper mass resonates with the structural motion, thus causing energy dissipation and response reduction under an earthquake excitation.

The theory of TMDs was initially presented for the undamped single-degree-of-freedom (SDOF) systems (Den Hartog, 1956). This concept has been further generalized and optimized for the damped structures (Tsai and Lin, 1993). The 726-ton TMD installed in Taipei 101 is a celebrated example of TMDs, which is designed to reduce the dynamic structural response by more than 30% (Kourakis, 2007). A conventional TMD system requires additional mass and space for its installation. The concept of TMD has been further optimized for practical applicability by isolating a part of the structure to be used as the tuned damping mass. The isolation of the roof of a 13-story building was studied and found feasible for reducing its seismic response (Villaverde, 2000). The roof of an elevated RCC tank has been proposed as a TMD to reduce its response by 20% (Jaiswal, 2004). Two TMD regimes for a 12-story building have been studied by isolating and converting its top two and top four stories respectively as tuned masses along with viscous dampers (Chey et al., 2008). The response control of a 43-story building has been proposed by converting its top floor as a TMD, and a reduction of 20% in its story drifts has been predicted (Makino, 2009). Two case studies have been done for examining the effectiveness of an existing overhead tank (OHT) as a TMD without incorporating any structural changes. It has been analytically found that for 50% or more water in the tank the response of the structure is reduced (Hemalatha and Jaya, 2008).

All the above propositions, for effectiveness, are either applicable to a new structure or require structural modification by the isolation of structural components from the main structure. TLDs are comparatively an easier and more attractive option, wherein the existing water tanks may be utilized as a damping device without any major modifications in the structural systems of the ES (Rai et al., 2010). The evolution of TLDs has been primarily in naval and aerospace engineering. The initial application of TLDs was conceptualized and proposed by W. Froude in 1862, while using two interconnected tanks of tuned frequencies to reduce the rolling motion of a ship (see Figure 2). The actual device was put into application by Sir P. Watts in 1883. Later, a U-shaped tank as roll stabilizer was proposed by Frahm (1911). Further, the response of offshore structures has been reduced by using the mud and crude oil storage tanks as stabilizers (Vandiver and Mitome, 1979). Modi and Welt (1987) were among the first to propose TLD applications for the ground structures. A few parametric studies on TLDs have been presented by Fujino et al. (1988). Thereafter, a number of researchers have studied the behaviour of TLDs. The practical applications of these dampers in the structures like Gold Tower Chiba, Shin Yokohoma Prince Hotel, Nagasaki Airport tower and Tokyo Airport tower have shown the response reduction up to 70% at a wind speed of 20 m/s (Tamura et al., 1995). It has been established that for a given mass ratio, a large modal damping in the first mode of vibration may be achieved by tuning for that frequency. A number of tall structures have come up with TLDs for the response control against wind (Rai et al., 2009).

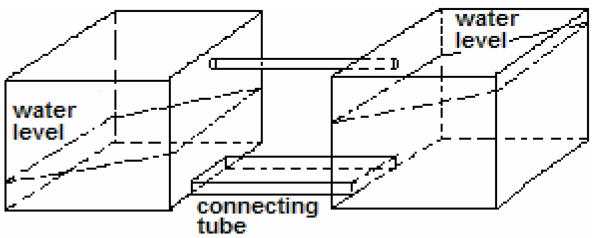


Fig. 2 Interconnected tanks as rolling stabilizer

The theory and analysis of TLDs are dealt on the basis of their analogy with TMDs, where the damper mass is in the form of a liquid (Yalla, 2001). TLDs are classified based on their physical characteristics as tuned liquid column dampers and tuned liquid sloshing dampers. The sloshing dampers with water as the sloshing liquid are termed as tuned sloshing water dampers (TSWDs).

The frequency tuning of the damper mass with the frequency of the structure in ES is vital for the effectiveness of the damping system but is difficult to achieve due to certain assessment approximations in the dynamic properties of the ES. The concept of multiple mass dampers (MMDs), with natural frequencies of the dampers distributed around the assessed natural frequencies of the ES, has been studied for a more robust performance of the dampers. The tuned multiple spatially distributed dampers have shown significant improvement over the performance of a single damper and are more effective in mitigating the motions of the ES under the earthquake excitations. For the same damping mass, the response reduction achieved by multiple dampers (say, five in place of one) is more than that due to a single damper (Kareem and Kline, 1995). A distributed TLD system by filling the hollow floor slabs with water has been found to increase the damping of the structure during the seismic excitations (Lieping et al., 2008). However, this method cannot be applied to the ES. The possibility of converting an OHT as a TSWD has been explored and found to be feasible for retrofitting the ES (Rai et al., 2010).

In this paper seismic retrofitting for the existing medium-height structures is proposed, wherein the existing OHT of the building is modified to the extent that it behaves as a multiple TSWD system. A few additional TSWDs are added at the roof of the building for a further improvement in its performance. The frequencies of the TSWDs are distributed around the estimated frequency of the existing structure to be retrofitted. The effectiveness ratio plots for retrofitting systems with respect to mass ratio, for the realistic ranges of tuning ratio and damping ratio, are developed. These charts reduce the computational demand and make the design methodology very simple. The proposed method is illustrated with the example of an existing structure.

STRUCTURAL RESPONSE CONTROL: GENERAL CONCEPT

The response of an SDOF structure under seismic excitations is governed by its in-built structural properties, mass m_s, stiffness k_s, and damping c_s. The derived dynamic properties of the structure are its natural frequency ω_s and damping ratio ξ_s, expressed as

$$\omega_s = \sqrt{k_s / m_s} \tag{1}$$

and

$$\xi_s = c_s / 2 m_s \omega_s \tag{2}$$

The influences of frequency and damping ratio on the response are incorporated in the design procedures through response curves (e.g., see Figure 3). A typical 5% damping ratio is implicit in the code-specified earthquake forces and design spectra (Chopra, 1995). A response correction factor is therefore suggested by Nawrotzki (2005) for a damping ratio other than 5% (see Figure 4). It is evident from Figures 3 and 4 that the response of a structure may be reduced by increasing its damping. With an increase in deformation, the inherent damping ratio also increases, but the stiffness of structure gets reduced (Chopra, 1995). This may be detrimental to the structure and should be avoided during a seismic event. The damping ratio of the ES can be increased without a loss of stiffness by incorporating a supplemental energy dissipater in the structural systems.

The time-dependent energy relationship during a seismic event may be expressed as

$$E(t) = E_k(t) + E_s(t) + E_h(t) + E_d(t) \tag{3}$$

where $E(t)$ represents the total energy input due to the earthquake, $E_k(t)$ represents the absolute kinetic energy, $E_s(t)$ represents the (recoverable) elastic strain energy, $E_h(t)$ represents the irrecoverable energy dissipated through inelastic, viscous and hysteretic actions, and $E_d(t)$ represents the energy dissipated by the supplemental damping system, at the time t. If D_m represents the deformation of the existing structure without any retrofitting measure, the deformation D_p after retrofitting (i.e., the installation of TSWDs) may be restricted to the maximum permissible deformation, i.e., $D_p < D_m$, for designing the TSWDs.

In conventional structures (see Figure 5(a)) $E_d(t)$ is not present. The input energy from the earthquake is, therefore, transformed into the kinetic and strain energies and is dissipated through the inherent energy dissipation capacity of the structure by the hysteretic actions represented by the damping ratio ξ_s of the structure. By attaching an energy dissipating device, such as TSWD, to the structure (see Figure 5(b)), a portion of the input seismic energy $E_d(t)$ is absorbed by this device. This results in a reduced response (i.e., D_p) of the structure. This phenomenon may be quantified through an increase in the effective damping ratio of the structure as a whole.

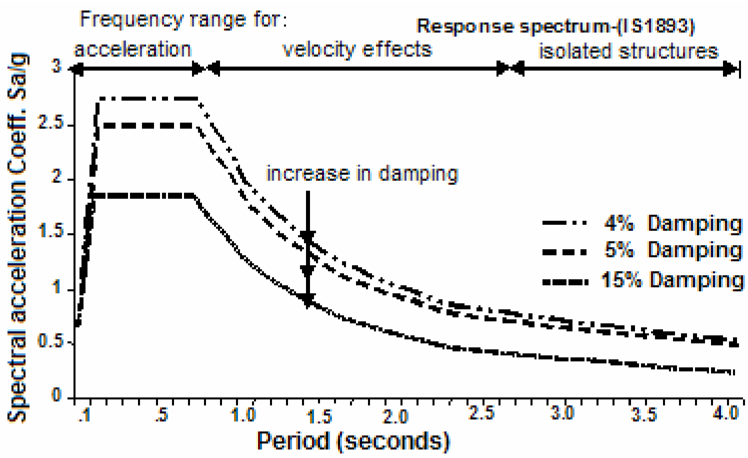


Fig. 3 Acceleration response spectrum for ground motion

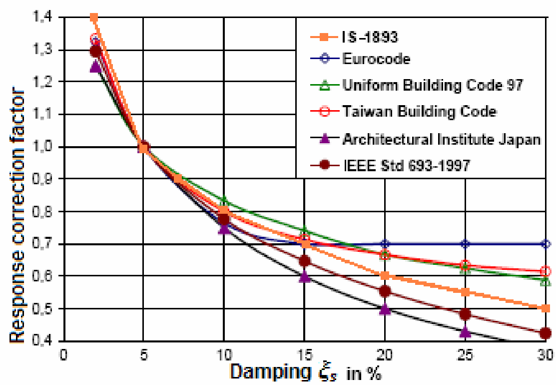
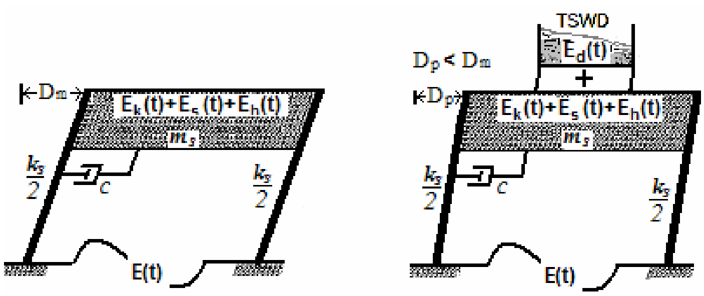


Fig. 4 Effect of damping ratio on structural response

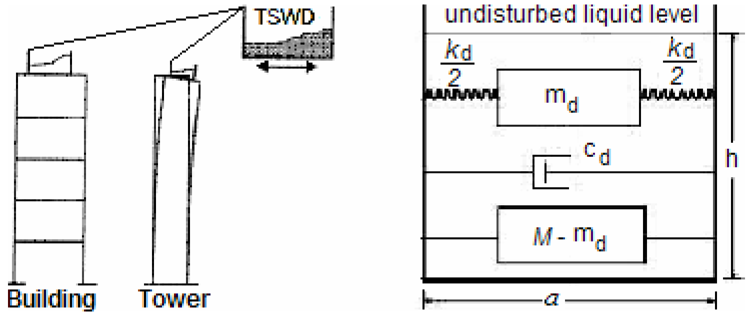


(a) (b)

Fig. 5 Seismic energy equations of (a) conventional structure and (b) structure with damping device

PROPERTIES OF TUNED SLOSHING WATER DAMPERS

A tuned sloshing damper with water as the sloshing liquid (i.e., TSWD) is the simplest form of the passive devices belonging to the family of tuned liquid dampers. A TSWD consists of a rigid vessel holding a given mass of water and placed at the top of the building (see Figure 6(a)). The water in the tank is tuned with the natural frequency of the supporting structure. The sloshing mass of the water thus resonates with the motion of the supporting structure. The energy dissipation here is caused by the sloshing of water contained in the vessel. A part of the seismic energy imparted to the structure is dissipated by the sloshing motion of the water, thereby modifying the resultant structural response within the acceptable limits. TSWDs have been viewed and explained as a variant of tuned mass dampers (TMDs), wherein water is the damping mass. A simplified model of liquid sloshing in tanks has been described by Reddy et al. (2008), based on the equivalent mechanical analogy with lumped masses, springs (for stiffness) and dashpot (for viscosity) (see Figure 6(b)).



(a) (b)

Fig. 6 (a) TSWD on structure; (b) Mechanical analogy for TSWD

The frequency of the sloshing water in a TSWD is given on the basis of linear wave theory as (Abramson, 1966)

$$\omega_n^2 = \frac{g(2n-1)\pi \tanh(2n-1)\pi r}{a} \tag{4}$$

This equation is valid for small excitation amplitudes. At larger excitation amplitudes, the behaviour of the sloshing water becomes nonlinear and the nonlinear frequency ω_d is determined by the following empirical relations (Yu et al., 1999):

$$\omega_d = \omega_n \left\{1.037\left(A_e/a\right)^{0.0035}\right\} \text{ for } A_e < 3\% \text{ of the tank dimension } a \tag{5a}$$

$$\omega_d = \omega_n \left\{1.59\left(A_e/a\right)^{0.125}\right\} \text{ for } A_e > 3\% \text{ of the tank dimension } a \tag{5b}$$

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

$$m_d = M\frac{8\tanh\left\{\left(2n-1\right)\pi r\right\}}{r\pi^3\left(2n-1\right)^3} \tag{6}$$

where ω_n is the linear sloshing frequency of the water in rad/s, ω_d is the nonlinear sloshing frequency of the water (i.e., the frequency of the TSWD) in rad/s, n is the sloshing mode number (taken as 1 for the natural frequency), M is the total mass of the water in the tank, m_d is the mass of water acting in the considered mode (i.e., the sloshing mass), g is the gravitational acceleration, h is the depth of water in the tank, a is the tank dimension in the direction of vibration, $r = h/a$, A_e is the vibration amplitude of the TSWD, which is equal to the structural displacement at the location of the TSWD, and ξ_d is the damping ratio of the TSWD.

The damping due to the viscosity of water in linear sloshing alone is of the order of 0.5%. However, from experimental experience it has been substantiated that the energy dissipated in a TSWD, due to non-linear sloshing and wave breaking, is much more. The damping ratio ξ_d of a TSWD is a function of the amplitude of excitation and the tank dimension A_e/a. The empirical relationships for TSWD damping ratio have been proposed as

$$\xi_d = 1.78\left(A_e/a\right)^{0.68} \tag{7a}$$

and

$$\xi_d = 0.5\left(A_e/a\right)^{0.35} \tag{7b}$$

by Yalla (2001) and Yu et al. (1999), respectively. The values of ξ_d as obtained from both the equations are comparable at small vibration amplitudes. The variation of ξ_d with A_e/a is plotted in Figure 7 for Equations (7a) and (7b). For brevity a mean of both is also plotted in the figure and is considered in the present study.

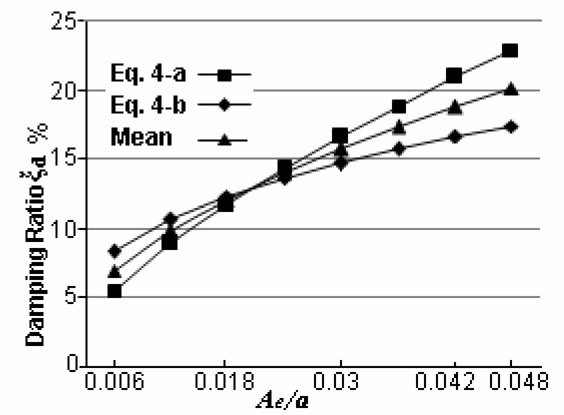


Fig. 7 Damping ratio of TSWD with respect to amplitude of excitation

RESPONSE CONTROL WITH TSWD FOR EXISTING STRUCTURES

The RC structures are assumed to possess a damping ratio of 5%. The analytical approach for a damped structure coupled with a damped damper (i.e., TSWD) is adopted for the retrofitting of the ES. A reasonably planned structure exhibits a substantial mass participation in its first mode of vibration. The ES may be assumed as the SDOF system corresponding to the first-mode frequency ω_s, participating mass m_s and damping ratio ξ_d. The dynamic magnification factor (DMF), denoted by H, for the structural response D_m of the damped SDOF under a harmonic excitation is given by

$$H = \frac{1}{2\xi_s\left(1-\xi_s^2\right)^{0.5}} \tag{8}$$

For all realistic purposes,

$$\xi_s = 1/2H \tag{9}$$

is considered to be a reasonable approximation for the ES. By attaching a TSWD with the ES, the coupled system becomes a 2-DOF system, as shown schematically in Figure 8. The TSWD has the mass m_d, stiffness k_d, viscous damping c_d, frequency ω_d and damping ratio ξ_d.

The DMF H_e of the retrofitted structure (i.e., a 2-DOF system) for the reduced structural response D_p is given as

$$H_e = \frac{1}{\sqrt{\mathrm{RE}^2 + \mathrm{IM}^2}} \tag{10a}$$

where

$$\mathrm{RE} = 1 - \beta^2 - \mu\beta^2 \frac{f^2\left\{f^2 - \beta^2 + \left(2\xi_d\beta\right)^2\right\}}{\left(f^2-\beta^2\right)^2 + \left(2f\xi_d\beta\right)^2} \tag{10b}$$

$$\text{IM} = 2\xi_s\beta + \frac{2\mu\beta^5}{\left(f^2-\beta^2\right)^2 + \left(2f\xi_d\beta\right)^2} \tag{10c}$$

$\beta = \omega_e/\omega_s$ is the frequency ratio, $f = \omega_d/\omega_s$ is the tuning ratio, and $\mu = m_d/m_s$ is the mass ratio. The equivalent damping ratio ξ_e of the coupled structure may be obtained as

$$\xi_e = \frac{1}{2H_e} \tag{11}$$

where H_e and ξ_e depend on f, μ, β, ξ_s and ξ_d. The effects of these parameters for a tuned coupling of damper and structure (i.e., $f = 1$ or $\omega_s = \omega_d$) with respect to frequency ratio are illustrated in Figure 9.

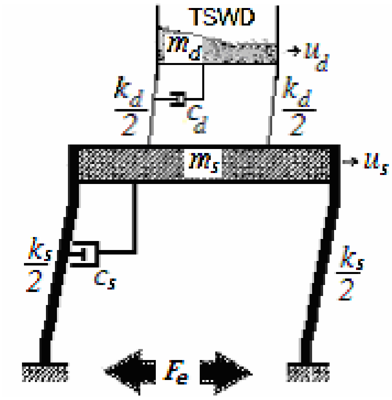


Fig. 8 Structure retrofitted with TSWD

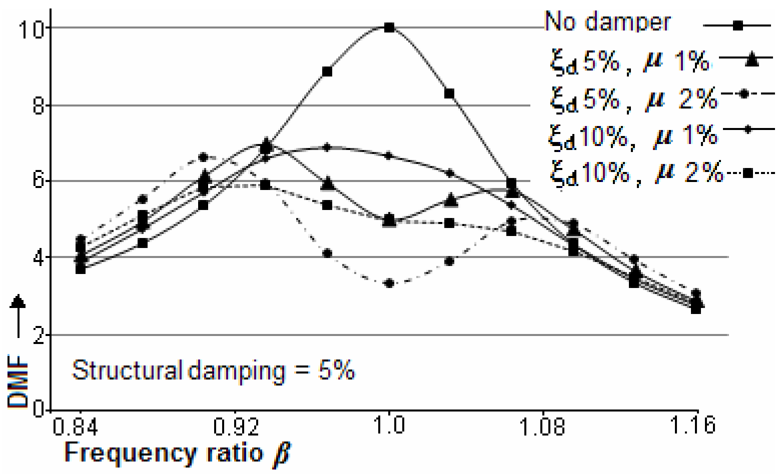


Fig. 9 Dynamic magnification factor for SDOF system with damper

The ES-TSWD coupling is considered detuned if $\omega_s \neq \omega_d$. The dynamic properties of ES are generally beyond the scope of any alterations. The remaining controllable parameters in the ES-TSWD coupling therefore are ω_d, m_d and ξ_d. The performance of the retrofitting system is governed by these parameters. The dampers of small damping ratios are more sensitive to the tuning with the host structures (i.e., ES), whereas the dampers of high damping ratios are comparatively robust with respect to the frequency tuning. An increase in the mass ratio reduces DMF, thus resulting in a higher structural response control. The design of the TSWD-retrofitted ES coupling is governed by Equations (10a)–(10c). The mutual tuning of the ES with TSWD is vital, but difficult to be achieved due to the approximations involved in the assessment of the dynamic properties of ES. This problem may be addressed by the concept of multiple TSWDs, as explained in the following sections.

MULTIPLE TSWDs FOR EXISTING STRUCTURES

The stiffness of the ES is derived from the cross-sectional properties of structural elements and elastic properties of the construction material, which may not be uniform as assumed in the design calculations. The mass of the structure may also vary due to the constructional and utility variations of the ES. These factors lead to a variation in the first-mode frequency assessment of the structure. Similarly, the damping ratio of a building cannot be assessed accurately as it depends on a number of factors. The damping ratio of the ES also varies with the nature of loading and deformation of ES.

The above-mentioned approximations are carried over to the estimated response of the structure. The problem is compounded by the fact that the natural frequency and damping ratio of the TSWD are dependent on the amplitude of vibration, which is same as the displacement of the ES at the location of the TSWD. These approximations may lead to an erroneous design of the TSWD and less effective response-control performance of the retrofitting system. This difficulty may be addressed by extending the concept of multiple mass dampers (MMDs) to TSWD (see Figure 10).

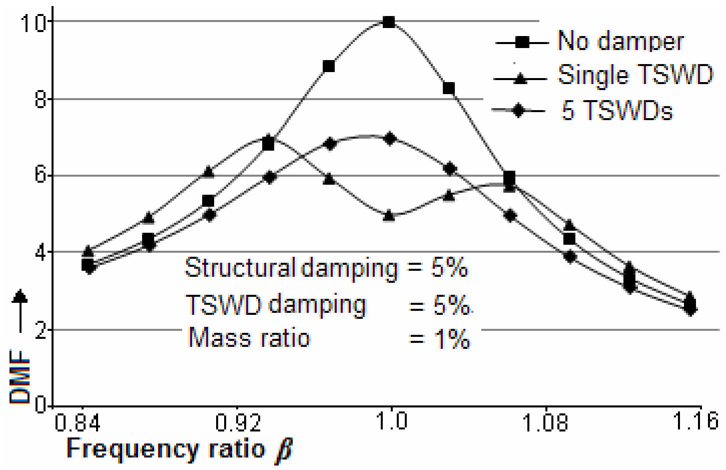


Fig. 10 Dynamic magnification factors for single and multiple TSWDs

The required sloshing mass for the desired results is large enough and multiple TSWDs are provided to meet this requirement. The natural frequencies of these TSWDs are varied and set around the assessed first-mode frequency of the ES. This can be achieved by slightly varying the length a of the TSWD (see Equations (4), (5a) and (5b)). The method of multiple TSWDs ensures that some part of the sloshing mass is always tuned with the ES and a major portion of the sloshing mass is only slightly detuned. Thus, a robust structural control performance is achieved at the same mass ratio. This concept is illustrated in Figure 10, with multiple TSWDs having 5 discrete frequencies as ω_d = $0.88\omega_s$, $0.94\omega_s$, $1.0\omega_s$, $1.06\omega_s$ and $1.12\omega_s$. The mass ratio assigned to each TSWD is 0.2μ. It can be observed that the multiple-TSWD system is more effective for a wider range of frequencies and tuning ratios.

EFFECTIVENESS RATIO CHARTS

The efficiency of the TSWD retrofitting system may be expressed by a non-dimensional parameter, effectiveness ratio E. This parameter may be expressed as a percentage reduction in the structural displacement (from D_m to D_p) due to the application of the retrofitting measure:

$$E = \left\{1 - \left(D_p / D_m\right)\right\} \times 100 \tag{12a}$$

or

$$E = \left[1 - \left\{\mathrm{DMF}_r / \mathrm{DMF}_o\right\}\right] \times 100 \tag{12b}$$

where DMF_o denotes the dynamic magnification factor of the unretrofitted structure and DMF_r denotes the dynamic magnification factor of the retrofitted structure. The effectiveness ratio of a TSWD retrofitting system depends on ξ_s, ξ_d, f and μ. The performance charts for the condition of maximum DMF, i.e., β = 1, and a pre-determined detuning range are developed from Equations (10a)–(10c), (12a) and (12b). Detuning here is defined as the percentage difference between the frequencies ω_s and ω_d of the ES and TSWD, respectively.

Three performance charts are plotted for the TSWD damping ratios of 8%, 12% and 20% in Figures 11(a)–11(c) for the structural damping ratios of 2%, 5% and 7%, respectively. The range considered for detuning is 16% (i.e., f ranges from 0.84 to 1.16). The solid lines in the charts are for the perfectly tuned conditions and the dotted lines are for the detuning of 16%. The intermediate values may be interpolated from these curves. These performance charts take care of the approximations involved in the assessment of the dynamic properties of the ES and facilitate a quick estimate of the required μ for the desired effectiveness E of the retrofitted structure. The retrofitting procedure with an application of the effectiveness performance charts is explained below with the example of an existing structure.

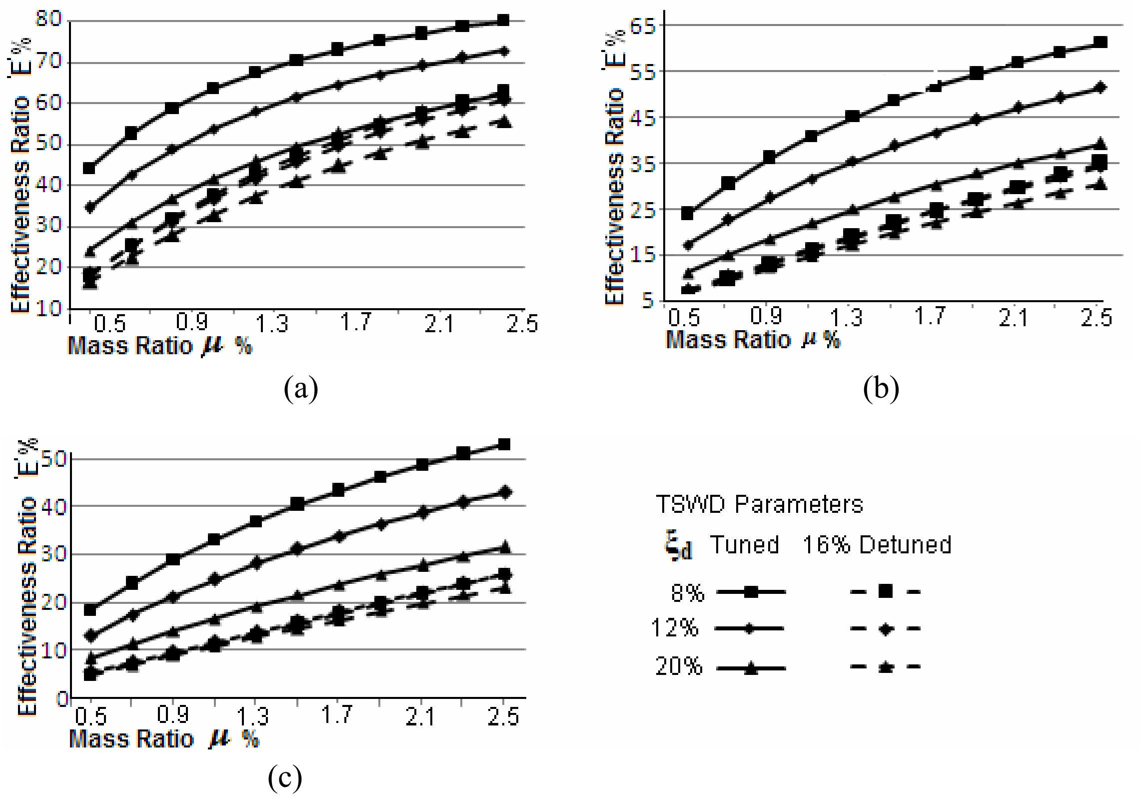


Fig. 11 Performance charts of TSWD system with respect to μ and ξ_d for (a) 2% structural damping ratio, (b) 5% structural damping ratio and (c) 7% structural damping ratio

RETROFITTING OF EXISTING STRUCTURE

1. Details of Structure

An existing four-story residential structure is considered as an example for the study of retrofitting with TSWDs. It is situated in Mumbai, and houses 8 flats with a centrally located staircase, over which an overhead tank (OHT) is placed. The supporting frame of the OHT is a part of the main RC structural framework. The structure is an adequately designed and constructed building, with due consideration of the prevalent code provisions as per IS 456 (BIS, 2000).

The typical floor plan and structural skeleton are shown in Figures 12 and 13, respectively. All the columns here are of the 250×350 mm cross-section, except for the column No. B3, which is of the 250×500 mm cross-section. A typical beam cross-section is 230×400 mm along the X-axis and 230×450 mm along the Z-axis. The positioning of the beams has been done in compatibility with the architectural requirements. The masonry is of burnt-clay bricks with 1:4 cement-sand mortar. The external walls are 230-mm thick and the internal partition walls are 115-mm thick. Salient design features considered in the analysis are tabulated in Table 1. The example structure may be considered as a representative sample of the well-designed and constructed residential building stock.

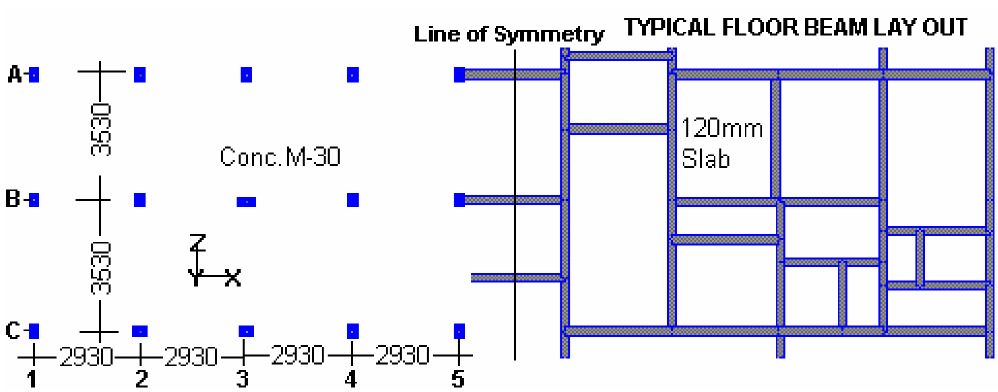


Fig. 12 Structural floor plan of existing structure

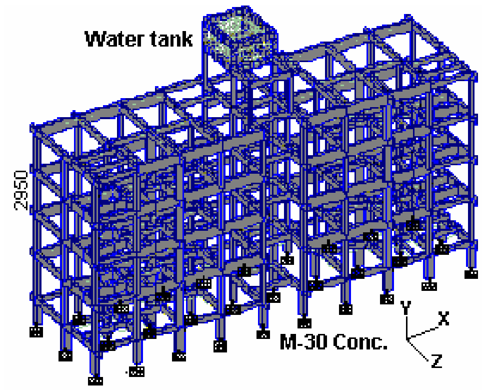


Fig. 13 RC frame of existing structure

Table 1: Salient Features of Existing Structure

S. No.	Feature		Description
1	Total Weight of Structure		11,64,000 kg with water tank full
2	Mass Participating in First Mode, m_s		76% (or 8,85,000 kg)
3	Structural Damping ξ_s		5% (as considered in design)
4	Seismic Zone		III as per IS 1893, Part 1 (BIS, 2002)
5	Frequency of Structure in First Mode, ω_s		1.135 Hz along X-axis and 1.195 Hz along Z-axis
6	Maximum Displacement D_m		Assuming the structure to behave linearly
	(a)	At the Base of Water Tank	22 mm along X-axis and 21 mm along Z-axis
	(b)	At the Roof Level	16 mm along X-axis and 16 mm along Z-axis
7	Maximum Permissible Displacement D_p		With 25% effectiveness ratio
	(a)	At the Base of Water Tank	16.5 mm along X-axis and 15.75 mm along Z-axis
	(b)	At the Roof Level	12 mm along X- and Z-axes

2. Structural Analysis

The example structure is analytically modeled and analyzed with the software STAAD PRO, for the inherent structural damping of 5% and for the seismic conditions of Zone III as per the provisions of IS 1893, Part 1 (BIS, 2002), in the following three cases:

Case 1: The RC frame alone is supporting the structure and only the gravitational loads are acting under the static condition (as has been the design consideration for most of the ES).

Case 2: The masonry walls are contributing as diagonal struts (see Figure 14) along with the RC frames in line with the provisions of the clause 7.10 of IS 1893, Part 1 (BIS, 2002). The dynamic forces due to the earthquake are acting along with the other gravitational loads.

Case 3: The RC frame alone is supporting the structure, i.e., the masonry walls are not contributing structurally. The dynamic forces due to the earthquake are acting along with the other gravitational loads.

3. Discussion on Analytical Results

The column stresses obtained from the analysis are normalized with respect to the maximum column stress under Case 1 (in the column A5) and are presented in Table 2. From the comparison of these stresses, it may be observed that under the seismic loading together with the stiffness contribution of the masonry as in Case 2, the designs of only two columns (i.e., A1 and C5) out of the 30 columns are governed by the seismic considerations. This implies that with safety factors already included in the design and the masonry acting as diagonal strut, the structure should be safe under the seismic loading. However, the performance of the masonry-infilled RC frames in the past earthquakes has been with disastrous consequences. This may be attributed to poor quality control of the masonry work. The masonry walls are constructed after the construction of the RC frames and generally are not properly packed at the top, below the RC frame beams, thus causing a lack of confinement and poor integration of the masonry with the RC frame for desirable stress-strain compatibility.

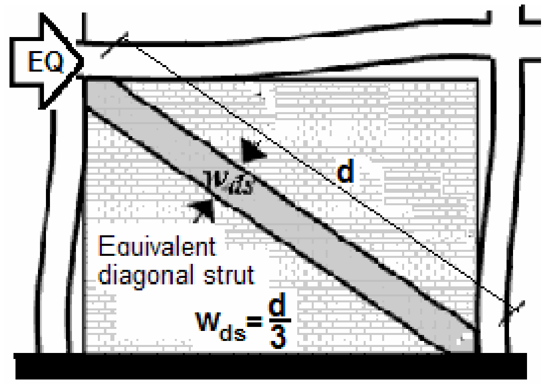


Fig. 14 Stiffness contribution of masonry

Table 2: Maximum Normalized Stress in Columns

Column No.	Maximum Normalized Stress			% Increase over Case 1	
	Case 1	**Case 2**	**Case 3**	**Case 2**	**Case 3**
A1	0.39	0.44	0.87	11.25	122.24
B1	0.64	0.64	1.14	0.00	79.25
C1	0.67	0.69	1.16	2.12	72.28
A2	0.50	0.50	0.95	0.00	90.98
B2	0.90	0.90	1.39	0.00	53.36
C2	0.75	0.78	1.04	3.37	38.06
A3	0.51	0.51	0.96	0.00	88.42
B3	0.59	0.59	1.18	0.00	100.72
C3	0.69	0.70	1.10	1.29	59.38
A4	0.57	0.58	1.09	3.06	91.54
B4	0.61	0.61	1.24	0.00	102.97
C4	0.68	0.70	1.28	2.74	88.81
A5	1.00	1.01	1.74	1.03	74.08
B5	0.74	0.74	1.26	0.00	69.33
C5	0.65	0.78	1.18	20.30	83.19

In view of the above-mentioned reasons the structural contribution of the masonry is ignored, and the RC frame alone should be considered for structural design as in Case 3. It is evident from the stresses in the columns that in Case 3 the seismic loading is the governing load case for all the columns, and thus the structure is grossly unsafe. Therefore, the existing structures, which have been designed for the Case-1 type conditions, are required to be retrofitted for the Case-3 type conditions. The maximum stress is in the column A5, which is exceeded by 74% under the seismic loading, as compared to the gravity loads only.

4. Retrofitting Strategy

The deformed shape of the existing structure in its first mode of vibration under the seismic loading is shown in Figure 15. The retrofitting is governed by the purpose of reducing the structural deformations from D_m to D_p (i.e., from 16 to 12 mm at the roof level, as shown in Table 1) under the earthquake excitation. This is achieved by incorporating TSWDs in the structure for achieving a higher equivalent damping ratio without any stiffness loss and structural damage for the worst loading combination (i.e., Case 3). The retrofitting design of the ES with TSWDs is based on the following facts and assumptions:

1. The contribution of the superimposed load (LL) to the total load in residential buildings is of the order of 12% (with a possible variation of ±6%). By assuming a stiffness variation of ±20% due to the execution and design inconsistencies, the cumulative frequency variation range of the ES is ±12%. Thus, the range of detuning is also assumed as ±12%.
2. The DMF is maximum at β = 1. The existing structure is to be retrofitted for this condition. The existing structure is considered as an SDOF system of the first-mode frequency and participating mass. Accordingly, the damper parameters, i.e., frequency and mass ratio, are determined.
3. The TSWDs are located at the points of maximum deformation (i.e., the roof of the structure and the base of the OHT) and are rigidly attached to the structure. The structural deformation at the location of the respective TSWD is the corresponding vibration amplitude (Yalla, 2001).
4. The structure has adequate safety margins (of the order of 50%) under the gravitational loading. The maximum stress due to the earthquake loading is however exceeded by 74%; hence, a response reduction of 25% is considered adequate for bringing the structure within safety limits.

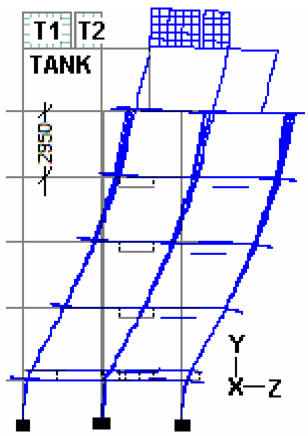


Fig. 15 Deformed shape of existing structure along Z-axis

5. Design of TSWD Retrofitting System

The dynamic properties of the ES are beyond the scope of modification. Hence, the design of a TSWD retrofitting system is limited to the determination of location, geometry and number of TSWDs for the target response reduction. The design procedure is simplified by the use of performance charts (see Figures 11(a)–11(c)). The steps for the retrofitting design of the ES are as given below:

1. The first-mode frequency ω_s, the corresponding participating mass m_s and damping ratio ξ_s, the maximum deformation D_m during the earthquake loading, the maximum permissible deformation D_p during the earthquake after retrofitting, and the target effectiveness ratio E are determined and tabulated as in Table 1.

2. For the structural damping ratio of 5%, the chart of Figure 11(b) is used in determining the mass ratio. For a TSWD of the damping ratio ξ_d of 12% and effectiveness ratio of 25% with 12% detuning, the required mass ratio is obtained as 1.4%. Thus, the total damping mass required is 12,390 kg.
3. Five frequencies of TSWDs (i.e., ω_d) are chosen within $0.88\omega_s - 1.12\omega_s$, with ω_s as the central frequency. The total damping mass is to be equally distributed (i.e., 2,478 kg each) in the 5 designated sizes of TSWDs. The chosen frequencies and corresponding tuning ratios are mentioned in Table 3 (see Columns 2, 3 and 4).
4. The plan dimensions of the TSWD Nt3 for $\omega_d = \omega_s$ are determined from Equations (4) and (5a) for a vibration amplitude of 12 mm (i.e., D_p at the roof level). The variation of tuning ratio with the depth of water is shown in Figure 16. It is observed that after a depth of 250 mm, the effect of depth on sloshing frequency diminishes. Hence, the depth of water in the TSWDs is fixed at 250 mm. The dimensions of all TSWDs are thus determined for the water depth of 250 mm (see Columns 5 and 6 in Table 3).
5. The dimensions of the TSWD Et are determined for a frequency $\omega_d = \omega_s$ and for a vibration amplitude equal to D_p at the tank base level (i.e., 15.75 mm) from Equations (4), (5a) and (5b). The dimensions of the TSWDs are fixed for the water depth of 250 mm (see Column 5 and 6 in the last row of Table 3).
6. The damping ratio for each size of TSWD is determined by taking the mean of the values obtained from Equations (7a) and (7b) (see Columns 7 and 8 in Table 3) with D_p as the amplitude of vibration.
7. The sloshing mass in each size of TSWD is determined from Equation (6) (see Column 9 in Table 3). Accordingly, the number of TSWDs required in each size is determined (see Column 10 in Table 3).

TABLE 3: Properties of Proposed TSWDs

Name Designated	**Frequency (Hz)**		**Tuning Ratio *f***	**Dimension *a* (mm)**		**Damping Ratio ξ_d (%)**		**Sloshing Mass m_d (kg)**	**No. of TSWDs**
	Z	**X**		**Z**	**X**	**Z**	**X**		
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Nt1	1.052	0.999	0.88	630	670	12	11.5	60.2	40
Nt2	1.123	1.067	0.94	570	610	12.9	12.2	47.0	52
Nt3	1.195	1.135	1.0	520	560	13.7	12.7	37.3	64
Nt4	1.267	1.203	1.06	480	510	14.5	13.4	29.4	80
Nt5	1.338	1.271	1.12	430	470	15.6	14.1	22.8	84
Et	1. 195	1.135	1	489	559	17.8	15.4	39	28

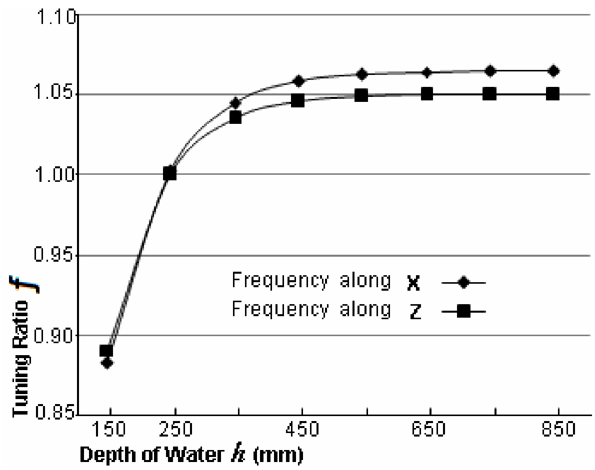


Fig. 16 Variation of tuning ratio with respect to depth of water

6. Performance Check of TSWD Retrofitting System

With the TSWD retrofitting system proposed in Table 3, the total sloshing mass available is 12,598 kg or the mass ratio provided is 1.42%. The magnification factor DMF_o of the structure without retrofitting for the condition $\beta = 1$ and 5% damping ratio is 10. The magnification factor DMF_r of the retrofitted structure with different first-mode frequencies of the structure, as mentioned in Columns 2 and 3 of Table 3, is evaluated by using Equation (10a). The effectiveness ratio of the retrofitting system for each frequency is then determined from Equations (12a) and (12b) and plotted in Figure 17. The cumulative approximation in the frequency assessment of the example structure is ±12% and it may be observed that for the frequency range of $0.88\omega_s - 1.12\omega_s$, an effectiveness ratio in excess of 29% is achievable with the mass ratio of 1.42%.

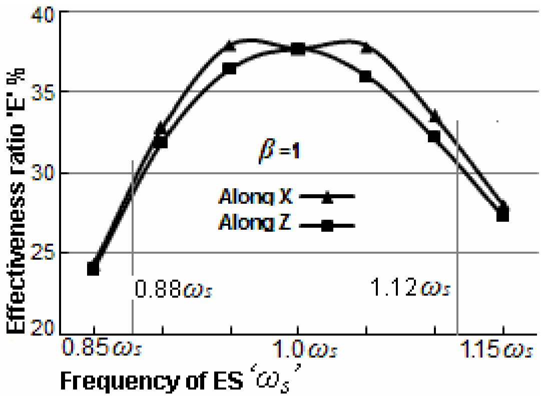
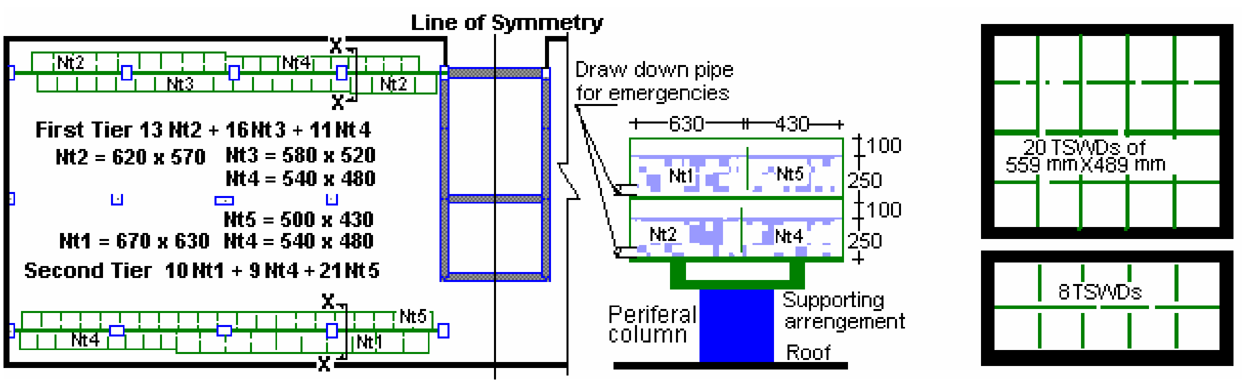


Fig. 17 Performance of multiple-TSWDs system

The proposed retrofitting regime may be considered adequate for the 25% structural response reduction under a dynamic loading. Thus, the maximum roof displacement may be restricted within the permissible limit for the first-mode frequency. The frequency of each TSWD will be different due to the variation in vibration amplitude, depending on the structural deformation at its location. However, the cumulative effect of all the TSWDs as a system will be similar to that presented in Figure 17.

7. Execution Scheme of TSWD Retrofitting System

The additional TSWDs (i.e., Nt1 to Nt5) may be fabricated from G.I. sheets in clusters. A total of 320 additional TSWDs in four clusters of 80 each are provided on the roof in two tiers, as shown in Figures 18(a) and 18(b).



(a) (b) (c)

Fig. 18 Execution scheme of TSWD retrofitting system: (a) Placement of TSWDs 'Nt' at roof level; (b) Section X-X, (c) OHT modified as TSWD 'Et'

The existing OHT is modified only in plan for making the TSWDs designated as Et, by inserting the 1-mm thin GI or acrylic sheet vertical partitions. There are two overhead tanks of 2.8×1.96 m (designated as T1) for the potable use and 2.8×0.98 m (designated as T2) for the flushing use, respectively. These tanks are divided in the TSWDs of 559×489 mm dimensions as shown in Figure 18(c). The drawdown pipe should be fixed above the threshold depth of 250 mm from the bottom of OHT. The sloshing mass of water in each TSWD designated as Et is 39 kg, thus making a total of 1,092 kg mass in 28 such TSWDs.

The internal partition walls between the TSWDs are to be kept 25 mm short from the top sheet to allow for the spillage due to sloshing, if any. All the TSWDs of one cluster are interconnected through holes at the bottom of the vertical partitions. The holes in the bottom serve as the auto-levelers of the water mass in a TSWD cluster.

The overall depth of the proposed retrofitting system is less than 1,000 mm (i.e., the parapet height) above the finished roof level. The new TSWDs (i.e., Nt1 to Nt5) are accommodated along the parapet in such a way that the weight of the TSWDs is directly transferred to the peripheral columns and major part of the roof remains available for the occupancy use. The increase in the total mass of the example structure due to the provision of additional TSWDs may be compensated by replacing the masonry parapet with MS pipe railings. This proposal accomplishes the retrofitting of the example structure without any architectural, structural or occupancy interference.

PERFORMANCE OF RETROFITTED STRUCTURE DURING EARTHQUAKES

For an unretrofitted structure of 5% damping ratio, the 29% effectiveness ratio for the retrofitting system translates into an effective structural damping ratio of 7% (refer Equations (11), (12a) and (12b)). Thus, an existing structure having an inherent damping of 5% may be considered to have achieved an effective damping of 7% after retrofitting, without any loss of stiffness.

The performances of the existing and retrofitted structures are evaluated with respect to the recorded ground motions of the El Centro 1940 earthquake, as in Chopra (1995), for different orientations of the structure and are presented in Figure 19. The maximum structural displacement of 17.6 mm of the unretrofitted structure is anticipated with its X-axis parallel to the east-west component of the ground motion. After retrofitting, this is reduced to 14.2 mm (i.e., the response reduction is 19%). The minimum structural displacement of 14.9 mm of the unretrofitted structure is anticipated with its Z-axis parallel to the north-south component of the ground motion. After retrofitting, this is reduced to 12.5 mm (i.e., the response reduction is 15%). Thus, after retrofitting, a response reduction ranging from 15% to 19%, depending on the orientation of the structure with respect to the ground motion, is predicted. Further, since the relation between mass ratio and effectiveness ratio is nearly linear, a higher effectiveness may be achieved by increasing the mass ratio.

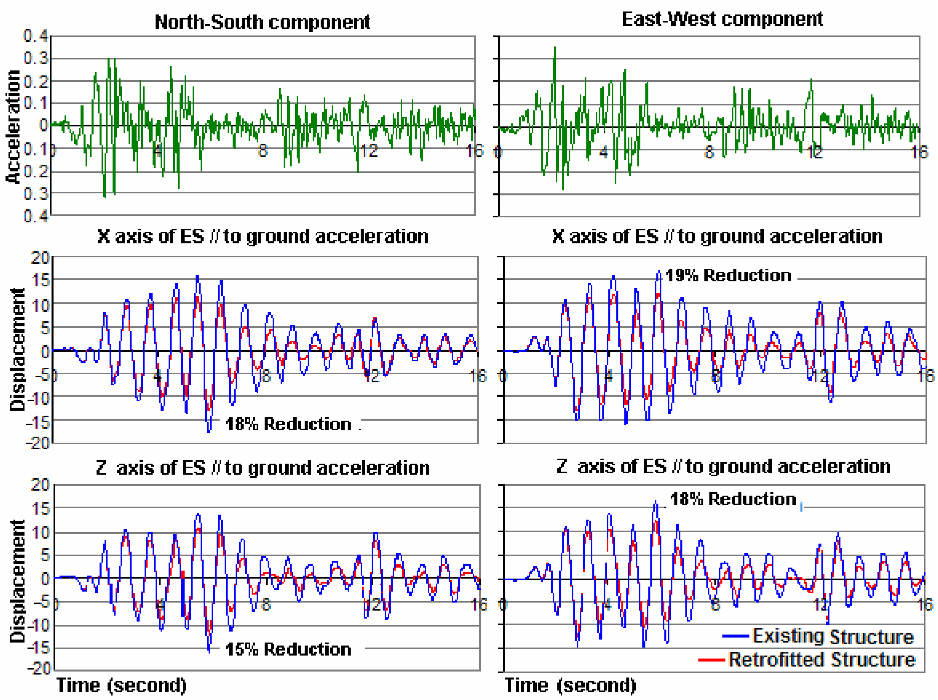


Fig. 19 Response of retrofitted structure against El Centro ground motion

CONCLUDING REMARKS

The proposed retrofitting system will ensure a more predictable performance of the masonry-infilled RC structure during an earthquake, as the effective damping ratio increases without any stiffness loss. The maximum response of the structure after retrofitting is reduced globally. This effect will be more pronounced for the ES with low damping ratios, as is evident from Figure 11(a). There exists an almost linear relation between effectiveness ratio and mass ratio; hence, the performance of the TSWD system may further be improved by increasing the mass ratio. A sloshing mass equivalent to the 0.12% mass ratio is readily available in the OHT for utilization as TSWD with nominal effort and cost.

The multiple TSWDs are effective for a complete range of practically possible frequencies and are feasible for all the existing structures of medium heights. The term, effectiveness ratio *E*, for the retrofitting system has been introduced to measure its performance numerically in an abstract form. The design charts have also been developed for the real-life structural ranges, in order to reduce the computation effort. TSWDs require a negligible trigger level due to the absence of mechanical friction as compared to TMDs. The retrofitting effect of TSWDs comes into action with the start of the sloshing, as initiated by the structural deformations. The rectangular TSWDs can be designed in conformity with the principal axes of the ES, thus offering functionality in all the possible directions in the horizontal plane.

The above-described regime provides an all-time sustainable preparedness against the earthquakes without any maintenance cost. The non-interfering nature of this retrofitting system is the most attractive feature for adoptability and application. The proposed system is very useful for the scattered and remotely placed but important installations that are sensitive to the vibratory loads. This system does not have any adverse effects on the existing structure to be retrofitted. The purpose of this paper was to illustrate the applicability of multiple TSWDs for existing structures with the use of simple design methodology and ease of installation. Furthermore, the TSWDs may be integrated with the plumbing system of the building and utilized against the fire hazard and water distress conditions.

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