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EFFECTIVENESS OF TUNED MASS DAMPERS (TMD) FOR EARTHQUAKE PROTECTION IN CHILEAN BUILDINGS

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Abstract

In Chile, several buildings have been provided with tuned mass dampers. They consist of pendulums located on the upper floor having a natural period similar to the building natural period. However, there are doubts about the real effect of these devices on reducing the motion of the building during different earthquakes. This work aims to theoretically evaluate the effectiveness of these devices. For this purpose, the influence of different parameters of the TMD (mass ratio, variation of period, nonlinearity, damping coefficient) and the building (linear or non-linear response) are analyzed. The movements consist of acceleration records from a database of 132 different Chilean earthquakes motions. Finally, the efficacy of a TMD in a typical Chilean building is analyzed.

Keywords: *Tuned mass damper, vibration control, earthquake protection.*

1. Introduction

Chile is one of the most seismic countries in the world and its earthquake resistant design for buildings has a long and successful history. However, the actual tendency in this matter is to advance to more resilient buildings, buildings that resist earthquakes with less damage. This has been handled, in many cases, by using new methods of seismic protection, like base isolation, energy dissipation devices and tuned mass dampers (TMD). The last of these technologies has shown to be effective for wind protection on tall building and chimneys, but it is not clear its benefit for earthquake protection, because earthquake motions are short transient processes that have great variation from event to event because they depend on many factors, like the source mechanism and local soil conditions. Nevertheless, in Chile several buildings have been implemented with TMD for earthquake protection because of its simplicity and easy of application.

Several authors have made theoretical advances in this field. Den Hartog [1] and Brock [2] obtained the optimal tune up solution for mono-frequency excitation. Later, Crandall and Mark [3] studied the system for white noise input. Other authors, like Wirsching and Campbell [4], study the minimal response under random excitation for systems with TMD absorbers. The effect of TMD on buildings for wind load excitation was approached, between others, by McNamara [5], and Wiesner [6] who reported dynamic response reductions in the order of 40%.

As for application of TMD to reduce seismic response, is worthy to mention the studies of Sadek et al. [7], that present a method of estimating the parameters of TMD for seismic applications, Kaynia et al. [8] and, later, Sladek and Kligner [9] that find that TMD dampers are not effective for seismic loads when nonlinear model are used. Lukkunaprasit and Wanitkorkul [10], analyze the effect of TMD on inelastic buildings subjected to moderate ground motions for distant earthquakes. Pinkaew et al. [11-12] consider the damage reduction of structures with TMD and, finally, Pourzeynali et al. [13] present a robust multi-objective optimization design of a TMD control device, to reduce the response of tall buildings for seismic excitation using genetic algorithms.

The effectiveness of TMD devices depends on the non-linearity of the response of the system and the precision of the tuned frequency of the device. Hence, some authors introduced systems that permit the automatic tuning of the TMD by means of a monitoring system and a mechanism that allows the variation of the stiffness during the response (Hybrid Mass Dampers) (Tanida et al. [14], Koite et al. [15] and Yamazaki [16-17]).

In the present paper, the effect of TMD on the seismic response of buildings will be approached by means of a parametric study of a two degree of freedom system subjected to a database of 132 Chilean earthquake records. Both linear and non-linear characteristics of the system are included, either for the damper or the structure, as well as the effect of detune of the TMD. Then, the case of a typical Chilean building with multiple degrees of freedom is considered.

Several buildings have been equipped with TMD at the top level in Chile, in some cases for the control of torsion problems. A list of cases is presented in table 1. In all cases the mass ratio of the TMD to the building mass is in the order of 2 to 3 % (approximately 6% of the effective mass of the first mode).

Name	**Type of Building**	**No. Floors**	**Location**	**Characteristics**
Parque Araucano	Office	20	Las Condes	2 TMD Weight=160 ton each
Geocentro Agustinas	Residential	36	Santiago	2 TMD Weight=200 ton each
Jardines de Infante	Residential	18	Ñuñoa	2 TMD Weight=200 ton each
Las Condes Capital	Residential	19	Las Condes	2 TMD Weight=150 ton each
Cerro Colorado	Residential	15	Las Condes	2 TMD Weight=115 ton each
1K	Residential	16	Las Condes	2 TMD Weight=not available
Parque Araucano	Office	20	Las Condes	Damper
Centro Plaza	Residential	16	Copiao	Not available

Table 1. Chilean Buildings with TMD for earthquake protection

Titanium	Office	27	Copiapo	2 TMD Weight=300 ton each
Trilogia Sur	Residential	23	Antofagasta	1 TMD Weight=90 ton
Brisas de Costa Laguna	Residential	23	Antofagasta	2 TMD Weight=not available
Cámara Chilena de la Construcción	Office	23	Providencia	1TMD

2. Mathematical formulation

Many authors have worked up the theory of TMD, such as Den Hartog [1], Brock [2], Warburton [18-19], Sladek et al. [9]. The following development will be based on those works.

Frequency $$\omega_d^2 = \frac{k_d}{m_d} \tag{1}$$

Frequency $$\omega_p^2 = \frac{K_p}{M_p} \tag{2}$$

Mass ratio $$\mu = \frac{m_d}{M_p} \tag{3}$$

Frequency ratio $$f = \frac{\omega_d}{\omega_p} \tag{4}$$

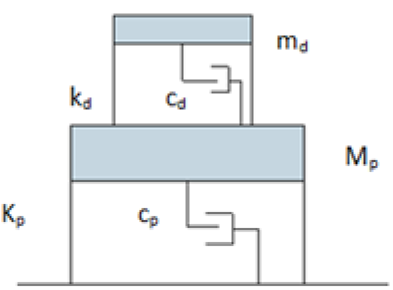

Fig. 1. Parameters definition.

Two kinds of base accelerations were considered for the determination of the optimum values of the mass and damping ratios: a) Steady state sinusoidal motion and b) White noise motion.

The first case considered is for mono-frequential acceleration at the base. The theory was first developed by Den Hartog [1] and completed afterwards by J. Brock [2]. The optimal values for mass ratio and damping ratio were stablished by means of numerical analysis by Hsiang-Chuang Tsai and Guan-Cheng Ling [20] (Eq.(5) and Eq.(6))

$$f_{OPT} = \left(\frac{\sqrt{1-0{,}5\mu}}{1+\mu} + \sqrt{1-2\xi_p^2 - 1}\right) - (a_1\mu + a_2\sqrt{\mu} + a_3)\xi_p\sqrt{\mu} - (a_4\mu + a_5\sqrt{\mu} + a_6)\xi_p^2\sqrt{\mu} \tag{5}$$

$a_1 = 0{,}426$ $a_2 = -1{,}034$ $a_3 = 2{,}375$ $a_4 = 20{,}49$ $a_5 = 16{,}903$ $a_6 = 3{,}730$

$$\xi_{d\,OPT} = \sqrt{\frac{3\mu}{8(1+\mu)(1-0.5\mu)}} + \left(b_1\xi_p + b_2\xi_p^2\right) - (b_3\xi_p + b_4\xi_p^2)\mu \tag{6}$$

$b_1 = 0{,}151$ $b_2 = -0{,}170$ $b_3 = 0{,}163$ $b_4 = 4{,}980$

The second case considers a white noise acceleration at the base. The optimum values of the parameters were obtained by Luis Rozas and Ruben Boroschek [21] (Eq.(7) and Eq.(8))(V Bakre y R. S. Jangid [22] establish analytical expresions for the optimal parameters of the TMD on damped structures subjected to random motion).

$$f_{OPT} = \frac{\sqrt{1-0{,}5\mu}}{1+\mu} - (a_1\mu + a_2\sqrt{\mu} + a_3)\xi_p - (a_4\mu + a_5\sqrt{\mu} + a_6)\xi_p^2 \quad (7)$$

$$a_1 = 1{,}419 \qquad a_2 = 0{,}577 \qquad a_3 = -1{,}977 \qquad a_4 = 1.468 \qquad a_5 = -2{,}712 \qquad a_6 = 0{,}005$$

$$\xi_{d_{OPT}} = \frac{1}{2}\sqrt{\frac{\mu(1-0.25\mu)}{(1+\mu)(1-0.5\mu)}} \quad (8)$$

The detune of the TMD can be due to the variation either in the stiffness of the structure or the device. In order to consider this nonlinear behavior, the restoring force (Eq. (10)) was modeled by means of a Bouc-Wen model [23].

$$F(t) = z(t)k_i + \big(u(t) - z(t)\big)k_f \quad (9)$$

$z(t)$ hysteretic displacement that obeys the following nonlinear differential equation Eq.(10):

$$\dot{z}(t) = A\dot{u}(t) - \beta|\dot{u}(t)||z(t)|^{n-1}z(t) - \gamma\dot{u}(t)|z(t)|^{n} \quad (10)$$

Considering the paper by Constantinou and Adnane [24], the following values were selected for the parameters of Eq. (10) $A = 1$ and $\beta = \gamma = 0.5$.

A, β and γ are nondimensional parameters which control the shape and the size of the hysteresis loop, while n is a scalar that governs the smoothness of the transition from elastic to plastic response. The elastic limit is defined by z_0 Eq. (11).

$$z_0 = \sqrt[n]{\frac{A}{\beta+\gamma}} \quad (11)$$

This model was selected because it is able to capture, in an analytical form, a range of shapes of hysteretic cycles which match the behavior of a wide class of hysteretical systems and also it is easy codify (fastest software implementation). The solution for u_p and u_d (building and TMD displacement) should be obtained by means of numerical procedures. The Runge-Kutta order 4 is used in this paper.

For multiple degrees of freedom the mass ratio μ corresponds to the ratio between the TMD and the largest effective translational modal mass of the structure in the direction of analysis. For buildings containing structural walls, modal mass of the first translational mode is typically between 45% and 65 % of the building mass. The building's damper to be considered is the damping of the corresponding mode.

3. Methodology

A TMD is aimed to reduce the response of the structure, either by story drift, displacement of the top story, the floor accelerations or the shear force at the base. The effectiveness of the TMD is investigated in relation to the response of the structure without TMD. The methodology used is shown schematically in Fig. 2.

As it is shown in Fig. 2, the reduction effect of a TMD depends on multiple factors, such as the characteristics of the earthquake record, the kind of building, and the parameters of the TMD. The first of these factors cannot be controlled by the designer.

Given the large number of variables involved, and the dispersion of the data, it was necessary to define a protocol that allowed the determination of the reduction factors associated with the device. Usually the average value is used for a low number of records, but that criteria produces uncertainty in the variation of the responses.

This methodology was implemented in a graphical interface, based on MATLAB that allows determining the best and worst cases of reduction for different type of response (maximum, accumulated and RMS).

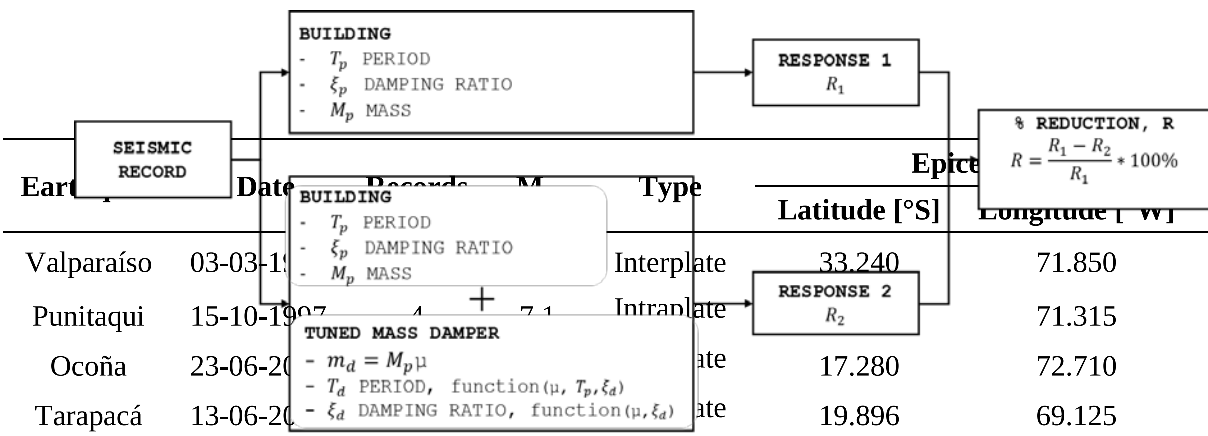

Fig. 2. Flow chart for determining the reduction due to a TMD on a structure.

4. Results

4.1. General

The records used in this study correspond to the earthquakes shown in Table 2.

Table 2. Database Chilean seismic records

Eart[illegible]	Date	[illegible]	M[illegible]	Type	Epice[illegible] Latitude [°S]	Longitude [°W]	Depth [km]
Valparaíso	03-03-1[illegible]	[illegible]	[illegible]	Interplate	33.240	71.850	33.0
Punitaqui	15-10-1997	4	7.1	Intraplate	[illegible]	71.315	56.0
Ocoña	23-06-20[illegible]	[illegible]	[illegible]	[illegible]ate	17.280	72.710	29.6
Tarapacá	13-06-20[illegible]	[illegible]	[illegible]	[illegible]ate	19.896	69.125	108.0

Tocopilla	14-11-2007	14	7.7	Interplate	22.314	70.078	47.7
Maule	27-02-2010	36	8.8	Interplate	36.290	73.239	30.0

If the optimum parameters given by equations (5) to (8) are used for the Chilean seismic records, a large dispersion in the reduction factor is obtained, for a range of period between 0.5 and 5 seconds (grey line Fig.3). This factor is positive for some records (up to 50%), but for other is negative, that is, there is an amplification that can be as much as 40%. The distribution of these values is plotted in a histogram (Fig. 4), each color represents a different period. The reduction factors are concentrated near the mean value (red line Fig.3) between 10% and 20% and about 33% of cases left out, as in a normal distribution, mean value plus or minus standard deviation (blue line Fig.3).

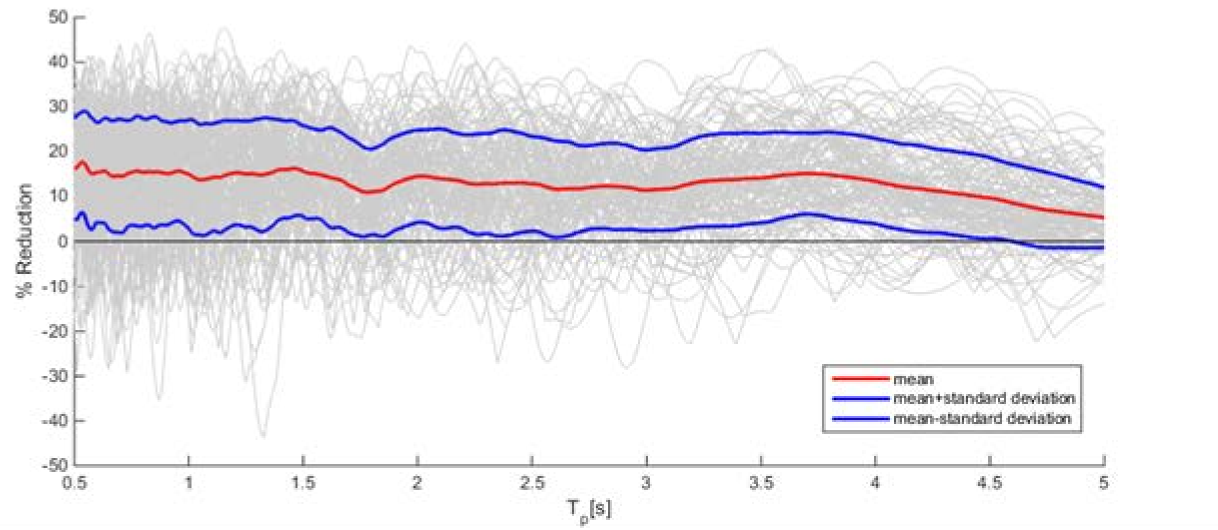

Fig. 3. Mean value of reduction factor and one standard deviation limit for 132 Chilean records. Mass ratio μ=4% and 5% critical viscous damping.

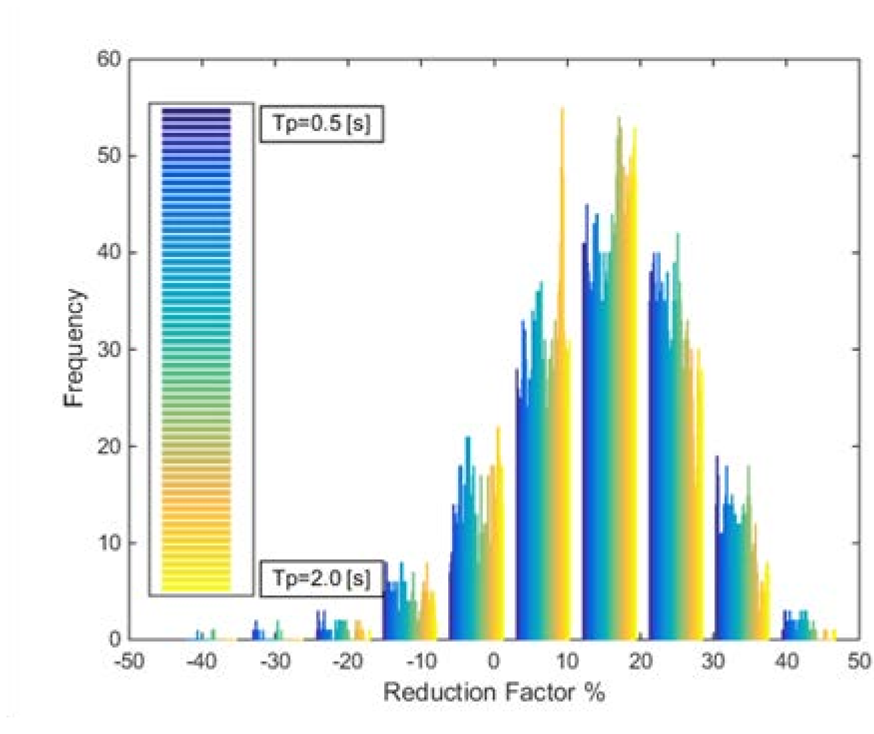

Fig. 4. Histogram, Reduction factors for a range of period. Mass ratio=4% and 5% critical viscous damping.

4.2. Sensitivity analysis

Once the optimum values of the parameters were established (f_{OPT} and $\xi_{d_{OPT}}$), a sensitivity analysis was performed for a SDOF structure for a range of periods between 0.5 and 2.0 seconds. The optimal tuned frequency f_{OPT} was changed in ±5% (f_{OPT} *0.95 and f_{OPT}*1.05) and the system was subjected to the database of 132 acceleration records. To provide a clearer representation, only mean values were plotted and no reduction factor in Fig.5.

This analysis was repeated 4 times to different mass ratio values, μ= 1, 2, 3 and 4%.

The effectiveness of the TMD diminishes when the frequency diverges from the optimal one, as could be expected, but the change is not too relevant (Fig. 5). In a similar way, the effectiveness is reduced when the system has plastic deformation (Fig.6). It can also be observed that the mass ratio has a big influence in the effectiveness of the TMD (Fig. 5). This analysis does not consider physical limitations that could be in practical applications, like the weight of the damper and the displacements.

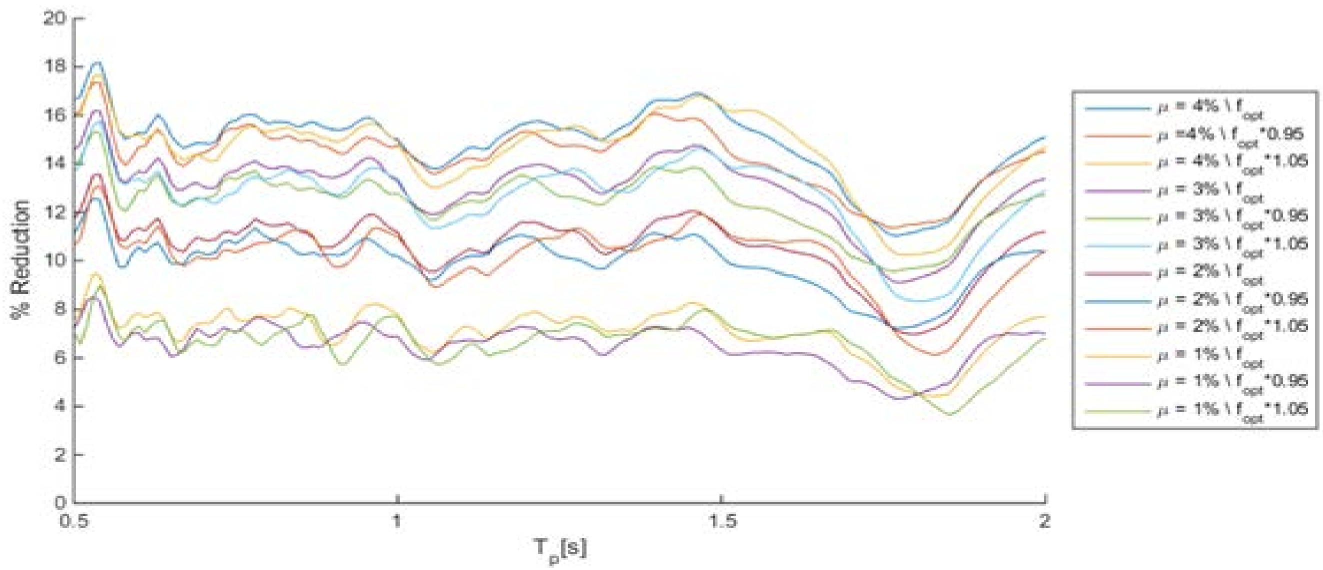

Fig. 5. Sensitivity analysis ($f_{OPT} \pm 5\%$) for different mass ratios (1-4%). Mean values of reduction factor for optimum parameter of the TMD obtained by white noise input

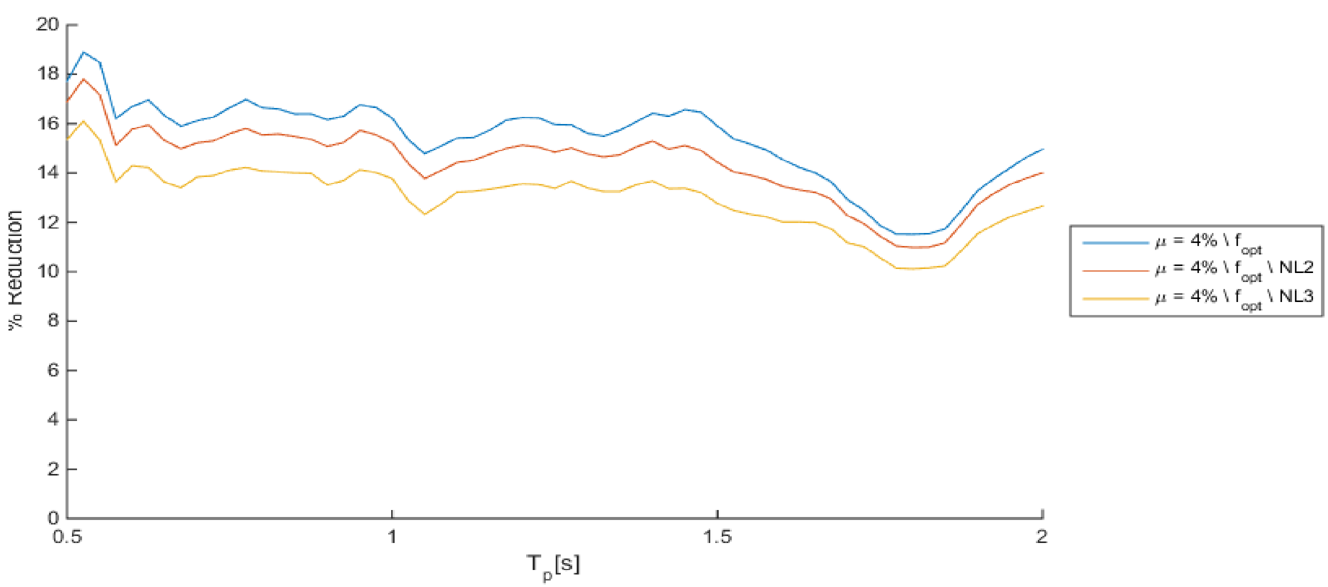

Fig. 6. Sensitivity analysis for nonlinear response. Impose two different ductility factors. NL2: Ductility demand = 2 (max displacement = $2z_0$) and NL3: Ductility demand = 3 (max displacement = $3z_0$)

5. Application to a typical Chilean building

As previously mentioned, a graphic interface was developed using MATLAB (GUIDE tools) to obtain the response for linear and nonlinear cases (see Annex A). This graphic interface contains the complete database records and gives the response for any linear and/or nonlinear case for any selected record.

In the numerical study, the response of a ten-story shear building is analyzed under 132 seismic records with and without the TMD.

The graphic interface objective is quickly to obtain results: mean values, to identify the best and worst cases of reduction for different type of responses and to determine optimum parameters of TMD (Eq. (5) to Eq. (8)).

A finite element model was developed using SAP2000 (Fig.7) for more accurate results and verify the results of graphic interface with the same input.

The TMD was modeled like a slab connected to the top floor by the using of link element (Fig.7a).

Residential building (Fig.7b), floor system: flat concrete reinforced slab. Spans: 5 to 8 m, thickness: 20 cm supported on shear walls and upturned beams at the perimeter. The vertical and lateral load systems are concrete walls.

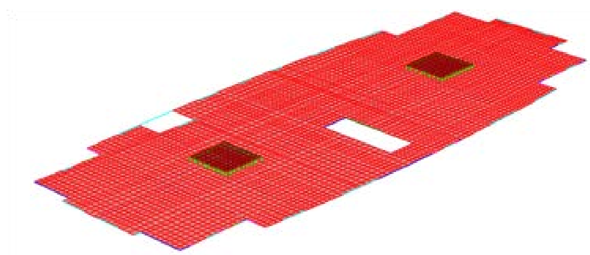

Fig. 7a. Finite element model of TMD.

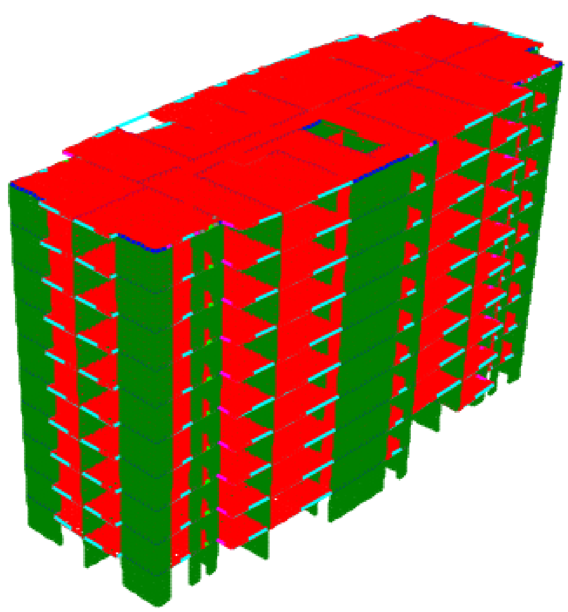

Fig. 7b. Finite element model of the building.

Fig. 8 shows the displacement time history for the building and TMD model shown in Fig. 7 under two seismic records selected by the graphic interface (best case Earthquake Maule, seismic data recorded at station Papudo R109 and worst case Earthquake Maule, seismic data recorded at station Maipu-Santiago R115) using the same finite element model properties, building period T=0,2891[s] and critical damping ratio β=5% and system properties mass ratio μ=6.35%.

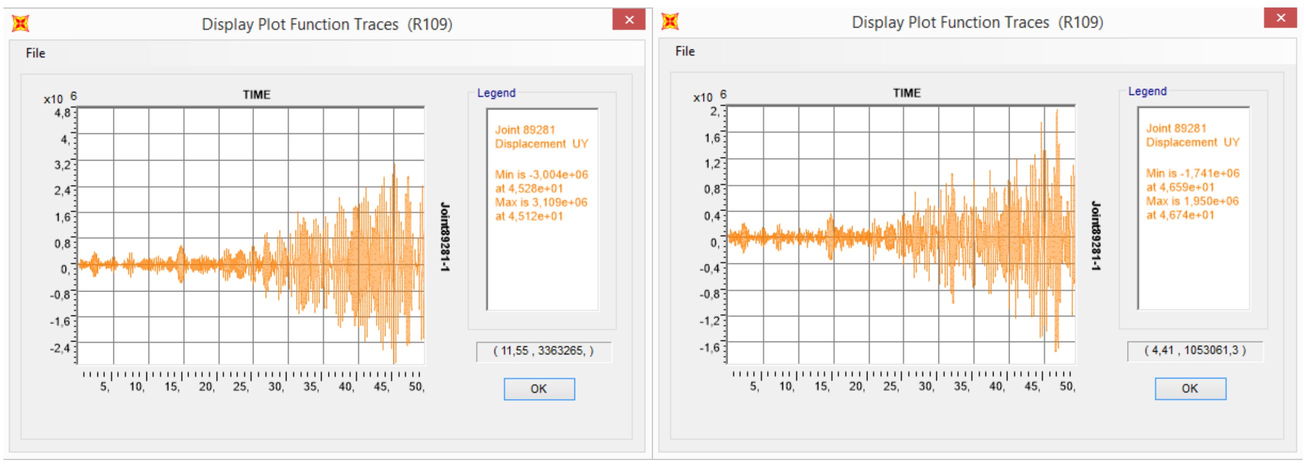

Fig. 8a – Displacement Time History response SAP2000, Building without and with TMD, R109. Reduction Factor R=37%

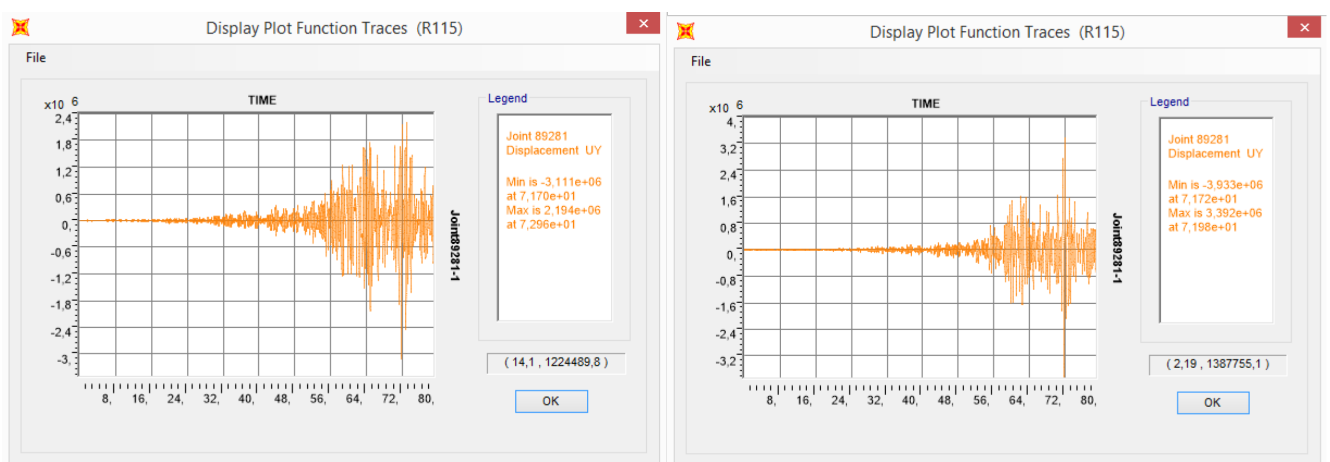

Fig. 8b –Displacement Time History response SAP2000, Building without and with TMD, R115. Reduction Factor R= -26%

6. Conclusions

A theoretical study has been presented for determining the effectiveness of the use of TMD devices for seismic protection of buildings. In order to do that, the response of simple 2 DOF systems for a database of 132 acceleration records, corresponding to seven Chilean earthquakes of magnitude greater than 7.0, was considered.

The characteristics of the TMD were determined by using the optimum values of the device's natural period and damping ratio, that is, those values that produce the maximum reduction of the response for either single frequency or white noise input motion. For this model, the influence of the following parameters on the reduction factor were considered: mass ratio, change in the tuned frequency of the TMD, and non-linear response of the building.

The following conclusions emerge from the results

- Considering optimum tuning and damping, there is a large dispersion in the results for the reduction factor (Fig. 3), which depends on the acceleration record considered. It can be observed that for all values of periods there are cases where the effect of the TMD is to increase the response of the structure instead of reducing it.
- The mean reduction for all records, for a mass ratio of 4%, is approximately 15% for low periods (range of periods between 0.5 and 2.0 seconds). For periods longer than 4 seconds, this value is reduced by half.
- By separating the records by soil type and near recording stations in a specific city (Santiago and Valparaiso), the mean value of the reduction factor remains the previous concluded behavior.
- For the mean value minus one standard deviation there is almost no reduction.
- The average reduction factor highly depends on the mass ratio. For μ=4% is near 15% while for μ=1% is only 7% (Fig. 5).
- If the frequency of the TMD is between 95% and 105% of the optimum frequency, the detuning is not relevant (the factor is reduced in only 1%, Fig. 5).
- The influence of nonlinear response of the structure (plastic deformation) is to reduce the effectiveness of the TMD. For the case with μ=4% and common values of ductility demand, the reduction factor diminish in near 2% (Fig. 6).
- A graphic interface was implemented in a MATLAB platform, to analyze a multi-storied building equipped with a TMD device. Any record of the database can be considered, for any mass ratio, structural damping or nonlinear behavior of the structure. The objective function can be the maximum displacement, the accumulative displacement or the RMS response of the structure. In addition, the graphic interface can select the acceleration records that give the best and the worst values for the reduction factor and the confidence interval for the mean response. By using this graphic interface it was observed that the cases where the structural response increases (negative reduction) are those in which the response spectrum has a valley (minimum). This can be explained by the fact that, under this situation, the effective natural frequency of the structure changes and, therefore, the response spectrum increases. The graphical interface works as a complement to design TMD, allowing quickly determine records that may cause problems (Fig.8b amplification was also detected in Fig.9).

7. Acknowledgements

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9. Annex A

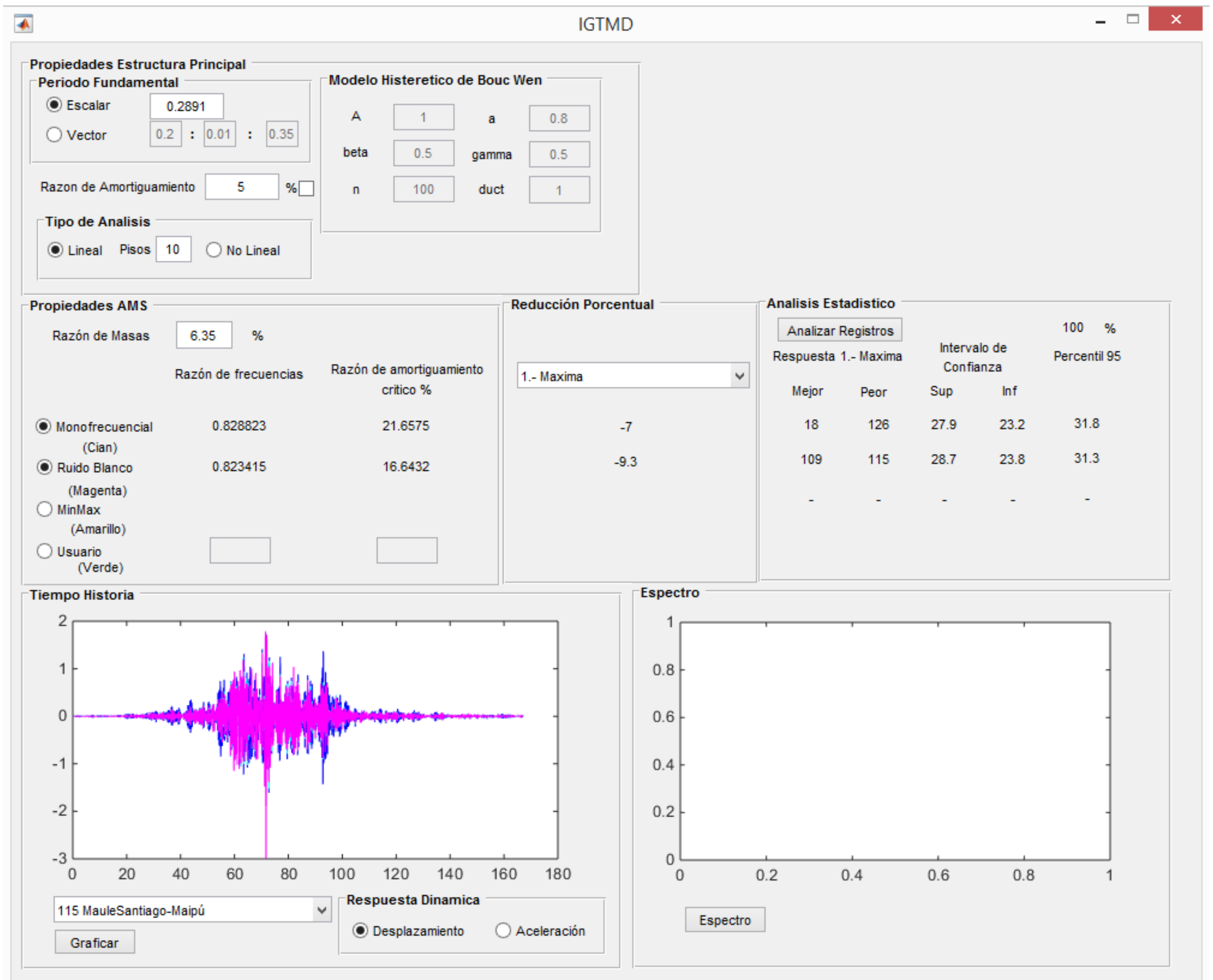

Fig. 9 –Displacement Time History response graphic interface, Building without and with TMD, R115. Reduction Factor R= -9%