Optimization of Tuned Mass Dampers for RC Structures with Projection in Plan

S.M. Nigdeli, and G. Bekdas

***Abstract*—** Irregularities of civil structures are an important issue when structures are under the effects of strong ground motions. Several irregularities may affect the seismic behavior of structures. Irregularities may lead important damages or collapses. Using cantilever members in reinforced concrete (RC) structures is an important irregularity in plan for vibrations in vertical direction. Also, these projections in plan can affect the response of the structure in horizontal direction and these structures may suffer from big displacements during earthquakes. In order to prevent these displacements at RC structures, a tuned mass damper (TMD) can be used to improve the seismic behavior. In this study, RC structures with projection in plan were passively controlled with an optimum TMD. The structure was compared with two equivalent structures without projection. The optimum parameters of TMD were found by using a metaheuristic algorithm called Harmony Search (HS). Different TMD parameter ranges were used in optimization and the optimum results were verified by using benchmark earthquakes. According to the different cases of the TMD parameters, the optimum TMD is effective on obtaining a better seismic behavior than structures without projection.

***Keywords*—** Projection in Plan, Reinforced Concrete Structure, Tuned Mass Damper, Seismic Behavior, Harmony Search, Optimization.

I. Introduction

TUNED mass damper (TMD) is a vibration absorbing device used in mechanical system including civil structures. TMDs have been used in civil structures in protection of earthquakes, strong winds and traffic loads.

The history of TMDs was started with the invention of Frahm in 1909 [1]. The absorber was formed by using a mass with stiffness element. In this form, the device was not suitable under excitation with changing frequency. By adding a damper to this absorber device, the general form of TMD was obtained by Ormondroyd and Den Hartog [2].

After the development of TMD, researchers have been working on the optimization of TMD parameters for different mechanical systems under various external excitations. In this part, the studies on structures with TMD are briefly given.

Den Hartog developed optimum frequency and damping ratio expressions for TMDs under harmonic excitation. These expressions were derived for undamped main system [3]. The research studies were continued with the optimization applications for damped main system [4-7].

Under harmonic and white noise random excitations, Warburton proposed simple frequency and damping ratio expressions for TMD tuning. These expressions are only depended to a preselected mass ratio and the performance of the TMD is depending on it [8]. Also, Sadek et al. obtained simple expressions for the same parameters by using a curve fitting method for numerically searched parameters. The amount of damping of main system is also a variable of the expressions in addition to mass ratio [9].

Because of the impossibility to derive TMD expressions for the structures with inherent damping, a numerical optimization was suggested by Rana and Soong [10]. Carotti and Turci optimized inertial tuned mass dampers by the use of phasors in the Argand-Gausss plane [11]. For wind and earthquake excitations, optimum close form TMD tuning expressions were proposed by Chang [12]. An extended random decrement method was employed by investigating displacement and acceleration response spectra for structures with and without TMD [13]. The effect of nonlinear viscous damping for TMD was studied by Rudinger [14].

Metaheuristic methods inspired from natural phenomenon have been employed for parameter estimation of TMDs. Genetic algorithm is the most employed algorithm [15-19]. In addition to that, particle swarm optimization [20, 21], bionic algorithm [22] and Harmony Search (HS) [23-29] were used for TMD optimization.

In this study, HS algorithm was employed to find optimum TMD parameters on civil structure with projection in plan. The seismic behavior of the structure with projection was compared with two types of equivalent structures without projection. The maximum structural displacement of the first story was tried to reduce to values lower than the response of the structures without projection by adding an optimum TMD on the top of the structure with projection in plan.

II. The Methodology of HS for TMD Optimization

Harmony Search is a music inspired metaheuristic algorithm. Geem et. al. imitated the music performance process in which a musician searches the best harmony in

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order to gain the admiration of audience [30]. The approach has been modified to solve several optimization problems in engineering. [23-36]

The methodology of HS modified for the optimization of TMD parameters can be explained in 6 steps.

Step 1: In the first step, the solution range for the HS parameters must be defined. The physical condition and economy is effective on selecting these ranges.

The use of a heavy mass may be unsuitable for a structure in mean of axial force capacity. Also, the increase of the mass and damping ratio will increase the value of damping coefficient. By the increase of this coefficient, the cost of damper will be more expensive.

In addition to mass and damping ratios, a range must be defined for the period of TMD. By selecting a feasible range, the optimization process may be shortened.

In this study, the solution range of TMD period was taken between 0.8 and 1.2 times of the critical period of the structure. The mass ratio range was taken between 1% and 10%. Different upper bounds of the damping ratio were investigated. The lower bound of the TMD damping ratio was taken as 5%. The upper bounds were taken as 30%, 40% and 50% for the cases 1, 2 and 3, respectively.

Then, properties of the structure must be entered to the program in addition to solution ranges. For a shear building assumption, these properties are mass and stiffness at all stories. Also, the damping ratio of the main structure must be defined. In this study, the damping ratio of the main structure is assumed as 5% for all vibration modes. The damping matrix was constructed according to Rayleigh damping which is proportional to the mass and stiffness matrices.

Also, special parameters of the HS optimization must be defined. These parameters are Harmony Memory Size (HMS), Harmony Memory Considering Rate (HMCR) and Pitch Adjusting Rate (PAR).

Step 2: Structure without TMD must be analyzed under earthquake excitations for the future comparisons for the stopping criteria and elimination. These analyses can be done in time and frequency domain.

The equations of motions were modeled by using Matlab Simulink. Runge Kutta method was chosen for solver with 10^{-3} s time step.

Step 3: The essential part of the HS algorithm starts in this step. The initial Harmony Memory (HM) matrix is generated by harmony vectors as many as HMS. These vectors contain possible optimum solutions for TMD mass, period and damping ratio. These values are randomly selected within the defined solution range. Also, the corresponding analyses for the vectors must be done for the comparisons of the responses with each other and the uncontrolled one.

Step 4: The main part of the optimization starts in this step. After the generation of the initial HM matrix, a new vector must be generated. The special rules of HS are used in generation of this vector.

A new vector can be randomly generated from the whole solution range or a smaller solution range around the existing values in HM matrix with the possibility of HMCR. The ratio between the smaller range and whole range is PAR.

Step 5: After generating a new vector, new one is added to HM matrix and the worst one in the defined response is eliminated. In this study, the maximum first story displacement is taken as the elimination factor.

Step 6: The stopping criteria are checked for the values stored in HM matrix. If the stopping criteria are satisfied, the optimization process is ended and the solutions are output. If not, the process must be continued from the Step 4 until the stopping criteria are satisfied.

In this study, two criteria are used for the objective function. The first one is related with the frequency domain analyses. The maximum acceleration transfer function of the first story calculated for the TMD controlled structure must be lower than the uncontrolled one. The transfer function values are not depended to external excitation. To find general optimum solution, this criterion is used.

Essentially, optimum results must be suitable for random excitations like earthquake. The maximum first story displacements are also compared for a stopping criterion. The value of the maximum first story displacements must be lower than a defined percentage of the uncontrolled value. This percentage is entered by user and the program is capable to increase this value after 200 iterations by 5% if defined percentage is not physically possible.

III. Numerical Example

A five story reinforced concrete (RC) structure with projections in plan (swp) (Fig. 1) was investigated under six different earthquake records. In this structure, cantilever slabs are not supported by the columns. These slabs have no advantage for the rigidity of the structure. The cantilever beams increase the weight of the structure without any additional advantage on rigidity at horizontal direction.

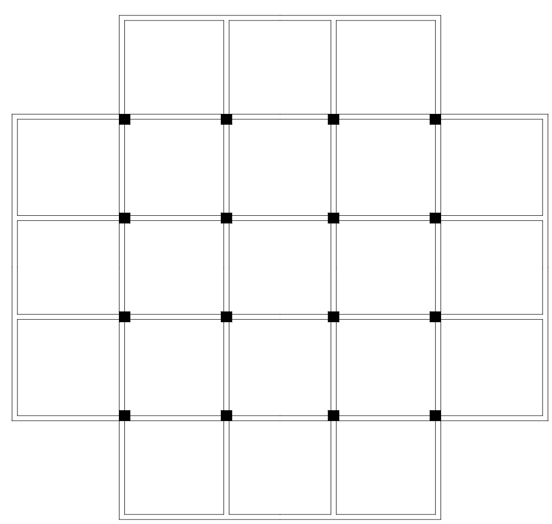

Fig. 1. Plan of swp structure

By implementing an optimum TMD on the top of the structure with projection, the seismic behavior of the structure was improved. The seismic responses of the structure were compared with two different structural plans without projections in plan.

The first structure (s1) has similar plan with swp but it is without protections (Fig. 2). Area and the shape of the second structure (s2) are the same with swp except the column supports under the extensions (Fig. 3).

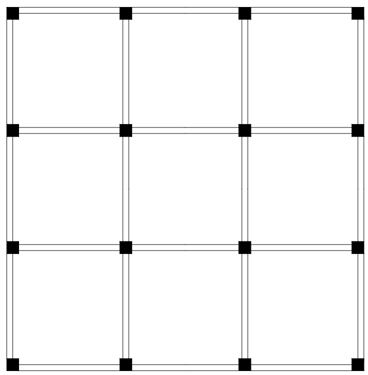

Fig. 2. Plan of s1 structure

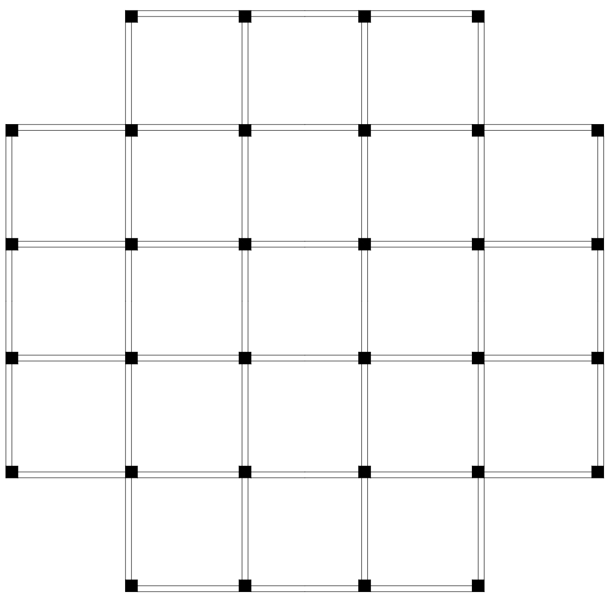

Fig. 3. Plan of s2 structure

The size of all slab are 4x4 m including the console slabs. The projection used in swp is the allowed limit in Turkish Earthquake Code (TEC2007) [37].

The size of columns and beams are 400x400 mm and 200x500 mm, respectively. The thickness of the slabs is 100 mm. The compressive strength and elasticity modulus of the concrete were taken as 25 MPa and 23500 MPa, respectively.

The mass, stiffness and critical period of the structures for a story can be seen in Table I. All story properties are the same for all structures.

Table I. Properties of the structures

	Mass (t)	Stiffness (MN/m)	Critical Period (s)
swp	347	279	0.78
s1	162	278	0.57
s2	367	560	0.53

The earthquake records used in the optimization process were taken from Pacific Earthquake Engineering Research Center (PEER) database website [38]. These records are given in Table II.

Table II. Earthquake records used in optimization

Earthquake	Date	Station	Component
Kobe	1995	0 KJMA	KJM000
Imperial Valley	1940	El Centro	I-ELC180
Erzincan	1992	Erzincan	ERZ-NS
Kern Country	1952	TAFT	TAF111
Northridge	1994	Sylmar	SYL360
Loma Prieta	1989	LGPC	LGP000

In Table III, the maximum first story displacements of compared structures are given. The maximum structural responses are occurred under Loma Prieta record. The maximum first story displacement for swp is 2.4 and 2.25 times of the responses of s1 and s2, respectively.

Table III. Maximum first story displacements of structures in mm

Earthquake	swp	s1	s2
Kobe	98.5	44.2	43.2
El Centro	25.1	20.5	20.1
Erzincan	40.7	16.8	19.6
Taft	14.1	8.2	8.2
Sylmar	52.7	40.6	39.1
Loma Prieta	109.0	45.6	48.5

Due to big displacements of swp, this structure was modified by implementing an optimum TMD on the top of the structure. The optimum mass ratio (μ), TMD period (T_d) and damping ratio (ξ_d) obtained by using the HS approach can be seen in Table IV for different damping ratio cases described in Section 2.

Table IV. Optimum TMD parameters

Parameters	Case 1	Case 2	Case 3
μ (%)	8.64	9.29	8.87
T_d (s)	0.90	0.93	0.91
ξ_d (%)	27.71	38.94	49.63

Under Kobe earthquake record, the maximum first story displacements are 98.5 mm, 44.2 mm and 43.2 mm for swp, s1 and s2, respectively. As seen from the history graphs given in Fig. 4, the maximum first story displacement (FSD) of swp is reduced to 54.0 mm, 48.6 mm and 44.9 mm for the cases 1, 2 and 3, respectively.

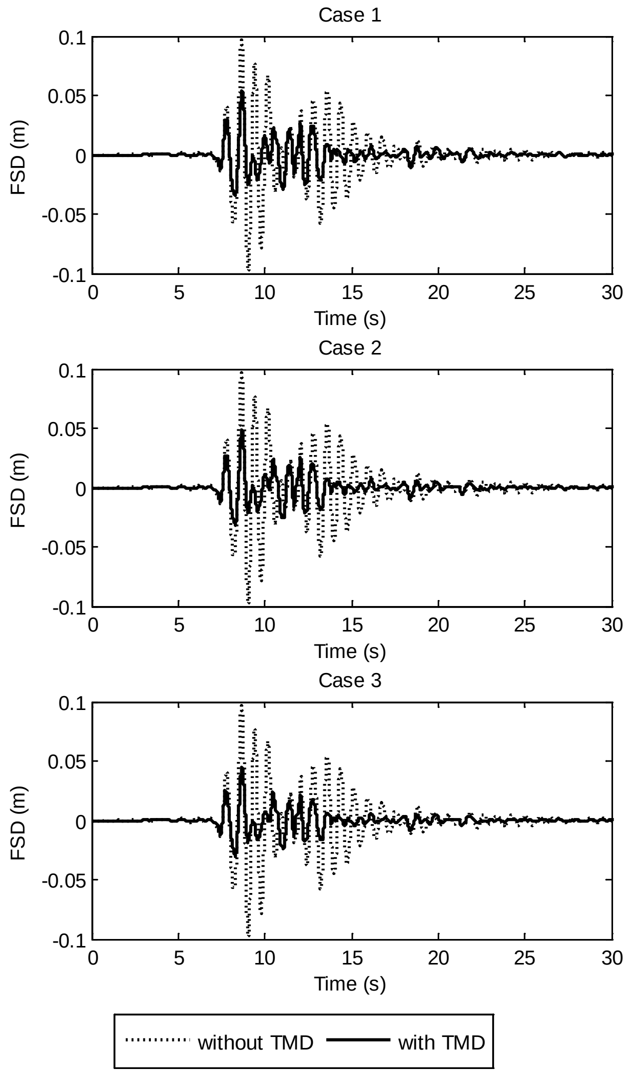

Fig. 4. FSD time histories of swp under Kobe excitation

The maximum first story displacement of swp is 25.1 mm under El Centro excitation. As seen in Fig. 5, it is possible to reduce this maximum displacement to lower values than the maximum first story displacements of s1 and s2.

Kobe, Erzincan and Loma Prieta excitations, which are recorded at near fault regions, are more effective earthquakes for the structures with projections in plan. Under these excitations, the displacement of swp is more than two times of the other types of structures. The optimum TMD is effective on reducing these values. Also, the maximum first story displacement under Loma Prieta excitation are reduced to lower values than other structures without irregularity for all cases.

Loma Prieta excitation is the most critical one for all types of uncontrolled structures while Kobe excitation is more critical than the others for TMD controlled cases. The first story time histories of swp are given in Fig. 6 and 7 for Erzincan and Loma Prieta excitations, respectively.

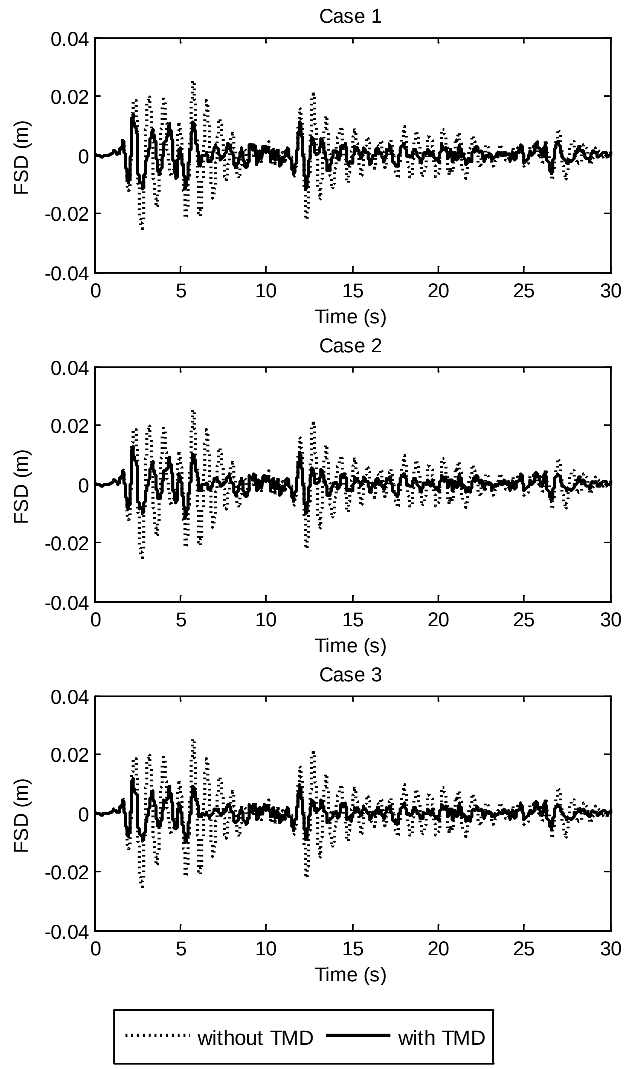

Fig. 5. FSD time histories of swp under El Centro excitation

The optimum TMD is effective under Taft record which is recorded at a far fault region (Fig. 8). For that reason, the optimum values are suitable for both of near and far fault excitations.

The maximum first storey displacement of swp under Northridge-Sylmar record is reduced to 38.1 mm, 36.1 mm and 34.4 mm from 52.7 mm for the cases 1, 2 and 3, respectively. This reduction can be seen in Fig. 9.

The maximum first story displacements of TMD controlled swp structure for different cases are given in Table V. According to results, the optimum TMD is effective to reduce the first story displacements of swp. For case 3, the maximum values are even better than the responses s1 and s2. Also, the maximum first story acceleration transfer function value at the first resonance peak is reduced to 2.22 dB, 4.01 dB and 6.78

dB from 11.04 dB for the cases 1, 2 and 3, respectively.

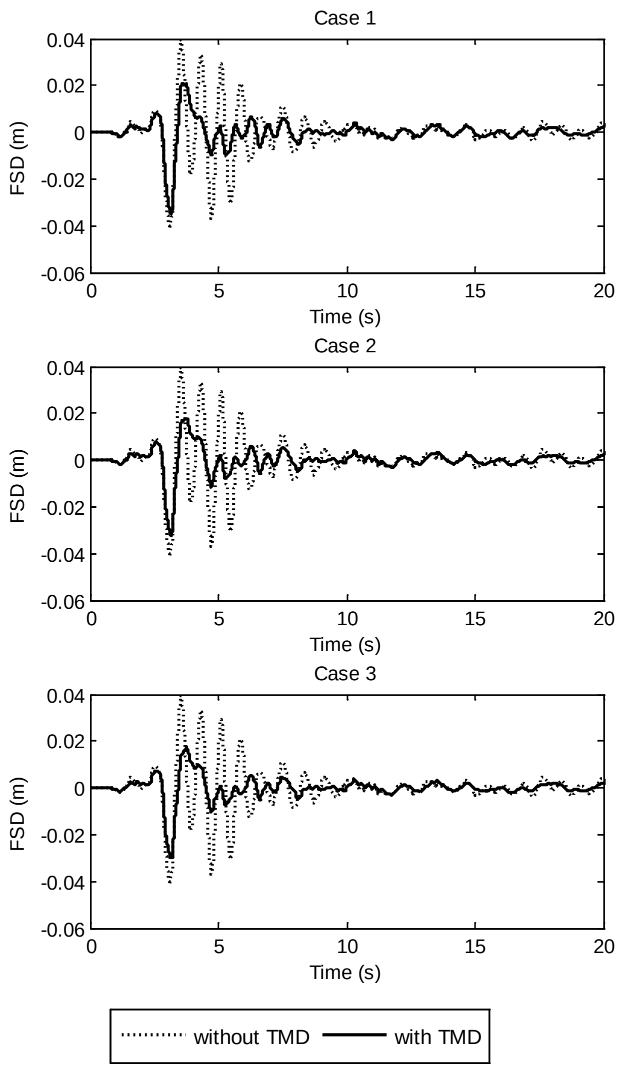

Fig. 6. FSD time histories of swp under Erzincan excitation

Table V. Maximum first story displacements of TMD controlled structure in mm

Earthquake	Case 1	Case 2	Case 3
Kobe	54.0	48.6	44.9
El Centro	13.7	12.8	11.9
Erzincan	34.8	32.2	30.4
Taft	7.4	6.7	6.2
Sylmar	38.1	36.1	34.4
Loma Prieta	40.5	38.0	34.5

Because of the unknown characteristic of seismic excitations, the optimum results must be suitable to different excitations. For that reason, the optimum TMD parameters were verified under benchmark earthquake excitations given in Table VI.

Table VI. Earthquake records used as benchmark

Earthquake	Date	Station	Component	PGA (g)
Cape Mendocino	1992	Petrolia	PET090	0.662
Chi-Chi	1999	TCU068	TCU068-W	0.566
Düzce	1999	Bolu	BOL090	0.822
Tabas	1978	Tabas	TAB-TR	0.852
Landers	1992	24 Lucerne	LCN000	0.785
Gazli	1976	Karakyr	GAZ090	0.718

In addition to reduce the maximum displacements, TMD is effective on reducing a steady-state response as seen in displacement time history graphs. Also, significant reductions on the frequency responses were obtained.

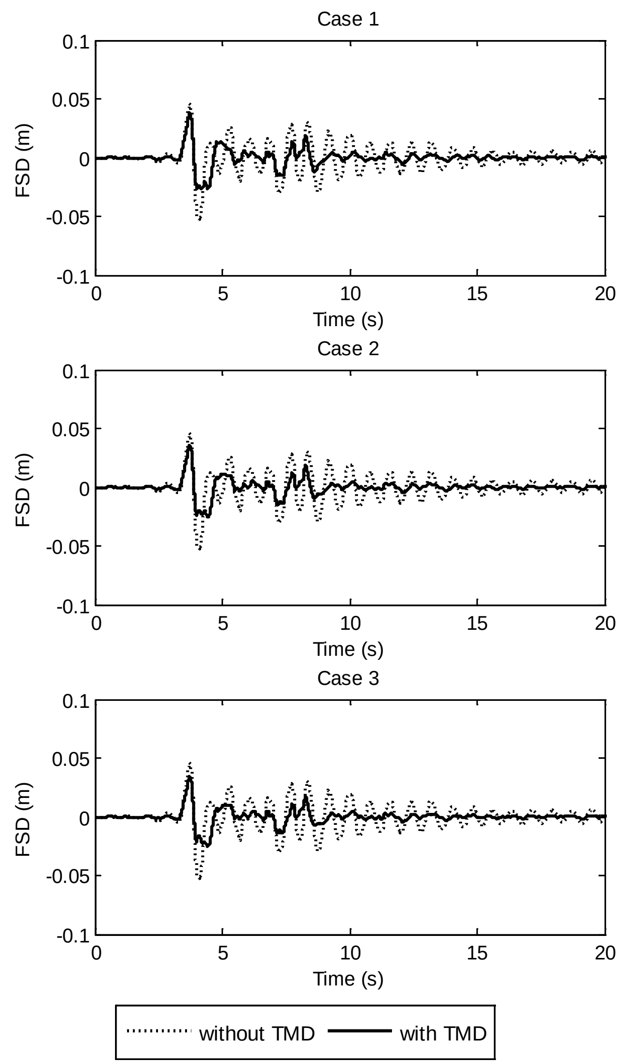

Fig. 7. FSD time histories of swp under Loma Prieta excitation

The maximum first storey displacements of swp under benchmark earthquakes are given in Table VII and the histories for the third case can be seen in Fig. 10.

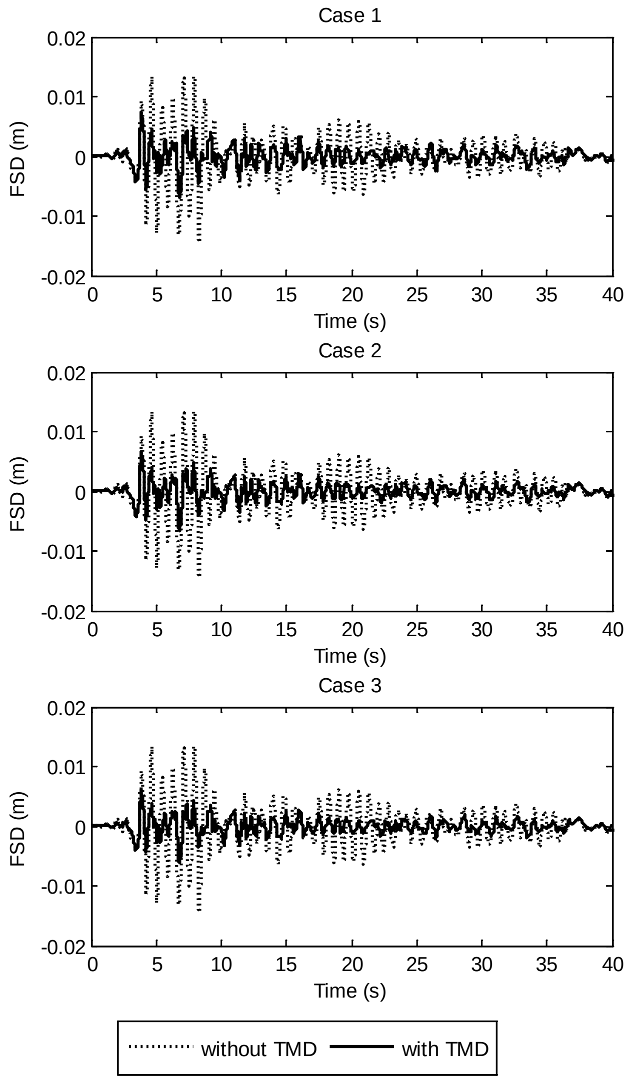

Fig. 8. FSD time histories of swp under Taft excitation

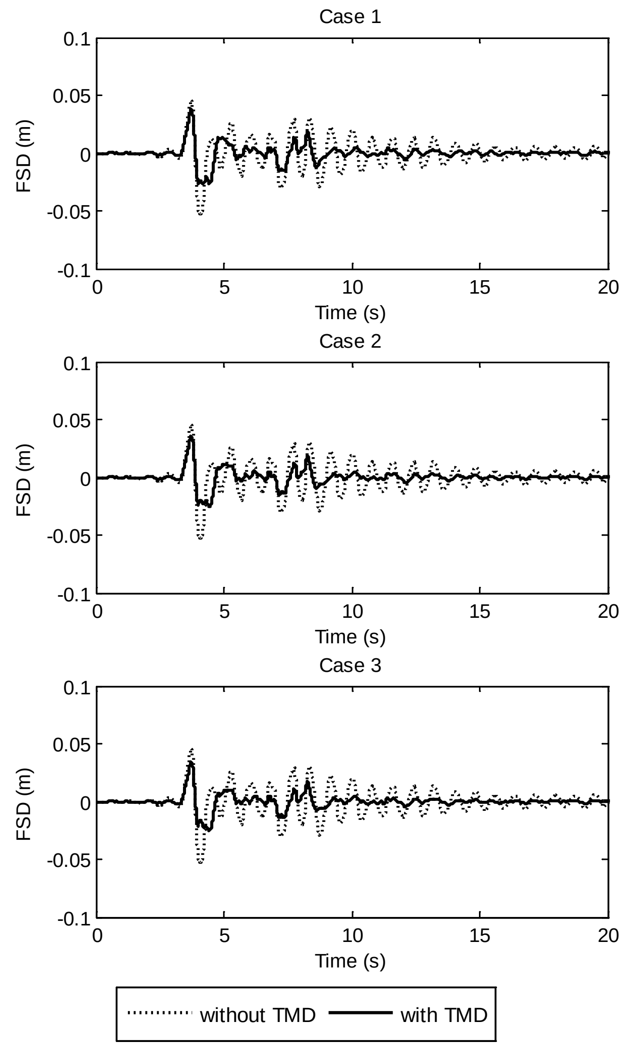

Fig. 9. FSD time histories of swp under Sylmar excitation

Table VII. Maximum first story displacements (in mm) of swp under benchmark earthquakes

Earthquake	Uncontrolled	Case 1	Case 2	Case 3
Cape Mendocino	81.4	43.1	38.1	34.3
Chi-Chi	43.8	36.5	33.3	30.9
Düzce	68.6	38.7	34.4	31.7
Tabas	89.2	32.5	30.8	27.9
Landers	20.2	11.6	10.6	9.8
Gazli	38.5	22.4	22.0	20.9

Although the optimization was conducted under optimization earthquakes, the optimum TMD is also effective on seismic performance under benchmark earthquakes. For different cases, the reduction of maximum FSD are between 47%-57.9%, 16.7%-29.5%, 43.6%-53.8%, 63.6%-68.7%, 42.6%-51.5% and 41.8%-45.7% for the excitations of Cape Mendocino, Chi-Chi, Düzce, Tabes, Landers and Gazli, respectively.

IV. Conclusion

The extremely big displacements of structure with projection in plan were reduced by using an optimum TMD. Three different cases of the optimization process were investigated. The upper limits of TMD damping ratio are 30%, 40% and 50% for the cases 1, 2 and 3, respectively. According to the analyses results, the increase of the upper bound of the damping ratio range is effective on improvement of seismic behavior as expected.

The structure with projection was compared with two different structures without projection. Although, the optimum results of case 1 and 2 are effective on reduction of displacements, it is not sufficient to reduce the maximum value of displacement under the values of the structures without projection. By using the optimum values of case 3, it is possible obtain smaller displacements than the structures without projection.

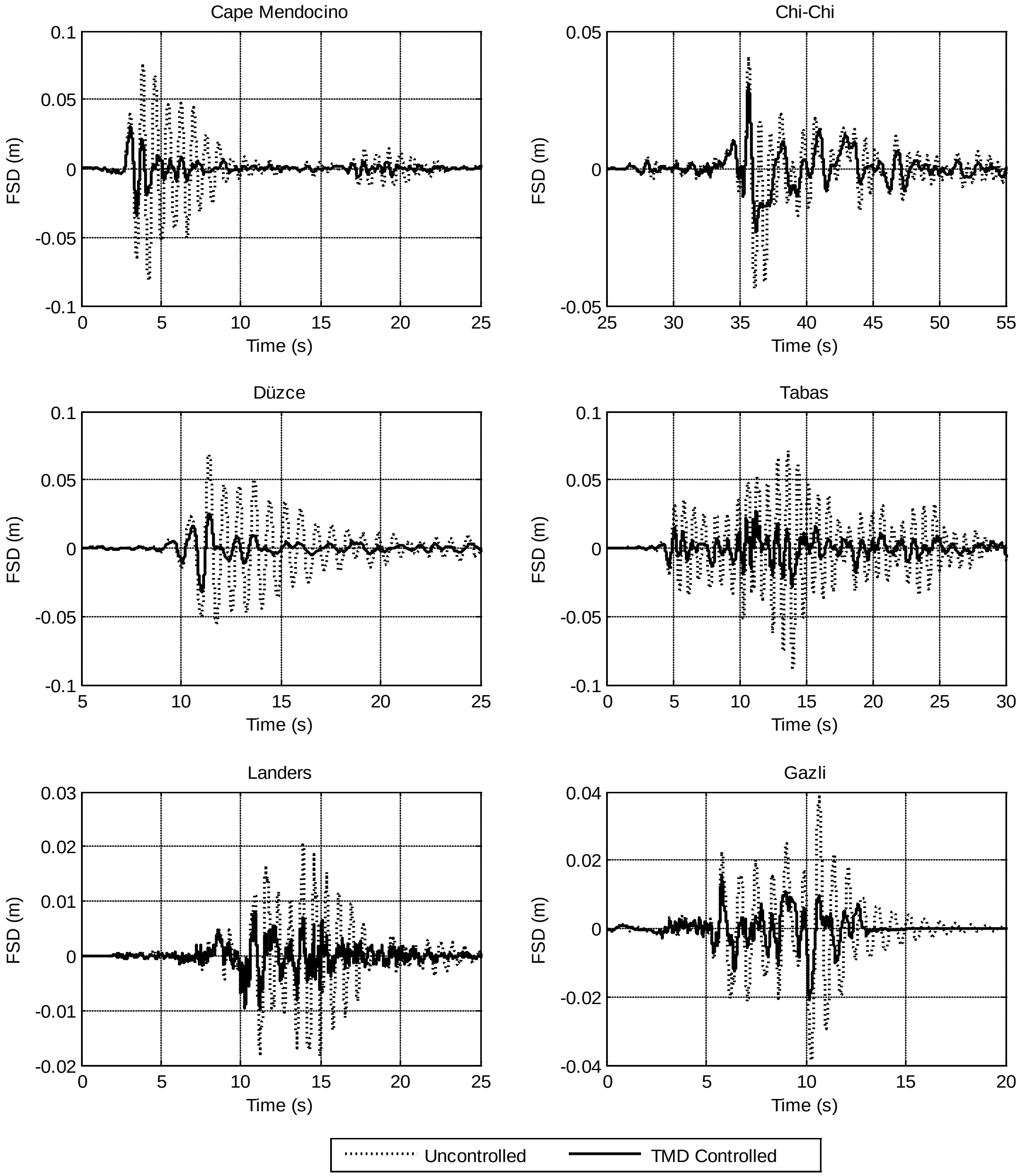

Fig. 10. FSD time histories for benchmark earthquakes (Case 3)

The optimum TMD is feasible method on improving the seismic behavior of structures with projection in plan. It must be noted that a TMD is only effective for the vibrations at the horizontal direction. The reinforced concrete design of cantilever slabs must be done according to the rules of regulations and structural behavior.

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