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The effect of base isolation and tuned mass dampers on the seismic response of RC high-rise buildings considering soil-structure interaction

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Abstract. The most effective passive vibration control and seismic resistance options in a reinforced concrete (RC) high-rise building (HRB) are the base isolation and the tuned mass damper (TMD) system. Many options, which may be suitable or not for different soil types, with different types of bearing systems, like rubber isolator, friction pendulum isolator and tension/compression isolator, are investigated to resist the base straining actions under five different earthquakes. TMD resists the seismic response, as a control system, by reducing top displacement or the total movement of the structure. Base isolation and TMDs work under seismic load in a different way, so the combination between base isolation and TMDs will reduce the harmful effect of the earthquakes in an effective and systematic way. In this paper, a comprehensive study of the combination of TMDs with three different base-isolator types for three different soil types and under five different earthquakes is conducted. The seismic response results under five different earthquakes of the studied nine RC HRB models (depicted by the top displacement, base shear force and base bending moment) are compared to show the most suitable hybrid passive vibration control system for three different soil types.

Keywords: base isolation; rubber isolator; friction pendulum isolator; tension/compression isolator; tuned mass damper (TMD); high-rise building (HRB); soil-structure interaction (SSI); seismic response; vibration control

1. Introduction

Earthquakes are destructive natural forces, especially in reinforced concrete (RC) high-rise buildings (HRBs). Base isolation is one of the successful ways of reducing the risk of earthquakes for structures where these additional installations reduce the movement resulting from earthquakes of foundations to the superstructure. Tuned Mass Damper (TMD) is a useful device to reduce the results of an earthquake for a building with a large displacement, so the combination of the two resistance systems is expected to produce a very effective vibration control system for earthquake resistance, therefore less earthquake response to the buildings. There are many types of base isolations, with advantages and disadvantages and can be used according to the nature of the establishment. Moreover, the soil is a basic element to transfer the loads from the building to the ground and to transfer the forces of the earthquakes from the soil to the building in which is known as the interaction between soil and structure and vice versa (soil-structure interaction, SSI).

Spyrakos *et al.* (2009a) investigated the effect of soil-structure interaction (SSI) on the response of base-isolated buildings and concluded that the effects of SSI are more pronounced on the modal properties of the system, especially for the case of squat and stiff base-isolated structures.

Spyrakos *et al.* (2009b) investigated the effects of soil-structure interaction (SSI) on the response of base-isolated multistory buildings founded on an elastic soil layer overlying rigid bedrock and subjected to a harmonic ground motion and by means of an extensive parametric study they demonstrated that SSI effects are significant, primarily for squat, light structures, founded on soil-stratum of low stiffness.

Varnava and Komodromos (2013) evaluated the effect of inherent nonlinearities in the analysis and design of a low-rise base-isolated steel building. The usage of a nonlinear model for the isolation system is found to be necessary in order to achieve a sufficiently accurate assessment of the structural response and a reliable estimation of the required width of the provided seismic gap. They concluded that the superstructure's inelasticity should be considered under high magnitude earthquakes and in the structural collision of seismically isolated structures to the surrounding moat wall.

Murase *et al.* (2013) investigated a hybrid passive control system in which a base-isolated building is connected to another building (free wall) with oil dampers and showed that this system is effective both for pulse-type ground motions and long-duration and long-period ground motions and has high redundancy and robustness for a broad range of disturbances.

Nath *et al.* (2013) studied experimentally and numerically three-storey, single-bay RC building models

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with and without base isolation and found that floor responses show amplification for the conventional building while 60 to 70% reduction has been observed for the isolated building.

Huang *et al.* (2013) investigated a modified complex mode superposition design response spectrum method and a graphical approach for parameters optimization of linear seismic base-isolation structures and they found that this method is more precise and convenient for utilizing the damping reduction factors and the design response spectrum, and also the proposed graphical approach for parameter optimization is concise and feasible.

Tsatsis *et al.* (2013) proposed a seismic isolation method that introduces a sliding surface that includes two synthetic liner layers at contact with each other creating an interface of small friction that enfolds the foundation soil. They showed that their proposed system serves as a fuse mechanism within the soil and considerably reduces the acceleration transmitted onto the structure, however, the isolated structure may be subjected to increased differential lateral displacement.

Melkumyan (2013) proposed a new approach for the seismic isolation of base-isolated building, namely the installation of a group/cluster of small size bearings (instead of one big one) in order to increase the overall effectiveness of the isolation system and concluded that their results indicated the high effectiveness of the proposed approach.

Mavronicola and Komodromos (2014) investigated the dynamic response of base-isolated buildings using bilinear models for lead rubber bearings (LRBs) subjected to pulse-like ground motions and assessed inaccuracies when the sharp bilinear model is used to model the LRBs instead of the more accurate and smoother Bouc-Wen model.

Tajammolian *et al.* (2014) investigated the effects of peak ground velocity (PGV) of near-field earthquakes on a base-isolated 2D single-story structure by single friction pendulum (SFP), double concave friction pendulum (DCFP) and triple concave friction pendulum (TCFP) bearings. They demonstrated that when rising the PGV, the isolator displacement and base shear of the structure increased. Finally, they concluded that the TCFP isolator was found more effective to control the near field effects than the other friction pendulum isolators.

Tiong *et al.* (2014) investigated the seismic performance of low-rise precast wall system with high damping rubber bearing (HDRB) base isolation. They used three types of HDRB for different kinds of structure in terms of vertical loading and it was revealed that the HDRB was not always an ideal selection to be used in isolating lightweight structure and that increasing the damping ratio of base isolation system did not guarantee better seismic performance in isolation of lightweight structure.

Luco (2014) examined the effects of soil-structure interaction on the performance of a nonlinear seismic base isolation system for a simple elastic structure and found that the seismic response of a structure resting on an inelastic base isolation system may be larger when the flexibility of the soil is considered than the corresponding response obtained by ignoring the effects of soil-structure interaction.

Tavakoli *et al.* (2015) evaluated the effect of a lead rubber bearing (LRB) system to increase the resistance of concrete moment resisting frames against progressive collapse and concluded that base isolation reduced the seismic effect and helped to localize failures and prevented spreading to intact span under seismic loads.

Islam *et al.* (2015) studied the retrofitting of vulnerable RC low to medium rise buildings by base isolation using lead rubber bearing (LRB) and high damping rubber bearing (HDRB) isolators in medium risk seismic region and concluded that these isolators reduce base shears, base moments and floor accelerations at soft to medium stiff soil.

Wei *et al.* (2016) studied the isolation performance of a spring-damper-rolling isolation system when artificially making the uneven friction distribution to be concave and their results showed that the concave friction distribution can dissipate the earthquake energy, and also change the structural natural period.

Patil *et al.* (2016) studied experimentally and analytically the seismic base isolation of structures using river sand as isolator and found encouraging results.

Vasiliadis (2016) performed a seismic evaluation and retrofitting with base isolation systems of inadequately designed low rise old RC buildings.

Shao *et al.* (2017) studied the effect of the simultaneous application a triple friction pendulum (TFP) system and lead-plug rubber bearing on the seismic performance of a long-span railway concrete upper-deck arch bridge and showed that the mixed isolation system performed very well for the seismic response of this long-span railway arch bridge.

Milanchian *et al.* (2017) proved that showed that by using the vertical seismic isolation (VSI) technique, a seismic response reduction up to 50% in flexible substructure and even more in a stiff substructure is achievable.

Hessabi *et al.* (2017) investigated the use of Tuned Mass Dampers (TMDs) for improving the seismic performance of base-isolated structures and specifically focuses on the effectiveness of this hybrid control strategy in structures that are equipped with nonlinear base isolation systems.

Amiri *et al.* (2017) investigated the effect of the seismic pounding of neighboring buildings isolated by Triple Friction Pendulum Bearing (TFPB) and concluded that the increment of the fundamental period of the TFPB base isolator could intensify the impact force up to nearly five-fold.

Djedoui *et al.* (2017) verified the efficiency of a hybrid vibration control for rigid buildings structures under strong earthquakes, consisting of a base isolator and tuned mass damper (TMD) or active tuned mass damper (ATMD). The hybrid control system was able to reduce the vibration amplitudes especially the base isolator displacement and acceleration without affecting the super-structure response regardless of the placement of the TMD control system.

Dumne *et al.* (2017) proposed two hybrid controls for response mitigation of adjacent buildings connected by dampers referred as coupled buildings of which the base of the taller building being isolated. These controls developed using magnetorheological dampers in combination with friction pendulum system and resilient friction base isolator, respectively. The results showed that these hybrid controls are more effective in reducing the responses compared to

Table 1 Soil properties

Soil type	Hard	Medium	Soft
ρ (Mg/m^3)	2.1	1.95	1.75
G (kPa)	200	25	10
v	0.35	0.40	0.45
E (N/mm^2)	70	30	15

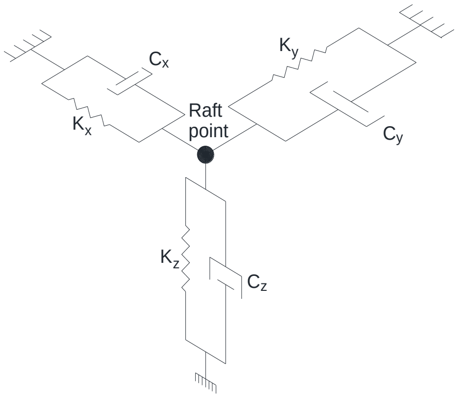


Fig. 1 3D view of the soil element

semi-active control, however, the second hybrid control performs more effectively both in the response reduction and pounding effect.

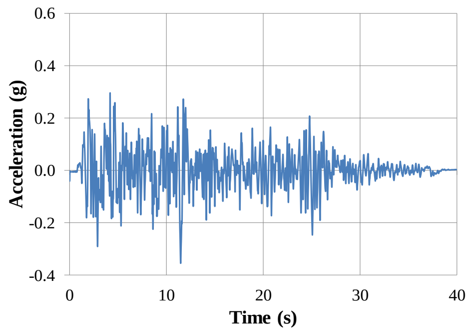
Dhankot and Soni (2017) described the behavior of triple friction pendulum (TFP) isolator under forward directivity and fling step effect. They concluded that near-fault ground motion with forward directivity pulses results in higher demands than the fling step pulses, and that the TFP bearing was more effective in reducing the base shear, absolute acceleration and isolator displacement compared to the usual single friction pendulum isolator.

Kontoni and Farghaly (2019) investigated the mitigation of the seismic response of a cable-stayed bridge with soil-structure-interaction effect subjected to four different earthquakes by using tuned mass dampers and spring dampers with different placements in four different mitigation schemes.

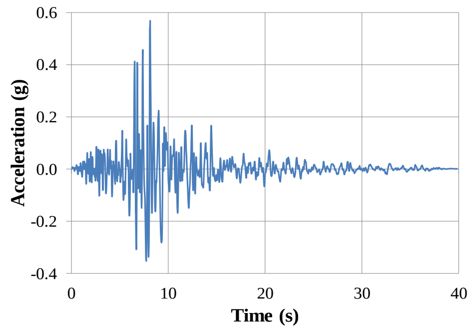
In this paper, a comprehensive study of the combination of TMDs with three different base-isolator types (rubber, friction pendulum, and tension/compression base isolators) for three different soil types (soft, medium and hard soil) and under five different earthquakes is made. The seismic response results under the five different earthquakes of the studied nine RC HRB models are compared to show the most suitable hybrid passive vibration control system for three different soil types.

2. Soil-structure interaction

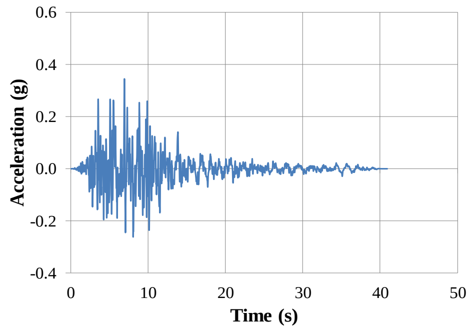
The effect of the soil under the structure's foundation has the very important role to transfer the load from the structure to the soil and the seismic vibration from the soil to the structure; so, the mechanical behavior of the soil will control the behavior of the superstructure. In this study, three soil types will be checked (hard, medium and soft soil) to show the effect of the soil type on the seismic



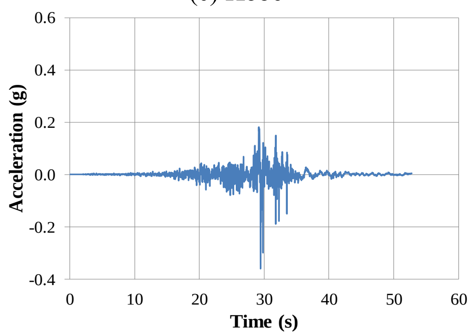
(a) El Centro



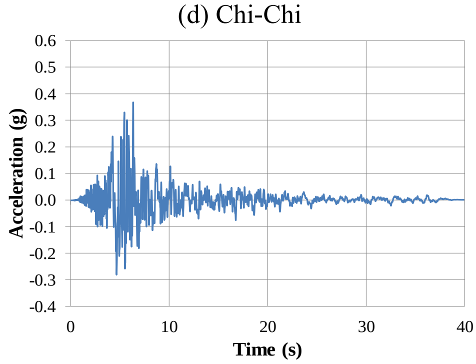
(b) Northridge



(c) Kobe



(d) Chi-Chi



(e) Loma Prieta

Fig. 2 Earthquake accelerograms

response of the base isolation and TMD combination system and to investigate the most suitable vibration control system under different earthquakes.

The properties of the used three types of soil (hard, medium and soft soil) are shown in Table 1. The stiffness and damping parameters of the soil in the vertical and horizontal directions for the 3D soil elements as shown in Fig. 1 can be easily are calculated (e.g., Newmark and Rosenblueth, 1971).

3. Ground excitations

In order to investigate the performance of the HRB under different seismic excitations, the HRB model is subjected to five different earthquakes: El Centro (USA, 1940), Northridge (USA, 1994), Kobe (Japan, 1995), Chi-Chi (Taiwan, 1999), and Loma Prieta (USA, 1989) and with earthquake accelerograms as shown in Fig. 2.

4. Description of the HRB model

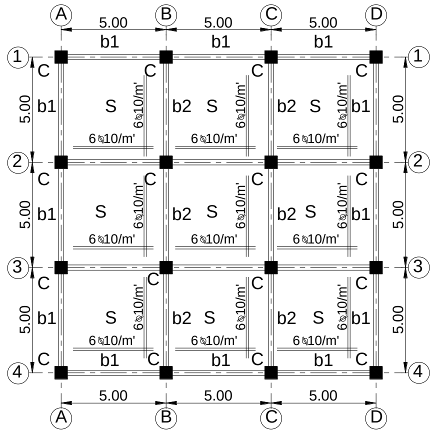
A RC HRB of 15 floors was modeled in SAP2000 as a 3D FEM multistory frame with frame elements for the columns and beams, and with shell elements for the slabs and raft foundation; the live load for all floors is equal to 2 kN/m^2 and five (5) different bidirectional earthquakes (El Centro, Northridge, Kobe, Chi-Chi, and Loma Prieta) with accelerograms as shown in Fig. 2 are applied for time history analysis for all modes.

Three different types of base isolation were used in this study: laminated rubber base isolation, friction pendulum base isolation and tension/compression (T/C) friction base isolation. All three base isolation types were defined in SAP2000 as like special elements to be used in the RC HRB in order to improve the seismic performance of the HRB under five different seismic excitations and three different soil types.

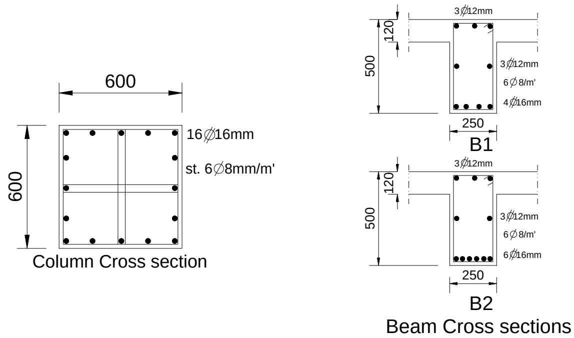
The structural plan of the model is shown in Fig. 3(a) with the slab reinforcements and beams definitions; all the columns "C" of the model have square cross-sections with dimensions 600x600 mm, all beams "b" have cross-section with dimensions equal to 250x500 mm and with reinforcement as shown in Fig. 3(b). The plan of the model was chosen as square in plane and the columns with square cross-section to satisfy the symmetry in both directions. The foundation system is chosen as raft foundation as shown in Fig. 3(c).

A tuned mass damper (TMD) system is one of the most effective techniques to resist earthquake effects. The placement of TMDs is as discussed by Farghaly and Ahmed (2012) with four TMDs distributed on the top of the HRB in equal distances. The type of TMDs used in this study is the bidirectional TMD (in two directions, i.e., x and y directions).

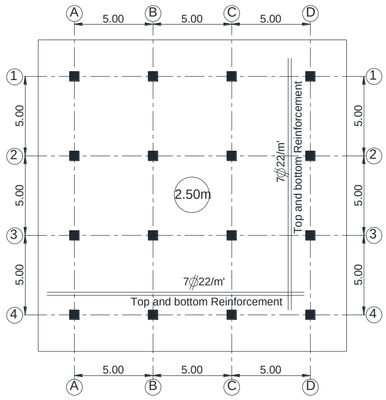
Figs. 4(a) to 4(e) represent the elevations of the different HRB models used in this study. Fig. 4(a) shows the fixed base model, as a reference case for all cases. Fig. 4(b) represents the raft foundation model with the SSI modeled as spring-dashpot elements. Fig. 4(c) shows the HRB model



(a) Structural plan



(b) Details of structural elements



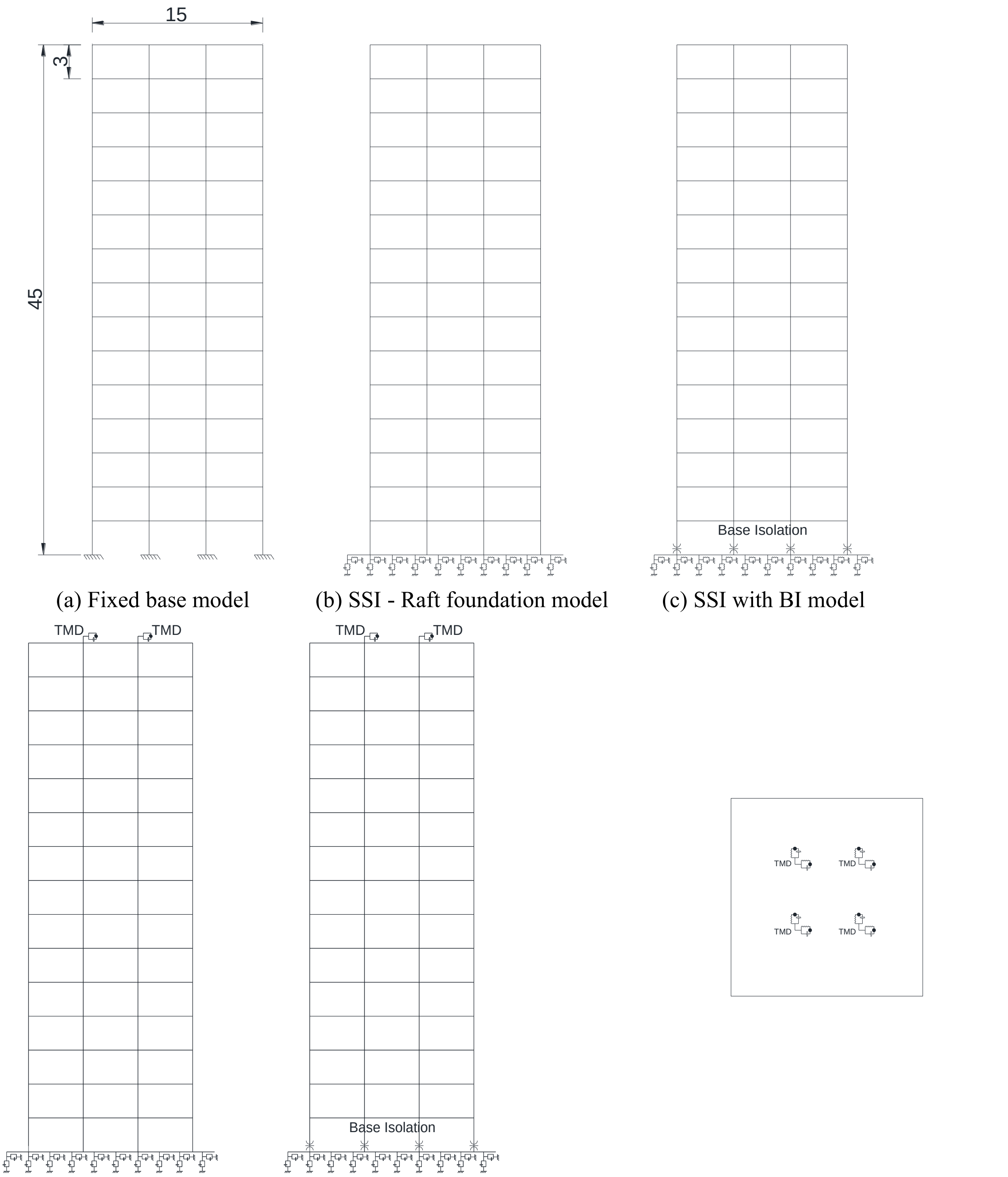
(c) Raft foundation details

Fig. 3 The structural plan and details of the structural elements and the raft foundation of the HRB model

with base isolation (BI) and with the SSI effect. Fig. 4(d) shows the HRB model with top 4 TMDs and with SSI effect. Fig. 4(e) shows the combination of top 4 TMDs and base isolation (BI) with the effect of SSI. Fig. 4(f) shows the roof plan of the model with 4 TMDs distributed 5m apart in both directions.

5. Results and discussion

The effect of SSI was taken into consideration with the raft foundation system and with different base isolation types to investigate the effect of the soil type on the seismic response of a HRB and to choose the best vibration control system with respect to the soil type (soft, medium, or hard



(a) Fixed base model (b) SSI - Raft foundation model (c) SSI with BI model

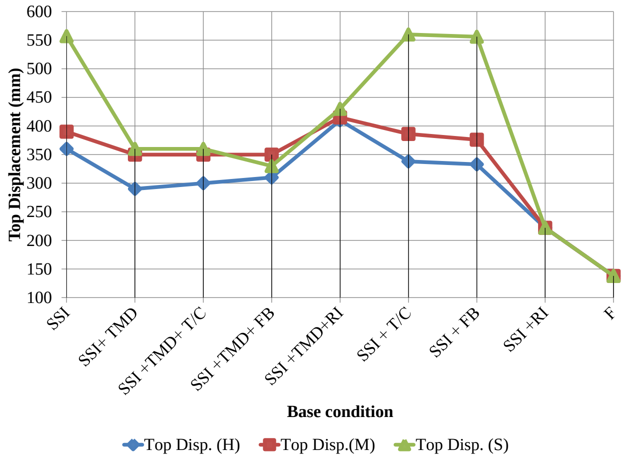
(d) SSI with TMDs model (e) SSI with BI and TMDs model (f) 4 TMDs at the top of the model

Fig. 4 The HRB models with different base conditions and additional TMDs at the top

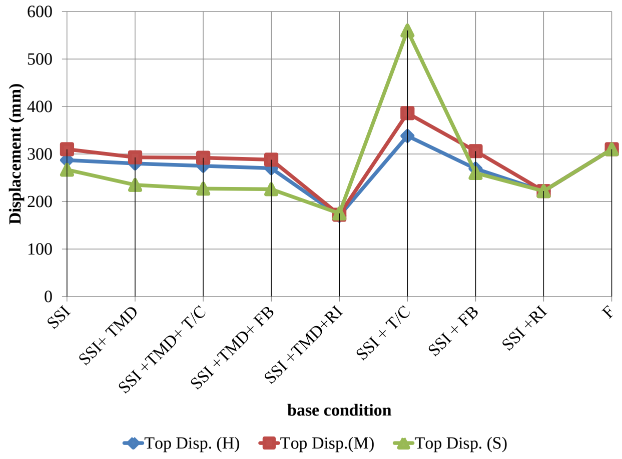
soils). The seismic response of the HRB models was considered to show the effect of the different earthquakes on the different vibration control systems in the HRB models including SSI, and the combination of the base isolation as a first vibration control with TMDs as a second vibration control method on the building subjected to earthquakes. Table 2 represents the symbols used and their definitions. As two vibration control systems for the HRB are first the base isolation to control the base forces generated from the ground to the superstructure which will reduce the forces in a way of lower base shear and base moment, and the second vibration control passive system is

Table 2 Symbol definitions

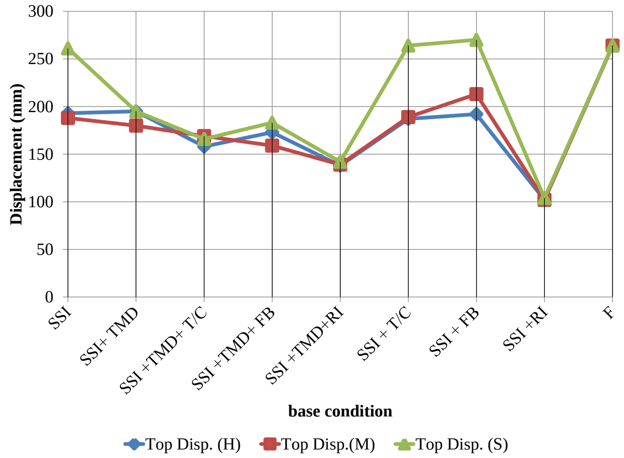
Symbol	Definition
F	Fixed base
S	model with Soft soil
M	model with Medium soil
H	model with Hard soil
SSI	Soil-Structure Interaction effect
RI	Rubber base Isolator
FB	Friction pendulum Base isolator
T/C	Tension / Compression base isolator



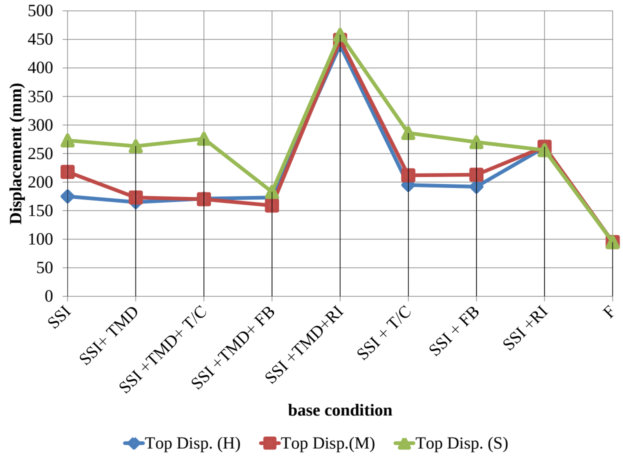
(a) El Centro earthquake



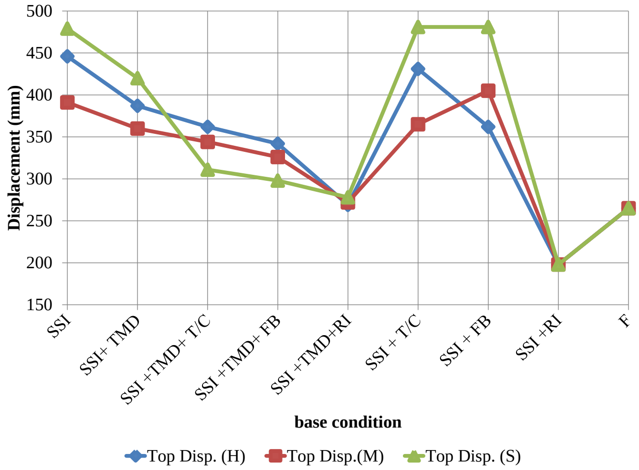
(b) Northridge earthquake



(c) Kobe earthquake



(d) Chi-Chi earthquake



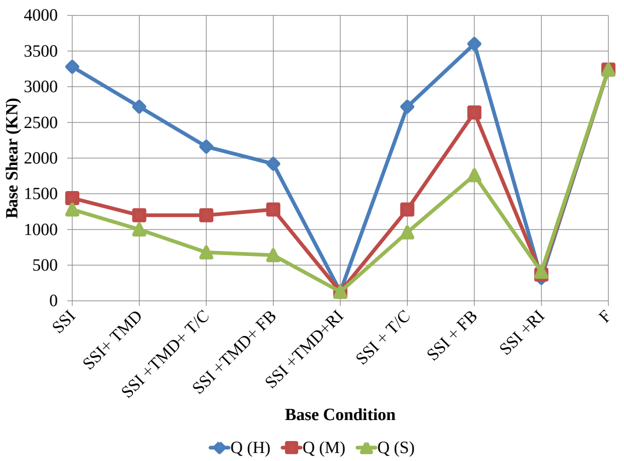
(e) Loma Prieta earthquake

Fig. 5 Top displacement of the HRB model with different base conditions and different soil types

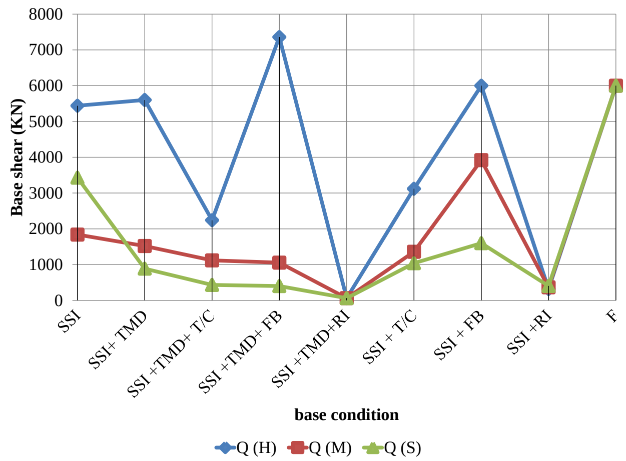
the TMD which will be held on the top of the building to reduce the top displacements, so the building will be controlled for both destructive responses whether they are high values of displacements or base forces.

Fig. 5 shows the top displacements of each HRB model for different soil types and different base conditions, where three types of base isolation (BI) were considered: rubber base isolator (RI), friction pendulum base isolator (FB) and tension/compression (T/C) base isolator, and also the combinations of the two famous vibration control systems: Base Isolation and TMDs.

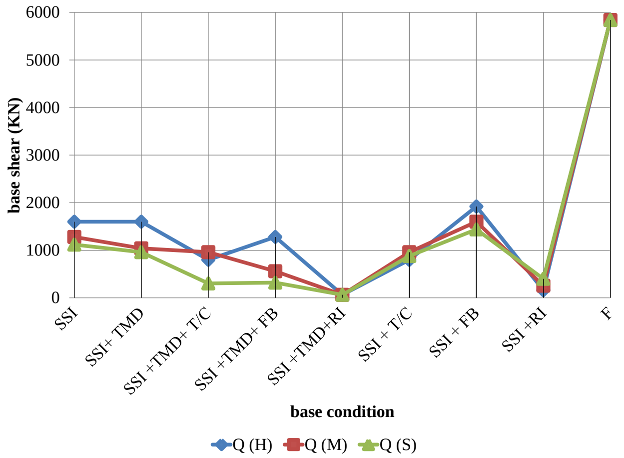
Fig. 5(a) represents the top displacements with different base conditions and vibration control systems for soft, medium and hard soils for the El Centro earthquake; the fixed base case (F) is used as a reference case in each model, which here records the lowest value of top displacement than all models; the effect of the soft soil on the top displacement records the highest values; the top



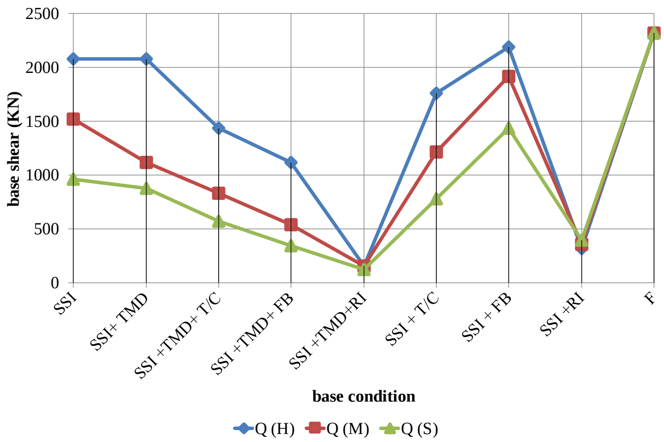
(a) El Centro earthquake



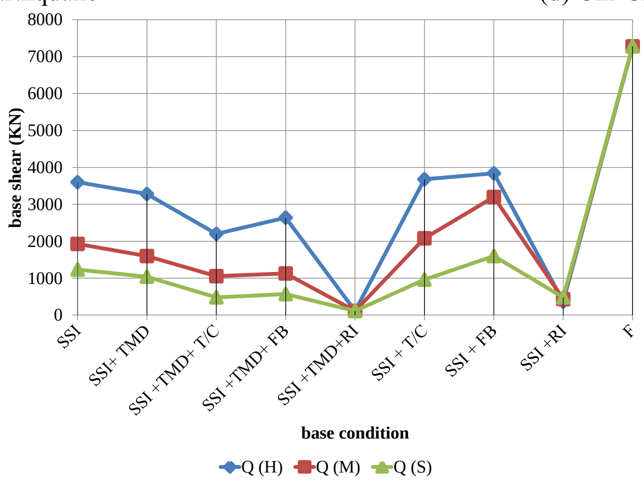
(b) Northridge earthquake



(c) Kobe earthquake



(d) Chi-Chi earthquake



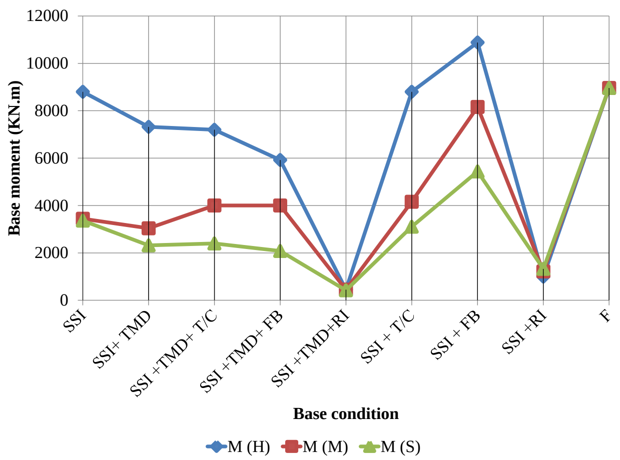
(e) Loma Prieta earthquake

Fig. 6 Base shear force of the HRB model with different base conditions and different soil types

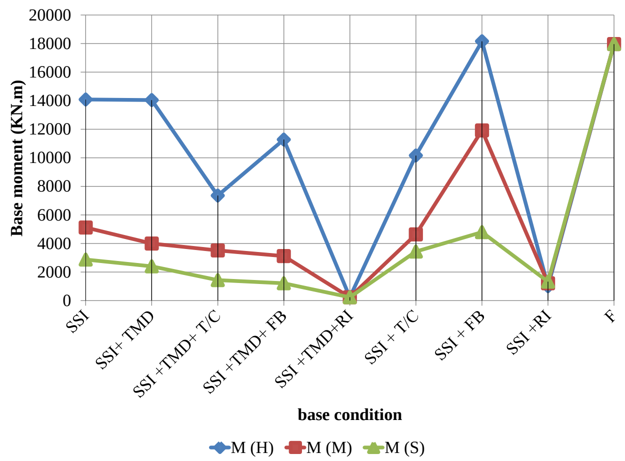
displacements of the RI for all types of soil are similar, but the use of TMDs with RI for all soil types give top displacements nearly larger than the F case by nearly 2.7 times; the soft soil with SSI effect records the maximum values of the top displacements especially for the T/C and FB cases (more than the F case by 3.7 times).

Fig. 5(b) represents the top displacements of the models subjected to the Northridge earthquake; the T/C records the maximum value with soft soil nearly 1.9 times larger than the F case; the values of the top displacements for all types of soils are nearly close and the combination of the RI and TMD records the smallest displacement values, less than the F case by nearly 1.7 times.

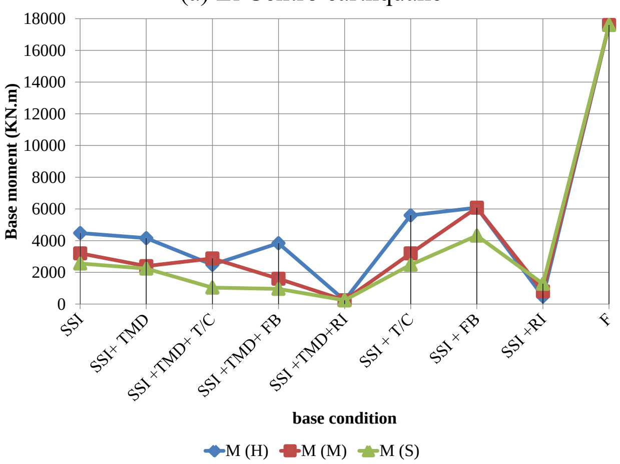
Fig. 5(c) shows the top displacements of the models subjected to the Kobe earthquake; the values of the top displacements are less than the El Centro and Northridge earthquakes; the F case records the maximum values of the top displacements, the values of the top displacements for



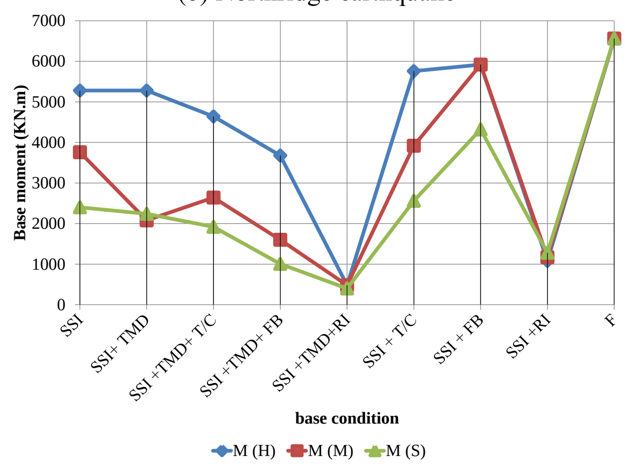
(a) El Centro earthquake



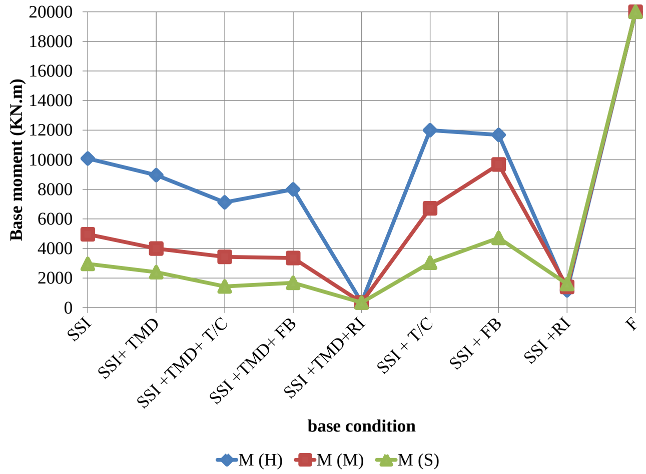
(b) Northridge earthquake



(c) Kobe earthquake



(d) Chi-Chi earthquake



(e) Loma Prieta earthquake

Fig. 7 Base bending moment of the HRB model with different base conditions and different soil types

all vibration control systems are close, and the SSI+RI case records the smallest top displacement (less than the fixed case by nearly 2.6 times).

Fig. 5(d) represents the top displacements for the models, subjected to the Chi-Chi earthquake; the F case is the lowest case value and the maximum value is recorded for all soil types in the TMD+RI control system case which is larger than the F case by 4.5 times, while for all other vibration control system cases the values are recorded larger than the F case by nearly 2 times.

Fig. 5(e) represents the top displacements for all models subjected to the Loma Prieta earthquake; the RI case records the lowest top displacements in all model cases (and is less than the F case by 1.3 times); the top displacement in the TMD+RI case nearly equal to the F case, and the values of the top displacements are close for all model cases. The SSI+RI case records the smallest top displacement (less than the fixed case by nearly 1.4 times).

Fig. 6 shows the base shear force of each model with different soil types and different base conditions. Fig. 6(a) represents the base shear force with different vibration control systems for soft, medium and hard soils for the El Centro earthquake; the fixed base (F) case is used as a reference case for each model, which records almost the larger value of base shear than all models; for hard soil, the base shear increases in all models with different vibration control systems and the TMD+RI case records the smallest value of base shear, less than the F case by nearly 70 times.

Fig. 6(b) represents the base shear force of each model subjected to Northridge earthquake, the TMD+RI case records the smallest values of base shear (less than F case by about 42 times) and the SSI+RI case also is less than the F case by nearly 20 times; the soft soil for all cases records the smallest values in all vibration control cases.

Fig. 6(c) shows the base shear force of the models subjected to the Kobe earthquake; the smaller values occur at the TMD+RI and RI cases, and the maximum values occur at the F case for all soil types (the ratio between the maximum and minimum values nearly equals to 43).

Fig. 6(d) represents the base shear force for model subjected to the Chi-Chi earthquake; the F case records the maximum values; the minimum values are recorded for all soil types at the TMD+RI and RI control systems cases, smaller than the F case by nearly 14.5 times; the main feature is the smallest values of the base shear with respect to the El Centro and Northridge earthquakes cases.

Fig. 6(e) represents the base shear force for all models subjected to the Loma Prieta earthquake, the TMD+RI and RI cases record the smallest base shear in all model cases (less than the F case by nearly 65 times), while the maximum base shear values appear in the hard soil models.

Fig. 7 shows the base moment of each model with different soil types and different vibration control systems.

Fig. 7(a) represents the base moment with different vibration control systems for soft, medium and hard soils for the El Centro earthquake; the F case is a reference case in each model, which records the larger value of base moment than all models except the FB; for hard soil, the base moment increases in all models with different vibration control systems TMD+RI case records the smallest value of the base moment, less than the F case by 19 times.

Fig. 7(b) represents the base bending moment of each model subjected to the Northridge earthquake, the TMD+RI records the smallest values of base shear (less than the F case by nearly 75 times) and the RI case also less than the F case by nearly 14 times, the soft soil for all cases record the smallest values in all cases.

Fig. 7(c) shows the base moment of the models subjected to the Kobe earthquake the smallest values occur at the TMD+RI and RI cases, and the maximum values occur at the F case for all types of soils (the ratio between the maximum and minimum values equals to 73).

Fig. 7(d) represents the base moment for model subjected to the Chi-Chi earthquake the F case is the maximum values and the minimum values are recorded for all soil types at the TMD+RI and RI vibration control systems cases is smaller than the F case by 13.7 times, but the main feature is the smallest values of base moment with respect to the El Centro and Northridge earthquakes cases.

Fig. 7(e) represents the base moment for all models subjected to the Loma Prieta earthquake, the TMD+RI and RI cases record the lowest base moment in all model cases (less than the F case by 56 times), the maximum base moment values appear in the hard soil models.

6. Conclusions

Nine 3D model cases of a RC high-rise building (HRB) with different passive vibration control systems to enhance its seismic performance considering SSI for three soil types (soft, medium and hard soil), were seismically studied under five different famous earthquakes (El Centro, Northridge, Kobe, Chi-Chi, and Loma Prieta); from the comparison of each case (F, SSI, SSI+TMDs, SSI+RI, SSI+FB, SSI+T/C, SSI+TMDs+RI, SSI+TMDs+FB, SSI+TMDs+T/C) the following conclusions can be drawn:

- The fixed base building seismic response is not a realistic case behavior of the high-rise building.
- The soil plays an important role in the seismic response of the superstructure.
- High-rise buildings founded on soft soil respond with high top displacements and low base forces.
- For different earthquakes, there are different suitable types of base isolation.
- The rubber base isolation (RI) is suitable for all earthquake frequencies and reduces the base forces by significant values.
- The combination of the rubber base isolation (RI) and TMDs increases the performance of the vibration control system used in the RC HRB and increases both the chances for building surviving under different earthquakes and the factor of safety of the structure.

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