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Performance of Dynamic Energy Absorbers in Multi-storey Structures with Incorporating Soil Structure Interaction

Ameer Jabar Abdulkareem[1], Hussein Kareem Sultan[1,2*], Abbas Abdulhussein Abd Noor[1]

[1] College of Engineering, Al-Muthanna University, Sammawah 00964, Iraq
[2] College of Engineering, Al-Ayen University, Thi-Qar, Nasiriyah 64001, Iraq

Corresponding Author Email: hussein.ksz@mu.edu.iq

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ABSTRACT

In our communities, the crucial role played by basic facilities such as hospitals, communication systems, roads, and bridges is highlighted. They are considered essential, particularly in the aftermath of natural disasters when services need to be sustained. The implementation of control systems during structural design allows structures to handle dynamic responses during turbulent events. Attention is typically given to the structural configuration during the design of a structural control system. The response of a structure during earthquakes can be influenced by the interaction with the underlying soil. In this study, the effects of dynamic response are assessed through numerical simulations, considering soil-structure interaction on a 3D moment-resisting steel frame with a viscous fluid-type energy dissipation system. Analysis includes seven seismic records selected based on frequency and content source, corresponding to building code design response spectra for earthquake-prone areas. The soil profiles used in the analysis align with seismic hazard areas. A 12-story building with a viscous damper underwent nonlinear time history analysis to study the effects of implementing or ignoring soil-structure interaction. When soil-structure interaction is taken into account, the results show a significant increase in dynamic response that affects story drift, displacement, and top floor acceleration.

1. INTRODUCTION

The moderate to high-intensity seismic events can cause catastrophic outcomes in buildings and other structures due to the level of structural harm. This type of damage can affect both the structural and non-structural components and under certain instances, can even cause injuries. Thus, the structures such as buildings and bridges need to be designed and constructed to resist seismic events, which will ultimately reduce the risk of damage and injury [1]. In the last several years, researchers try to discover some effective ways of controlling seismic loads to ensure people's lives and minimize the earthquake damage level [2, 3]. Seismic design is aimed at developing structures that are earthquake-resistant as well as durable, reliable, and above all, minimize the risk of death or injury. Special techniques and technologies, which include the ability to control the response of structures during earthquakes, as well as a decrease in the risk of damage and failure are a must [4-8]. Historically, energy dissipation was conceived through the deformation and damage of structure elements [9, 10]. Several methods and approaches are used in the construction of structures like bridges, buildings, and dams, which are aimed at dissipating energy and conserving the structural integrity of the structures. To illustrate this, engineers use displacement-based design while including enough ductility for the energy dissipation [11-16]. The other method is employing control systems such as seismic isolation that are normally used in the critical facilities to limit seismic response and enable the facilities to stay in operation during and after the earthquake [17-19].

Not long ago, conventional structural design is determined to be inadequate for purposes of preventing buildings and other structures from collapsing during earthquakes. As a consequence, it is necessary to employ solution which allow for fast reoccupation of buildings and minimise the need for repairs and disturbance of function even after strong to large earthquakes [20]. An efficient solution to the above is using control systems with the structures, which reduces the displacements and seismic forces. Utilization of control systems as an alternative to designing new structures or retrofitting existing ones will now be classified as standard practice in building codes, i.e., ASCE 7-16 and Eurocode [21]. This is especially important because some buildings and other structures may not always be fully secured using the regular structural designs after the occurrence of at least moderate to strong earthquakes. However, it is the time for alternatives to be adopted that allow for immediate occupancy, reduce the extent of repairs and minimization of the destroyed functions [22]. Previous research has demonstrated that implementing control systems can decrease the overall expense of a structure during its lifetime, in comparison to traditional design methods. This is due to the fact that control systems decrease damage, ensure post-earthquake functionality, and lower the requirement for repairs [23].

Control systems are widely adopted in many buildings worldwide to enhance their dynamic performance during earthquakes. Some notable examples include the Churchill Hotel in San Diego, CA, USA, the St. Francis Towers in Mandaluyong, Philippines, the Opera House in San Francisco, CA, USA, the King County Court House in Seattle, Washington, USA, and 3Com in Foster City, CA, USA [24, 25]. Though this, traditional structure engineering is usually not given attention to the influence of soil structure interactions. While the dynamic behavior of structures is studied by structural mechanics, the application of equations of motion and discrete elements makes it possible to correctly calculate displacements and stresses [26]. In the application of soil mechanical analysis, the soils' effect is also taken into account, hence the displacement and stress of the underground structure are different [27]. The mentioned interaction between structural system and soil is called as "Soil-Structure Interaction" (SSI). As it is not easy to give the comprehensive concept of SSI, it describes the interactions between the ground and the construction which is more rigid [28].

For example, when doing dynamic SSI analysis, amplification of seismic waves in the ground and the dynamic interaction between different soil layers should be consider as a factor. Additionally, dynamic SSI analysis also requires accounting for the dynamic behavior of the structure in response to the soil motion. This includes analyzing the transfer of forces between the structure and soil, as well as the effect of soil deformation on the structural response [29].

Other studies have demonstrated that the dynamic response of structures can be significantly impacted by dynamic SSI considerations. This impact is almost seen in three aspects: i) the increasing in damping within the system due to the transference of the structure's energy into the ground; ii) the change in the dynamic characteristics of the soil-structure system such as frequencies and modes of vibration; and iii) the soil moving properties influence the analysis [30]. Recent studies have shown that dynamic SSI effects have a significant impact on structural response in terms of base shear, performance levels and drift when supported by soft ground [31-33].

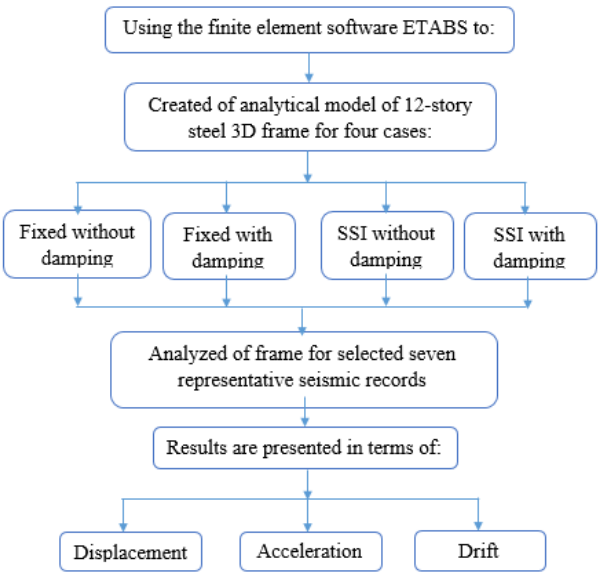

Figure 1. Overview of the flowchart of the research process

In order to evaluate the impact of dynamic SSI on a steel frame with a viscous damper device, a 12-story steel 3D frame was analyzed with and without the control system installed. Seven representative seismic records were selected based on representative features such as frequency content, and these records were matched with the corresponding response spectra of the high seismic hazard zone as defined by the design criteria. The matched records were then filtered through the modeled soil profile to obtain surface records. Using the same profile data, the foundation stiffness was calculated at ground level and a more accurate structural and soil analysis was performed in the transition zone between both systems. The analysis considered the ground stiffness and earthquakes acting at the surface. The structure's analytical model was created using the finite element software ETABS, with the objective of analyzing its seismic performance [34]. The analysis comprised four cases: fixed base and flexible base with and without viscous dampers. The results were presented in terms of storey displacement, maximum storey displacement, inter-story drift, maximum inter-story drift, top storey acceleration, and maximum storey acceleration with and without viscous dampers. Figure 1 shows the flowchart of the research processes.

2. SEISMIC MOTIONS

2.1 Selected seismic motions

Seismic acceleration records were carefully selected from the Pacific Earthquake Research Center (PEER) for the NGA-West2 database according to the guideline [35]. Criteria for selecting ground motion records from the PEER database included an average of at least 3 different records or 7 records. These chosen records were required to span a wide range of frequencies, represent events of similar magnitude and distance to the epicenter, and have a similar rupture mechanism to those found at the case study. Additionally, each record had to be unique and reflect the seismic activity expected in that specific area. The criteria for selecting ground motion records from the PEER database are illustrated in Table 1.

Table 1. Criteria to select ground motion records form PEER database [34]

Summary of PEER Ground Motion Database Search Criteria				
	Magnitude	**Rup (km)**	**Vs30 (m/sec)**	**Scale Factor**
Min	6	10	360	0.1
Max	8	30	760	10

Table 2. Seven selected seismic motion records [35]

Summary of Data of Selected Records					
Record Sequence Number	**Earthquake Name**	**Year**	**Magnitude**	**Rup (km)**	**Vs30 (m/sec)**
28	Parkfield	1966	6.19	17.64	408.93
57	San Fernando	1971	6.61	22.63	450.28
164	Imperial Valley-06	1979	6.53	15.19	471.53
286	Irpinia_ Italy-01	1980	6.9	21.26	496.46
302	Irpinia_ Italy-02	1980	6.2	22.69	574.88
524	N. Palm Springs	1986	6.06	26.88	379.32

After surveying with PEER according to the criteria, Table 2 shows seven selected ground motion records and a summary of some of their most representative characteristics. Figure 1 provides a summary of research processes used to achieve the objectives of this study.

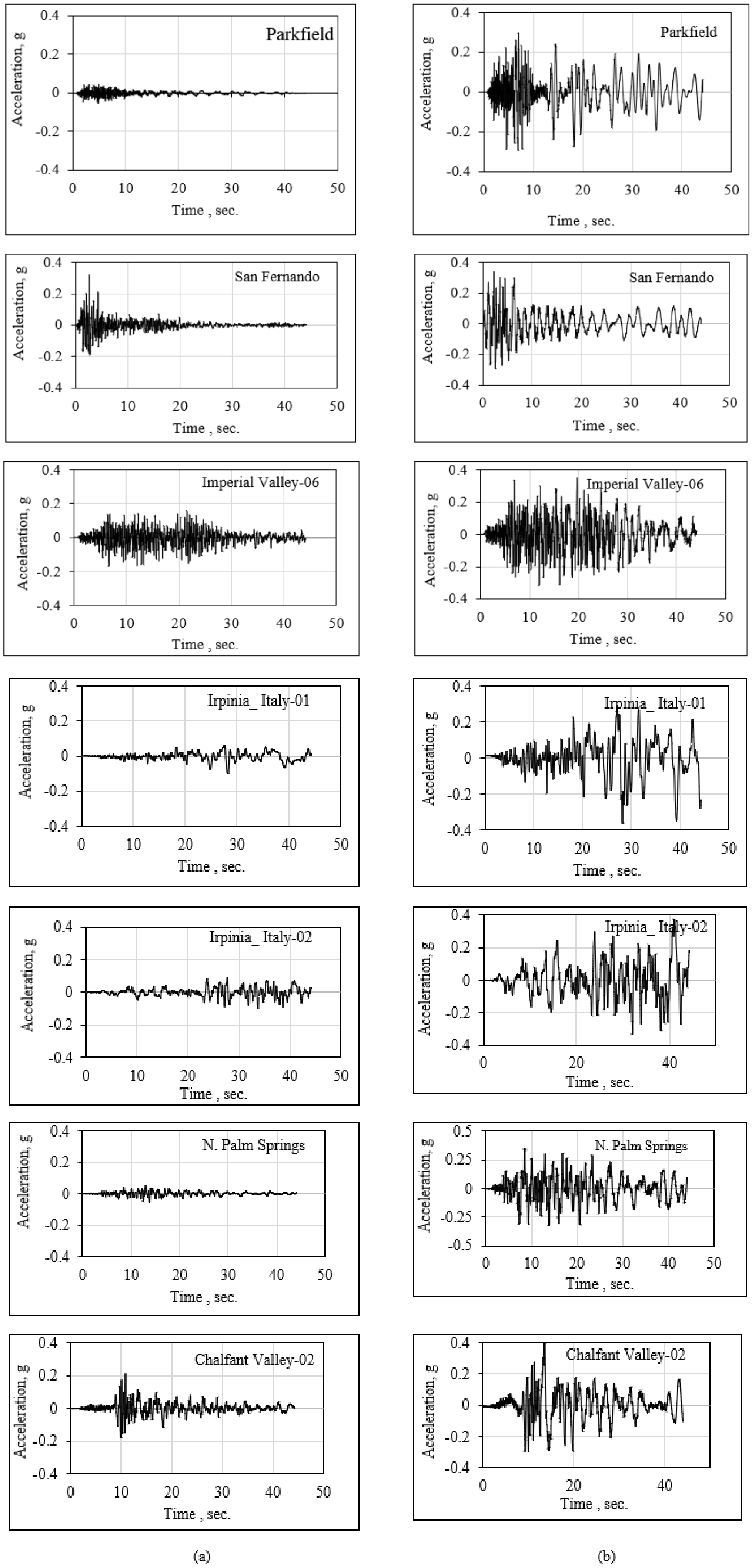

Figure 2. (a) Real acceleration time series; (b) Modified acceleration time series

2.2 Target and matched response spectrum

The target response spectrum of the design was defined according to ASCE 7-16 and the parameters are soil type D, s_s 1.22, s_1 0.56, SDS 0.8231, SD1 0.56, with an importance coefficient 1.25 [36].

To ensure the compatibility of acceleration records with the case study location, they were matched according to the spectrum of interest, even though they were chosen from a different location. The matching process involved preserving the non-stationary properties of the reference ground motion records while modifying the existing acceleration records. Time-domain matching techniques were used to achieve this, where a tapered cosine wavelet was implemented to tune the acceleration recordings. This procedure resulted in drift-free recordings in the corresponding displacements and velocities. The tuning process guaranteed stability, efficiency, and speed for numerically solving spectral matching [37, 38]. SeismoMatch by seismoSoft [39] well approved tool which adopted to do spectral matching to modify the initial series to get converges spectral matching. After doing the spectral matching, Figures 2-4 show comparison between original and modified series, real and matched response spectrum, and real and matched Peak ground acceleration PGA respectively.

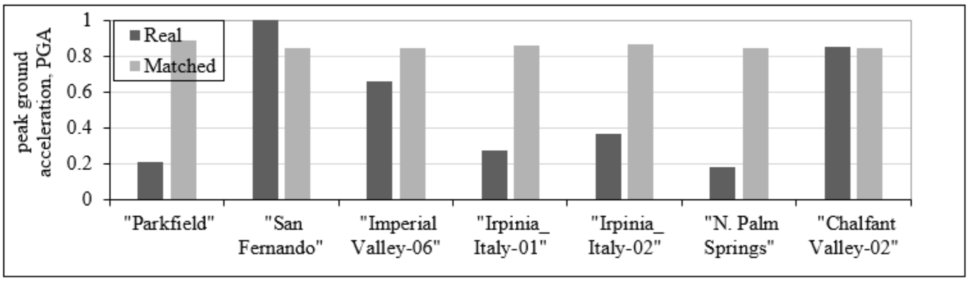

Figure 3. Comparison between peak ground acceleration for real and matched time series

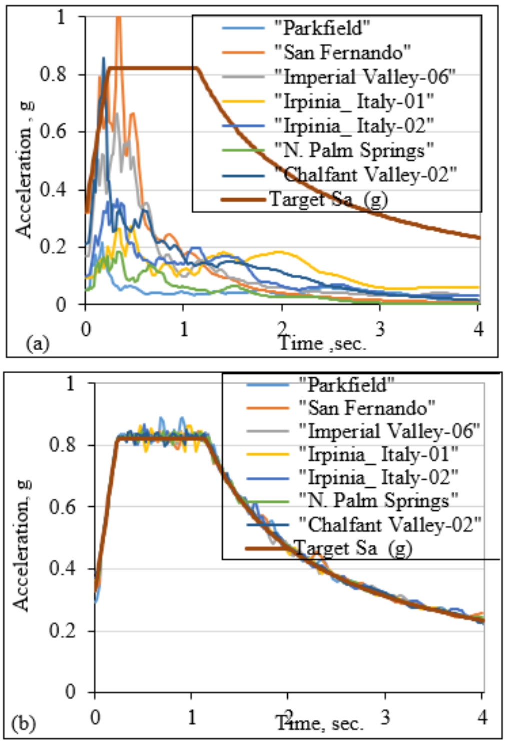

Figure 4. Response spectrum for a) real time series, b) modified time series

2.3 Soil profile

For rigid structural systems, in general, foundation deformation can represent an important component of system flexibility, and ignoring it can lead to inadequate characterization of properties as fundamental mode frequency and damping ratio [40]. Foundation damping results from the relative motion of the foundation and supporting soil, causing displacement and rotation of the structure with respect to the free field. Differences between the ground input motion and the free-field motion result in energy dissipation through radiation damping and hysteretic soil damping, which affect the overall system damping [41]. The site effect is caused by the amplification of seismic waves as they travel from rocks to the surface. This amplification is the result of seismic waves passing through layers different from the ground profile. The most common physical properties used to characterize these soil layers include thickness (H), shear wave velocity (Vs), specific gravity (γ), material friction angle (Φ), elastic modulus (E), and soil shear modulus (G). Figure 4 presents a summary of the soil layers utilized in this study, highlighting their representative characteristics.

The implementation of soil effects can be done using soil profiles modeled in ETABS to find solutions to ground response problems in the frequency domain. Its input acceleration record is represented as the sum of a series of sine waves of different amplitudes, frequencies and the phase angle.

2.4 Soil structure interaction

Using the soil profile data shown in Figure 5, the foundation stiffness is calculated at the surface level and included in the flexible base model. This calculation is performed using the following formula from the FEMA recommendations [42].

$$K_{x,sur} \& = \frac{GB}{2-v}\left[3.4\left(\frac{L}{B}\right)^{0.65}+1.2\right] \quad (1)$$

$$K_{z,sur} \& = \frac{GB}{1-v}\left[1.55\left(\frac{L}{B}\right)^{0.75}+0.8\right] \quad (2)$$

$$K_{yy,sur} \& = \frac{GB^3}{2-v}\left[0.47\left(\frac{L}{B}\right)^{2.4}+0.034\right] \quad (3)$$

where, $K_{x,sur}$, $K_{z,sur}$, and $K_{yy,sur}$ are the stiffnesses for the translation along the X-axis, Z-axis, and the rocking effect about the Y-axis, respectively, G is the shear modulus, v is the Poisson ratio, B is the rectangular foundation width, and L is the rectangular foundation length.

For the flexible base model, a foundation beam 1 meters wide and discretized in segments of 1.5 meters long, is implemented. Using Eqs. (1) through (3), the following stiff ness values are obtained: $K_{x,sur}$ = 155890 kN/m, $K_{z,sur}$ = 200376 kN/m, and $K_{yy,sur}$ = 35408 kN^{-m}.

Soil Layer Name	Evaluation of Top Layer (m)	Unit Weight (kN/m³)	Shear Modulus (kPa)	Poisson Ratio	Cohesion (kPa)	Friction Angle (d)
Clay	0	18.65	46280	0.3	13	25
Clay with lens	-8	20	111790	0.32	15	34
Hard clay	-22	21.8	659500	0.28	20	31
Peat clay	-33	20	1198520	0.35	21	18

Figure 5. Soil profile data for different layers

3. NUMERICAL MODEL

A 12-story frame is modeled in ETABS considering the geometry shown in Figure 6, both with and without viscous dampers. The loads applied on the model is: Dead load is 6 kN/m^2 and the live load is 4 kN/m^2.

A viscous damper was incorporated into the model using a link element with a nonlinear exponential damper [43]. Non-linear properties were introduced following the methodology considering moderate damage levels for moderate-height buildings [44]. First, calculate the response reduction factor B as follows:

$$B = \frac{D_{max}}{D_{obj}} \tag{4}$$

where, D_{max} is the maximum drift obtained in the structural analysis and D_{obj} is the target drift. In this case, the FEMA moderate damage level of 0.0051. A target of 35% effective damping of the structure is set. This means that the viscous damper should contribute 30% of the total structural damping. The damping coefficient C calculated for each floor using the following formula:

$$C = \zeta \frac{k_i}{\mu_i} * \frac{T}{\pi} * \frac{1}{cos^2_{\theta_j}} \tag{5}$$

where, ζ is the damping ratio, k_i is the stiffness of the ith floor, μ_i is the number of viscous dampers per floor, T is the fundamental period of the structure, and θ_j is the tilt angle of the viscous dampers. The following nonlinear properties of the viscous damper have been determined: Damping coefficient C = 2553.59 kN-seg/m, velocity exponent α = 0.5, brace stiffness K = 202630.16 kN/m, physical properties of HEB200 taken from the axial stiffness equation of the brace element steel section. Maximum damping force can be determined using the following formula:

$$F = C(V)^{\alpha} \tag{6}$$

$$V = \frac{2\pi}{T} 0.02 \times H_{\text{story}} \times \text{Cos}\ (\theta) \tag{7}$$

where, F is the damping force, V is the velocity, T is the fundamental period, H_{story} is the analyzed story height, and θ is the damper inclination angle.

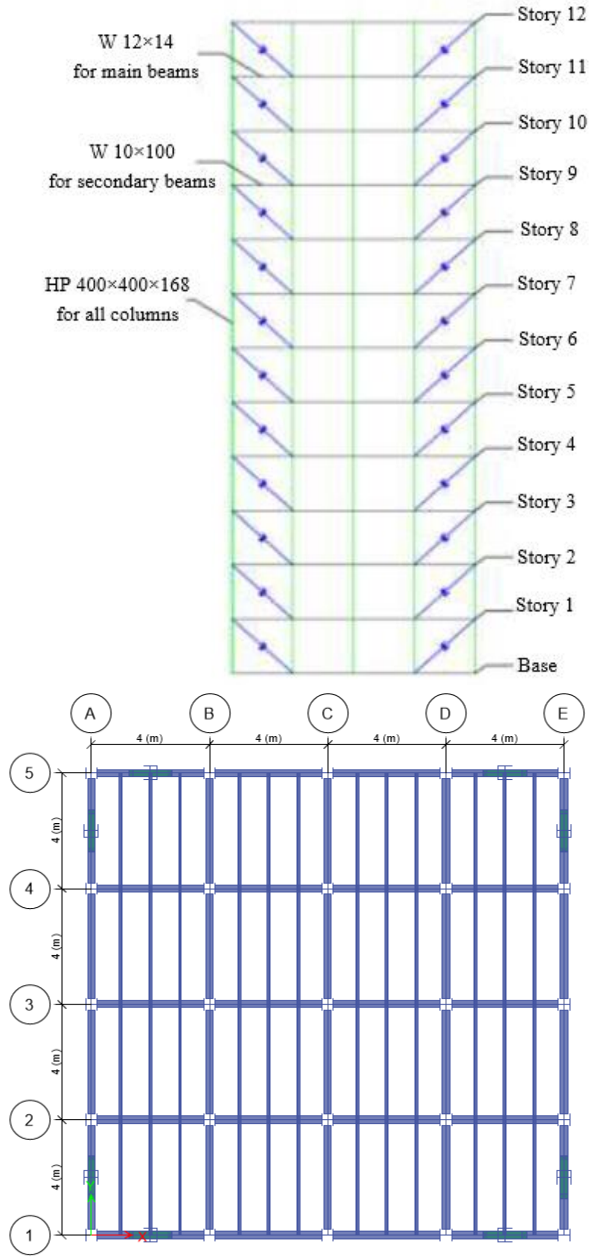

Figure 6. A 12-story steel frame

4. RESULTS

4.1 Displacement

Figure 7 shows lateral displacement during nonlinear analysis using 7 time series for 4 cases: fixed without damper, fixed with dampers, SI without dampers, and SI with dampers respectively. After taking the average maximum lateral displacement of 7 analysis runs, Figure 8 shows the change in lateral displacement when including the effect of soil-structure interaction with the structure. The results showed that the inclusion of the soil structure interaction instead of the fixed base without the use of dampers increased the lateral displacement by 17.98%, whereas by including the dampers the increase was 40.69%.

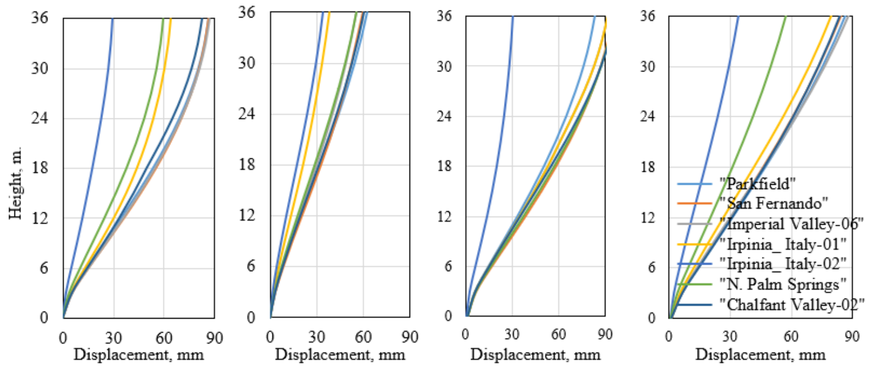

Figure 7. Lateral displacement during nonlinear analysis using 7 time series for 4 cases

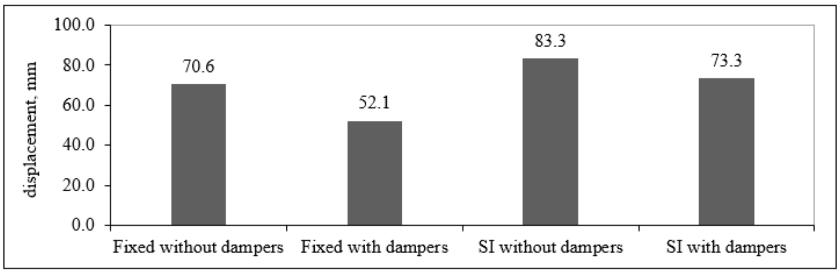

Figure 8. The change in lateral displacement when including the effect of soil-structure interaction with the structure

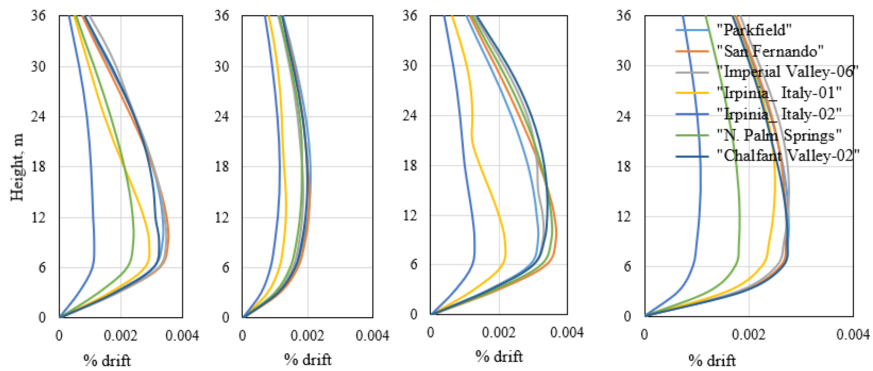

Figure 9. Lateral inter-story drift during nonlinear analysis using 7 time series for 4 cases

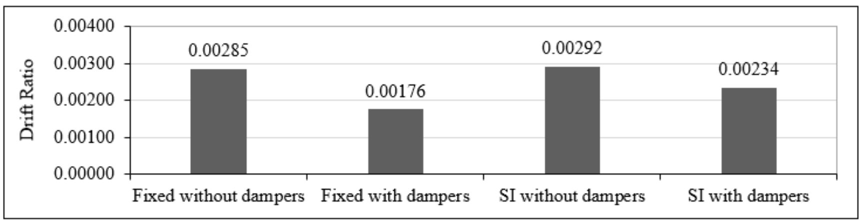

Figure 10. The change in inter-story drift when including the effect of soil-structure interaction with the structure

4.2 Drift

With the same methodology that was adopted for displacement, Figure 9 shows the inter story drift for each floor during the nonlinear analysis of the structure. Figure 10 shows that the amount of inter storey drift values as an average of the seven series and for four cases. The results show the significant contribution of dampers in reducing the lateral inter-story drift, as it was reduced by 38.24% for the fixed base, while the reduction percentage reached 19.86% when including the effect of soil interaction. On the other hand, the soil interaction increased the lateral inter-story drift by 2.45% and 32.95% without and with the use of dampers, respectively.

4.3 Acceleration

An important determinant that can be considered for the role of including soil interaction in a structure is the top floor acceleration of the structure. Figure 11 shows the acceleration values at the highest peak of the structure obtained from the analysis using the first series of earthquakes employed in this study. After the nonlinear analysis of all the study cases and all the seven series, Table 3 shows the highest value of acceleration occurred at the highest floor of the structure.

Figure 12 shows the rate of acceleration for the seven cases of nonlinear analysis, it is clear that the effect of including soil interaction with the structure, where it is noted that the soil interaction worked to increase the amount of acceleration and for both cases without and with the use of dampers. Where the rate of increase was 6.43% without dampers and 1.37% with dampers.

Table 3. The highest value of acceleration occurred at the highest floor of the structure

Earthquake Name	Fixed Without Dampers	Fixed with Dampers	SI Without Dampers	SI with Dampers
Parkfield	1948	2096	1718	2091
San Fernando	1990	2659	1889	2409
Imperial Valley-06	2154	2312	2427	2095
Irpinia_ Italy-01	1374	1374	2323	2620
Irpinia_ Italy-02	1512	1328	1542	1287
N. Palm Springs	1628	2563	1484	1838
Chalfant Valley-02	2010	1899	2046	2090

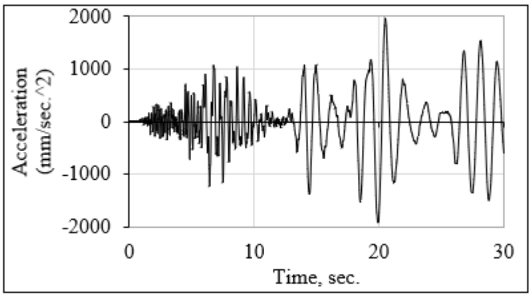

Figure 11. Acceleration values at the highest peak of the structure obtained from the analysis using the first series of earthquakes

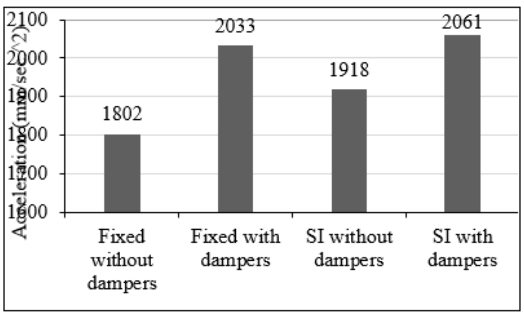

Figure 12. Acceleration for the seven cases of nonlinear analysis

5. CONCLUSIONS

The SSI effect of a steel 3D frame structure implementing a viscous damper has been investigated. The following conclusions for 12-story 3D framed building that were used as a case study:

1) It is very important to consider the impact of SSI when performing a global analysis of any kind of structure, even more so if the structure falls into a category of high importance to the community. This is because there is a notable difference in the results when considering the effects of SSI in the analysis. In this case study, the displacement increases for selected properties of the soil supporting the structure.
2) The results of this study show that using a damper has an inverse effect on the acceleration and displacement response. The maximum displacement decreased by about 26% on average, while the acceleration response shows a small noticeable increase of less than 13%.
3) Despite the use of dampers and the inclusion of soil-structure interaction, the acceleration values vary between the upward and downward motions. This variation can be attributed to the nature and frequency content of the ground motion, as well as the response characteristics of the model to the ground motion.
4) The inclusion of soil-structure interaction in the building leads to an increase in relative lateral displacement. This is due to the additional flexibility and reduction in stiffness resulting from the interaction with the soil.
5) Comparing the fixed-base and flexible-base models, the average floor-to-floor drift increased by about 32.95% when considering the SSI.
6) The use of viscous dampers allows for dynamic control during seismic events, potentially reducing the amount and level of damage that both structural and nonstructural elements can withstand. This is a result of the additional capacity to dissipate the energy provided by the control system.
7) Including the effect of soil structure interaction in the modeling representation is an absolute necessity because it reflects the reality of the structure's behavior, and the designers of structure must also have the decision to choose the materials used in construction based on the SSI response effect in terms of lateral displacement and the change in the natural frequency of the structure.

6. SUGGESTION FOR FUTURE RESEARCHES

- Investigating the influence of different types of dynamic energy absorbers on the overall seismic performance of multi-storey structures considering varying soil conditions.
- Exploring innovative design approaches for dynamic energy absorbers that optimize their effectiveness in mitigating seismic forces while accounting for soil-structure interaction effects.

Analyzing the long-term durability and maintenance requirements of dynamic energy absorbers in multi-storey structures to ensure their sustained effectiveness over time, especially in the presence of soil-structure interaction.

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