

## Influence of Soil-Structure Interaction on the Seismic Response of the Structure on Mat Foundation

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### Abstract

The disasters that occur due to seismic activities not only affect the structure but also soil beneath it. Neglecting the effect of Soil-Structure Interaction (SSI) in design leads to unsafe design. This paper focuses on the behavior of the structure under El-Centro earthquake considering soil-structure interaction (SSI). Seismic response of G+10 storied building in various seismic zones of India is obtained using Time-history method. The direct approach i.e., finite element analysis is used to analyze effect of SSI. The model with mat foundation and soil is compared with fixed base model in SAP 2000 v.20. The behavior of the structure is studied by parameters like inter-storey drift ratio, lateral storey displacements, response spectrum curves for spectral acceleration and spectral velocity for various damping and time period of different seismic zones of India. The parameter like inter-storey drift ratio can determine safety of the structures. From inter-storey drift ratios, the buildings in zone IV and zone V were found to be unsafe. The lateral storey drift was found to increase by 47-87% considering SSI in zone II and 60-95% considering SSI in Zone II, IV and V. It also increased with increase in storey number. The spectral acceleration, spectral velocity and time period increased by considering effects of SSI in each seismic zone. The spectral acceleration and spectral velocity found to decrease with increase in damping and increase in seismic zones from zone II to V. Further to reduce the effect of SSI the structures can be equipped with base isolators and various types of dampers. It is clear that from zone III to V, SSI should be included for structures on soft soil and for retrofitting of the structure. Some experimental studies can further be performed and the numerical modelling can include parameters like P-delta, angle of incidence of ground motions and various structural systems can be implemented in this study.

**Keywords:** Soil-Structure Interaction; Seismic Zone; Inter-storey Drift Ratio; Response Spectrum Curves; Time Period; SAP 2000.

### 1. Introduction

After the San Fernando earthquake (1971), effects of soil-structure interaction (SSI) are taken into account for research. The damages that occurred during earthquake led to a need to analyze the nature of the soil under earthquake action. The motion of structure affects the behavior of soil and vice-versa is known as soil-structure interaction (SSI). The seismic response of the soil, foundation and structure subjected to a free-field ground motion assessed by SSI analysis. The structures like buildings, bridges, dams, nuclear power plants and so on are drastically affected by the effects of SSI. Saeed and et al. studied abutment bridges which includes effects of non-linearity in soil and structure with far-field soil response [1]. Fernanda et al. carried out the study including SSI effects for nuclear power plant [2].

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The SSI analysis can be done by direct and substructure approaches. Jabini et al. compared the both substructure and direct approaches of SSI on two midrise steel moment resisting frames [3]. The winkler method is widely used in substructure approach. Hossein et al. evaluated the seismic performance and vulnerability of the structure by using non-linear winkler approach [4]. As physical modelling of soil is challenging, Al-Isawi et al. used Abaqus software to analyze soil behavior with damping, kinematic and inertial effects [5]. Bao et al. performed experimental, analytical and numerical analysis for comparison of Pasternak model and Winkler SSI model for structures partially embedded in soils and predicted the pre-dominant natural frequency of the structures [6]. Jingbo et al. proposed a novel approach of substructure method to input earthquake waves in 3D model with SSI [7]. The numerical methods of direct approach like finite element method (FEM), spectral element method (SEM) and boundary element method (BEM) is currently used methods for SSI analysis. Hessam et al. and Gouasmia et al. showed the importance of considering nonlinear SSI effects in finite element (FE) approach of SSI [8, 9]. Omar et al. showed FE method for better response than experimental methods and the numerical methods are best suitable for dynamic problems [10]. Rayhani and Naggar performed both physical modelling and numerical modelling for layered soil [11]. SEM was one of the powerful numerical techniques used for dynamic tasks. Boudaa and et al. used SEM to study vibration of beams on non-classical support [12]. Monsalve et al. estimated earthquake-induced direct losses using the performance assessment calculation tool in tall buildings and recommends including SSI effects to avoid underestimation [13].

Suleyman et al. proposed a model for SSI including interface of soil, footing and structure [14]. Zhidong et al. used response spectrum to study the effect of soil on shallow foundation considering coupling of both horizontal and rocking component of foundation motion [15]. Aidin et al. found that the structures undergo less inelastic deformations when soil undergoes less inelastic deformations and for more ductile structures the soil undergo fewer plastic deformations [16]. Pallavi et al. the shape of the structure also governs seismic response of the structure considering SSI [17]. Saeid et al. studied collapse performance of moment frames with SSI effect using FEMA-P695 [18]. Muberra et al. found out that strength reduction factor in Turkish Seismic Design Code was reduced by incorporating SSI effects in in time domain [19].

Many researchers studied effect of soil on pile foundations. Aslan prepared the experimental model of soil-pile-structure interaction (SPSI) on soft soil [20]. Andreas et al. presented an analytical solution for SDOF oscillators on footings and piles and found out that structure supported on pile gives double radiation damping that on spread footing [21]. The analytical method was used to obtain solutions for stress, strain and displacement in end-bearing piles was validated against in situ pile test by Dunja et al. [22]. Behzad et al. concluded that the presence of pile and its type changes the dynamic behaviour of superstructure and it significantly affects the damage level in both structural and non-structural components [23]. Hytham et al. also studied the effect of SSI on steel frame structure with and without infill wall and further extended this to study the effect of pounding [24]. Basha et al. found out the best position of the belt truss system and out trigger including SSI [25]. Nishant et al. investigated the importance of including SSI in design codes [26]. The recent study about SSI focuses on the structures attached with base isolators, tuned mass dampers and other equipment to reduce lateral forces' effect. Dao assessed SSI effects on the base-isolated building with friction bearings [27]. Miari et al. conducted a parametric study of base-isolated building on neighboring structure [28]. Researchers also study the structure-soil-structure interaction (SSSI). Lu et al. studied the structures built on rigid, circular surface foundation on half-space, homogenous and elastic soil and presented a new approach to developing simple models for structure-soil-structure interaction SSSI [29].

The main aim of this paper is to analyse the response of the structure considering SSI effects. The most of the previous research are based on winkler method of analysis of SSI. But this method has many limitations like the springs are independent as there is no interaction between them and the spring constant depends on geometry of beam, stiffness of beam, type and nature of soil. So, in this paper finite element (FE) approach is used to investigate SSI effects on the G+10 building with mat foundation in various different seismic zones of India. The soft soil is considered for this study as the study shows that the SSI effects are vulnerable on soft soil. The time history data of El-Centro earthquake was used for realistic effect. The seismic parameters like inter-storey drift, lateral storey displacement, time period and response spectra curves in terms of spectral acceleration and spectral velocities for various damping ratio are considered. The time period and damping are the two major phenomenon that affects the SSI. The G+10 RC frame with and without SSI are modelled to compare the SSI effects in each seismic zone II, III, IV and V. Results indicate that there is need to implement SSI for realistic design. Further experimental study can be performed. Also, the numerical modelling can include parameters like P-delta, angle of incidence of ground motions and various structural systems.

## 2. Research Methodology

The Soil structure interaction is interaction of the ground, substructure and structure due to seismic activity. The structures on soft soil are generally affected due to SSI. This study is carried out using finite element analysis in SAP 2000 v.20. Generally, in India designers do not consider the SSI effect in design. This study will help designers to include SSI in the design as well as some key parameters like interstorey drift, lateral storey displacements, response

spectra for various damping and time period are described in the results. As the safety of the structures and behavior of the structure during El-Centro seismic input can be interpreted from these parameters. The flowchart in Figure 1 shows the main steps that are carried out during analysis of the structure.

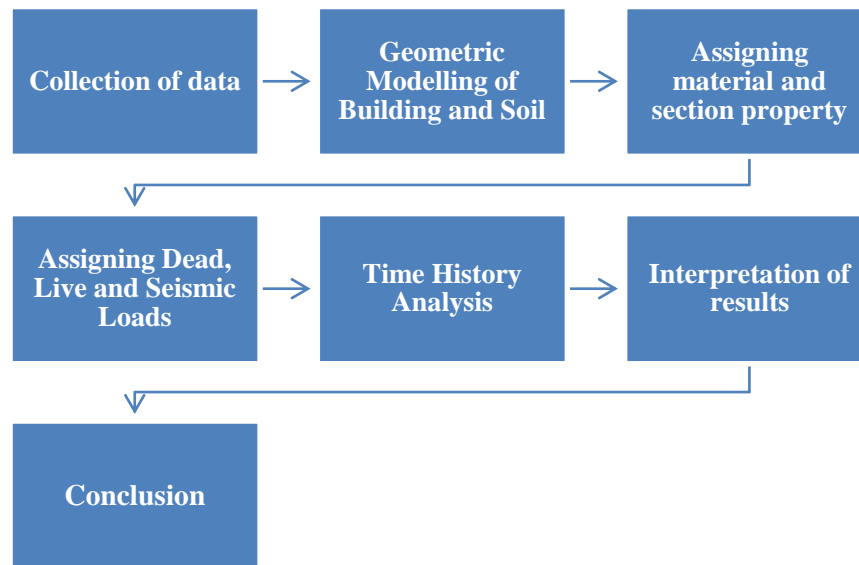


Figure 1. Flowchart of the research methodology

## 2.1. Soil Data and Modelling

The soil considered in this study was soft soil with the properties as given in Table 1. The depth of the soil considered was 10m below ground level. The modelling of the soil in SAP 2000 v.20 software was done using finite element method. The mat foundation of M25 grade of concrete with depth of 1m was considered. The infinite soil is converted into finite by considering the boundary limits to the soil. The corners of soil model are restrained in both X and Y directions whereas the interior part of the soil in X-Z plane is restrained in Y plane and Y-Z plane is restrained in Z plane. The bottom most part of the soil is restrained in all three directions.

Table 1. Property of soft soil [30]

Unit Weight ( $\gamma$ ) (kN/m <sup>3</sup> )	19
Shear Modulus (G) (kN/m <sup>2</sup> )	20833.33
Modulus of Elasticity (E) (kN/m <sup>2</sup> )	$5 \times 10^4$
Poisson's ratio ( $\mu$ )	0.2
Friction angle	20°
Dilatancy Angle	0°

## 2.2. Features of Selected Frames and Foundation

In this study, G+10 RC frames of in seismic zone II, III, IV and V of India are considered. For incorporation of SSI effects models are analyzed with mat foundation and soft soil. Model-1 consists of building with fixed base i.e. without SSI and model-2 consists of building with mat foundation on soft soil. The frames are considered as moment resisting frame with 3 bays. The Figures 2.a and 2.b represents the models developed in the SAP 2000 v.20 software with and without SSI. The storey height and bay width are 3m for all frames. The design of the building IS-875 Part I (1987), Part II (1987) and Part III (2015), IS-456:2000, IS-1893:2016 (Part 1) are considered for dead loads, live loads, wind loads, design of plain and reinforced concrete structures and design of structures for seismic loads. For concrete, M25 grade and for steel, Fe500 grade is used. The hysteresis curve for concrete is taken as takeda and for steel, it is taken as kinematic. The steel being ductile material and kinematic model dissipates large amount of energy so it indicated an appropriate model for steel. The takeda model is same as the kinematic model and appropriate for concrete. Figures 3 and 4 shows takeda and kinematic hysteresis models for increasing cyclic load [31]. Moment of inertia for beam and column is modified in accordance with IS-1893:2015. Moment of inertia is taken as 0.70 for beams and 0.35 for columns. For seismic design the zone factor considered for building in zone II, III, IV and V is taken as 0.10, 0.16, 0.24 and 0.36 respectively. The importance factor (I) for all the building is considered as 1 with response reduction factor (R) as 3. For live load 50% of reduction in seismic load is considered according to IS-1893:2016 (Part-1)

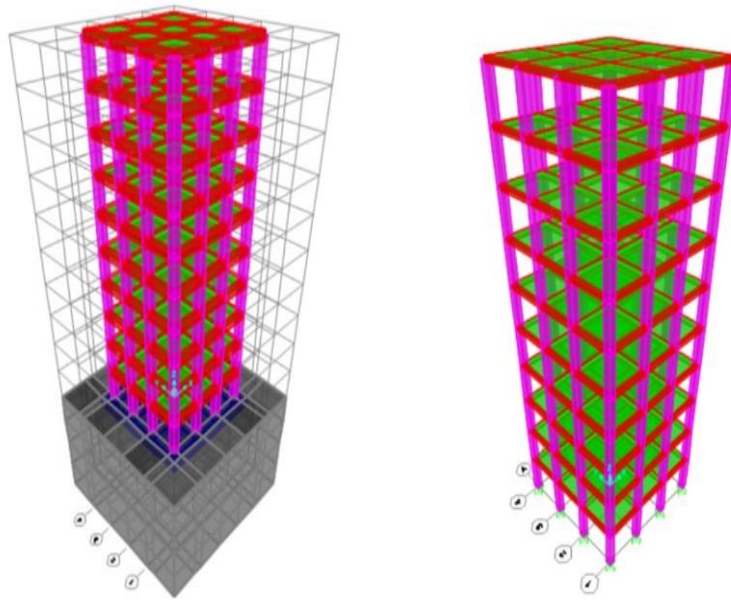


Figure 2. Model of a structure (a) with soft soil and mat foundation (b) with fixed base

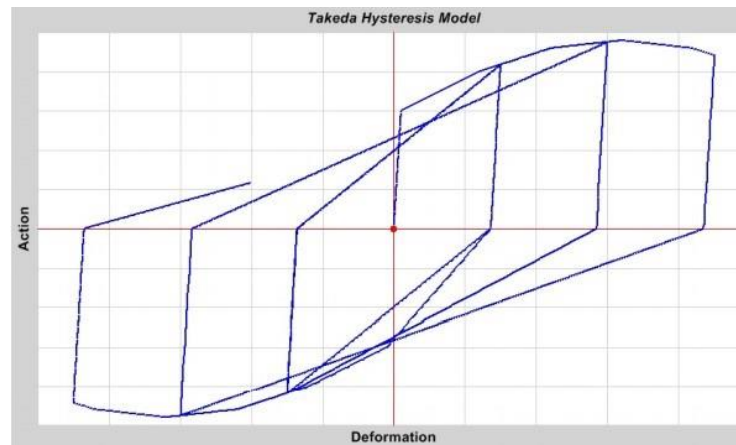


Figure 3. Takeda Hysteresis Model [31]

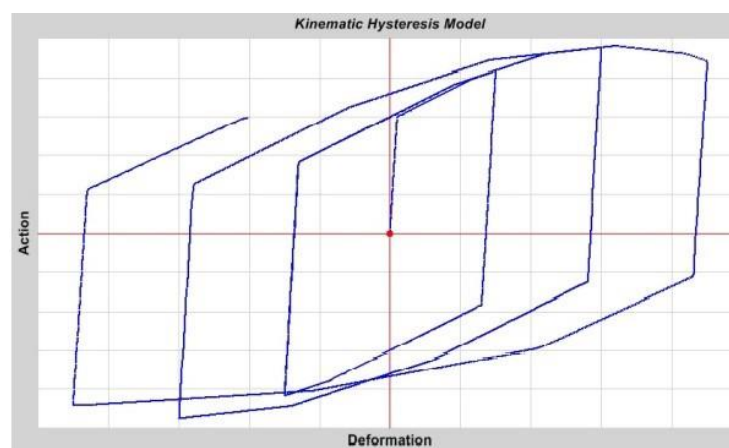


Figure 4. Kinematic Hysteresis Model [31]

### 2.3. Procedure for Numerical Modelling of the Structures

The building models with and without SSI are modelled in SAP 2000 v.20. Initially, geometric modelling material, section property, loads are defined. The dynamic analysis is performed for design of lateral loads. Time history analysis is performed using El-Centro data. The Time-history analysis gives both non-linear and linear calculates the response under seismic excitations and specific time period.

Figure 5 shows the time history data of El-Centro earthquake. The modal type is used as Eigen vector. As it uses the full stiffness and mass matrices and considers vertical modes [31]. The fast non-linear modal analysis (FNA) is used in this study. It is accurate and efficient than direct-integration time-history analysis and hence can be used in modelling of substructure, soil and foundation [31]. The load combinations are defined as per IS-456:2000 and for SSI models all the load cases are converted to non-linear cases. The inter-storey drift ratio for each storey is calculated from lateral displacement corresponding to each storey. The response spectrum curves and time period against each mode is also observed. All these parameters are compared in each seismic zone and for model with SSI and without SSI. The effect of SSI and various zones has been observed in this study.

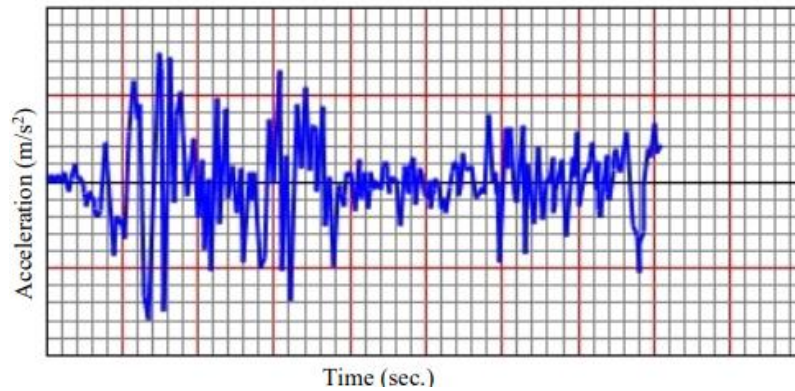


Figure 5. Acceleration-Time graph for El- Centro earthquake

### 3. Results and Discussions

#### 3.1. Inter-storey Drift Ratio

The inter-storey drift ratio is one of the important parameters used in design. According to IS 1893-2016(Part-1), It is the relative displacement between the floor above/below the storey under consideration. The following Equation 1 gives the inter-storey drift ratio,

$$\text{Inter-storey Drift} = ((\Delta_{i+1} - \Delta_i) / h) \quad (1)$$

where  $\Delta_{i+1}$  is displacement of upper and  $\Delta_i$  is displacement of lower floors, and  $h$  is the storey height under considerations.

Table 2 and Figures 6.a and 6.b show the inter-storey drift ratios of each storey in various seismic zones of India with and without SSI respectively. The values of inter-storey drift increases significantly when the effects of SSI are considered. It was found that inter-storey drift increases with increase in zone from zone II to V in both the cases. The inter-storey drift was found highest at storey no. 4. According to Indian code the storey drift was limited to 0.004 times the height of storey this was safe for Zones II and III building and found to be unsafe for Zones IV and V buildings. But in case of buildings with SSI only building in Zone II was found to be safe and all other buildings in Zone II, III, and IV was found to be unsafe. The inter-storey drift is related to damage level of the system was found by Ghobarah [32]. According to Ghobarah, for ductile moment resisting frames up to 0.2% there will be no damage to the structure. Further, if the inter-storey drift increases from 0.4-1% the damage level changes from light to moderate level of damage.

Table 2. Inter-storey drift ratio of each storey in various seismic zones with and without SSI

Storey no.	Interstorey drift ratio (%)							
	Without SSI				With SSI			
	Zone V	Zone IV	Zone III	Zone II	Zone V	Zone IV	Zone III	Zone II
10	0.00089	0.00059	0.00040	0.00025	0.00384	0.00329	0.00219	0.00091
9	0.00172	0.00115	0.00090	0.00048	0.00450	0.00358	0.00239	0.00099
8	0.00245	0.00163	0.00133	0.00068	0.00540	0.00387	0.00258	0.00107
7	0.00301	0.00201	0.00150	0.00084	0.00580	0.00411	0.00274	0.00114
6	0.00341	0.00227	0.00168	0.00095	0.00610	0.00430	0.00286	0.00119
5	0.00368	0.00245	0.00180	0.00102	0.00670	0.00444	0.00296	0.00123
4	0.00377	0.00251	0.00190	0.00105	0.00710	0.00454	0.00302	0.00126
3	0.00236	0.00157	0.00110	0.00066	0.00520	0.00310	0.00210	0.00129
2	0.00208	0.00139	0.00100	0.00058	0.00490	0.00290	0.00190	0.00137
1	0.00109	0.00073	0.00063	0.00030	0.00280	0.00220	0.00120	0.00090



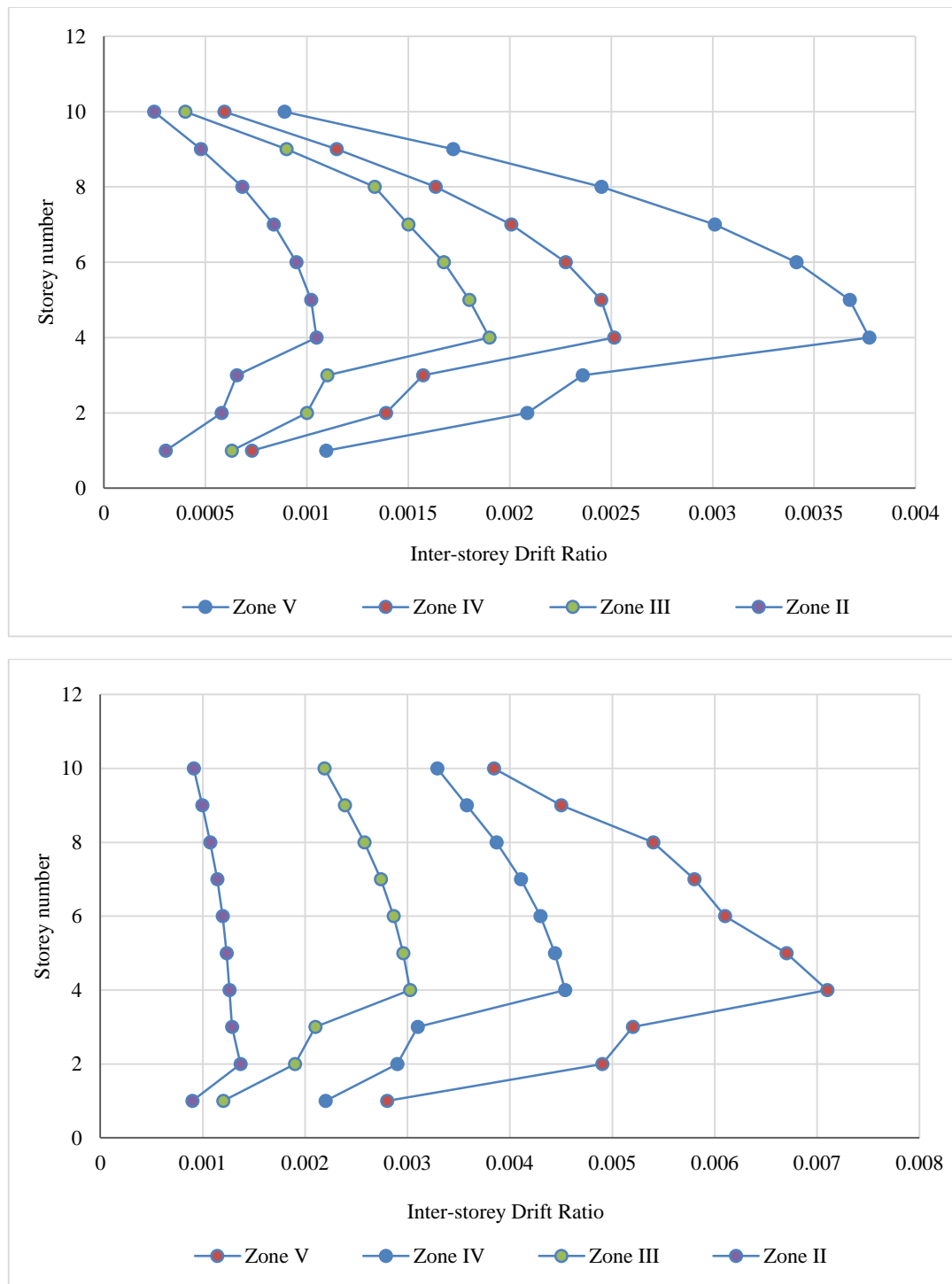


Figure 6. Plot of Inter-storey drift and storey number in various seismic zones (a) without SSI; (b) with SSI

### 3.2. Lateral Storey Displacement

The lateral storey displacement is the lateral movement due to lateral forces. The lateral storey displacement determines the behavior of the structure. The Figures 7.a and 7.b show the plot of lateral storey displacement and storey number in various seismic zones without SSI and with SSI. The lateral storey displacement gradually increases from seismic zone II to V and increased with increase in storey. When the SSI effect was considered the increase in lateral storey displacement was from 47 to 87 % in zone II. In Zone III, IV and V lateral storey drift increased from 60 to 95 %. It was found that soil flexibility increased the lateral displacements in the structure considering SSI. The result is validated by Chore also found that lateral displacements increased by 56–98 % when the effect of SSI is taken into consideration [33].

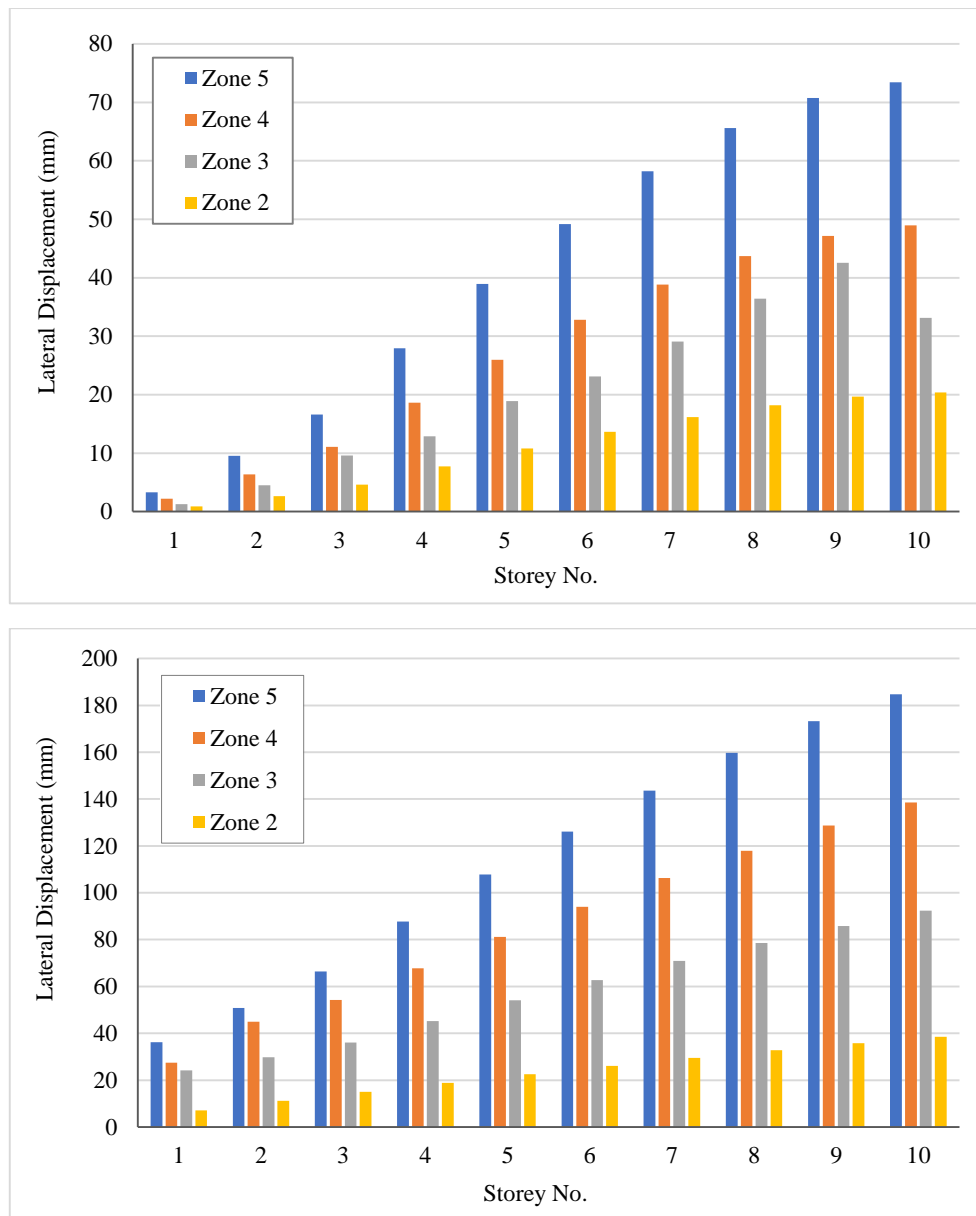


Figure 7. Plot of lateral storey displacement and storey number in various seismic zones (a) without SSI; (b) with SSI

### 3.3. Response Spectrum Curves

The response spectrum curves provide the dynamic behavior of the structure by Spectral acceleration, spectral velocity and spectral displacement for the specific time history data and specific damping. The maximum peak responses can be known from these curves under seismic excitations. In the present study spectral acceleration and spectral velocity are studied to understand the effect of SSI under El-Centro earthquake for various damping and seismic zones.

#### 3.3.1. Spectral Acceleration with Respect to Time

Figures 8 to 11 show the spectral acceleration with time period graph for zone V, IV, III and II with and without SSI respectively. It was found that the spectral acceleration decreases with increase in damping. The maximum spectral acceleration was about 4.8, 1.8, 1.6  $\text{m/s}^2$  for 0, 0.05 and 0.1 damping respectively in zone 5 without SSI case. Considering SSI, it increased to 9.05, 4.05, 3.15  $\text{m/s}^2$  for 0, 0.05 and 0.1 damping respectively in zone 5. The increase in peak spectral acceleration was found near to the natural frequency. Similar trend was observed in seismic zone II, III, IV for various damping ratios. Maximum spectral accelerations for each case were found in range of 0.3 sec to 0.6 sec. It concluded that considering SSI effect the spectral accelerations are found to increase in each zone. Hence, for the safety of the structures SSI effects should be included in the design. To reduce the spectral acceleration under seismic excitation the damping can be increased to ensure safety. The spectral acceleration also increased with increase in seismic zone from II to V.

### 3.3.2. Spectral Velocity with Respect to Time

Figures 12 to 15 show the spectral velocity with time period graph for zone V, IV, III and II with and without SSI respectively. It was found that the spectral velocity decreases with increase in damping. The maximum spectral velocities was about 0.112, 0.0528, 0.041 m/s for 0, 0.05 and 0.1 damping respectively in zone 5 without SSI case. Considering SSI, it increased to 0.592, 0.368, 0.272 m/s for 0, 0.05 and 0.1 damping respectively in zone 5. The maximum spectral velocity was found to decrease near the natural frequency. Similar increasing trend was observed in seismic zone II, III, IV for various damping ratios. Hence SSI effects should be considered in the design.

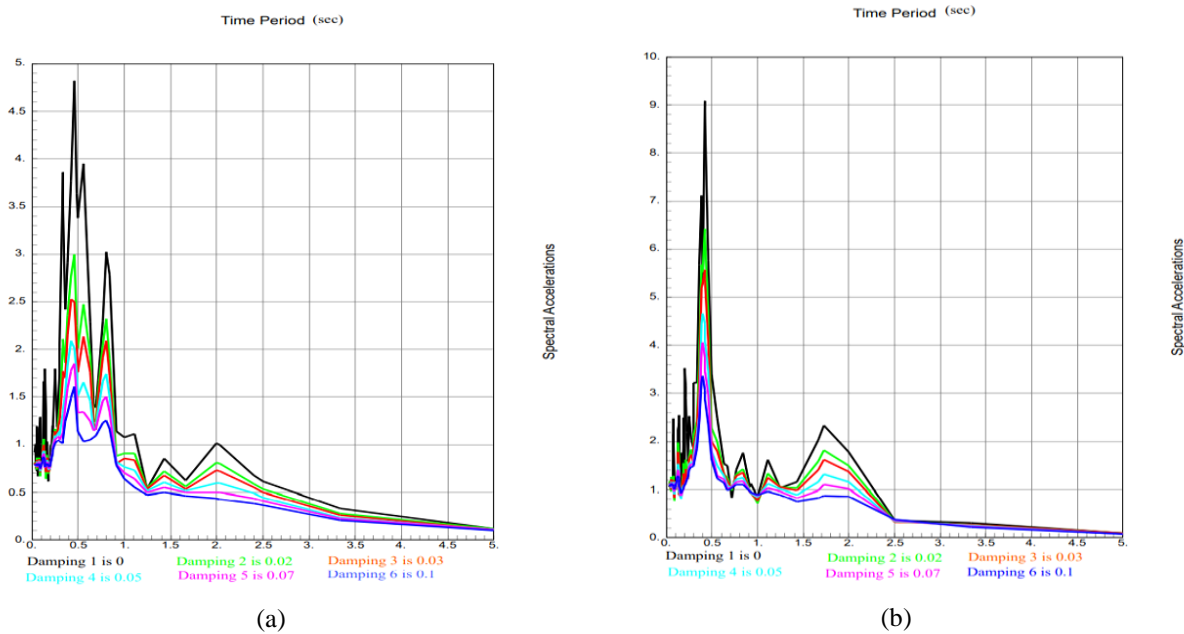


Figure 8. Plot of spectral acceleration ( $\text{m/s}^2$ ) vs. time period in Zone V for different damping (a) without SSI; (b) with SSI

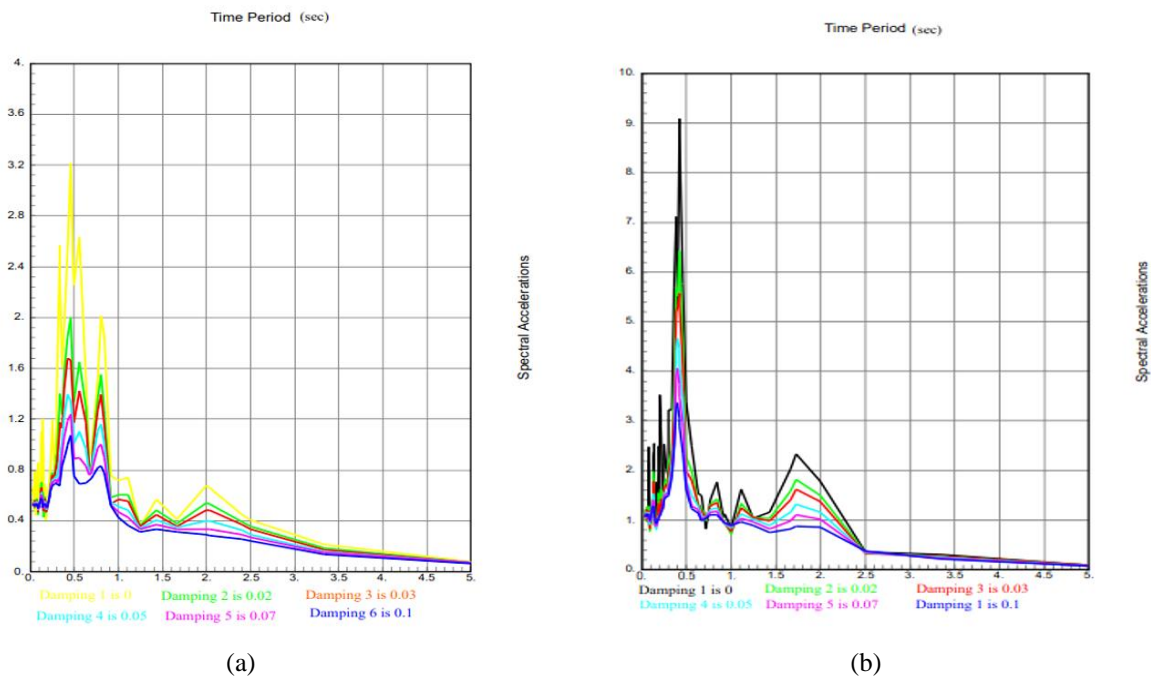


Figure 9. Plot of spectral acceleration ( $\text{m/s}^2$ ) vs. time period in Zone IV for different damping (a) without SSI (b) with SSI



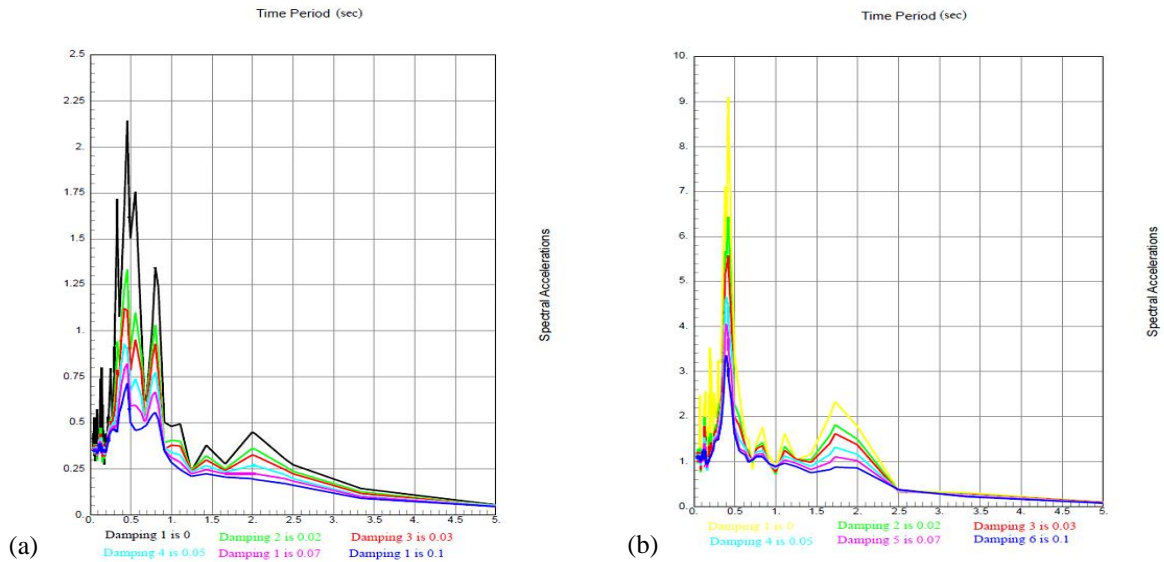


Figure 10. Plot of spectral acceleration ( $\text{m/s}^2$ ) vs. time period in Zone III for different damping (a) without SSI (b) with SSI

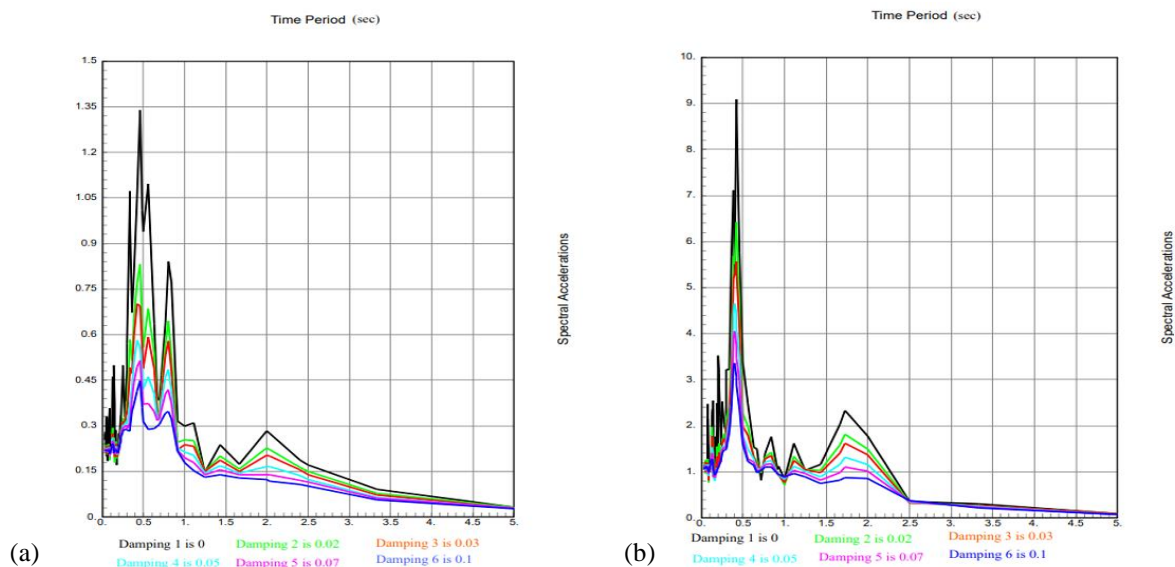


Figure 11. Plot of spectral acceleration ( $\text{m/s}^2$ ) vs. time period in Zone II for different damping (a) without SSI (b) with SSI

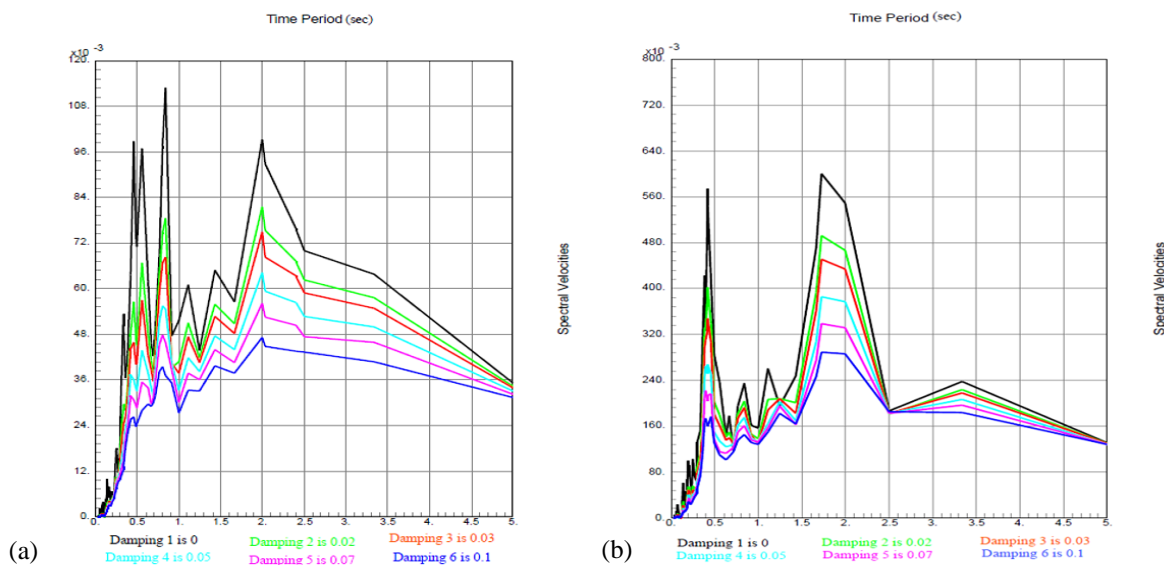


Figure 12. Plot of spectral velocities ( $\text{m/s}$ ) vs. time period in Zone V for different damping (a) without SSI (b) with SSI

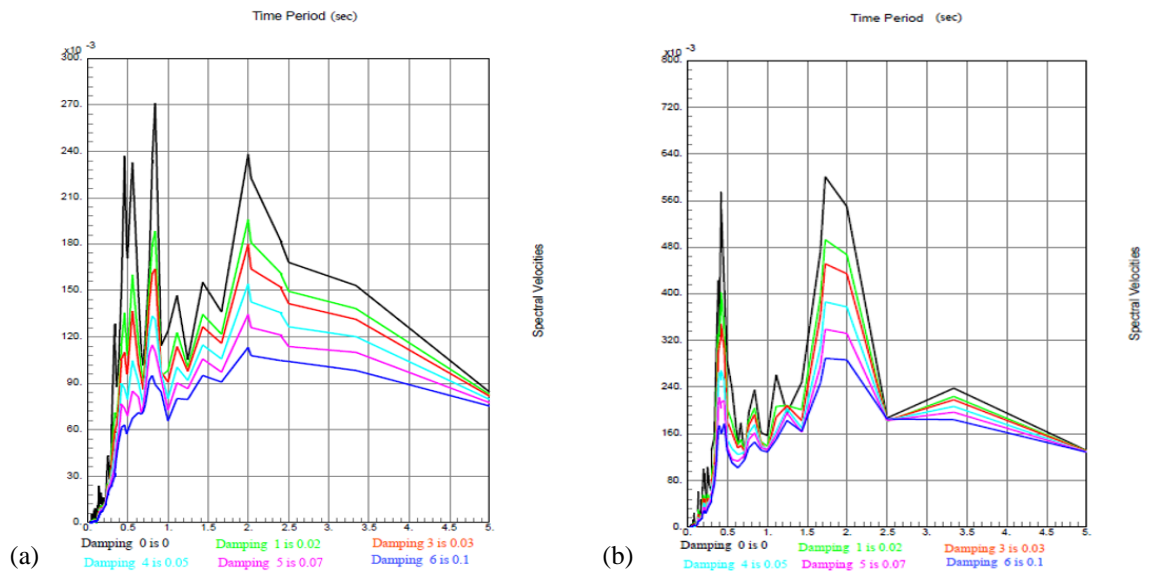


Figure 13. Plot of spectral velocities (m/s) vs. time period in Zone IV for different damping (a) without SSI (b) with SSI

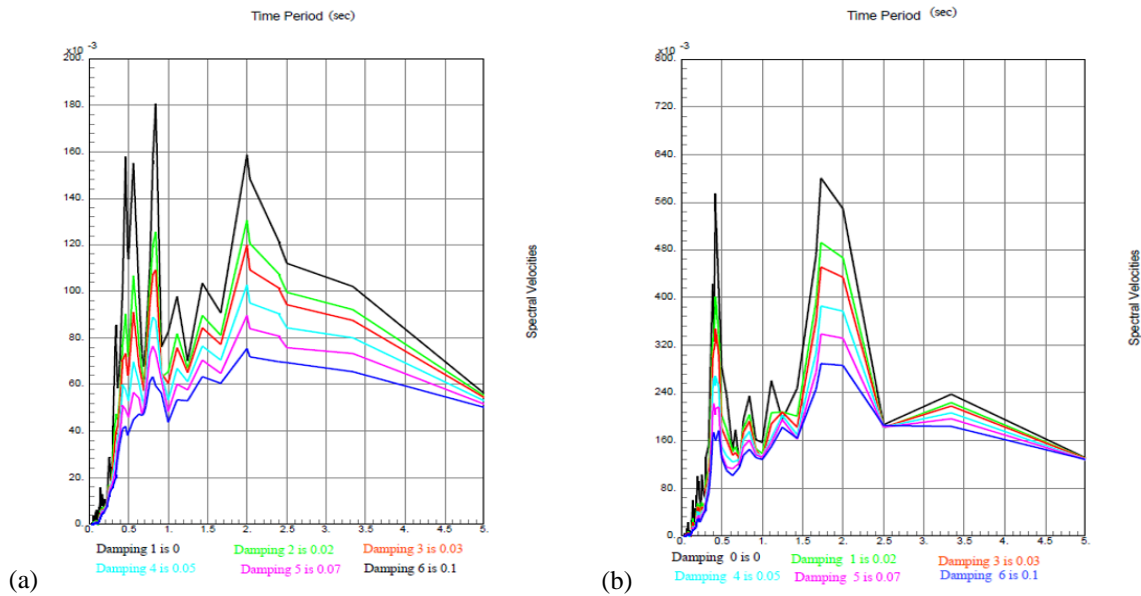


Figure 14. Plot of spectral velocities (m/s) vs. time period in Zone III for different damping (a) without SSI (b) with SSI

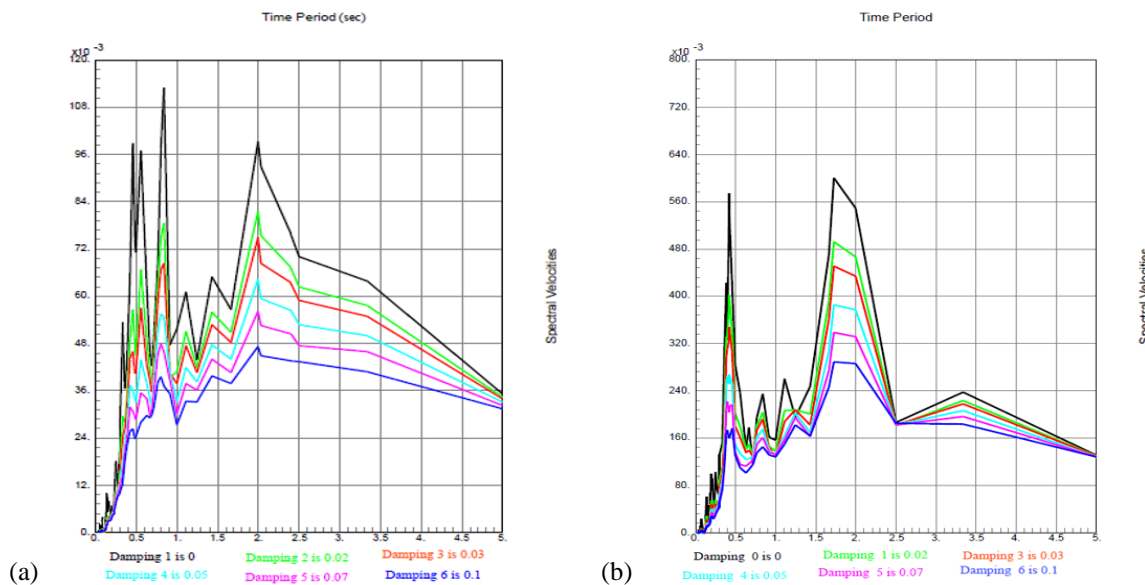


Figure 15. Plot of spectral velocities (m/s) vs. time period in Zone II for different damping (a) without SSI (b) with SSI

### 3.4. Time Period

The time required (in seconds) by a building to complete the cycle of oscillation is called fundamental natural period of the building. It is inherent property of the building. Figures 16 (a) to 16(e) show the different mode shapes of the building. It was found that time period decreased with increase in mode. The time period increased when effect of SSI was considered. Thus, ductility demand of the structures increased with time period. The result is validated from a study conducted by Singh & Mala for G+9 building that time period increases for the building with SSI effect due to the flexibility of soil [34]. Table 3 and Figure 17 showed the effect of SSI on time period.

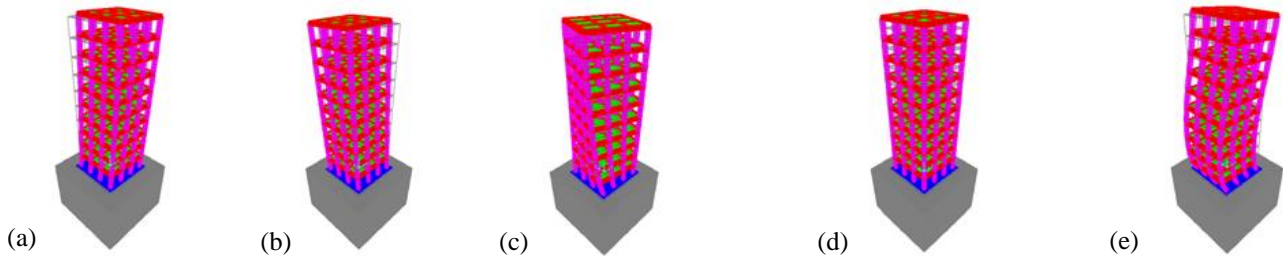


Figure 16. Mode shapes of the building with SSI

Table 3. Time period (sec) in different modes with and without SSI

Mode	Time Period (sec)	
	Without SSI	With SSI
1	1.72677	2.404225
2	1.72677	2.402187
3	0.920919	2.033527
4	0.421776	0.805443
5	0.395582	0.804766

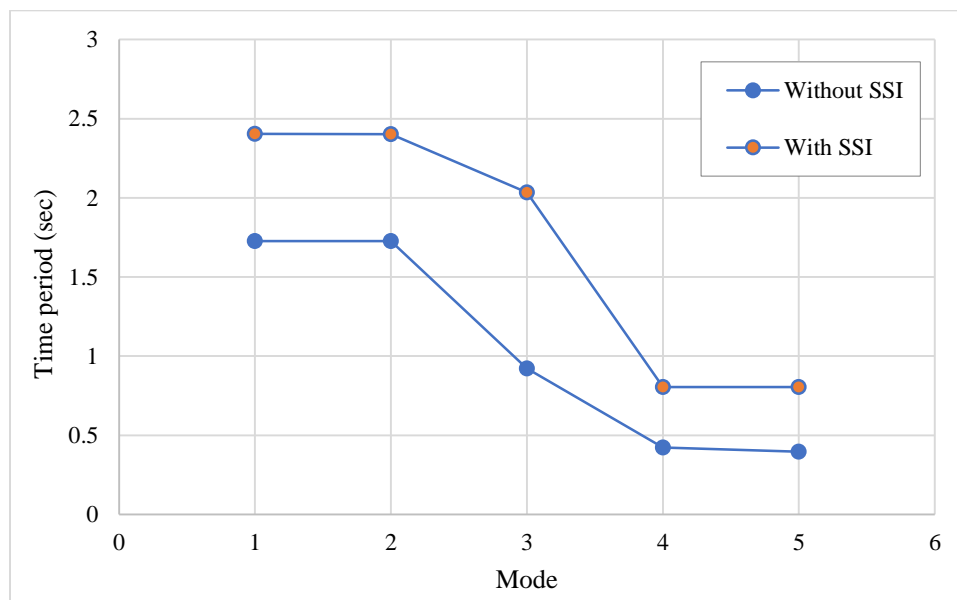


Figure 17. Variation of Time period (sec) in different modes without and with SSI effects

## 4. Conclusions

This study was implemented to study the seismic parameters during El- Centro earthquake considering SSI effect. The models with SSI and without SSI in various seismic zones of India was considered. The parameters like inter-storey drift ratio, spectral acceleration and time period studied and results are discussed below:

- The inter-storey drift of the buildings with SSI was found to be higher than those without SSI. The buildings in Zone II and III was found to be safe in fixed base case but when SSI was considered the buildings in zone III, IV and V suffered light to moderate level of damage. The increase in zone factor leads to increase in inter-storey drift ratio and maximum spectral acceleration.

- The lateral storey displacement increased from seismic zone II to V with increase in storey. Considering SSI effect, the increase in lateral storey displacement was observed from 47 to 87 % in seismic zone II. In seismic zone III, IV and V, lateral storey drift increased from 60 to 95 %. The soil flexibility increased the lateral displacements in the structure considering SSI.
- From the response spectrum curves, it was observed that the increase in damping from 0 to 0.1 decreased spectral acceleration in all seismic zones. It was found maximum in zone V for SSI case. The maximum spectral acceleration was found in time period 0.3-0.6 sec. The increase in peak acceleration was found near to the natural frequency for all seismic zones. The spectral acceleration increased gradually from zone II to V.
- The spectral velocities also decreased with increase in damping. The maximum spectral velocities were found in zone V for SSI case. The decrease in peak acceleration was found near to the natural frequency for all seismic zones.
- The SSI effect increased time period and ductility demand in the structures. This is caused due to flexibility of the structures.

From this study, it is clear that there is need to include SSI specially for soft soil in zone III, IV and V in design by designers. The realistic responses can be obtained by implementing the soil beneath the structure. To reduce the response on the structure during seismic excitations, it is recommended to use appropriate mitigation measures like base isolators or dampers specially during retrofitting of the structures. Further the study can be extended by including experimental studies and numerical modelling by including realistic forces like pounding of the adjacent structure. The parameters like P-delta, angle of incidence of ground motions and various structural systems can be implemented in this study.

## 5. Declarations

### 5.1. Author Contributions

G. A. and A. M. contributed to the conceptualization, methodology, use of software, validation of results, and drafting of manuscript and implementation of the research, to the analysis of the results and to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript

### 5.2. Data Availability Statement

The data presented in this study are available in [Doi:10.1201/b17240-42].

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### 5.4. Acknowledgements

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### 5.5. Conflicts of Interest

The authors declare no conflict of interest.

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