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Research Paper

Simple Soil Effect Analysis in a Base and Mid-Story Isolated 15-Story Building

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Abstract: In this study, the effect of soil-structure interaction on seismic performance is investigated by considering a 15-story building incorporating base and mid-story seismic isolation. The cases that are taken into account are the fixed base model, base-isolated model, and base and mid-story isolated model. All three models are analyzed by excluding and including soil-structure interaction. Three different earthquakes are used for the time-history analysis. It is concluded that the seismic performance is enhanced by the implementation of base and mid-story isolation to the structure. In addition, it is observed that soil-structure interaction had a small effect on the seismic performance of the structure depending on the base type.

Keywords: Seismic Isolation, Soil, Earthquake, Structural Dynamics

1. Introduction

Turkey is a country which is located in a region with high seismic activity. As it is known, 92% of the country's surface area and 94% of its population are located in the earthquake zone. Throughout history, many lives and property have been lost in Turkey as a result of earthquakes. Dynamic forces acting on the structure cause heavy damage to the structure. Structural control is provided with additional elements added to the structure in order to prevent or minimize the damage level that may occur in the structure against the dynamic forces that directly affect the structure such as earthquakes. In this study, seismic isolation systems (base isolation) are analyzed by considering soil effects. Seismic isolation is a method that protects the structure from the effects of the earthquake by creating a layer between the structure and the ground, by means of earthquake isolation devices implemented between the building and the foundation. With the help of this method, the floor displacements of the building are controlled by increasing the damping ratio and energy consumption capacity of the building.

The response of the soil under the effect of an earthquake has an impact on the structure and the response of the structure also has an impact on the soil, this situation is called the soil-structure interaction (SSI). The earthquake waves spread through the soil and reach the foundation of the building, while some of them are reflected back, some of them pass to the superstructure and cause displacements in the structure. In order to investigate the seismic performance of buildings in more detail and to ensure safety against damages caused by earthquakes, SSI should be taken into account. In the literature, there are many studies merely about base isolation or only considers SSI. However, the number of studies in which both base and mid-story (inter-story) isolation and the SSI were studied together is little if any. For these reasons, in this section, studies on both base and mid-story isolation and SSI are covered.

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In a study, seismic isolation was implemented in two buildings [1]. One of the buildings has 16 floors and the 22nd column on the 8th floor of the building was cut from the middle height and lead core rubber bearings (LRB) were implemented. Due to the reduction of the seismic force acting on the structure with this process, it was obtained that there was no need to strengthen the superstructure [1]. A study of a 9-story reinforced concrete/steel composite structure in Tokyo suburbs is given in [2]. Since retrofitting was not allowed on the floors used for residential purposes, the researchers considered applying mid-floor seismic isolation to the weak floor. They observed that, for the structure below the isolation layer, the seismic forces acting on the structure decreased significantly [2]. To investigate the reliability requirements of isolation system components for the protection of critical structures and facilities, a study on a four-story structure with second-floor level isolation representing a critical structure is presented in [3]. The impact of base isolation systems on both structural performance and liquefaction potential, including SSI, is also studied in [4]. Four different types of structures and three different types of soil conditions were analyzed for two different ground motions. The description of the systems used in more than 130 buildings incorporating various seismic isolation methods, including base isolation, mid-story isolation, and retrofitting is given in [5]. The dynamic characteristics and seismic responses of mid-story isolated buildings using a simplified three-degree-of-freedom model with equivalent linear properties are presented in [6]. Both the effectiveness and applicability of inter-floor and multi-layer insulation systems were also investigated [7]. The effectiveness of multi-story structures with seismic isolators at different story levels is investigated in [8]. In their work, they conducted parametric studies on the time domain considering ten different earthquakes from the Greek-Mediterranean region. Dynamic behavior of buildings isolated from the ground and middle floors were also investigated experimentally in [9]. Using a simple continuous shear beam model, an SSI study of a mid-story isolated structure resting on layered soil on the bedrock is given in [10]. Closed-form solutions were used to investigate the dynamic effects of SSI on the mid-story isolated building. Although the research numbered [10] is an important study that considers both SSI and mid-story isolation, the distinction of it from our paper is that it uses a simple beam model, and the floor models are different. A technique was proposed for the base isolation method that cannot be applied to high-rise buildings due to the restrictive conditions in the earthquake codes [11]. The aim was to distribute the ductility of the structure along the elevation of the building by implementing the damping elements at the base and between the upper stories of the structure [11]. Performance evaluation should be made by comparing the internal force and deformation values determined for existing structures and new structures to the limit values specified in the codes [12]. An interesting study about the effect of soil-structure interaction on reinforced concrete buildings is presented in [13]. A mode synthesis-based approach is used to describe a simplified two-degree-of-freedom model of a mid-story isolated structure for calculating the optimal stiffness and damping parameters of the isolation system [14].

The main scope of this study is to investigate the response reduction performance of isolation systems between floors by considering SSI in a multi-story building under the effect of earthquakes. A 15-story building with seismic isolation on the ground and the middle floor is considered as an example structure. Analyzes were carried out in the time domain for three different earthquake motions. SSI is examined for different ground conditions. The results are presented comparatively. It should be noted here that SSI is implemented simply by not considering a complex soil model. The numerical example, models, and results are given in the following sections.

2. Numerical Example

In this section, the modeling of the buildings and structural systems considered in this research, the mechanical properties and dimensions of the rubber bearings used in the seismic isolation system, the soil type, and the earthquake records for performing the dynamic analysis are presented.

The building which is considered as residential/commercial type has 15 floors and is a reinforced concrete structure. In order to compare the seismic performance of the base and mid-story isolation three different models are taken into account. These models are; fixed-base conventional building, building with base isolation, and building incorporating both base and mid-story isolation. The soil type is chosen as medium-dense sand.

2.1. Modelling of the Superstructure

A building with a 15-story reinforced concrete frame system, which is intended to be used as an office, is modelled in the SAP 2000 software. The frame system consists of column and beam elements. The flooring type is a plate with beams, and it works in two directions. The building has three spans in each direction, and each span is 4 meters. The floor area of the building is 144 m^2. The story height is 3 m. The total height of the building is 45 m.

2.1.1. Material Properties and Dimensions

According to TS 500 [15] The elasticity modulus of the concrete is E_c=32 000 MPa, characteristic compressive strength is f_{ck}=30 MPa, equivalent cubic compressive strength is 37 MPa, the Poisson ratio is ν=0.2, thermal expansion coefficient $\alpha_t = 10^{-5}/^0C$ and the characteristic axial tensile strength is f_{ctk}=1.9 MPa [15]. The steel properties are as follows; elasticity modulus E_s=200 000 MPa, yield strength f_{yk}=420 MPa, the coefficient of thermal expansion $\alpha_s=10^{-5}$ 1/^{o}C, and Poisson ratio ν=0.30 [16].

Considering the limit values specified in TS 498 [17] and TBDY 2018 [18], the dimensions of the columns are chosen as 0.6x0.6 m. The net concrete cover on the columns is 30 mm. As a result of the calculations, it was deemed appropriate to select the column reinforcement at the minimum level of reinforcement ratio. The dimensions of the beams are selected as 0.5x0.6 m. The floor thickness is determined as 15 cm. In models where SSI is not taken into account, the base is modeled as fixed and isolated. In Fig. 1, a 15-story model with a fixed base is shown.

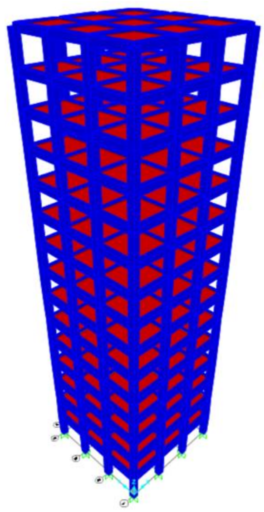

Figure 1. 15-Story fixed base model

2.1.2. Properties of the Seismic Isolation

Lead rubber bearings (LRB) are used in the models. Rubber bearings have high displacement capacity and show rigid behavior under dynamic loads. The dimensions of the rubber bearings used in the models are shown in Fig. 2. [19] was used to determine the properties of the bearings. The top layer width of the LRB is 0.707 m, the bottom layer width is 0.667 m, the total height is h=0.48 m, the total number of intermediate layers is 16, and the thickness of each intermediate layer is t=0.025 m, total thickness of the layers is t_r=0.3355 m, and the total area is A_{LRB}=0.3927 m^2. In addition the total area of the core is A=0.0024 m^2. The shear modulus of LRB is G= 0.7 MPa, the elasticity modulus is E_{LRB}=249131.9 kN/m^2, the total effective stiffness of the system is K_{eff}=889.95 kN/m, the horizontal stiffness K_H=816.386 kN/m, vertical stiffness K_V=291621.662 kN/m, energy dissipation per cycle is W_D=31.46 kN-m, rotational inertia is 0.009721 kN/m, effective stiffness in u1 is 889950.58 kN/m, effective stiffnesses in u2 and u3 are 889.95 kN/m, effective damping in u2 and u3 direction is 0.05, and the stiffness in u2 and u3 direction is 8201 kN/m. The displacement capacity of LRB is 0.33 m, with an axial load capacity of 1382.15 kN. In Fig. 3, base isolation and both base and mid-story isolation application of the 15-story building are shown. Seismic hazard-based analysis is not carried out in this study. To focus more on the soil effect instead of the isolation behavior, a simple LRB design was considered. The isolation parameters are the same for both base and mid-story LRBs.

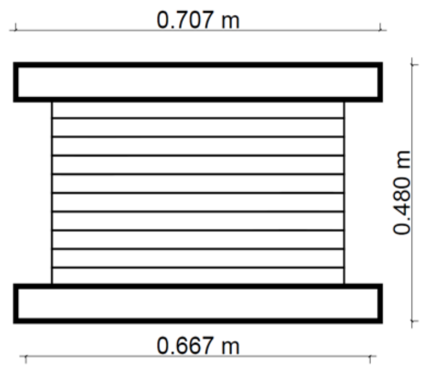

Figure 2. Cross section of lead rubber bearings

2.1.3. Load Combinations

The uniform. distributed live load (Q) in commercial-residential type models is determined as 2 kN/m^2 according to TS 498 [17]. The exterior facades of the models are considered as walls and the loading is defined as G_{Wall}=6 kN/m^2. The coating load is defined as G_{coat}=1.5 kN/m^2 to the flooring. The live load coefficient is defined as n=0.3 type according to TBDY 2018 [18]. It is obtained that the structural system meets the boundary conditions defined in [18].

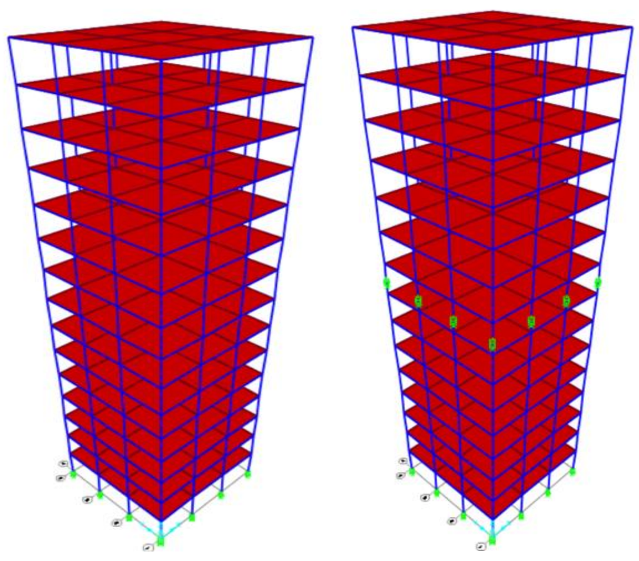

Figure 3. Base isolated 15-story model (left), base and mid-story isolated 15-story model (right)

2.2. Soil Properties

Today, during the design of the superstructure, it is generally accepted that the structure is rigidly connected to the ground, and SSI is not taken into account. In this study, the ground in the vertical direction is modeled as a shear frame with elastic springs and damping. Soil conditions are presented in Table 1. In Table 1, Poisson ratio (v), density (ρ), shear wave velocity to a depth of 30 m (V_s), and shear modulus (G) of the soil are presented. The selected soil class is medium-dense sand and corresponds to the ZD soil class according to [18]. In Fig. 4, the ground profile in the 15-story building with both base and mid-story isolation is shown. Soil model in this research is linear. We modelled the soil with elastic springs and dashpots as Winkler soil model.

Table 1. Soil Conditions

Soil	v	ρ kNs^2/m^4	V_s m/s	G kN/m^2
Medium-Dense Sand	0.48	1.90	300	171000

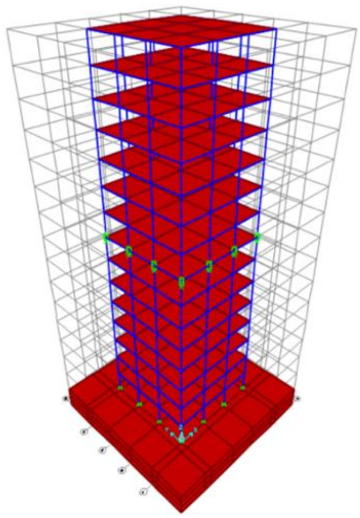

Figure 4. Soil profiles of base and mid-story isolated 15-story model

2.3. Earthquakes Used in Time-History Analysis

There are many active faults in Turkey due to its geological location. The main reason for the earthquakes is the compression in the North Anatolian Fault and the East Anatolian Fault. For this reason, the Kocaeli/Gölcük earthquake that occurred on the North Anatolian Fault on 17 August 1999 with a magnitude of 7.4 is chosen as the first earthquake. The second earthquake record is the Kobe earthquake record, which took place on January 17, 1995, in Kobe, Japan, with a magnitude of 6.9. The third record is the Loma Prieta earthquake that took place in California, USA on October 1989. The earthquake with a magnitude of 6.9 lasted about 15 seconds. Earthquake records were taken from the PEER database [20]. The maximum ground acceleration (PGA), maximum ground velocity (PGV), and maximum displacement values (PGD) of the earthquakes are 222.49 cm/s^2, 69.72 cm/s, and 62.32 cm, respectively, for the Kocaeli earthquake. These values are 270.76 cm/s^2, 33.57 cm/s, and 26.1 cm for the Kobe earthquake, and 447.33 cm/s^2, 51.39 cm/s, and 8.12 cm for the Loma Prieta earthquake. In this section, spectrum analyzes are not included due to space constraints however they can be obtained from [21].

3. Results of the Dynamic Analysis

Considered cases are; fixed-base buildings, base-isolated buildings, and both base and mid-story isolated buildings. Kocaeli earthquake results are presented below.

3.1. Time History Analysis for the Kocaeli Earthquake

Firstly, natural building periods, base shear forces, and overturning moments are calculated. In addition relative story drift comparisons, top story acceleration comparisons, relative story acceleration comparisons for each story, peak story displacement comparisons and relative story displacement comparisons were performed. In Table 2, the period, base shear and overturning moment values of the models are given.

Table 2. Structural properties for Kocaeli earthquake

Models	Period (s)	Base shear force (kN)	Overturning moment (kNm)
Fixed base	1.45	7605	207864
Base Isolated	4.14	4715	139269
Base and mid-story isolated	3.39	4149	122556

As can be seen from Table 2, the implementation of isolation increases the period by 2.9 times compared to conventional (fixed base) building, while reducing the base shear and overturning moment values by approximately 60%. In comparison with the base isolated model, LRB implementation to the middle story reduces the period by 22%, the base shear force and overturning moment by 19%. Moreover, the limit displacement capacities and the limit axial load capacities of the LRBs are checked according to their boundary conditions. In Table 3, the displacement values of the LRBs and the axial load values of the models are presented. The displacement capacity of the LRBs is 0.33 meters and the axial load capacity they can withstand is 1382.15 kN. All models met these conditions. The checks given in Table 3 were also carried out for the Loma Prieta and Kobe earthquakes. And it was seen that, the models met the conditions under these earthquakes as well. However, those tables are not given in this section.

Table 3. Peak values of lead rubber bearings for Kocaeli earthquake

Models	Displacement (m)	Axial load (kN)
Base isolated	0.23	942.7
Base and mid-story isolated	0.20	841.43

As a result of the dynamic analysis, the comparison of the relative story drifts for the Kocaeli earthquake is shown in Fig. 5 for the case where SSI is not taken into account, and in Fig. 6 for the case where it is taken into account. As it can be understood from Figs. 5 & 6 that the relative story drifts are decreased in the base-isolated structure. The additional implementation of seismic isolators to the mid-story is more effective in reducing the relative story drifts. In addition, when SSI is taken into account, it is seen that the relative floor drifts have increased.

Moreover, the structural accelerations which have a significant effect on comfort and safety in buildings, are also examined. Relative floor accelerations are given in Fig.7 for the case without SSI. In Fig. 8 SSI is taken into account. Relative floor accelerations decreased by an average of 13%

compared to the conventional model with the base isolation application. As a result of the implementation of isolation to mid-story, story accelerations decreased by 11% on average in comparison with the base-isolated. Considering SSI, relative floor acceleration values increased by 5% on average in the fixed base model, 3% on average in the model with base isolation, and 2% on average in the model with both base and mid-story isolation. The results of the Kobe earthquake are given in the next section.

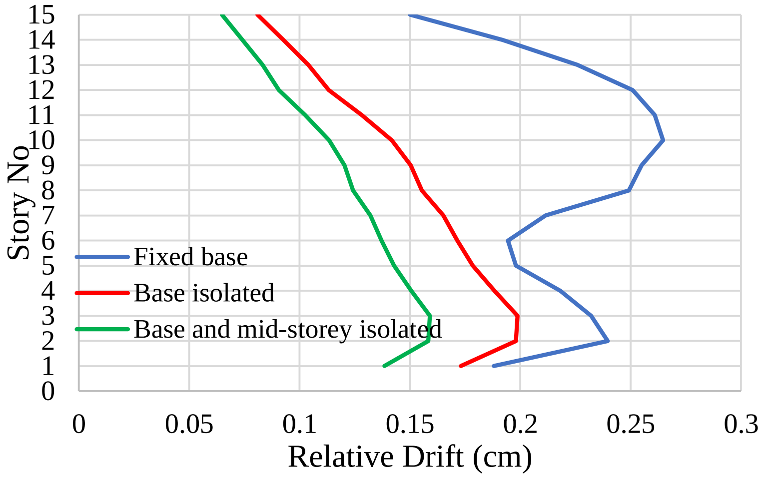

Figure 5. Relative drift comparison for the Kocaeli earthquake

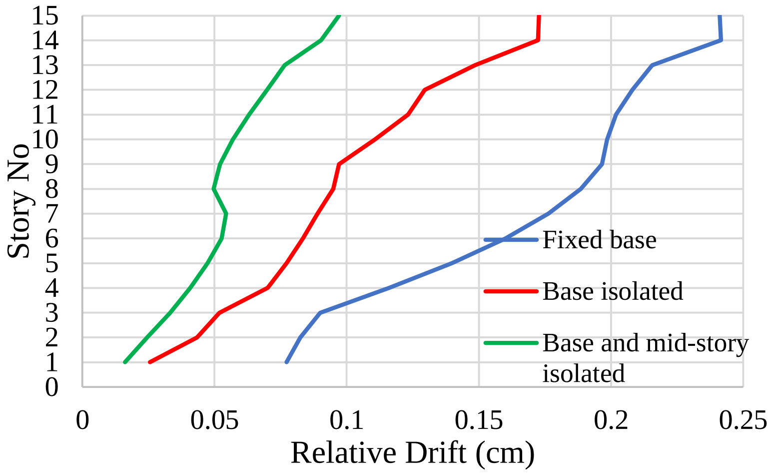

Figure 6. Relative drift comparison for the Kocaeli earthquake considering SSI

3.2. Time History Analysis for Kobe Earthquake

For Kobe earthquake base shear and overturning moment values were obtained to be higher than the Kocaeli earthquake. The time history comparison of the acceleration values of the Kobe earthquake is presented in Fig. 9 for the case where SSI is not taken into account. As can be seen from Fig. 9 that the peak story acceleration decreased as a result of the seismic isolation application. Considering the SSI, the time history of the top floor acceleration is shown in Fig. 10. Similar to the results of the Kocaeli earthquake, the relatively fixed base floor accelerations decreased significantly when SSI is taken into account. Finally, the results of the Loma Prieta earthquake are given below.

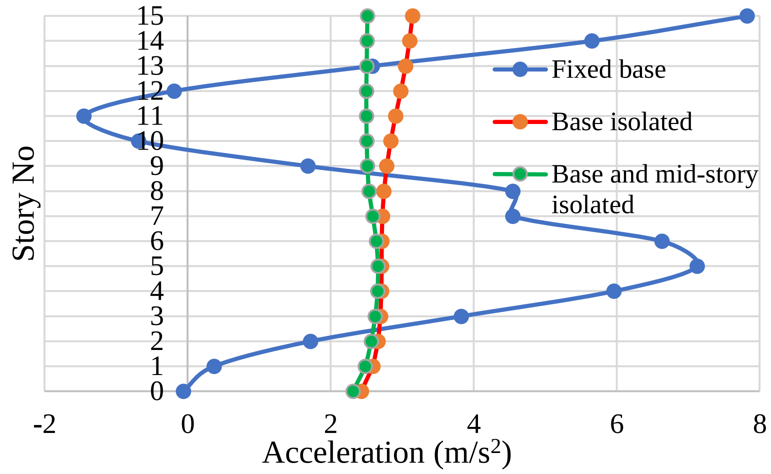

Figure 7. Relative story acceleration comparison for the Kocaeli earthquake

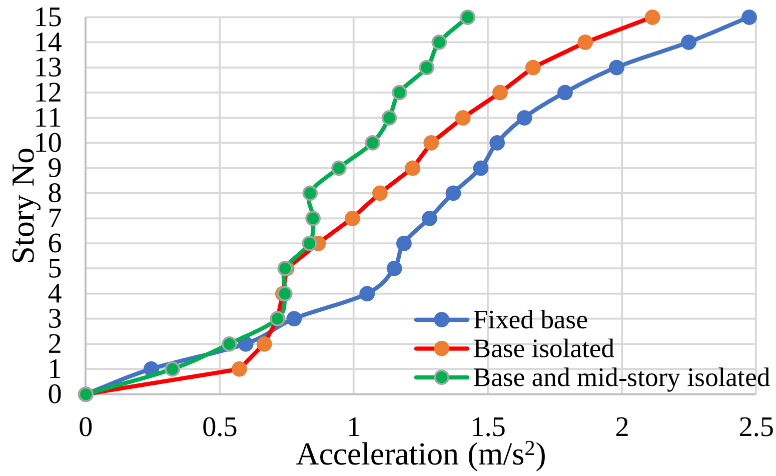

Figure 8. Relative acceleration comparison for the Kocaeli earthquake considering SSI

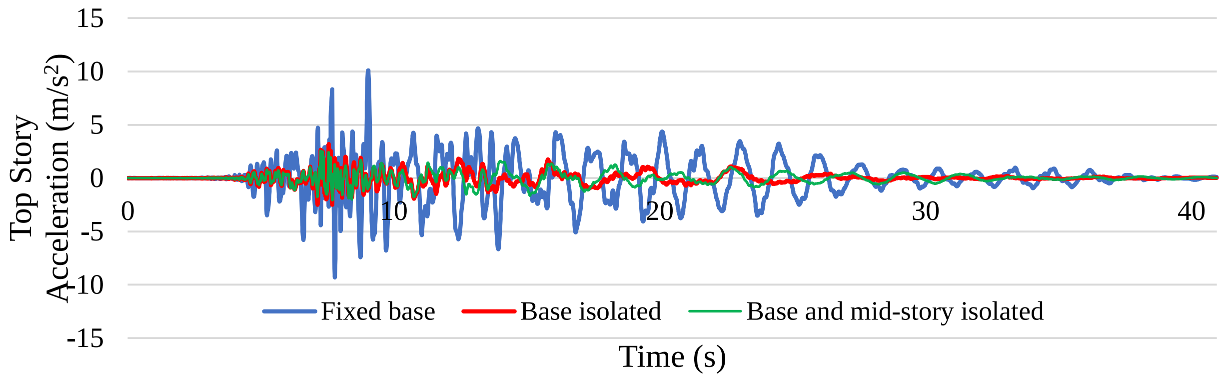

Figure 9. Top story acceleration comparison for the Kobe earthquake

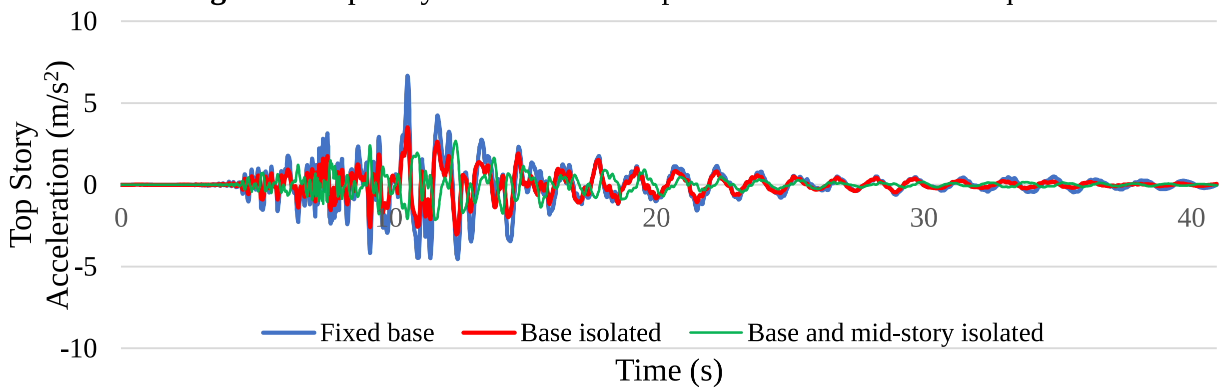

Figure 10. Top story acceleration comparison for the Kobe earthquake considering SSI

3.3. Time History Analysis of the Loma Prieta Earthquake

In Table 4, the period, base shear, and overturning moment values for the Loma Prieta earthquake are presented. While the seismic isolation application increases the period compared to the conventional building, it decreases the base shear and overturning moment values. Base and mid-story isolated case increase the period compared to the base-isolated model. In addition, combined usage of base and mid-story isolation reduces the base shear force and overturning moment affecting the structure. The same values for the case with SSI are also presented in Table 5. It is obtained from Tables 4 & 5 that the period, base shear force, and overturning moment values increase when SSI is taken into account.

Table 4. Values of the structural period, base shear, and overturning moment for the Loma Prieta earthquake

Models	Period (s)	Base shear force (kN)	Overturning moment (kNm)
Fixed base	1.45	7124	197471
Base Isolated	4.14	4532	125623
Base and mid-story isolated	3.39	4234	112147

Table 5. Values of the structural period, base shear, and overturning moment for the Loma Prieta earthquake (SSI considered)

Models	Period (s)	Base shear force (kN)	Overturning moment (kNm)
Fixed base	1.61	7488	207926
Base Isolated	4.84	4790	131729
Base and mid-story isolated	3.96	4466	116857

Unlike the results for the other two earthquakes, the relative story displacements under the effect of the Loma Prieta earthquake are presented in this section. Relative story displacements are given in Fig. 11 for the case when SSI is taken into account. As a result of the implementation of isolation elements to the mid-story, story displacements decreased by 15% on average compared to the model with base isolation. When SSI is taken into account, the top floor displacements are increased compared to the case where SSI is not included.

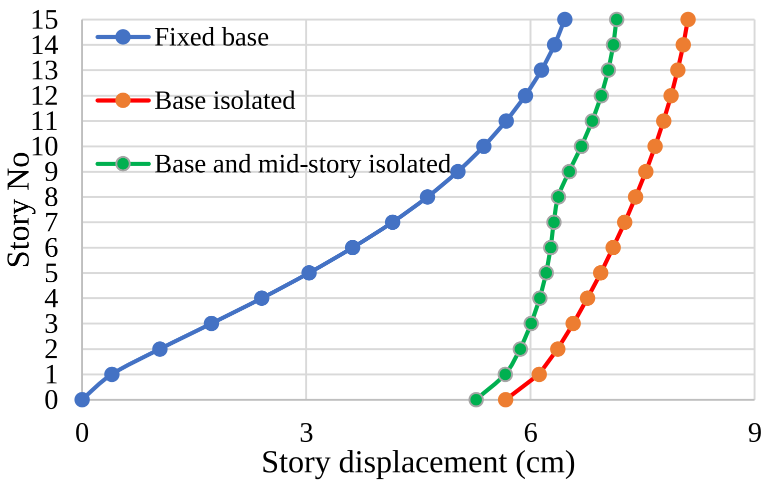

Figure 11. Story displacement comparison for Loma Prieta earthquake

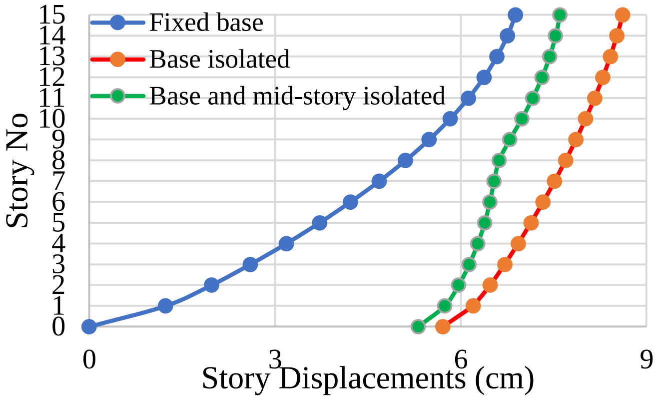

Figure 12. Story displacement comparison for the Loma Prieta earthquake considering SSI

Relative story displacement comparisons for all investigated earthquakes are given in Fig. 13. The outcomes of this chart were considered in the conclusions section. Lastly, it must be stated here that a study on mid-story seismic isolation in low-rise buildings, which constituted an idea for this research, can be found in [22].

4. Conclusions

It is obtained in this study that, base and mid-story isolation has a positive impact on the earthquake performance of the 15-story building. In addition, taking into account SSI increases the structural responses like acceleration, velocity, and displacement. But this outcome is not always valid. It should be noted here that, in these cases, the earthquake effects may change, and structural response behavior may vary according to the base type. It is also seen that structural performance change may vary from %2 to %20 depending on the selected base type. Moreover, consideration of SSI decreases the structural response reduction performance of the seismic isolation. Also, structural height has a significant impact on the performance of the seismic isolation considering SSI.

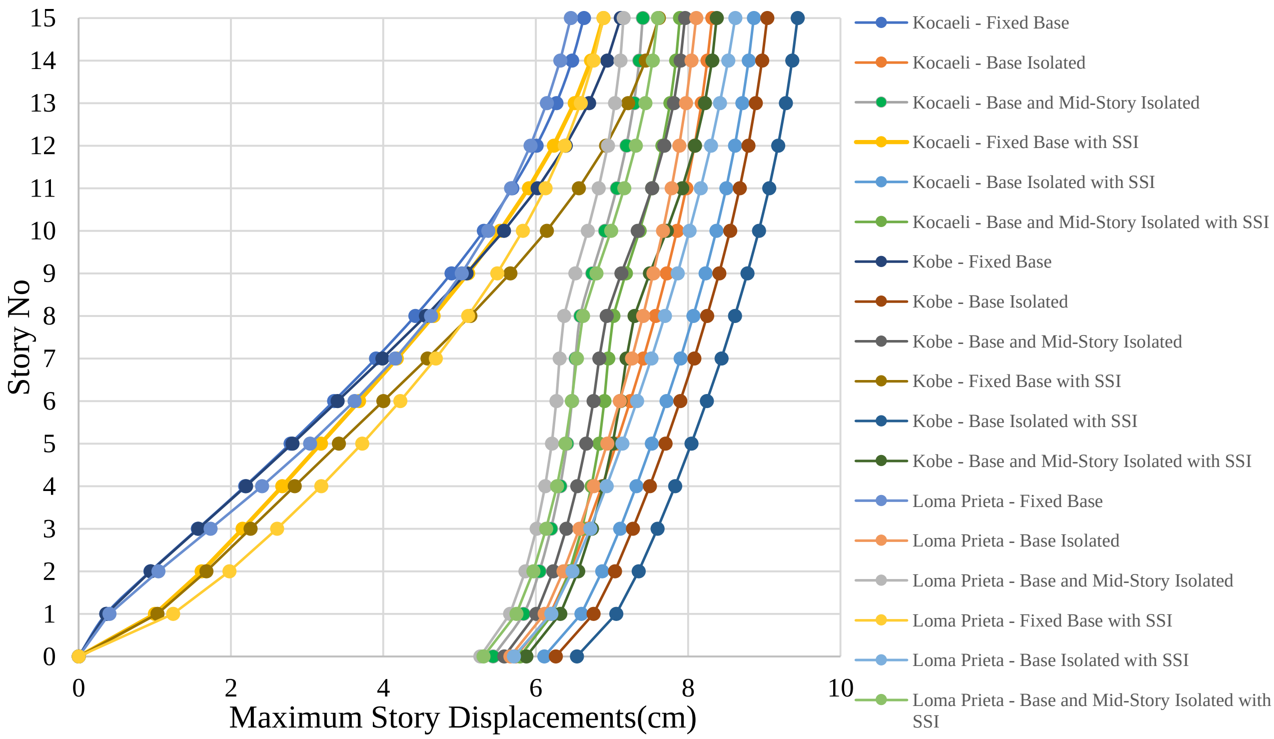

Figure 13. Relative story displacement comparison for all cases and all earthquakes considered in this study

An increasing desire to determine and enhance the seismic performance of buildings may result in the usage of mid-story isolation. The implementation of mid-story isolation may increase the seismic performance of the weak upper and lower stories and buildings with different structural types. In addition, this system may be used for retrofitting existing buildings. Retrofitting with mid-story isolation may meet the seismic requirements with relatively low-cost criteria. Finally, mid-story isolation may be a good solution for high-rise and mid-rise buildings that can experience hardships in conventional retrofitting.

Authors' Contributions

AY designed this study. AY was also the advisor of this research in every step and wrote up the entire article. HT composed the models, performed the dynamic analysis, and prepared the results in a comparative way with various curves and tables.

Both authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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