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ANALYTICAL STUDIES ON R.C BUILDING WITH MIDDLE STOREY ISOLATION UNDER CONSIDERATION OF SOIL STRUCTURE INTERACTION

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ABSTRACT

Rapid urbanization is causing an increased demand for the construction of tall buildings in areas susceptible to seismic activity and ensuring that these structures can withstand seismic forces while maintaining their serviceability in the engineering challenges. As such, implementing seismic isolation technologies is one method employed to reduce the effects of seismic forces on structural performance. However, limited information exists concerning how the interaction between the soil and the building impacts mid-storey-isolated buildings. In this research, we investigate the seismic performance of reinforced concrete, high-rise buildings which utilize mid-storey-isolation (MSI) systems and also account for soil-structure interaction (SSI). Using a combination of linear time-history analysis in SAP2000 and modelling two structural forms one with a fixed base and another with MSI are examined the dynamic response of each structure under non-SSI and SSI conditions, measuring fundamental natural period, story displacement, story drift, and base shear. The findings reveal that using an MSI significantly enhances the overall seismic performance of tall buildings by increasing their fundamental period, reducing their base shear, and decreasing their story displacements when compared to the fixed-base form. Additionally, considering the soil allows for additional flexibility during the analysis of the buildings response to seismic loading.

Keywords: Middle storey isolation, Soil structure interaction, Seismic response, Time history analysis, High rise buildings.

1. INTRODUCTION

As cities grow due to rapid urbanisation and population pressure, there is increasing need for multi-storey and high-rise buildings, and a requirement for incrementally higher buildings in metropolitan areas with a limited supply of land accessed relatively easily. The vertical construction gives some efficiency in land use in accommodating urban population growth but retains adverse structural characteristics linked to growth in building height and

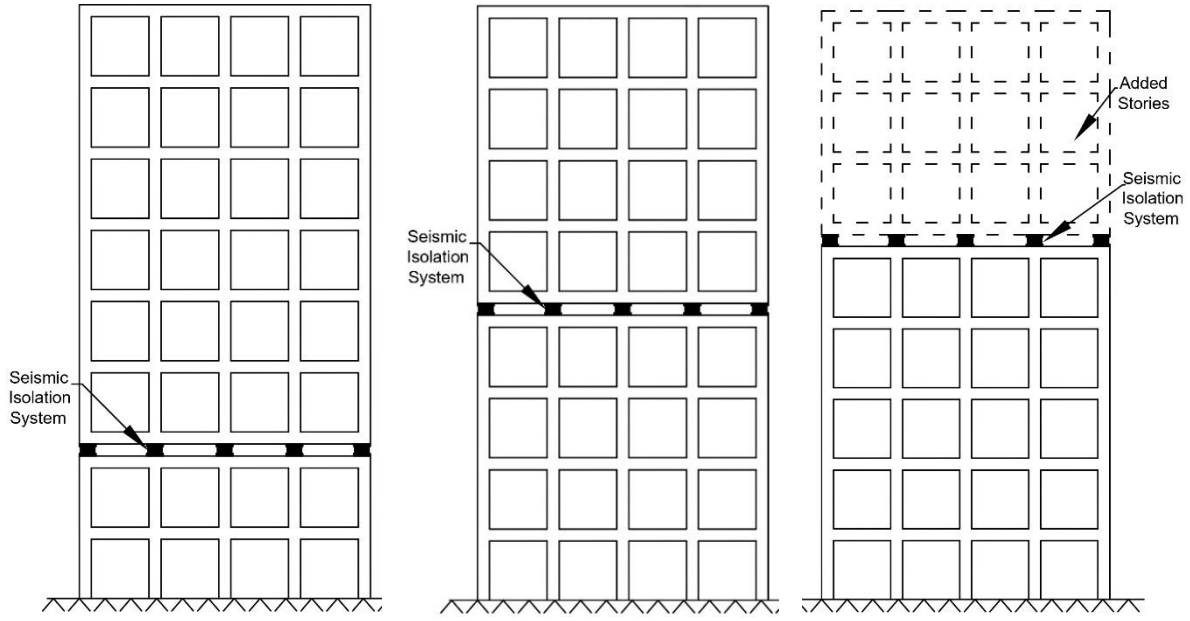
flexibility such as varying sensitivity to dynamic loads like earthquakes and motion of wind forces [1-3]. The dynamic behaviour is altered in tall buildings with longer periods and smaller lateral stiffnesses, exposing them to seismic excitation with an increase of excessive lateral building motion with inter-storey drift and vibration of the structure giving adverse influence on safety and serviceability performance of the structure as a whole [4-6]. The structural motion excessive in extent and generally of damaging kind subsequently threatens stability of the building with severe damage being caused in mechanical systems, non-structural parts of the building and its contents apart from damaging deformation of the building itself and its structural components giving rise to disastrous economic loss [7–9]. So serious has such a phenomenon of lack of control of structural response caused by earthquakes and motion of the ground been evidenced in previous earthquakes throughout the world that in some sections of mains earthquake which had the good fortune to escape serious catastrophe it was found that amongst the worst victims were reinforced concrete and steel structures which suffered to also great of a degree by way of excessive lateral deformation and lack of capacity of energy absorption [10–12]. We note this and preach caution in the case of design of buildings which is to be capable of limiting the building degrees of response in a strong shaking of the structure during the earthquakes [10]. Typical direction of earthquake design procedures assumes a fixed-base in which that an assumption is made of a rigid body on the ground and the motion transferred through into the structure itself from the ground directly into the superstructure [13–15]. When such assumptions are made, inertia forces generated during a strong earthquake have the potential to produce large base-shear forces and additional internal stresses in structural elements [16–18]. The traditional approach has been to resist such effects by increasing the strength, stiffness, and ductility of the structure by proper choice of structural configuration, and materials detailing [19–21]. Although such measures are adequate to prevent collapse of the structure and safeguard life, they entail considerable inelastic deformation, and structural damage when exposed to violent earthquake shaking [22–24]. If stiffening of structure becomes necessary to prevent excessive distortion, the use of more rigid structures means larger forces become imparted to the building leading to even larger demand on structural members [25–27]. Thus, on balance, modern practice in structural design oriented progressively towards vibration control approaches that seek to reduce structural response by less ratio of resisting forces to the earthquake forces [28–30]. Of the several the approaches to vibration control that have emerged in recent years, one of the most effective is the development of isolation systems, which ultimately separate the superstructure from ground motion [31–33]. By the use of isolating devices of low dynamic stiffness located between the superstructure and the

supporting foundation, the isolation system tends to decouple the structure from ground motion and permit a relative displacement between superstructure and ground. Not unduly concerned in developing a system to resist earthquake forces, the purpose of the control through isolation is to increase the flexibility of the structure and modify the dynamic characteristics of the resultant structural system in such a way as to lengthen the natural period of vibration of the structure. Skewing the natural period away from the natural period of excitation of earthquake ground motions thus leads to decreased resonance effects between the building and the main frequency content of the earthquake motion and decreases the amount of seismic energy transferred to the superstructure [34–36].

Many analytical, numerical and experimental studies compare the performance of isolated structures versus conventional buildings. These studies show that isolated structures perform better in earthquakes than fixed–base buildings. Seismic isolation significantly reduces base shear, floor accelerations and inter-storey drift of buildings subject to earthquake ground shaking [37–39]. Consequently, isolated structures sustain less structural damage and are more functional following earthquakes. Reduced levels of acceleration also protect non-structural components and sensitive equipment located in buildings particularly for hospitals, emergency facilities and critical infrastructure [40–42]. Due to these benefits, seismic isolation is widely adopted as an effective method of improving the seismic performance of buildings in earthquake prone regions [43-45]. Notwithstanding the marked improvements in seismic response obtained, base isolation in tall buildings may be inhibited for various practical reasons. Positioning isolation devices at the level of the foundation in general, requires more complicated construction methods, larger foundation systems and additional cost [46–48]. The design of tall base-isolated buildings entails particular concern regarding lateral stability, the demand at the separation interface and system compatibility. For this reason, alternative isolation forms are being sought which may provide for effective vibration reduction, with reduced cost, and complexity [49–51]. One other alternative that appears promising is the inter-storey isolation, isolating the structure at some level the above ground. This approach does not place the isolation units at the base of the structure but rather provides such at an intermediate level in the structure. The portion of the building above the isolation level behaves as an isolated superstructure, while the lower portion of the building serves as its stabilizing substructure and foundation [52–54]. The advantages provided by this arrangement include little, or even no modification of the foundation, lower cost and simpler adaptation to existing buildings, and, in some instance, consideration of critical portions of a structure rather than the entire structure as a whole. Middle-storey isolation is particularly useful when additional stories

are placed on existing buildings, and when foundation condition causes difficulties with a conventional base isolation system [55–57].

Various conceptual configurations of middle-storey isolation systems in multi-storey buildings are illustrated in Fig. 1 (inter-storey isolated buildings with large upper structural mass; middle-storey isolated buildings; inter-storey isolation used in vertical expansion of existing structures). The aim of these systems is to improve the overall performance of the entire structure through control over the transfer of seismic forces between portions of structures.



(a) Inter-storey isolated building with large upper structural mass

(b) Middle-storey isolated building

(c) Inter-storey isolated building with added stories on existing building

Fig. 1. Inter-storey Isolation System in building at various Heights

Previous studies have indicated that inter-storey isolation systems can be characterized as effecting reduction in seismic forcing deformation overall structural displacement, and dynamic response of the building of all other storeys above it subjected to reasonable earthquake loading [58–60]. Isolation of a portion of the structure modifies the dynamic response of the buildings and reduces the demand on structural components above that point. Isolation devices themselves will allow a part of the energy to be dissipated within themselves in controlled deformation thus reducing the overall structural response [61–63].

Another critical factor influencing the seismic response of buildings is the interaction between the structure and the supporting soil. In many structural analyses, the foundation is

assumed to be perfectly rigid and fixed to the ground; however, this assumption may not accurately represent real field conditions. In reality, the flexibility of the soil can significantly influence the dynamic behaviour of structures during seismic excitation [64–66]. This phenomenon, commonly referred to as soil–structure interaction (SSI), describes the mutual interaction between the structure, foundation, and surrounding soil during dynamic loading conditions [67–69]. SSI can alter the natural vibration characteristics of structures by increasing the overall flexibility of the structural system and modifying the distribution of seismic forces. As a result, structural parameters such as displacement response, base shear, and internal force distribution may be significantly affected [70–72]. The interaction between the structure, foundation, and surrounding soil during seismic loading is illustrated in Fig. 2, which presents a schematic representation of soil–structure interaction affecting structural response during earthquake excitation.

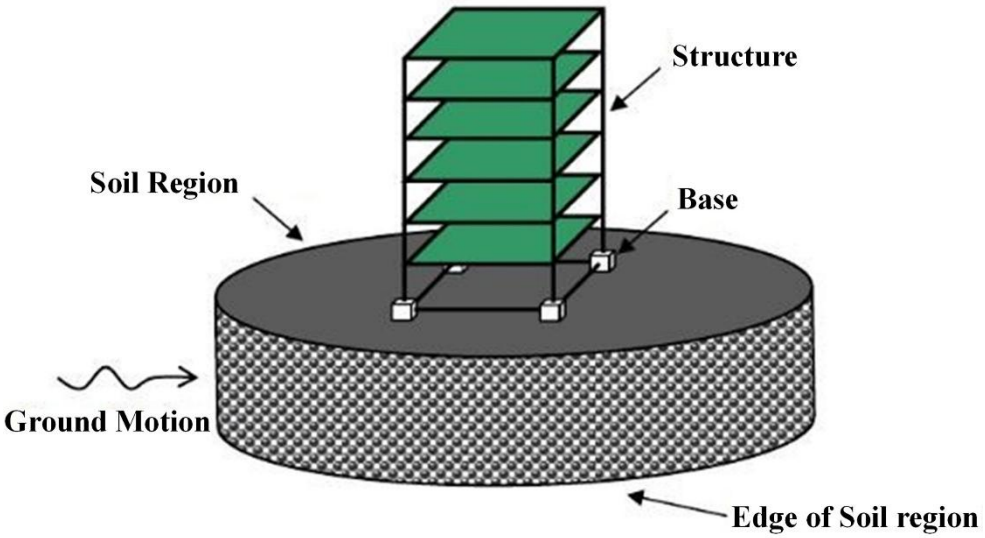


Fig. 2. Schematic representation of Soil Structure Interaction affecting structural response during seismic loading [91].

In general, the structure and soil below it interact most significantly with soft or medium soil deposits that deform considerably as a result, and where soil deformations constitute a significant part of the overall dynamic response of the building [73–75]. Studies made analytically and experimentally have shown that neglecting the effects soil may have, and assuming the structure is either simply founded or braced against an infinite rigid foundation, can lead in some cases to erroneous predictions of its seismic demand or performance [76–78]. In some circumstances the structure produces so little displacement at the top that the displacement response is the top storey is rather less, tending to match the approximate centre

of stiffness of the structure. Counter intuitively, ignoring the flexibility of the soil can predict overly large values for force in the structure, or too small a movement response, based on soil properties and structure [79–81].

Historically, extensive research has been performed to investigate seismic isolation systems and soil and structure interaction separately; however, most published research has primarily analysed base-isolated structures using fixed-base assumptions. Fewer studies have been completed that examine the combined effects of middle-storey isolation systems and soil structure interaction on the seismic performance of RC buildings [82–85]. The combined effects of both mechanisms can greatly influence the overall structural response; this is of particular concern for multi-storey buildings located in regions with highly variable soil conditions. Therefore, an assessment of the combined effects of middle-storey isolation systems and soil–structure interaction on the structural performance of buildings is crucial to improving the reliability of seismic performance assessment. Understanding how these components interact will provide further information to develop more effective vibration control techniques for multi-storey/high-rise buildings [86–90]. Such investigations will help develop safe and resilient structural systems, which can withstand the forces of an earthquake and reduce damage and maintain functional performance.

This study looks at how the middle-storey isolation system (MSIS) and the structure/soil interface impact the overall performance of reinforced concrete (RC) buildings under seismic loading. The authors compare a conventional (fixed) concrete (RC) building with a middle-storey isolated (MSI) concrete (RC) building to evaluate how the use of a middle-storey isolation system impacts the overall structural response. The authors developed finite-element models of a 12-storey RC building and applied linear time-history analysis to evaluate the seismic performance of each model. The study assessed how three different types of soil (hard, medium, and soft) affected the overall response of the structure by simulating realistic foundation behaviour. The key parameters used to compare the ability of the middle-storey isolation system to reduce the seismic demands on a structure and improve its performance were the natural period, base shear, and storey displacements.

2. RESEARCH SIGNIFICANCE

Tall buildings are being constructed at an increasing rate due to a growing demand for vertical urban development. Tall buildings are more flexible and sensitive to dynamic loads such as earthquakes and wind compared to low buildings. Conventional seismic design methods focus on increasing a building's structural strength, stiffness and ductility to prevent collapse;

however, these methods still allow for large amounts of structural damage during major seismic events, resulting in large repair costs and downtime of the building. Vibration control technologies (e.g., base isolation systems and supplemental damping systems) have been increasingly adopted by modern structural engineering to mitigate seismic response by dissipating energy and/or altering the dynamic characteristics of buildings. Base isolation systems decouple the superstructure from the movement of the ground, thereby increasing the fundamental period of the structure and significantly attenuating the transmission of seismic forces; however, damping devices will also increase the amount of energy dissipated through damping and reduce structural vibrations. While vibration control technology has been proven effective in reducing the seismic response of tall buildings, there is still uncertainty with respect to the application and performance of vibration control systems in tall buildings due to the complex interactions between structural configuration, mass distribution and control mechanisms. Therefore, the current research project is of particular significance because it evaluates the seismic performance of tall buildings with advanced vibration control systems using analytical techniques, including evaluation of the maximum displacement, maximum base shear, and maximum storey drift. The results of the current research project will provide additional insight into vibration control technologies improving the structural resilience and seismic safety of tall buildings and ultimately assist researchers in developing efficient seismic design strategies for earthquake-resistant tall buildings in seismically active regions.

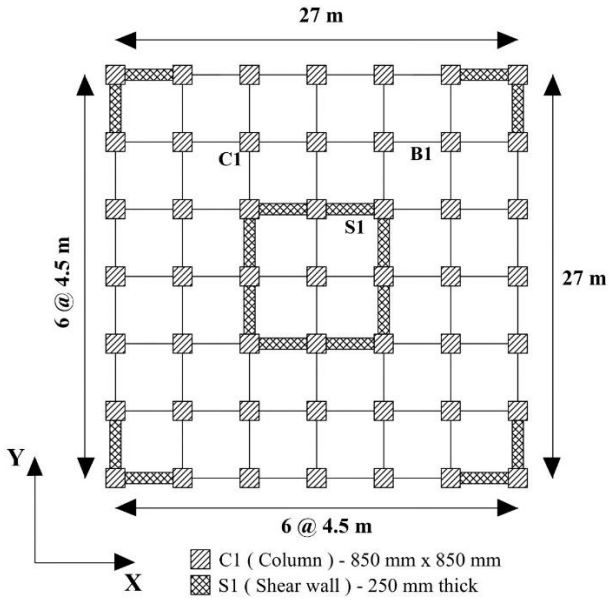
3. ANALYTICAL PROGRAM

The objective of this study is to evaluate the effectiveness of middle-storey isolation systems in reinforced concrete buildings considering soil structure interaction (SSI). The analytical program focuses on modelling and analysing the seismic performance of structures by incorporating SSI effects. Linear Time History Analysis (LTHA) is carried out on two twelve-storey building models: a conventional fixed-base structure and a building with a middle-storey isolation system. The analysis is performed using the finite element software SAP2000 (Version 25). Before conducting this analysis, the required input data for the numerical models, such as the ground motion records, soil parameters and isolation system properties, were collected and incorporated into the finite element program SAP2000. The purpose of the analysis was to conduct a comparative study on the seismic responses of both types of structural configurations under different soil conditions. Both responses were compared to determine how middle-storey isolation would help reduce the response of the building to earthquake loadings. SAP2000 is a very popular finite element program for performing two-dimensional

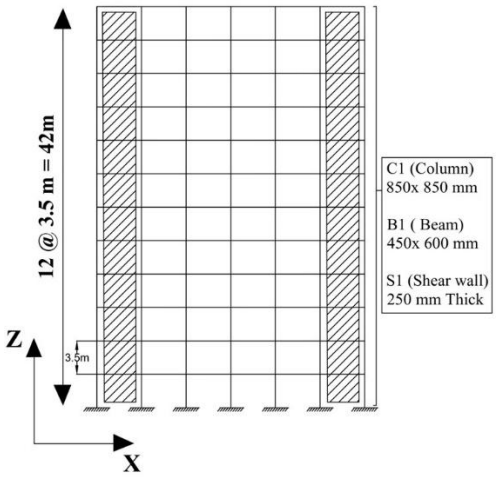
and three-dimensional static and dynamic analyses. Additionally, SAP2000 provides a very efficient way of modelling and including the different types of devices that could be used with isolation, including linear bearings, low-damping rubber bearings, lead rubber bearings, flat sliding bearings, and friction pendulum bearings. Furthermore, SAP2000 provides a linear time history analysis, which allows the user to evaluate the response of a structure to time-dependent loadings such as earthquake ground motions.

3.1. Building Model Description

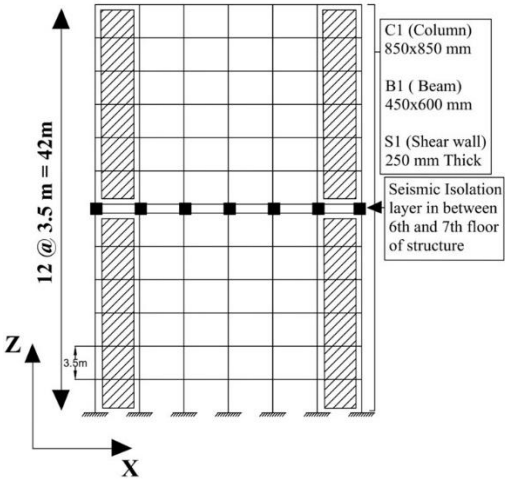
Figure 3a provides the plan layout for the 12-storey building that is being evaluated in this study. The building has six bays in both the X and Y directions, each with a span of 4.5 m, giving the building a total plan area of 27 m × 27 m. The elevation views of both the fixed-base and middle-storey isolated (MSI) building are shown in Figures 3b and 3c, respectively.



a) Typical floor plan view of 12-storey building



b) Profile view of fixed-base building model



c) Profile view of MSI building model

Fig. 3. Structural layout of fied-base and middle storey isolated building models

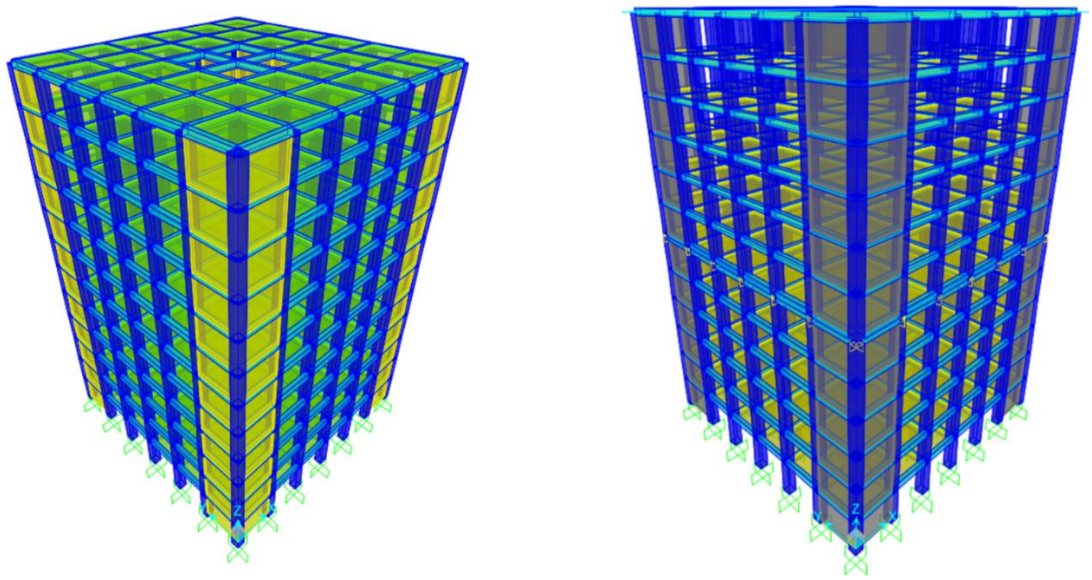
The building has a total of 12 levels, each level being approximately three and a half metres high. Both configurations use steel and concrete (reinforced concrete) framing systems. There are three types of structural members in this building, including 850 mm × 850 mm columns, 450 mm × 600 mm beams, and 150 mm-thick slabs. In addition, there will also be shear walls made of reinforced concrete with a thickness of 250 mm. The geometric properties of each these configurations are captured in Table 1.

Table 1. Geometric and structural properties of the building models

Description	**Building Data**	
Type of building	Fixed-base Building	Middle-storey Isolated Building
No. of storeys	12	12
$length \times width$	$27m \times 27m$	$27m \times 27m$
Storey height	$3.5m$	$3.5m$
Column dimension	$850mm \times 850mm$	$850mm \times 850mm$
Beam dimension	$450mm \times 600mm$	$450mm \times 600mm$
Slab thickness	$150mm$	$150mm$
Shear wall thickness	$250mm$	$250mm$
Type of Isolator used	-	Lead Core rubber bearing
Location of Isolation System	-	$In\ betwwen 6^{th} and\ 7^{th} floor$
Natural period	$1.5517sec$	$1.7527sec$
Seismic weight of building	$1.4522 \times 10^5 KN$	$Upper\ structure - 6.9587 \times 10^4 KN$ $Lower\ structure - 7.5633 \times 10^4 KN$

The compressive strength of the concrete used for all structural components is 40 MPa (grade M40). Steel reinforcement for longitudinal and transverse reinforcement will be provided by high yield strength deformed (HYSD) bars with a yield strength equal to 500 MPa. The shear walls are provided with symmetric locations along the building's core and at the perimeter, providing an increased level of structural stiffness while also providing lateral load and torsional load resistance. The seismic zone the building is assumed to be in is Zone V according to IS 1893:2016, with an importance factor (I) of 1.5, which categorises the building as an important structure. Each model will have the following loading assumed: floor live load = 3 kN/m²; floor finish load = 1.5 kN/m²; wall load on beams = 5.25 kN/m. All models will be supported by a 6-m-deep mat foundation. The two configurations of buildings analysed for this study are a conventional fixed-base building and a middle-storey isolated (MSI) building. Between Level 6 and Level 7 of the MSI configuration, lead-core rubber bearings (LCRBs) have been installed, which is shown in Figure 3 (c). This combination subdivides the structure into an upper substructure and a lower one, providing for a reduction in seismic force transfer to the upper part of the building. Three-dimensional extruded views of the fixed-base isolated

building model and middle-storey isolated building model appear in Fig 3 (a) and Fig 3 (b). The Figure 4 indicates the extruded view of fixed based and middle storey isolated building models.



(a) Fixed Base Building Model **(b)** Middle Storey Isolated Building Model

Fig. 4. Extruded view of fixed based and middle storey isolated building models

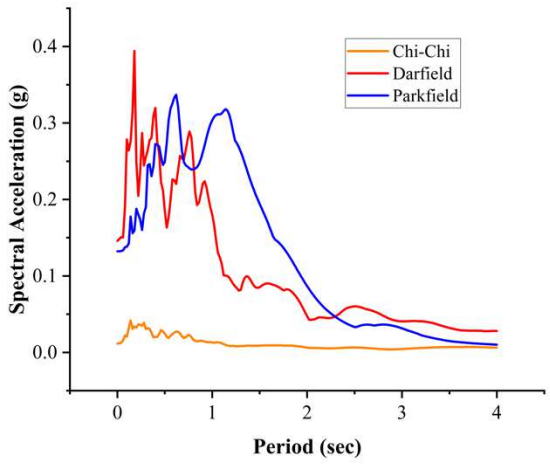
3.2. Earthquake Ground Motion Data

The ground motions used were used to investigate the seismic performance of the structure models "by means of nonlinear time-history analysis (LTHA)" performed under the recorded earthquake ground motions. By using the Time-history analysis to study the buildings response is more realistic as we're imposing the actual records directly to the model. Three earthquake records as well as select, were selected to be different faults/frequencies, etc…these include Chi-Chi (1999), Darfield (2010), and Parkfield (2004). These were selected, since they varied between them and were more moderate to just powerful etc. And fall in a particular frequency content that can be used in multi-storey buildings. They were also all derived from PEER ground motion and scaled accordingly to the design response spectrum etc. We also have a strike-slip and reverse fault and were selected to be compared in the study. All is summarized in Table 2.

Table 2. Characteristics of selected earthquake ground motions

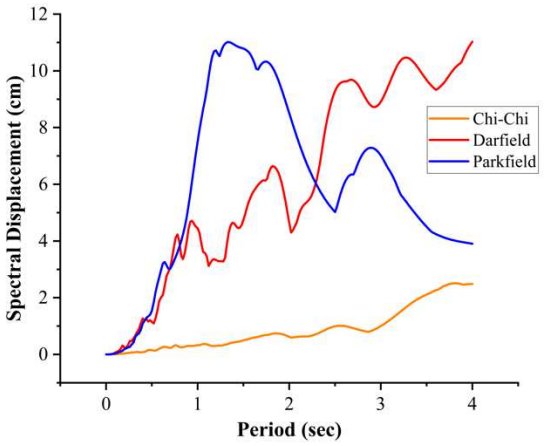
Earthquake	year	Moment Magnitude (M_W)	Fault Mechanism	V_s30 ($^m/_s$)
Chi-Chi	1999	6.36	Strike-slip	542
Darfield	2010	6.0	Reverse Oblique	481
Parkfield	2004	6.2	Reverse	375

The selected earthquake ground motions for the nonlinear time-history analysis are shown in Fig. 5(a), where the acceleration time histories of the selected records are shown. The time histories represent the variation of ground acceleration with time. The selected ground motions are shown in Fig. 5(b) for their response spectra, which represent the maximum structural response over a span of vibration periods. The response spectra were considered so that the selected earthquake records are representative of the seismic demand used in the analysis.



(a)

Fig. 5(a) The acceleration response spectra of distinct earthquakes



(b)

Fig. 5(b) The displacement response spectra od distinct earthquakes

3.2.1. Spectral Matching of Ground Motions

Spectral matching was performed to ensure that the selected earthquake ground motions are consistent with the target design response spectrum requirement. Records of real earthquake require for specific site conditions for analysis to fit the design spectrum drew from the PEER database. For this reason, the ground motions were modified by spectral matching in order that the response spectra closely follow the target spectrum. This procedure eliminates variability in ground motion characteristics and allows for the more accurate evaluation of results from nonlinear time-history analyses. The matched response spectra for these motions are shown in Fig. 6.

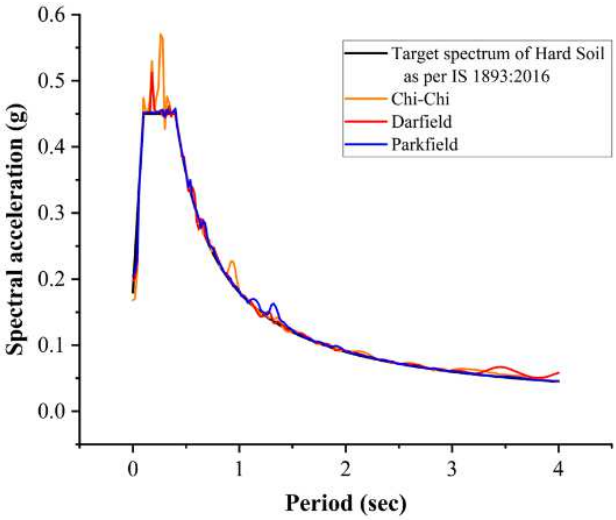


Fig. 6. Response spectrum data of earthquake records after spectral matching

3.3. Soil Profile and Geotechnical Properties

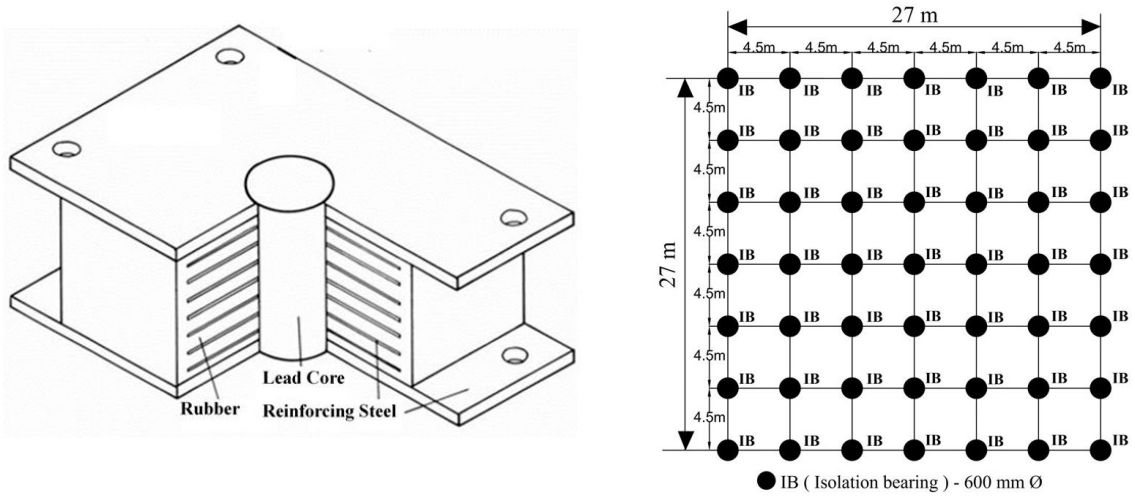
The soil characteristics conditioner the seismic response of the structure. For modelling the soil-structure interaction, three types of soil have been analysed type 1 being hard soil, type 2 medium stiff soil, type 3 soft soil). The soil profile, with a total depth of 30 m comprising of six layers was modelled beneath the foundation. The geotechnical parameters baseline data for the values of shear modulus, Ge, elastic moduli, Ee, and Poisson's, ν, of the soil and its density ρ, are from work done by others which are prescribed to be used for soil-structure interaction analysis. The soil properties are shown in the Table 3.

Table 3. Soil properties used in SSI Analysis

Soil Type	Thickness (m)	Shear modulus $G\left(KN/m^2\right)$	Elastic modulus $\left(KN/m^2\right)$	Poisson Ratio(v)	Density $\left(KN/m^3\right)$
Hard soil	5	30000	72000	0.20	18
Medium stiff soil	5	20000	50000	0.25	20
Soft soil	5	10000	26000	0.30	22

3.4. Base Isolation System

The isolation system adopted here in this work are LRBs. Lead Core Rubber Bearings (LRBs) have been used for the middle-storey isolated building models. Lead Core Rubber bearings (LRBs), consisting of a core of lead, are sandwiched by steel shims, are used for vertical load-carrying capacity and are surrounded by layers of reinforced rubber so as to enhance lateral flexibility. The central lead core deforms plastically under the effects of loading during earthquakes, permitting considerable energy dissipation. The configuration and installation of the LRB in the building model in a sectional view is shown in Fig. 7.



(a) (b)

Fig. 7. Lead core rubber bearing (LRB) used in the study: a) Schematic configuration of LRB; b) Plan view of Isolation system at middle-storey isolated building model.

The design specification of the LRBs considered in this study is adopted from the earlier study where the diameter was 600 mm, the total rubber thickness was 110 mm, and the lead core diameter was 90 mm. The shear modulus of rubber in this work is taken as 1 N/mm², the initial yield stress of lead is taken as 10 N/mm². Other mechanical properties principally effective stiffness, equivalent stiffness, yield force and vertical stiffness used in the numerical model are reported in Table 4.

Table 4. Mechanical properties of Lead core Rubber Bearings (LRB) used in the numerical model

Isolator Description	Data
Type of Isolator	Lead Core Rubber Bearing (LRB)
Effective diameter $(mm)D_0$	600
Total thickness of rubber, $D_t(mm)$	110
Diameter of lead core, $D_L(mm)$	90
Shear modulus of rubber, G	$1N/mm^2$
Initial yield stress of lead, σ_{YL0}	$10\ N/mm^2$
Effective stiffness $K_{eff}(KN/m\ )$	13,110
Equivalent stiffness $K_e\ (KN/m\ )$	1,580
Vertical stiffness $K_L(KN/mm)$	2,800
Yield force$F_Y\ (KN)$	63.0

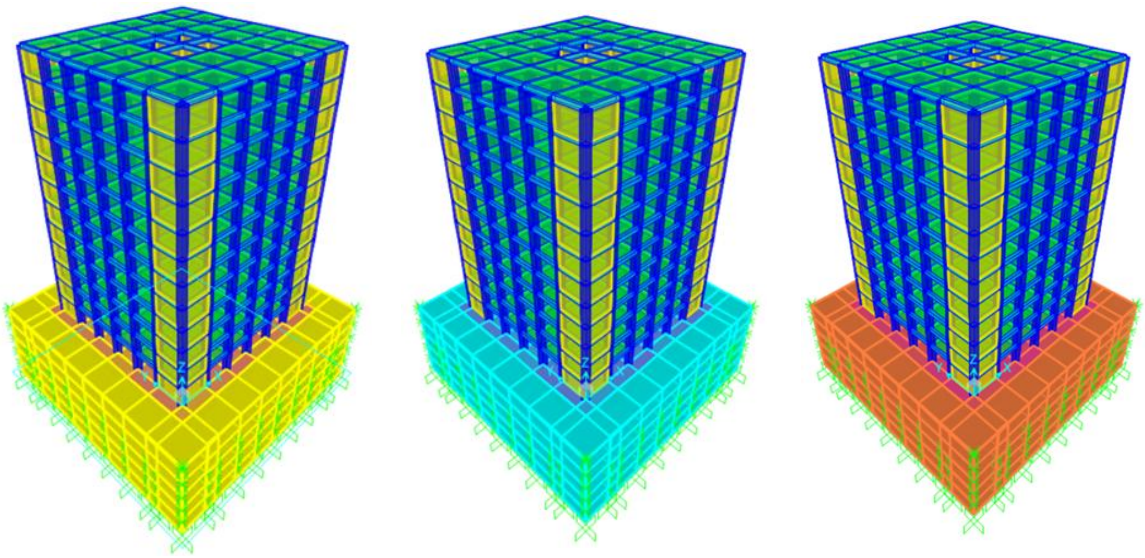
No of Isolators	49

In the model, the LRBs were installed at the top of the columns up to the sixth storey resulting in a middle-storey isolation system between the 6th and 7th storey. The bridge between these isolators in terms of their hysteretic behaviour due to seismic excitation was considered in SAP2000 using nonlinear link elements with six spring components.

3.5. Soil Structure Interaction Modelling

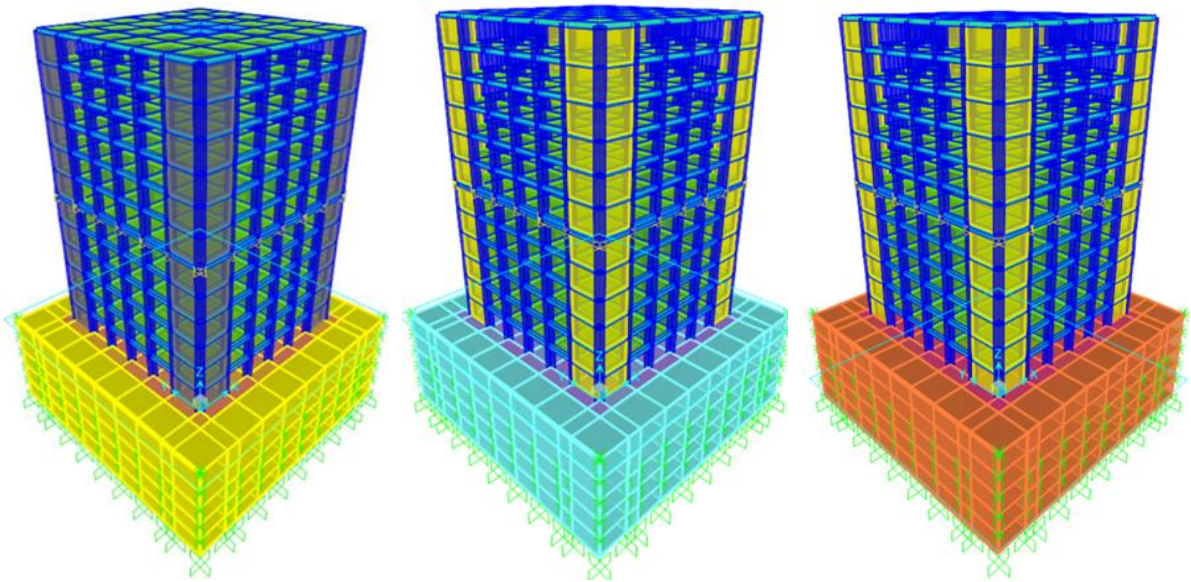
As an extension of the study to be discussed below, effects of soil–structure interaction (SSI) on the seismic response of the isolated and fixed-base version of a 12-storey building models are studied in this research work. The classification of soil was classified into three, hard soil, medium stiff soil and soft soil in identifying the effects of site conditions on isolation system. Method to accommodate SSI effects also varied in that, the direct approach where the soil domain and the structural system is jointly modelled and solved simultaneously are used in this paper. The modelling phase began with developing the general configuration of both building models considering the structural properties presented in Table 1. In both configurations, the foundation system was simplified to a mat foundation, with a depth of 6 m. A linear elastic solid element was used to define the foundation, which acted to ensure that the loading of the superstructure would be imparted evenly throughout to the supporting soil media. This foundation typology distributes superstructure loads to the supporting soils in this manner, and assists in reducing the chances of differential settlement accordingly. For both the fixed-base and middle-storey isolated building configurations, the foundation was rigidly connected to the soil domain pertaining to each soil condition; the difference being the addition of a sixth-storey system of seismic isolation to the top of the storey in the middle-storey isolated model. For the assessment of SSI, the surrounding soil was described as a three-dimensional continuum by solid elements representing a bounded volume of deformable matter responding within the set of equations of solid mechanics. Interface elements were added along the soil–foundation boundaries to obtain the respective, relative interaction behaviour of the soil and the system; this relative interaction behaviour is taken account of by the use of interface elements, which enable the transfer of forces and displacements between the soil and the system to be described more realistically. The soil types are of different geotechnical properties and exhibit very different responses from the structure: hard soil is stiff and of low compressibility and the SSI effects are also relatively small; medium stiff soil is of less stiffness than the first and produces a mild SSI influence; soft soil is noted as low stiffness hence of high compressibility behaviour and this can produce a significant SSI effect. A suitable meshing was done for the structures, soil continuum and interface elements during the numerical

modelling. The SSI models for the fixed-base and middle-storey isolated buildings on different soil conditions is shown in Fig. 8 and Fig. 9 respectively.



a) Hard soil **b)** Medium stiff soil **c)** Soft soil

Fig. 8. Fixed base building models under different soil conditions



a) Hard soil **b)** Medium stiff soil **c)** Soft soil

Fig. 9. Middle storey isolated building models under different soil conditions

4. RESULTS AND DISCUSSION

After Modelling, the fixed base and middle-storey isolated building models under SSI and NSSI were analysed in SAP 2000 for the consideration of soil structure interaction. The linear time history analysis was used to determine the three considered parameters, Natural period of vibration, Base shear, and Top storey displacements of the structure. Further results of the said

parameters were discussed in this section for the knowledge of isolation systems for buildings in the context of soil-structure interaction.

4.1. Natural vibration periods at different modes of vibration

The natural period of vibration is the period that corresponds to the natural frequency at which a structure will oscillate if it is imparted an initial vibration motion and allowed to vibrate freely. It is a property of the structure, and the mass and stiffness of the structure will play a role in this frequency period. Seismic performance is assessed based on this period as ground motion may induce high vibrations, causing destruction to structural systems if they resonate with this motion. Comparing the natural period of vibration at different modes will give insight into the dynamic properties of both the fixed-base structure as well as the middle-storey isolated structure. The comparison of natural vibration periods at different modes for the fixed base structure and the middle-storey isolated structure without soil structure interaction (NSSI) is shown in Fig. 10 and with soil structure interaction (SSI) in Fig. 11.

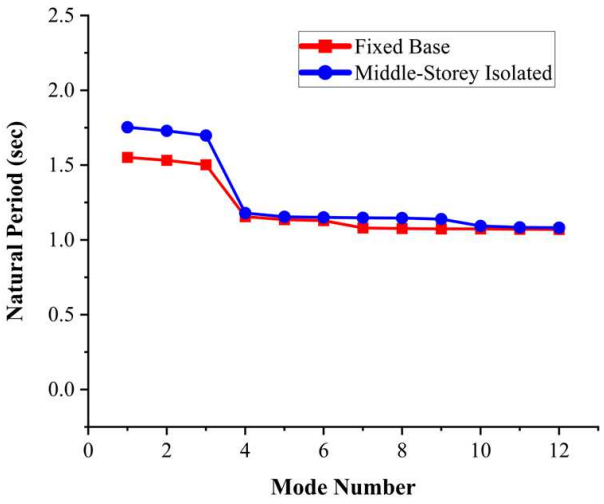
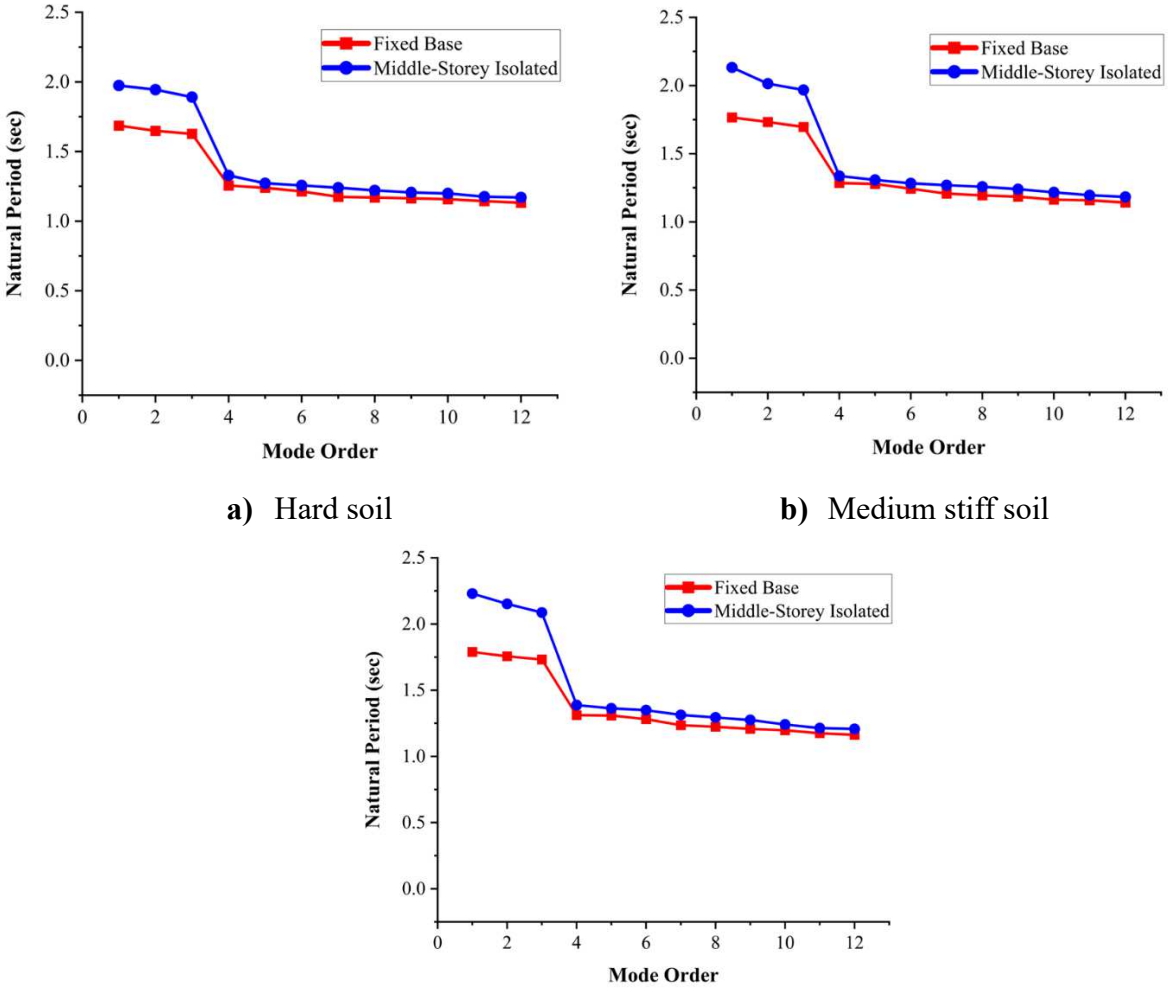


Fig. 10. Comparison of natural vibration periods for fixed-base and middle-storey isolated buildings without SSI considerations.



a) Hard soil **b)** Medium stiff soil

(c) Soft soil

Fig. 11. Comparison of natural vibration periods under SSI for different soil conditions: a) hard soil, b) medium stiff soil and c) soft soil.

To quantify the influence of middle-storey isolation, the percentage increase in natural period is reported, using the fundamental mode of vibration instead, as it represents the first, and hence, strongest mode of vibration of the structure. As it governs most of the dynamic behaviour of the structure it is highly used in seismic performance, and performance based designs. The percentage increase in fundamental period for middle-storey isolated buildings with respect to fixed-base model for both NSSI and SSI conditions is shown in Table 5 and graphically in Fig. 12.

Table 5. Percentages increase in Fundamental mode of vibration

Condition	Fixed-Base structure (sec)	Middle-storey isolated structure (sec)	Percentage increase in fundamental mode of vibration at middle-storey

			isolated structure with respect to fixed base (%)
NSSI	1.551794	1.752705	11.46291019
Hard soil	1.685946591	1.973997223	14.59225113
Medium stiff soil	1.765832946	2.13298245	17.21296413
Soft soil	1.788877087	2.229914809	19.7782319

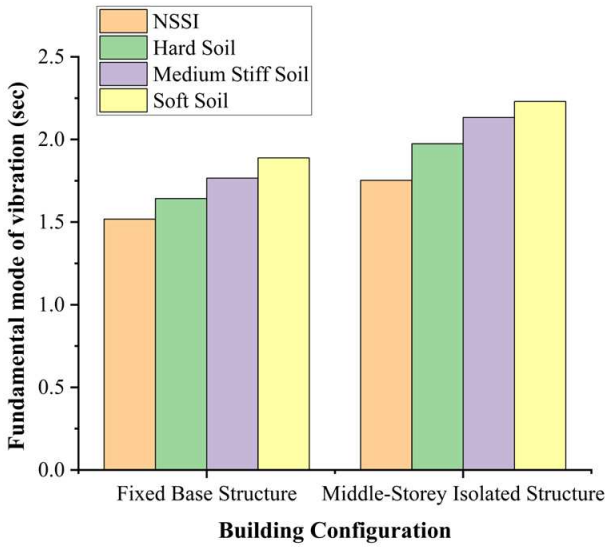


Fig. 12. Comparison in Fundamental mode of vibration for Fixed-base and Middle-storey isolated building models (with NSSI and SSI consideration).

The results indicate that the middle-storey isolated building for soft soil case has longest natural periods for all vibration modes, including the fundamental mode as well. This increase is because of the added flexibility by soft soil and the isolation system located at the middle storey. On the contrary, the fixed-base building for NSSI is having the shortest natural periods (rigidly connected to building no flexibility from soil). Around 11.46% to 19.77% increase in the fundamental period is obtained for middle-storey isolated system in comparison with fixed-base model. This increase is due to additional flexibility of the isolation system, thus reducing the overall natural frequency of structure. In first mode of vibration a big part of the horizontal displacement occurs at the isolation level, such that the part of the structure above seems to move like a rigid body. A longer natural period may reduce the likelihood of resonance with the main frequencies of the ground on which it is built at the time of an earthquake. For the second and higher of vibration modes the influence of the isolation system is not that significant but definitely the natural periods remain bigger than those of fixed-base structure. These in the higher modes may be refer to bending, torsion deformation above the isolation level whose

contribution is less for overall state of earthquake response due to the energy-dissipating effect of isolation system.

4.2. Base Shear

Base Shear is a vital parameter of seismic Design as per Indian Codes. The total horizontal force acting at the base of a structure during an earthquake. It is the total horizontal force that is transferred to the foundation and is used to determine if earthquake loads will be resisted; based on an estimation of the level of base shear, may be accordingly Grovelled, or upright, as the case may be. Properly estimated base shear leads to the correct distribution of earthquake forces along the height of a building and avoids undue concentration of loads that might otherwise lead to failure. Base shear is also used to determine whether structural components and connections are capable of transferring earthquake forces to the foundation. According to IS 1893 (part 1): 2016, the design base shear is calculated using the following expression:

$$V_b = \frac{Z \times I \times (S_a/g)}{2 \times R} \times W$$

where

Z = Zone factor representing seismicity of the location

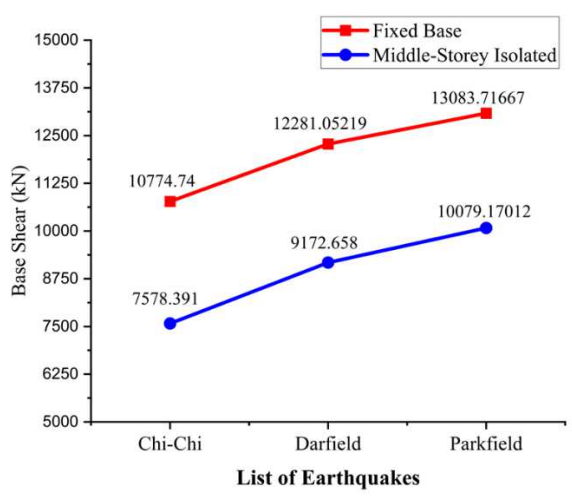
I = Importance factor of the structure

$\boldsymbol{S_a/g}$ = Average response acceleration coefficient

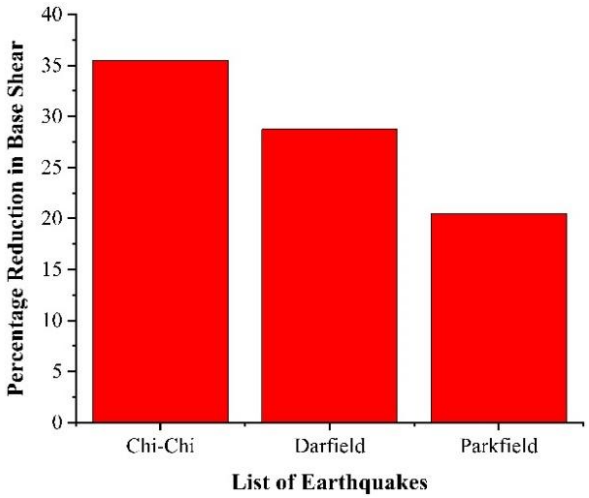
R = Response reduction factor depending on structural system ductility

W = Seismic weight of the structure

The comparison of base shear values for fixed-base and middle-storey isolated building models under NSSI conditions is shown in Fig. 13, while the results considering soil structure interaction (SSI) are presented in Fig. 14.



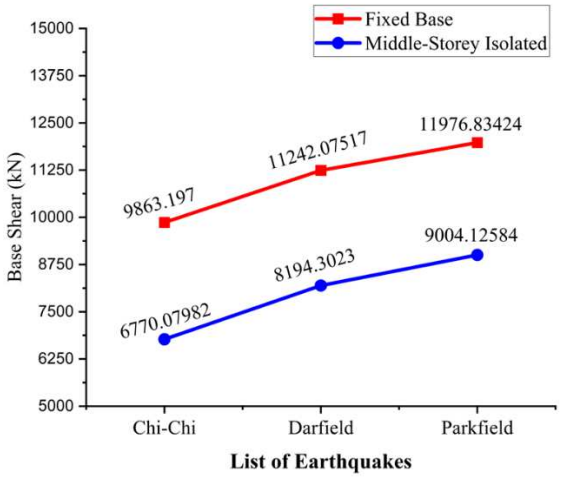
a) Comparison in Base Shear with NSSI condition



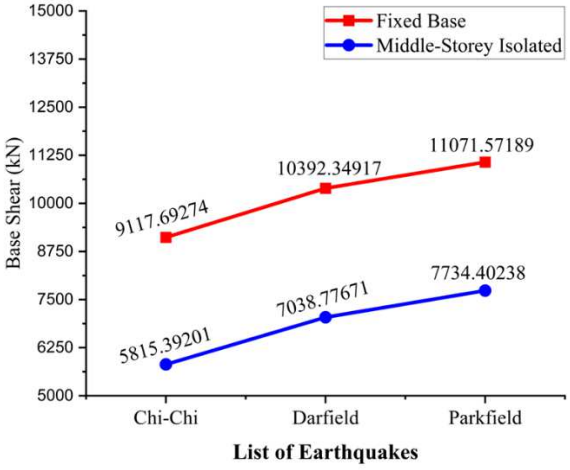
b) Comparison of percentage reduction in base shear at Middle-storey

isolated structure with respect to fixed base

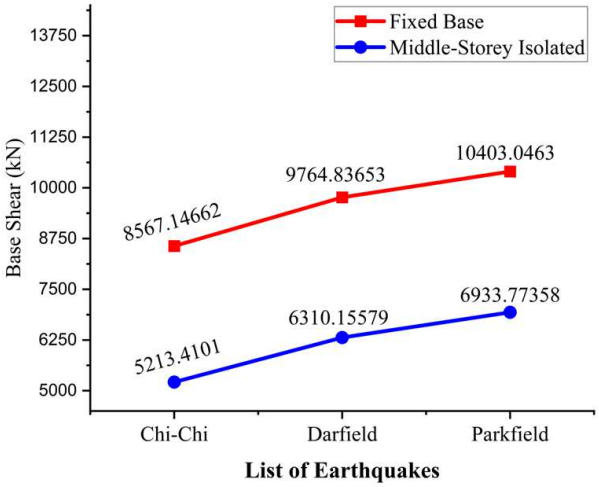
Fig. 13. Comparison in Base shear of Fixed Base and Middle-storey isolated building models (with NSSI consideration)



a) Comparison in Base shear at Hard Soil



b) Comparison in Base shear at Medium stiff soil



c) Comparison in Base shear at Soft Soil

Fig. 14. Comparison in Base shear of fixed base and Middle storey isolated building models (with SSI consideration)

To study the effectiveness of the isolated model of the middle-storey, the percentage reduction in base shear of the said model with respect to the fixed-base model was determined for all configurations. The same has been reported as Table 6 and represented graphically in Fig. 15. The analysis results made using SAP2000 indicated that the model representing the

fixed-base building under NSSI conditions displayed the maximum base shear owing to the premise of a rigid foundation. Under this, flexibility of soil is essentially neglected, and the seismic forces essentially transmitted directly to the structure, seen as Fig. 13. In comparison, the model underneath the middle-storey under soft soil conditions display the least base shear owing to its configuration. Since the configuration utilizes the flexibility of soft soil and isolation system concurrently, the structure is able to dissipate more of the seismic energy; therefore, the transmission to the base reflected in the base shear encountered is far less, indicated as Fig. 14. Table 6 shows that the reduction in base shear for the middle-storey isolated model compared to the fixed-base model varies from 22.96% to 39.14%.

Table 6. Percentage reduction in base shear of middle-storey isolated building with respect to fixed-base model

List of Earthquakes	Percentage Reduction in Base shear at Middle-Storey Isolated Structure with respect to Fixed base with NSSI and SSI Considerations (%)			
	NSSI	Hard soil	Medium soil	Soft soil
Chi-Chi Taiwan	13.19394	21.23519	28.4749	31.78
Darfield	10.44901	18.78279	25.14552	26.16
Parkfield	8.17734	17.12329	23.52071	24.762

The maximum reduction of 39.14% occurs for soft soil conditions where the flexibility of the soft soils increases the effectiveness of the isolation system at decoupling the upper structure from seismic forces, as illustrated in Fig. 15.

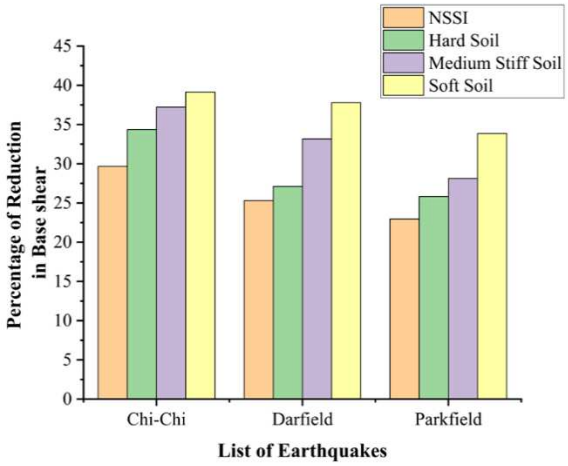


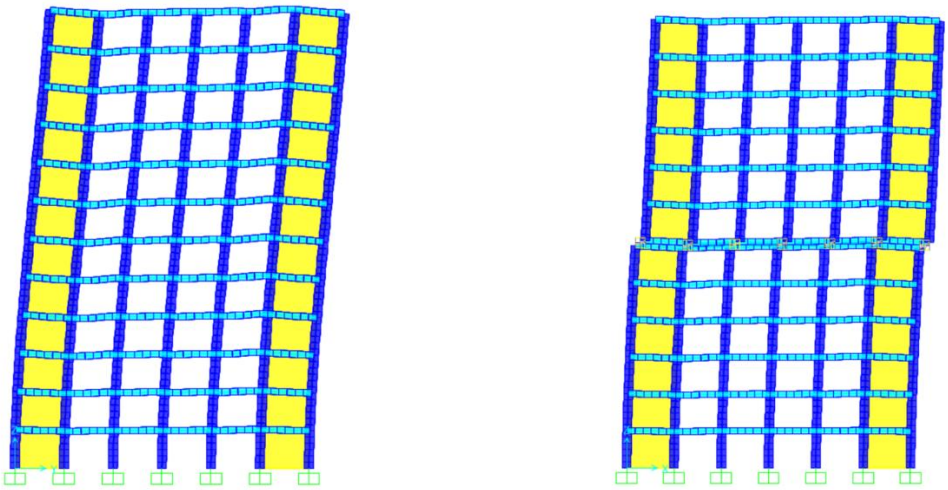
Fig. 15. Comparison of Percentage reduction in Base shear at Middle-Storey Isolated Structure with respect to Fixed base for NSSI and SSI condition

In contrast, the NSSI condition has the lowest reduction at 22.96% because rigid foundations limit the effects of soil's flexibility, despite the upper structure being partially decoupled from

seismic force transfer by using a middle-storey isolation system; the overall base shear reduction is limited by the lack of deformed soil beneath it (see Fig. 15). The findings demonstrate that middle-storey isolation can effectively reduce the transfer of seismic forces into a structure. The reduction in base shear enhances seismic performance and reduces the likelihood of structural vibrations occurring when the structure experiences an earthquake. Therefore, the greatest base shear reduction will be observed when using the combination of middle-storey isolation with soft soil conditions, but soil properties and foundation design must be given careful attention in order to provide adequate support for the structure. Furthermore, the isolation system must be designed to accommodate potential increases in relative displacements between the isolated and non-isolated building systems.

4.3. Deformed Shape

The deformed shapes of the structural models subjected to earthquake loading are illustrated in Fig. 16 the deformed shapes of the buildings subjected to earthquake loading for comparison of the pattern of deformation of the structure of the fixed-base building with the middle-storey isolated model. In the fixed-base building (Fig. 16a) the deformation is distributed along the height of the building in the usual sway action. There is no isolation with the base rigidly anchored to the foundation; hence all quantities associated with the earthquake are transmitted throughout the building and each part of the structure is deformed from the base to the top storey. In the middle-storey isolated model (Fig. 16b), it will be noticed that the deformation is concentrated at the level of the isolation. With the isolation system, as will be seen, there is relative movement of the lower and upper part of the building. The latter consequently is deformed less than the building with a rigid foundation connection. The behaviour indicates that the middle-storey isolation system absorbs a large part of the earthquake energy, so that the deformation demand on the upper structure is limited, thus allowing a more controlled response of the structure, which is beneficial in reducing damage potential in earthquake shaking.

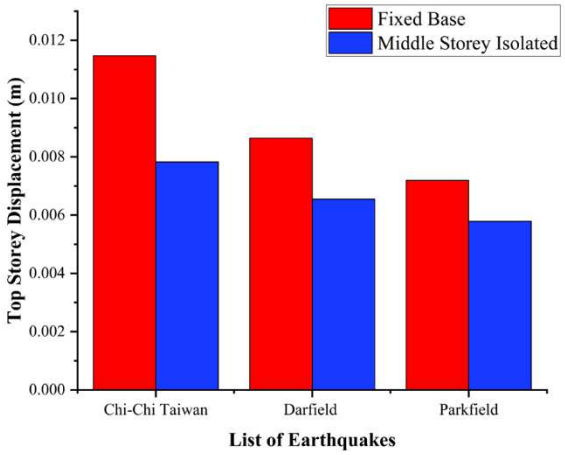


a) Fixed Base structure **b)** Middle storey isolated structure

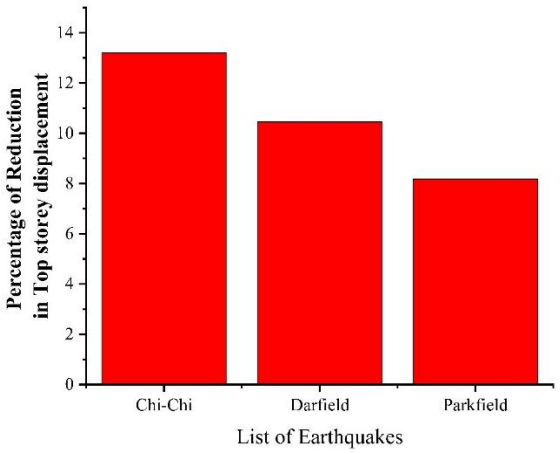
Fig. 16. Deformed shapes of buildings with different configuration

4.4. Storey Displacement

Storey Displacement is defined as the maximum relative displacement of the top storey of the building resulting from seismic (or wind) loading. This is one of the important parameters used to assess the general structural response of the building to ground shaking. Similarly, storey displacements are also used to evaluate the performance of seismic protection systems lateral load resisting systems and isolation systems. At a first approximation, the displacement of the building varies based on its height, stiffness, geometry, position and nature of seismic protection system, and soil conditions. For safe performance of the structural system, storey displacements need to be held down to a permissible limit, generally recommended not to exceed 0.004 times the storey height of the building, as dictated by IS 1893 (Part 1): 2016 for the maximum inter-storey drift that significantly govern the top storey displacement. In buildings provided with isolation systems, this limit of inter-storey drift is similarly considered for the additional flexibility provided by the isolator to the building model. The scatter of top storey displacements is similarly presented for the fixed base and middle storey isolated building models under the respective NSSI and SSI conditions in Fig. 17 and Fig. 18.

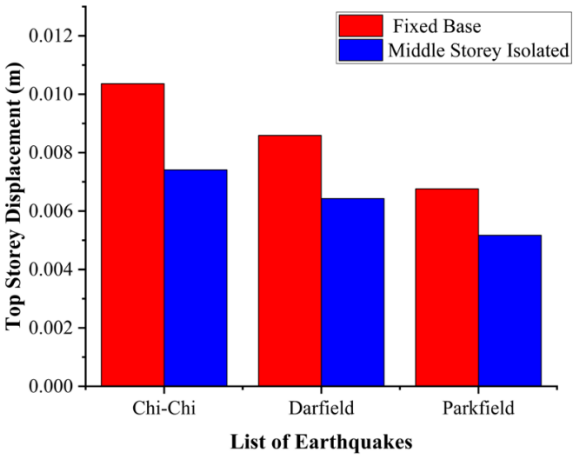


a) Comparison in Top storey displacement with NSSI consideration

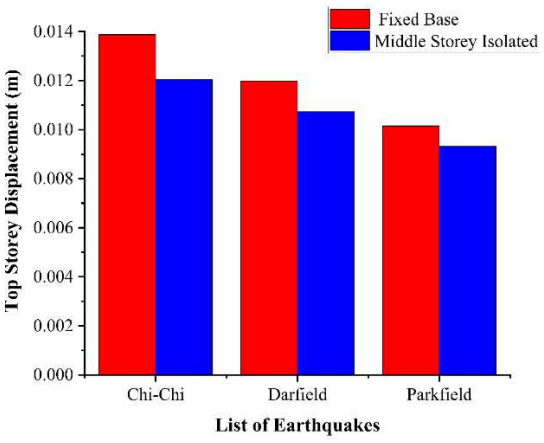


b) Comparison of percentage reduction in Top storey displacement at Middle-storey isolated structure with respect to fixed base

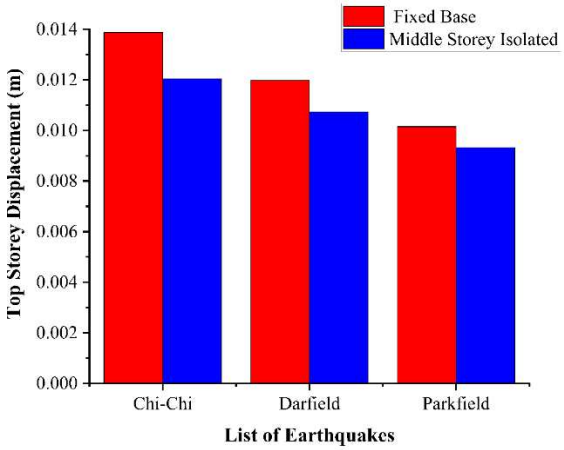
Fig. 17. Comparison in top storey displacement of fixed-base and middle-storey isolated building models (NSSI condition)



a) Comparison in top storey displacements for Hard Soil



b) Comparison in top storey displacements for Medium stiff soil



c) Comparison in top storey displacements for Soft Soil

Fig. 18. Comparison in top storey displacements of fixed base and Middle storey isolated building models (with SSI consideration)

To appraise the performance of the isolation system for difference soil condition, percentage reduction in the top storey displacement of the middle storey isolated building with respect to that from the fixed base model is presented in Table 7 and graphically depicted in in Fig. 19.

Table 7. Percentage Reduction in Top storey displacements

List of Earthquakes	Percentage Reduction in Base shear at Top-Storey Isolated Structure with respect to Fixed base with NSSI and SSI Considerations (%)			
	NSSI	Hard soil	Medium soil	Soft soil
Chi-Chi Taiwan	13.19394	21.23519	28.4749	31.78
Darfield	10.44901	18.78279	25.14552	26.16
Parkfield	8.17734	17.12329	23.52071	24.762

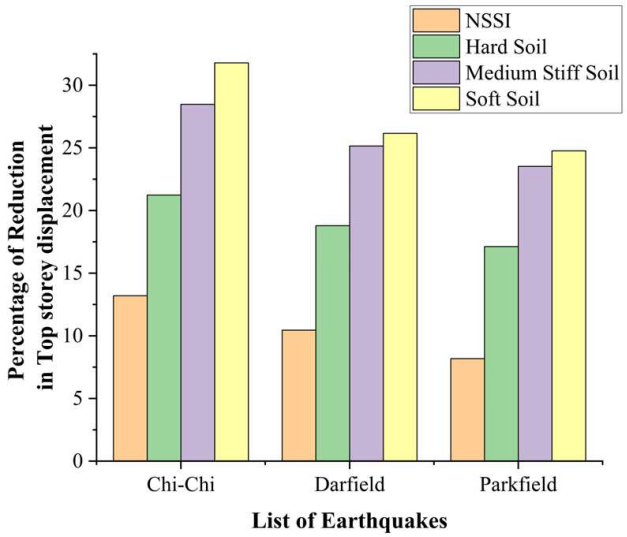


Fig. 19. Comparison of Percentage reduction in top storey displacements at Middle-Storey Isolated Structure with respect to Fixed base for NSSI and SSI condition

Displacement values of the different building models are collected from the seismic analysis of the building models in SAP2000. As perceived from the results, top storey displacement of fixed base building model under NSSI conditions hints at the highest value since the assumption made here is of a very painfully rigid foundation where soil flexibility is ignored. The seismic events are directly transmitted to the building as a consequence of this and result in bigger lateral displacements towards the top storey. The middle-storey isolated building model, on the other hand, exhibits the lowest top storey displacement in comparison with all the others considering hard soil condition. This may possibly be because of the higher stiffness of hard soil prevents excessive base movement. At the same time the isolation system ensure that some of the seismic forces affect the upper portion of the building as well, thus reducing the demand for its displacement. The percentage reduction in top storey displacement of the middle-storey isolated structure in comparison with the displacement of the fixed-base model varies from 8.17% to 31.78% as shown in Table7. The best among all configurations is of the reduction of 31.78% for the soft soil condition since this is the hardest case of soil flexibility and the isolation system more successfully decouples the upper structure from ground motion than analogous cases in which soil stiffness is neglected. On the other hand, the NSSI condition results in the lowest reduction of 8.17% because assuming the base rigid restricts the deviations of the structure generated by the soil flexibility contributions. Nevertheless, the middle-storey isolation system provides a considerable reduction in displacement as compared to the fixed base structure. All models of the building in terms of maximum top storey displacement fall well within the permissible limit of the 0.004 times the storey height (0.015 m) as specified in Clause 7.11.1 of IS 1893 (Part 1): 2016. Reducing the overall recovery of the structure reduces both structural and non-structural damage during earthquakes. This improvement is most significant for soft-soil sites where flexibility of the ground increases building displacement.

5. CONCLUSIONS

5.1. Conclusions from Study of Vibration Control Design Strategies

Vibration control design can improve the safety and resilience of high-rise buildings located in earthquake-prone areas. This review paper has studied the concepts and applications of base-isolation and inter-storey isolation systems for high-rise buildings based on their concepts and

characteristics as well as the performance of notable real building applications. This study has also reviewed the type of isolation bearings and the embodiment of performance of vibration control strategies of high-rise buildings to reduce their seismic response. From the literature survey, the following conclusions are reached:

- Vibration control approaches such as base isolation and inter-storey isolation design are effective approaches that effectively shift the natural period of a building and its participation factor from the frequency range and the state of motion where ground motion and wave amplification take place, thereby improving seismic performance.
- The base-isolated high-rise building may show less robustness due to higher mode effect and long-period ground motion and thus it is concluded that the base-isolation technique is least suited for the highlight building due to such disadvantages.
- The building at the storey level can isolate also and such treatment is the combination effect of seismic isolation and tuned mass damping (TMD). The inter-storey isolation can be applied to narrow partition for achieving better vibration control and seismic performance compared to the un-noticed techniques of base-isolated superstructures.
- The design concepts of inter-storey isolation can be applied as a seismic retrofit strategy application when a building is inserted to go vertical expansion such schemes of inter-storey isolation are said to be the added-storey isolation.

However, mere seismic isolation may not fulfil the performance criteria required of high-rise buildings, and by appending additional structural features like dampers, shear walls, and outriggers to the seismic isolators, for improved effectiveness in controlling both deformations and seismic and wind response of the structure.

5.2. Conclusions from Analytical Study on RC Building with Middle-Storey Isolation Considering Soil–Structure Interaction

Analysed the seismic performance of fixed-base and middle-storey isolated 12-storey reinforced concrete building models, both on ground (non-soil-structure interaction, NSSI, and soil-structure interaction, SSI, in site condition). The comparative studies made on the natural period, base shear and top storey displacement as the main response parameters along with the significant role of SSI for the earthquake performance studies, have drawn the following conclusions from the analytical studies:

Extended Natural Period

- The middle-storey isolated building observed to possess the longest natural period in all vibration modes including fundamental period, under soft soil.

- The natural period of the middle-storey isolated models remains 118.46% to 119.87.79 longer compared to that of numerical fixed-base building models (under NSSI and SSI).

Base Shear Reduction

- The smallest base shear among all configurations occurred in isolated building model under soft soil.
- Reduced base shear of middle-storey isolated model compared to numerical fixed-base models 22.96 to 39.14 per cent reductions (under NSSI and SSI).

Reduction in Top Storey Displacement

- The small values of top storey displacement occurred in mid-storey isolated numerical building models under hard soil.
- Percentage decrease in top storey displacement was from 8.17% to 31.78% for NSSI, and SSI.
- The maximum top storey displacement for all the building configurations was well within the limit prescribed in IS 1893 (Part 1):2016, Clause 7.11.1 that permits a maximum set of four thousandth of the storey height of 0.004 of storey height (0.015 m)

The study concludes that middle-storey isolation greatly improves the seismic performance of the buildings by increasing natural period and reducing both base shear and top storey displacement". The demand on the effectiveness of the system is higher on soft soils where the seismic response is heightened. The study promotes to incorporate the mechanism into seismic analysis and design.

Author Contributions

Lingeshwaran N – Supervision, Methodology, Reviews.
Gudipati Chaitanya Avinash – Report, Objectives, Project Work.
Syed Rizwana – Paper writing, review, References.
Manoj Kumar Thirumella – Analysis, Execution.

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Ethics, Consent to Participate, and Consent to Publish: Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

Declarations & Conflict of interest: The authors declare no competing interests**.**

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