

Performance of Base Isolated RCC High-rise Building with Fluid Viscous Damper considering Soil-Structure Interaction

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Abstract

Soil-Structure Interaction (SSI) influences how base-isolated buildings respond to earthquakes, yet it is often neglected in practice due to analysis complexity. This study shows a research gap exists regarding hybrid systems combining base isolation with fluid viscous dampers on soft soil. This study uses nonlinear time history analysis on a RC structure to evaluate performance under three earthquake records. The results demonstrate that all advanced model system (II-V) significantly outperform the conventional fixed-base model. While base isolation achieved the good base shear reduction (61%) compared to Model-I. The novelty lies in evaluating the hybrid Model-V under SSI; while it maintained force reduction, it amplified foundation level acceleration to 2.10 m/s^2 an 80% increases relative to the rigid-base hybrid proving that neglecting SSI is unconservative. Conversely, Model-II (fixed-base with dampers) is most robust, yielding 72% drift and 33% force reduction compared to Model-I. These findings emphasize that soft soil sites, SSI must be integral to seismic design.

Keywords—High-Rise Building, Base-Isolation, Dampers, Soil-Structure Interaction, ETABS

1. INTRODUCTION

Mid to high-rise buildings constructed on soft soil deposits similar to Kathmandu Valley; seismic wave amplification increases spectral displacement and story drift compared to identical structures on firm ground [1], [2]. This amplification arises from the contrast between stiff bedrock and compliant surface materials [3], [4]. Unlike low-rise, high-rise structures on soft soil experiences prolonged, large amplitude motions that challenged conventional seismic design approached, often leading to unacceptable drift concentration and collapse risk.

Fluid viscous dampers (FVDs) generate velocity-dependent resistance, converting seismic energy into heat [5]. Optimally configured FVDs reduce story drift by 50-70% under design-level earthquakes [6], [7]. Base isolation (BI) lengthens the fundamental period, shifting away from earthquake dominant frequencies [8], [9], achieving base shear reductions of 60% and moment reduction of 70% [9], [10]. Hybrid system (BI+FVDs) aim to combine force reduction with displacement control, reportedly reducing roof drift by over 90% [5].

However, existing studies have limitations: Firstly, Most FVD optimization research assumes rigid foundations, ignoring soil compliance [6]; Secondly, BI effectiveness is well documented for stiff soils but degrades unpredictably on soft deposits [5], [11]; Thirdly Hybrid system evaluations rarely incorporate soil-structure interaction (SSI), showing an optimistic bias; Fourthly, Past work focuses on low to mid-rise buildings, leaving high-rise (G+15 and above) behavior on soft soil under hybrid protection largely unverified.

Similarly, when foundation soil is flexible, the coupled soil-foundation structure system behaves differently from rigid-base predictions [12]. For base-isolated buildings, SSI can increase roof drifts by 30-45% and lengthen the isolated period by up to 35% on soft soil compared to hard rock sites [2], [11]. Moreover, [11] demonstrated that using linear Winkler springs alone common in practice overestimates isolation benefits on soft ground. For FVD equipped structures, [6] showed that damper layouts optimized for rigid foundations become sub-optimal under soil compliance, requiring higher damping coefficients and repositioned of devices. These finding indicate that neglecting SSI not only reduces accuracy but may produce unconservative designs yet most hybrid system studies continue to ignore this interaction.

Despite growing recognition of SSI importance, no prior study has systematically evaluated the combined performance of base isolation and fluid viscous dampers together under SSI for high-rise (G+15) buildings on soft soil (Type D). Existing hybrid system research assumes rigid foundations [11], and past SSI studies focus on single protection systems only [2].

Moreover, on soft soil, base isolation alone risks excessive displacement and foundation rocking [13], while dampers alone cannot achieve period shift. Their hybrid application, if properly worked with SSI could control both force transmission and deformation simultaneously. This study provides the comparative quantification of five configurations (fixed-base, FVD-only, BI-only, Hybrid System, and Hybrid +SSI- inclusive) for a (G+15) RC building on Type-D soil using three real earthquake records. Unlike prior studies that treat SSI as an afterthought, this study evaluates whether hybrid system benefits persist when soil flexibility is incorporated and identifies condition under which that do not.

2. RESEARCH OBJECTIVES

The specific objectives of this study are:

- To quantify the percentage reduction in base shear, maximum story drift, story displacement, story shear and story acceleration for five structural configurations (fixed-base, fixed-base with FVDs, base-isolated, hybrid base and hybrid with SSI) under three earthquake records.
- To compare the seismic performance of the hybrid system with and without SSI incorporation, identifying critical performance parameters where SSI leads to unconservative design predictions.
- To determine, for a (G+15) RC building on Type-D soft soil, which seismic protection strategy (FVD-only, BI-only, or hybrid) provides the most robust and predictable

performance when SSI is fully accounted for.

3. METHODOLOGY

A conceptual frame work for the detailed analysis of this study is shown in flowchart as below:

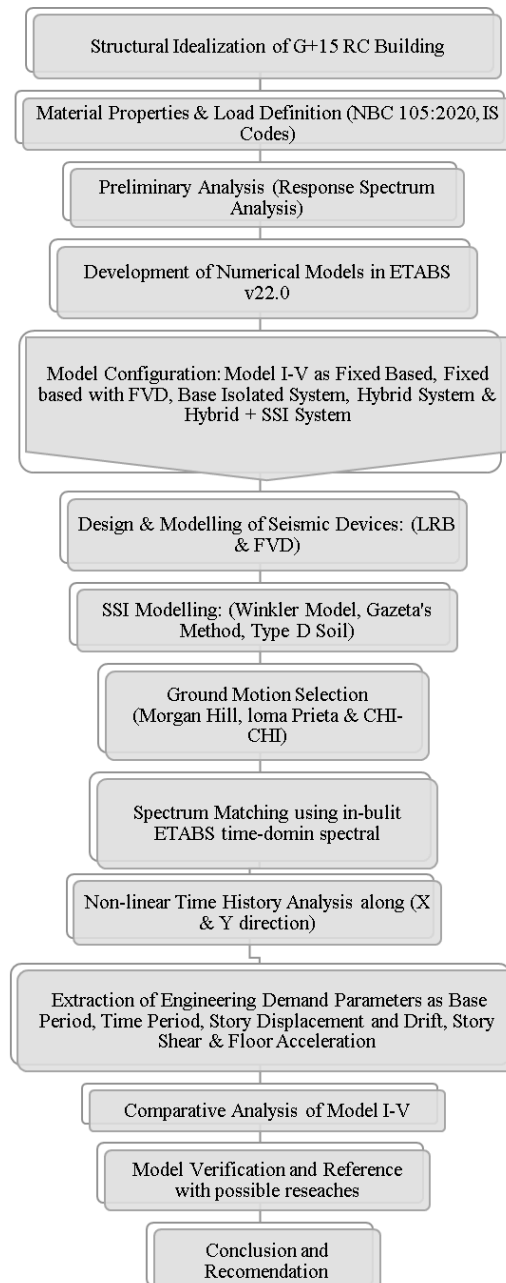


Figure 1: Methodological framework

A. Material Properties and Specification

The symmetric (G+15) reinforced concrete structure, typical of high-rise apartments in urban Nepal, has been modelled with all dimensions and loads set as per NBC 105:2020 and IS 875 (Part I & II). The structure has been first analyzed using the response spectrum method as per NBC 105:2020. Finally, the sizes of beams, columns, and reinforcement are calculated for further non-linear time history analysis:

Table 1: Idealization of Structure

S.No.	Specification	Remarks	
1	Type of building	RCC Framed	
2	Plan Dimension (X*Y)	40.5 m*39.6 m	
3	Number of Story	15 (Base + Floors)	
4	Total Height	48m (3 m per floor)	
5	Soil Type (as per NBC 105:2020)	Type D	
6	Seismic Zone Factor	0.35 (Kathmandu)	
7	Grade of Concrete & Steel	M30 & Fe 500	
8	Beam Size	0.725*0.700 m	
9	Column Size	0.975*0.900 m	
10	Slab Thickness	0.150 m	
11	Stiffness Modification Factor (for non-linear analysis)	As per ASCE 41:2013	
12	Seismic Load combination	As per NBC 105:2020	
13	Load Applied	Dead Load	As per IS 875 Part 1
		Partition Load	1KN/m (In all floor)
		Live Load	As per IS 875 Part 2

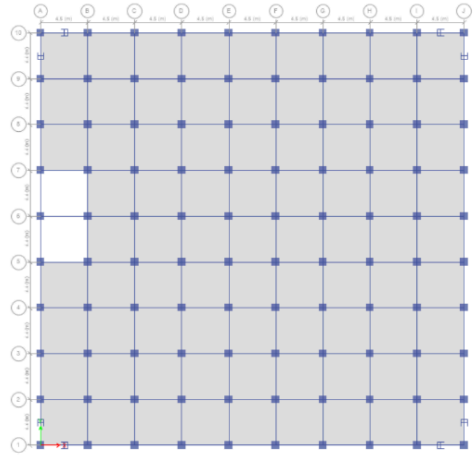
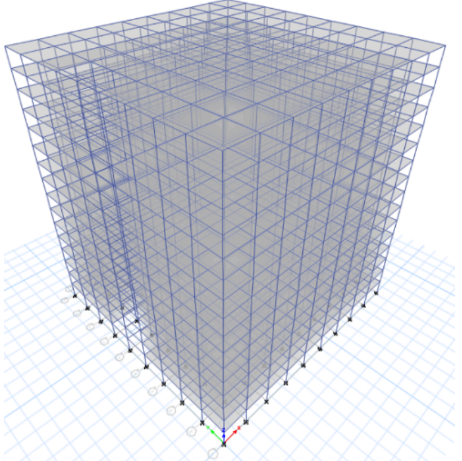
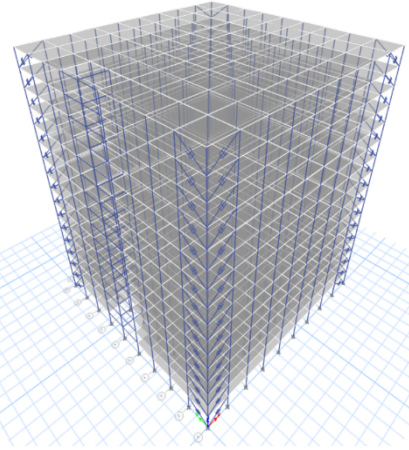
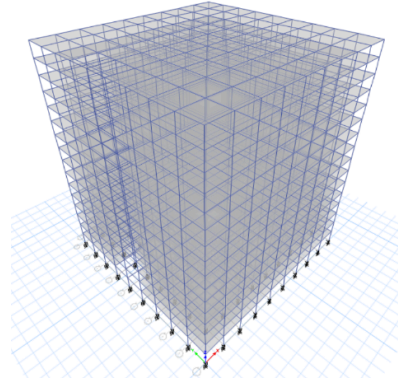
B. Basis of Model Selection

The Specific RC (G+15) model is selected based on the following two key criteria to ensure it serves as relevant, rigorous and comparative benchmark for seismic performance analysis.

- The Model reflects the current shift in Nepal's eagerness to high-rise apartments and commercial complexes. A symmetric structure will define this new generation of mid to high-rise development, where larger floor plans (40.5m * 39.6m) accommodate modern living and service needs under a single roof.

- The symmetric plan and consistency story height eliminates irregularities that could complicate the analysis. This allows for a fair and direct comparison between five seismic control schemes by finding the effects of the control technologies on response with the metrics like base shear, story drift, displacement and acceleration; following models are analyzed as shown in figure below:

Table 2: Modelling Scenarios

 <p>Figure 2: Representative structural plan for Models I-V</p>	 <p>Figure 3: Model-I (Fixed Based System)</p>
 <p>Figure 4: Model-II (Fixed Based with fluid viscous dampers at all four corners)</p>	 <p>Figure 5: Model-III (Building with Base isolation System)</p>

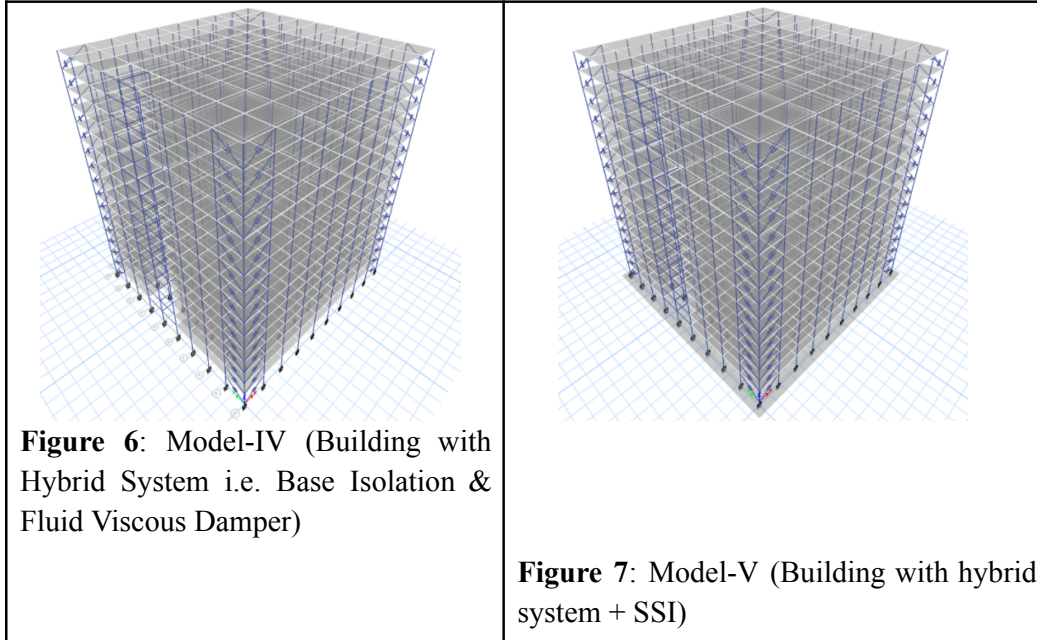


Figure 6: Model-IV (Building with Hybrid System i.e. Base Isolation & Fluid Viscous Damper)

Figure 7: Model-V (Building with hybrid system + SSI)

C. Spectrum-Matched Ground Motion

To perform non-linear time history analysis, three ground motion records: Morgan Hill, Loma Prieta and CHI-CHI are selected based on NBC 105:2020 criteria. The suite shows a magnitude range of M_w 6.19-7.62 and site to source distance of 43-84 km, capturing diverse seismic intensities and both strike-slip and reverse-oblique mechanisms. Following Clause 9.3.2.2 the records are matched to a target spectrum matching performed in ETABS v22.0 to preserve the physical non-stationary characteristics of the motions. In accordance with clause 9.3.2.2 (c) a final scale factor of 1.0 applied to the matched motions for use across all five structural models.

D. Numerical modelling of Seismic Base Isolation, Fluid Viscous Damper and Soil-Structure Interaction

The design and calculation are done as per the available codes, practices, formulas and some of the assumptions are taken during the calculation for the better target to the results.

a. Design of Lead Rubber Bearing (LRB)

The design of Lead Rubber Bearing (LRB) for model-III is done as per NBC: 105:2020 & UBC-1997 & Theory of Practice by KELLY and NAEIM. Particularly in the context of Kathmandu Valley, the soil profile falls under Type D very soft soil with an undrained shear strength below 12.5 KN/m^2 . While an exact code for this soil type might not exist, we use them with similar to soil type S_E from UBC-1997 for computational of seismic coefficient such as

Cv and Ca. This approach helps in the design of LRB in accordance with the seismic provisions of UBC-1997, even in the absence of an exact soil type match. Incorporating with the equivalent visco-elastic model, the procedure of the NK method following ASCE 7 (2002) has been adopted and finally the input values for ETABS such as Rotational Inertia, Effective stiffness (U1, U2, & U3), Distance from End-J (U2 & U3), Stiffness (U2 & U3), and Yield Strength (U2 & U3) for the external and internal columns has been calculated as:

Table 2: Input Values in ETABS for external and internal columns

Finally Input values for ETABS	Data for External Column	Unit	Data for Internal Column	Unit
Rotational Inertia	0.295569884	kN/m	0.412228	kN/m
For U1 Effective stiffness	2491678.331	kN/m	2894763	kN/m
For U2 & U3 Effective Stiffness	2491.678	kN-m	2894.763	kN-m
For U2 & U3 Effective Damping	0.05		0.05	
For U2 & U3 Distance from End-J	0.00593	m	0.00593	m
For U2 & U3 stiffness	22959.82538	kN/m	26674.09	kN/m
For U2 & U3 yield strength	136.1596534	kN	158.19	kN

b. Design of Fluid Viscous Damper (FVD)

Seismic dampers are the device that absorb the seismic energy and reduce the deformation of structures during any ground motions[14].

Viscous dampers provide a force that always resists structure motion. This force is proportional to the velocity between the ends of the damper. The damping law is as follows:

$$F = C.V^\alpha \dots\dots\dots (Eq. a;)$$

Where:

F: damper force

C: damping coefficient

V: velocity

α : Damping exponent that can range from 0.01 to 1.00 (Linear behavior equal to 1.00, whereas value other than 1.00 indicate nonlinear dampers).

Similarly, for this study velocity exponent (α) of 0.5 is selected to represent nonlinear fluid viscous behavior. This value (α) of 0.5 is widely regarded as the industry standard for seismic protection, as it optimizes energy dissipation while preventing excessive force transmission to the structural joints [15]. we are planning orientation of damper placed symmetrically and along the perimeter, there are two dampers in each direction on each side of the building's center of mass, satisfying the redundancy [7], [16] requirement defined by ASCE 7-16. In total there are 8 dampers per floor (likely 4 in the X-direction and 4 in the Y-direction), thus we use the simplified formula of damping coefficient for one direction:

$$C_i = \frac{\zeta_d K_{story} T}{\pi n \cos^2 \theta} \dots \dots \dots \text{(Eq. b;)} \quad (1)$$

Where,

T: Fundamental period of the building

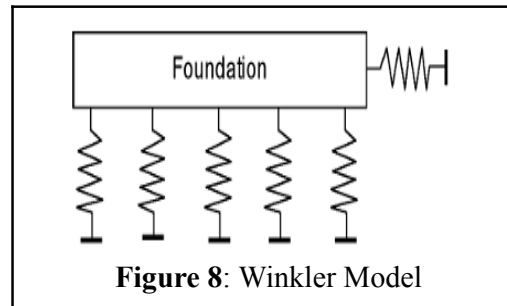
K_{story} : Lateral stiffness of the story

θ : The angle of the damper brace

E. Design of Soil-Structure Interaction

The SSI effect is incorporated using a Winkler Spring model, characterized by the modulus of subgrade reaction (k_s). This model is specifically chosen to isolate the effects of foundation rocking and translation on the performance of the base isolators and dampers. By representing the soil as a series of elastic springs, the study captures the crucial period-lengthening effect of the soil without the computational complexity of volumetric soil modelling, making it a healthy and reproducible approach for high-rise seismic analysis & idealization of Winkler model is shown in figure 2.

Similarly, the effect of soil-structure interaction is accounted by the means of equivalent springs possessing six degrees of freedom (DOF). The stiffness values associated with each of these six DOFs are determined according to Gazeta's (1991). Rocking stiffness is captured in the model through distributed vertical soil springs acting over the finite area of the raft foundation. Furthermore, the equivalent analog velocities for the vertical and horizontal directions, denoted as V_{la} are derived using the Modified Lysmer Velocity, as recommended by Gazeta's (1991).



Also, the Modulus of Elasticity, Poisson's ratio and the unit weight of the soil mass are taken as per Bowels (Bowels, 1998)

Table 3: Input Values in ETABS for SSI spring stiffness

S.No.	Stiffness Type	Values
1	Vertical Stiffness, K_v	443 kN/m/m ²
2	Horizontal Stiffness, K_h	353 kN/m/m ²
3	Vertical Damping Coefficient C_v	0.091 kN-s/m/m ²
4	Horizontal Damping Coefficient C_h	0.050kN-s/m/m ²

4. RESULT & DISCUSSION

Five models are constructed, with differing specification as mentioned above. To assess their response to dynamic loading, particularly considering seismic activity, analysis are conducted using the Time history analysis (FSA). The focus of the analysis is to evaluate and contrast the seismic responses of fixed base models against those employing different seismic protection model and effect of SSI on hybrid model, thus highlighting the impact of all these models on structural behavior under dynamic loading conditions.

A. Base Shear

The results show 42% reduction in adding of fluid viscous dampers to a fixed-base structure illustrating the capability of supplemental damping to absorb seismic energy which aligns with the findings of [2], [5], similarly there is 61% of reduction in base shear with the application of base-isolated system which is consistent with [6] and 67.3% of reduction in base shear in the application of both of above and finally; consideration of SSI in the hybrid system has instead slightly increased the base shear to 60%, indicating soil flexibility [7], [8]. The inclusion of soil-structure interaction (Model-V) moderates the benefit but still maintain good reduction compared to the fixed-base design, showing hybrid systems remain effective on flexible soil sites.

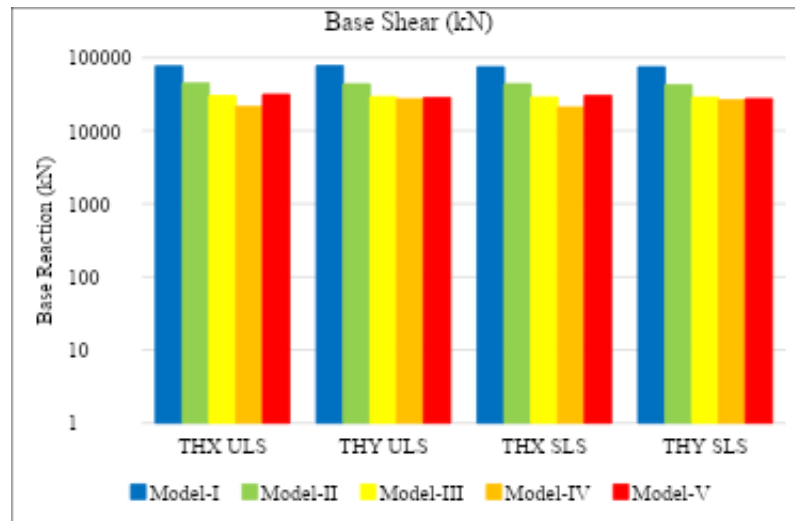


Figure 9: Base Reaction

B. Time Period

Model III and IV with the introduce of base isolation layers shifts the structure’s fundamental period from 1.307 second to 2.975 seconds, a significant increase which moves dynamic response away from energy-rich region of the seismic spectrum. Similarly, when soil flexibility is incorporated into the hybrid system, the shift of fundamental period to 3.050 second over the rigid-base reflects the additional compliance which further decouples the structure from the high-frequency ground motion. Finally; these findings do align with the studies by [17], [18] which stated that the greatest natural period increases were shown by BI building with the aspect ratio up to 4.0 on soft soil.

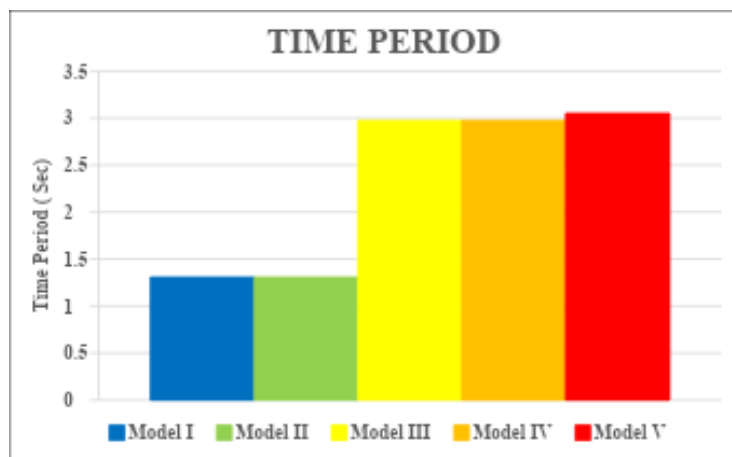


Figure 10: Time Period

C. Maximum Story Displacement

The time history analysis shows the model with fluid viscous damper reduces the superstructure displacement by 70 % compared to fixed-based model which align with studies that FVDs are highly effective in reducing displacement[7]. Hybrid Model-IV shows roof displacement of 25 % aims to balance displacement reduction with force reduction. Finally; the beneficial reduction in displacement from 107 mm to 75 mm observed in Model-V align with the finding of [2] indicating that the soil profile considered in this study exhibit characteristics where SSI provides a beneficial filtering effect, along some increases observed in certain earthquake cases.

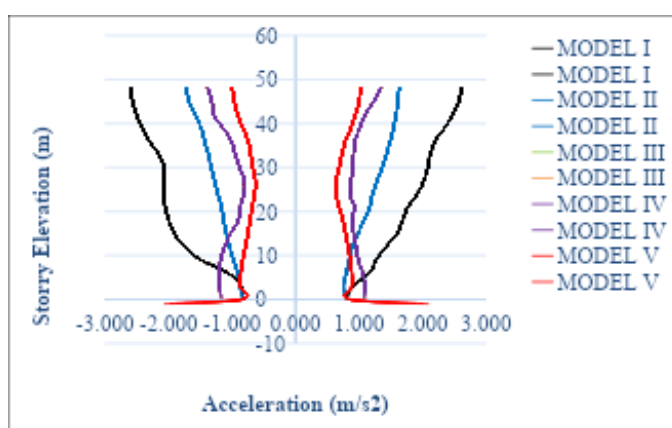


Figure 11: Max story displacement

D. Maximum Story Drift

Model with FVDs shows greatest reduction of 72 %, model with base isolation with 20 % reduction creates concentration at isolation level while protecting superstructure [19]. Similarly, hybrid model balances throughout by 68 % reduction in drift as isolation reduces base drift and dampers control upper stories. Finally, 59 % reduction through Model-V aligning with[2]. This finding mandates the use of nonlinear time history analysis for the performance-based design of isolated structures.

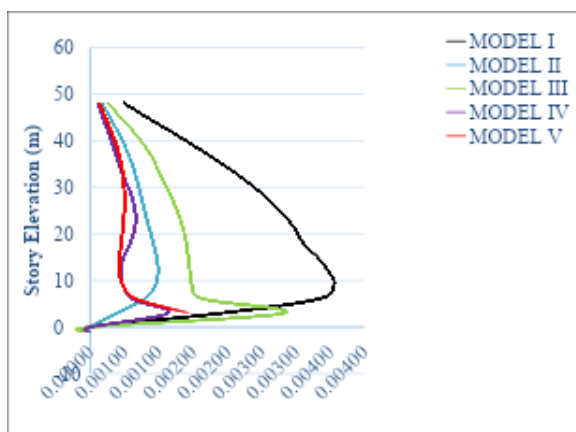


Figure 12: Max story drift

E. Story Shear

The Model (II-III) reduced the average shear by 33-61% and fundamentally redistributed the demand, causing the maximum story shear to occur at mid-height. The hybrid system with soil-structure interaction Model-V shows elevated shear at the base level, its overall base shear remains lower than fixed-base structure compared to its previous models which align with [2], [11] stated that when SSI considered the effectiveness of the base isolation system may decrease, and the effect is prominent in softer soil condition.

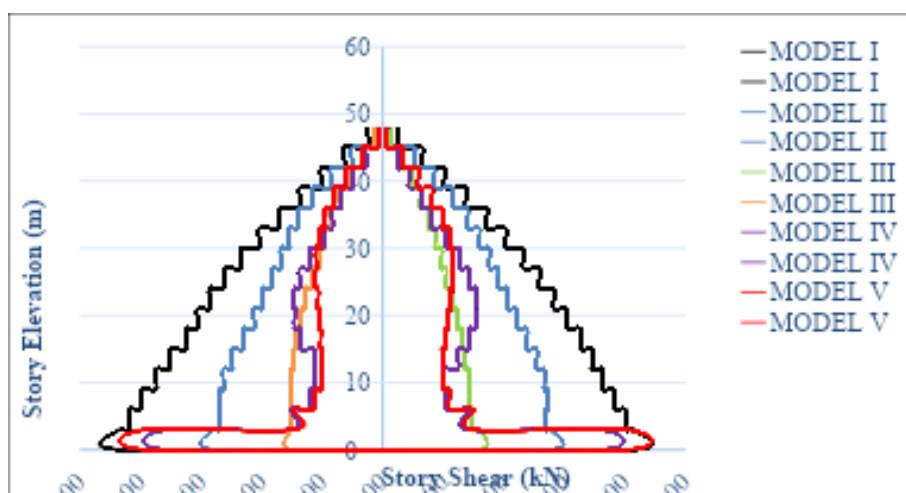


Figure 13: Story Shear

F. Story Acceleration

The base isolated model and hybrid model shows most uniform and greatest reduction of about 47-49 % in superstructure accelerations which validates the core findings of [10], whereas the model with FVD provides a substantial 34-38 % reduction demonstrating effectiveness even without period shift; however as noted by [5], dampers are generally less effective at reducing acceleration than displacements, which data confirms 34 % vs 72 % drift reduction. Finally, model with SSI has the roof acceleration reduction of 60% relative to Model I, and inclusion of SSI resulted in increased acceleration at the foundation level (-1.0 m) to 2.10 m/s^2 , reflecting the dynamic interaction between the structure and soft soil. This is foundation rocking and swaying amplification due to soil flexibility, this directly confirms the mechanism described by [2], [11], where SSI introduces additional degree of freedom that can amplify motions at the foundation level.

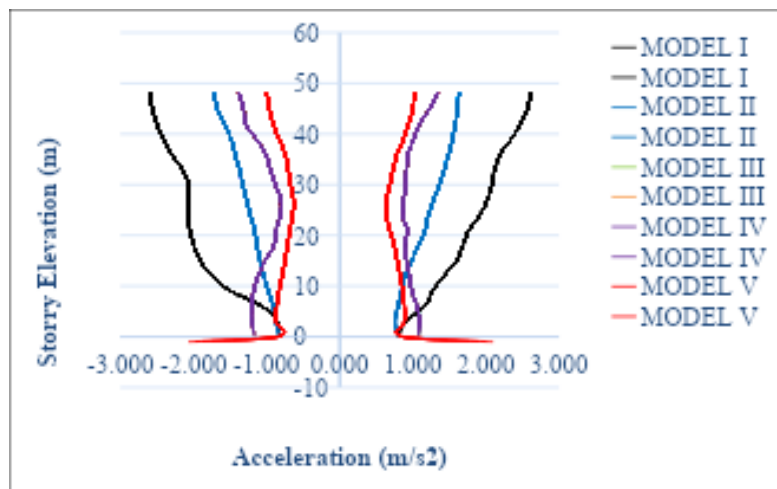


Figure 14: Story Acceleration

5. CONCLUSION & RECOMMENDATION

This study analyzed seismic protection for a 15-story RC building on soft soil, focusing on the trade-offs between force reduction and SSI-induced sensitivity.

- Based on a Model-I baseline base shear of 77,417 kN, Base isolation (Model-III) and Hybrid systems (Model-IV) showed effective for force reduction, achieving up to 61% and 67% mitigation, respectively.
- Fluid Viscous Dampers (Model-II) provided the most balanced superstructure protection, yielding a 72% reduction in drift and 70% reduction in displacement.
- Incorporating SSI (Model-V) revealed a critical design vulnerability; while displacement was filtered to 75mm, foundation level acceleration increased to 2.10 m/s². This proves that rigid-base assumptions understate foundation demand by failing to account for soil-induced rocking.

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