Behavior of Adjacent Building on the Effect of Pounding Under Seismic Excitation

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Abstract:
Urban densification and limited land availability have led to closely spaced buildings, greatly increasing the risk of seismic pounding during earthquakes. This study explores the dynamic interaction between neighboring structures with different properties and emphasizes the importance of soil-structure interaction (SSI) in affecting seismic responses. Using nonlinear finite element modeling with ABAQUS software, the behavior of two adjacent buildings under various boundary conditions—viscous, Novak and Mitwally, and infinite element—was simulated. Seismic input from the 1994 Northridge earthquake was used to analyze displacement and acceleration responses. The findings show that pounding significantly increases inter-story drift, base shear, and structural deformation, especially when separation gaps are inadequate and stiffness contrasts are high. The study indicates that applying infinite element boundary conditions can reduce pounding effects by up to 40% in displacement and 20% in acceleration. It also highlights that including SSI in seismic analysis is crucial for accurately predicting and mitigating pounding effects in high-seismic-risk urban areas. The results recommend new design guidelines that incorporate SSI and structural response to improve seismic resilience and urban safety.

KEYWORDS: Seismic pounding, soil-structure interaction (SSI), finite element modeling, adjacent buildings, boundary conditions, displacement response, acceleration response, inter-story drift, structural impact, ABAQUS simulation.

1. INTRODUCTION:

Earthquakes consistently show a strong ability to cause significant damage to artificial structures, especially exceptionally tall buildings, which are highly vulnerable (Far, 2019a). These structures are common in densely populated urban areas (Far, 2019b). Due to rising land prices, such buildings are often built close together, increasing their risk of seismic pounding. The most well-known earthquakes, such as El Centro (1940), Northridge (1994), and Kobe (1995), have demonstrated the destructive effects of seismic activity on buildings located near each other. Factors like soil type and the spacing between buildings increase the likelihood of tall structures collapsing during strong earthquakes. Understanding soil-structure interaction (SSI) is essential for comprehending how these structures respond to seismic events. These interactions are especially evident in neighboring buildings with similar foundation systems, where the risk of pounding and subsequent structural damage is even higher. It has long been recognized that seismic pounding between nearby structures is a significant hazard. Research on this issue dates back to the 1906 California earthquake. However, early studies were limited due to a lack of understanding of soil-structure interaction (SSI), which often led to its exclusion from analyses. One of the earliest and most common methods to prevent pounding involved calculating and maintaining a safe separation gap between adjacent structures. This approach has been widely examined and discussed in the literature by researchers such as Kluge et al. (2020) and Khatami et al. (2020a, b). On March 28^{th}, 2025, a magnitude 7.7 earthquake struck Myanmar. The tremor traveled over 1000 km to Bangkok, causing strong shaking due to Bangkok's soft soil. In Turkey (2020), buildings with mismatched heights and stiffness experienced significant pounding damage to beams, columns, and masonry walls. Similarly, in China (2008), New Zealand (2011), and Nepal (2015), pounding between adjacent structures resulted in severe damage, including cracked masonry, deformed columns, and partial collapses in closely spaced buildings. This illustrates how seismic energy impacts structures during pounding. The collapse highlights the importance of assessing seismic interactions not only between neighboring buildings but also between buildings and their surrounding soil, considering local amplification. The characteristics of pounding, including its occurrence and impact on structures, are discussed in Table 1.

Table 1 - Significant effects of pounding and its features on buildings in the past

Earthquake & Year	Location	Building Types	Pounding Features	Damage Observed	Significance
Mexico City, (1985).	Avenida Juárez	6-storey & 12-storey office towers	Significant height difference, <100 mm gap	Beam/column cracking, floor slab damage	Classical case of out-of-phase motion
Bhuj, I., (2001).	Bhuj Town	G+3 & G+5 residential RC blocks	Poor detailing, slight separation	Joint cracking, column shear failure	Example of pounding in the Indian seismic zone
Christchurch, N. (2011).	Colombo Street	Brick masonry & RC framed building	Brittle vs. ductile system collision	Façade collapse, debris hazard	Highlights the vulnerability of URM (Unreinforced Masonry)
Nepal Earthquake (2015).	Bhaktapur, Patan	Traditional masonry & concrete buildings	Narrow urban streets (<50 mm gap)	Wall cracks, corner collapse	Shows pounding in dense heritage areas
Turkey (2020)	Sivrice Town	G+4 and G+7 RC flats	Different natural frequencies	Beam damage, localized slab crushing	Recent proof of theoretical pounding models

2. Problem Statement and Objectives

The boundary condition is a key component of numerical models. To study the effect of transmitting boundaries on adjacent structures, a finite element model for adjacent structures has been analyzed for the high seismic zone of Bihar state. A building in a densely populated area of Muzaffarpur city has decided to study how transmission limits affect other buildings. In order to conduct SSI-related analyses of nearby buildings, the non-linear finite element (FE) plain strain model was used to simulate two symmetrical nearby structures with building heights of 25 m and 20 m, respectively (Figure 4). The three types of transmitting boundaries are the infinite element boundaries in ABAQUS employed to study the model (Lysmer & Kuhlemeyer, 1969; Novak & Mitwally, 1988; Bettess, 1977). The three boundary conditions will be denoted as BC-1, BC-2, and BC-3 following Lysmer and Kuhlemeyer (1969), Novak and Mitwally (1988), and Bettess (1977). In Abaqus 6.14, the 8-noded quadrilateral element is also used. The following areas are divided into sub-problems (objectives) in order to solve the problem statement:

- In order to learn how nearby structures react when hit by earthquakes.
- To determine how factors such as building height, mass, stiffness, and separation gap affect the outcome.
- To identify critical factors that exacerbate or mitigate pounding effects.
- To suggest design recommendations to minimize pounding risks.

3. Literature Review

When soils undergo nonlinear deformations, the seismic resilience of a structure can be reduced due to interactions between the superstructure and the earth systems. Most research on soil-structure interaction (SSI) has concentrated on how specific structures, such as buildings, bridges, or frames, behave and how the supporting soil affects them. However, because of limited land and a growing population, buildings are often constructed close to one another, which may alter each structure's dynamic behavior through mutual interactions. SSI influences the dynamic response of superstructures based on soil properties and time-dependent stresses. Since the connection between the earth and the structure varies, seismic inputs may differ from those for a building with a stable foundation, as the demands on the elements and mode shapes can change. This effect, observed in recent earthquakes, highlights the importance of soil reactions and their inclusion in analysis and design. **Cadir et al. (2021)** studied the stability improvement of soft clay slopes under seismic loading using stone columns. The study utilized finite element analysis software. **Gattulli et al. (2019)** proposed a technique to reduce the effect of pounding, in which couplers were applied between neighboring buildings. They showed to be effective in dynamic responses to the factor of structure soil (SS)-structure interaction (SSI), **Mavronicola, Spatz, Tsatsoulis, Ioannidis, Spik, Kidani, and Kelleher (2020).** Based on the effects of the directionality of ground motion on pounding between buildings separated by the base, it was stated as the main emphasis that directionality of ground motion has a strong influence on the peak response and was mainly subject to the angle at which the seismic waves hit the structure, the gap in the separation, flexibility in the structure, and eccentricities in mass. **Kontoni and Farghaly (2018)** explored the seismic performance of adjacent buildings of varied heights under the implications of double pounding by considering the case using SSI. It is the implication that SSI is so important in the evaluation of seismic double pounding that it relies on the findings. **Qi and Knappett (2020)** have explored different types of foundations and those on liquefiable soils and their effect on SSSI. They concluded that the intensity of pounding increases as the seismic wave passes closer to the ground due to the presence of liquid soils. **Tubaldi et al. (2020)** on the ground mined a fluid viscous damper between two adjacent buildings; they did not consider SSI, in any case. The study concluded that the damping method was potentially a practical idea; however, its application was hindered by the need for frequent structural adjustments. **Zhang et al. (2018)** applied the Transfer Matrix Method (MS-TMM) and ANSYS program to investigate structural pounding without the SSI concept. They found that the pounding force and frequency increased as the gap distance was reduced. The torsional behavior of adjacent structures connected was investigated by **Farahani et al. (2019)** during earthquakes, and they pointed out the size of the separation gap as an important factor, but SSI was not considered.

4. Soil-Structure Interaction

Over the years, the focus has been on incorporating the SSI impacts in the evaluation of other neighboring buildings during seismic loading. This interaction has been analyzed using various methods of analysis to gain a deeper understanding. As an example, **Mahmood et al. (2012)** have examined the interactions between soil flexibility and structural pounding in the context of the 1995 Kobe earthquake. Their results demonstrated a decrease in lateral displacements and an increase in acceleration, implying a reduction in the intensity of pounding. Moreover, other studies have gone ahead to encompass structure-soil-structure interaction (SSSI). As an example, **Ghandil and Aldaikh (2016)** analyzed the pounding between two adjacent buildings on soft ground under seismic loading. They found that in some cases, the limits to the minimum distance that were established in design guidelines needed to be achieved in order to prevent pounding. There have been multiple seismic excitations in recent years that have damaged adjacent buildings. The importance of SSI for static and dynamic loads has piqued the attention of structural engineers.

4.1.Behavior of SSI

This phenomenon is known as soil-structure interaction (SSI), and it occurs when the movement of the soil influences the reaction of the structure and vice versa. It is now well established that structures built under seismic excitation must be analyzed under soil-structure interaction, boundary conditions, material behavior, ground response, and various modelling aspects. Under dynamic conditions, the reaction of both the structure and the soil might be affected by an interaction between the two.
The SSI can be studied in two parts as
(a) Kinematic interaction and
(b) Inertial interaction
A comparison was made between the seismic response of a building built on rigid rock and that of a structure built on flexible soil mass that is underlain by rock in order to highlight the key aspects of SSI. The structure is shown in Fig. 3.1a as being built on rock and having control motion at point A at its base. Regardless of the building's height, the input acceleration that causes horizontal inertial loads to be imposed remains constant. Under the assumption that the rock is stiff, the stresses caused by the overturning moment and transverse shear do not cause any further deformation at the base. Therefore, control motion is the same as the resultant horizontal displacement at the base.
Figure 1 illustrates the basic concept of the structural stability index (SSI), along with two distinct methods for analyzing any structure: the direct approach and the substructure approach.

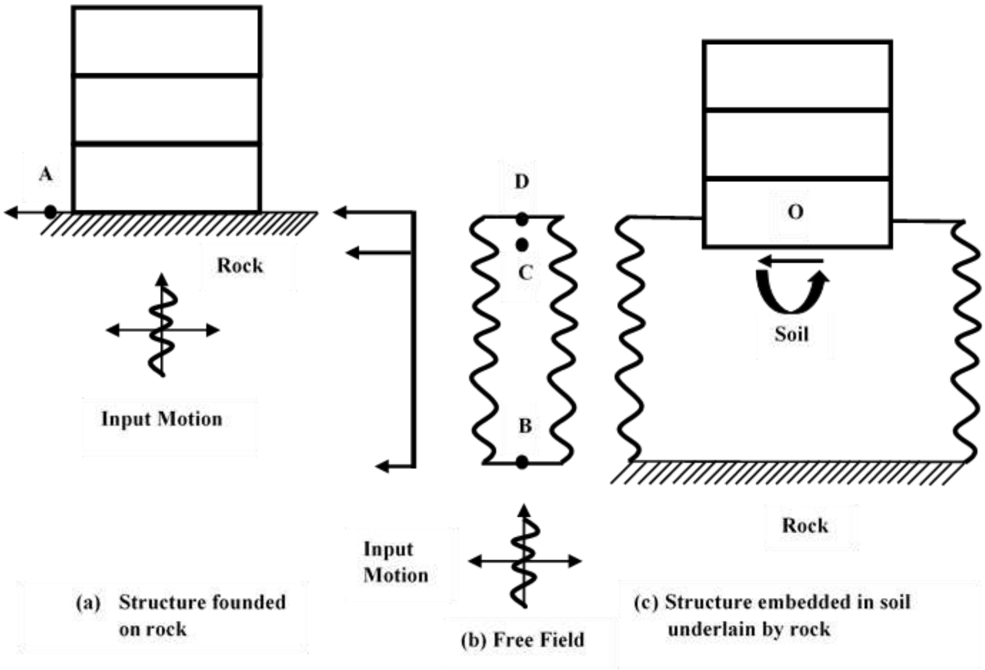

Figure 1: Phenomena of SSI (after Wolf, 1989)

4.2.Significance of SSI

The behavior of soil-structure interaction effects is one of the most hotly debated aspects of seismic design and requalification of operational nuclear power plants, when it comes to the study of surface-based or immersed structures in the soil. Nuclear power plants have far-reaching consequences; thus, it is crucial that their designs can withstand extreme environments safely. Given the prevalence of large-scale projects on very soft soils, including earth dams, concrete structures, and nuclear power plants, the SSI issue has emerged as a key aspect of structural engineering. Special consideration for SSI issues may also be necessary for subterranean constructions, buildings, bridges, and tunnels. Dynamic soil-structure interaction is often part of Earthquake engineering issues. Amplification effects in the ground are becoming an especially relevant issue when one considers pathways through the ground to the building. As are those in earthquakes. Although the overall intensity of vibration attenuates with distance from the energy source, some parts of the frequency content may be amplified during wave propagation, dependent on the dynamic features of the soil along the propagation path, notably the natural period of vibration and reflection. The seismic behavior can be expressed as soil stiffness and both types of damping.

It has long been believed that soil-structure interaction (SSI) improves a construction's seismic response. Because of this, design guidelines either allow for or imply that SSI might be eliminated, resulting in a lower total seismic coefficient. Accounting for SSI often boosts a structure's flexibility, natural period, and effective damping ratio, which is why this is done. As a result of these alterations, the base shear demand is reduced in comparison to a base-fixed structure. Because of these presumptions, designers often choose to disregard SSI in order to streamline analysis.

Nevertheless, data collected from several earthquake-affected locations present an opposing viewpoint. Notable examples include the 1989 Loma Prieta earthquake, which damaged many pile-supported bridges **(Yashinsky, 1998),** and the 1995 Kobe Earthquake, which caused the collapse of Hanshin Expressway Route 3 (Fukae section), which **Mylonakis and Gazetas studied (2000)**. In addition, the asymmetrical structures destroyed by the 2015 Nepal Earthquake and supported on stacked rafts were subject to SSI analysis by **Badry and Satyam (2017).** Superstructure geometric asymmetry, they found, may amplify the negative impacts of SSI. Based on these findings, it seems that the conventional wisdom about SSI's universal benefits does not apply to all building types and soil types. This calls for reviewing findings from previous studies.

4.3.Equation used in SSI

A foundation-structure embedded system is schematically presented in Figure 3.2. The dynamic stiffness matrix needs to be calculated; for this purpose, the foundation, structure, and ground level are shown in Figure 2 as F, S, and GL, respectively

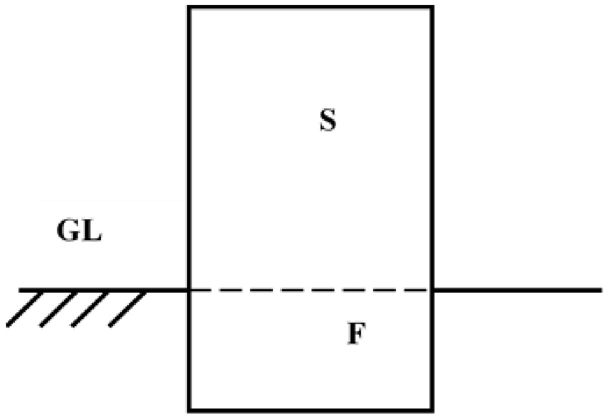

Figure 2: Foundation embedded system in soil (after Kitada et al., 1999)

Equation (1) provides the foundation-structure interaction, which may be expressed as

$$two \begin{pmatrix} K_{SS} & K_{SF} \\ K_{SS}^{T} & K_{FF} + S^{(S)} \end{pmatrix} \begin{Bmatrix} U_S \\ U_F \end{Bmatrix} = \begin{Bmatrix} 0 \\ S^S \Delta^S \end{Bmatrix} \text{...................... (I)}$$

It depicts the building's displacements, namely those of the superstructure and base, and K_{SS}, K_{SF}, K_{FF} represents the dynamic stiffness matrix for superstructures.

$S^{(S)}$ = Resistance produced by seismic excitation

$\Delta^{(S)}$ = Excitation vector

The coefficient of the dynamic stiffness matrix of the superstructure represents the interaction with various parts of the system. The responses of the structural node with the structure, the structure with the foundation, and the foundation with the foundation are represented as SS, SF, and FF, respectively. In order to assess the soil-structure interaction, we use the input motion vector of the foundation and the dynamic impedance function matrix. Inertial and kinematic interactions are the two main components of SSI that may be seen in a structural system. The structure's dynamic equation of motion may be expressed as

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{\ddot{u}_g\} \text{.......................... (II)}$$

5. Method of Analysis

To analyse the problem involving SSI, it is important to classify the methods that could be used to identify the phenomenon of SSI. The methods can be classified as:

- Direct Method and Substructure Method

- Frequency Domain Analysis and Time Domain Analysis Methods
- Rigorous Boundary and Approximate Boundary Methods
- Linear Analysis and Nonlinear Analysis

- **Direct Method and Substructure Method:**

Figure 4.2 shows the direct technique, which uses the usual finite element method to simulate the structure and a nearby near field of limited soil. By implementing transmission boundaries at the near-field/far-field interface, we can better understand the influence of the surrounding unbounded soil (far field). The radiation criterion has been satisfied by many transmission boundary types during the last 20 years, one of which is the viscous boundary **(Lysmer & Kuhlemeyer, 1969).** The artificial boundary is used to apply the radiation condition, rather than infinity, where it would generally be expressed.

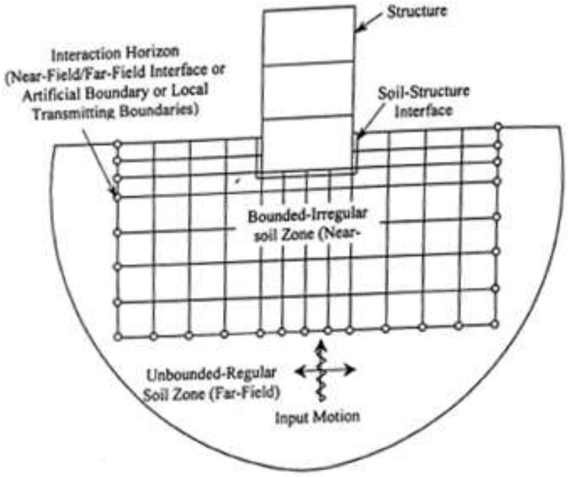

Figure 3: Dynamic Systems for the Direct Method of Analysis

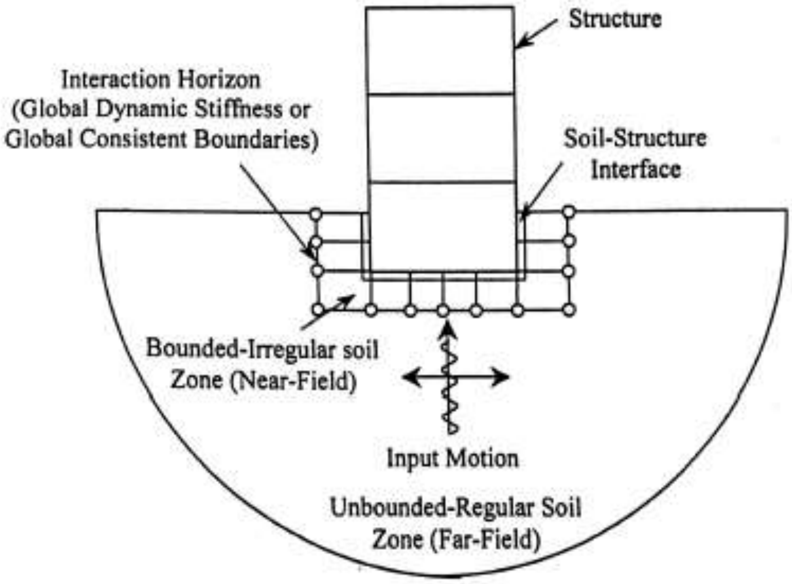

Figure 4: Dynamic Systems for the Direct Method of Analysis

The substructure approach (Fig. 4) splits the soil-structure system in half, with one half consisting of a structure that could include nonlinear soil or soil with an uneven boundary and the other half having unbounded soil **(Wolf, 1985 and 1989).** As a whole, the soil-structure interface links these substructures. Although the structure may not be linear, it is presumed that the unbounded soil is. In most cases, nonlinear soil next to a structure may be considered an integral component of that structure; hence, if necessary, the nonlinearity of the soil in that vicinity might also be accounted for. A global, time- and space-invariant boundary condition in the form of a force-displacement relationship represents the response of unbounded soil on the overall soil-structure interface. Because the boundary-element technique discretizes just the margins of an unbounded medium, reducing the spatial dimension by one, and satisfying the radiation condition precisely at infinity as part of the basic solution, it is a strong procedure for modeling unbounded media. Several hybrids and coupling approaches have been developed based on the substructure method **(Estorff & Kausel, 1989).**

- **Frequency Domain Analysis and Time Domain Analysis**

In the frequency domain, excitation is broken down into a Fourier series, and the response is determined separately for each Fourier term corresponding to a specific frequency. This method is straightforward to apply in static cases. Aside from that, there are two significant downsides. The first issue is that structural and geotechnical analysts may find the process of time-frequency domain transformations to be abstract. Applying ideas from the time domain to the sequence of events from one time step to the next is a more natural way to think about it. The second limitation is that the frequency domain cannot capture nonlinear behavior in the structure and soil around it, as it is only capable of handling linear reactions. This limitation makes it challenging to predict the extent of damage during an earthquake, as damage typically involves nonlinear effects. These factors can be accounted for in time domain analysis.

- **Rigorous Boundary and Approximate Boundary Methods**

By first solving it in the frequency domain and then in the time domain, the rigorous methodology outlined in the substructure technique of analysis is global in space and time. A perfect satisfaction of the radiation requirement at infinity is achieved in this model. These limits are local in both space and time, and the direct technique of analysis in the time domain makes use of the approximation modeling in order to overcome the artificial barrier; the transmitting boundary is used.

- **Linear Analysis and Nonlinear Analysis**

Materials are categorized according to their linearity or nonlinearity. Linear analysis helps evaluate field tests conducted under low-amplitude responses, as it provides information about fundamental material constants. However, linear analysis alone cannot fully address the problem. Under seismic conditions, it is crucial to account for nonlinearities, as earthquakes induce nonlinear behavior in both the soil and the structure. The scattering of the dynamic stiffness matrix in the time domain is both space-time and time-domain global, as per the substructure technique. The computation of this method is very costly because convolution integral enrolment, therefore, makes the substructure method of analysis less appealing in the time domain. They formulate an approximation analysis that is both local in space and local in time to reduce the computing load due to the global coupling of the high-fidelity version of the interaction force-displacement relationship of unbounded media. Transmitting boundary analysis, a direct approach of unbounded soil-structure interaction, makes use of this type.

6. Material Damping and Radiation Damping

To conduct a realistic dynamic analysis, "damping" is a must. To get a good idea of dissipation processes that are not explicitly modeled, linear analysts employ comparable linear damping. There are two common forms of damping in linear dynamic analysis using eigenmodes: Proportional to nodal forces, structural damping, and proportional to the structure mass and stiffness, Rayleigh damping. In ABAQUS, each mode whose damping cannot be defined as the percentage of critical damping can be defined. Despite the possibility of including different forms of damping as distinct dashpots or constitutive model components, only the last is possible when working with the direct type of integration. In this case, we discover that modal and Rayleigh damping, alongside forms of direct integration with Rayleigh damping, show the best results in regard to linear dynamic analysis. The amplitude of a stress wave diminishes as it propagates through the crust of the Earth. Two primary processes are responsible for this attenuation. The first is known as material damping, and it occurs when the materials a wave passes through absorb some of its energy. A second effect is radiation damping, which occurs when a wave's energy disperses across a wider area as it travels away from its origin. Earthquakes impact a significant portion of the Earth's surface. However, the response of a single structure and a relatively limited location are typically of importance to engineers. It is customary to terminate the model at a small distance from the region of interest rather than modeling the entire area affected by an earthquake, which is rarely desirable and not usually possible. The model now has arbitrary borders, which contribute to this truncation of forces. By enforcing suitable boundary constraints, the presence of the geological media outside of these artificial borders is mimicked, with the assumption that they are unbounded (semi-infinite). Structures and the ground vibrate together during an earthquake, affecting how each other reacts. We refer to this phenomenon as dynamic SSI. The degree to which SSI affects a structure's reaction is conditional on the kind of foundation, the ground's stiffness, and the structure's dynamic properties, such as its natural period and damping factor.

6.1.Selection of Damping

The mass component in Rayleigh damping is equivalent to a damper that connects each node to the ground, and the stiffness component is equivalent to a damper that connects units. By choosing an appropriate coefficient, a response irrelevant to frequency can be obtained approximately within a limited frequency range. In the dynamic equation, the mass matrix K is connected to the damping matrix C and the stiffness matrix K. The minimum critical damping ratio ξ_{min} and minimum center frequency ω_{min} of Rayleigh damping can be determined by estimating the minimum of the damping ratio curve of the superposition results:

$$\boldsymbol{C} = \boldsymbol{\alpha M} + \boldsymbol{\beta K} \quad \text{(III)}$$

$$\xi_{\min} = (\alpha \cdot \beta)^{\frac{1}{2}} \quad \text{(IV)}$$

$$\omega_{\min} = (\alpha/\beta)^{\frac{1}{2}} \quad \text{(V)}$$

6.1.1. Seismic Energy Dissipation

There are several pathways for seismic energy dissipation within the soil-structure system. The impedance barriers (free surface, soil/rock layers, any foundation, etc.) may reflect some of the energy that enters this system back into the domain outside. Figure 4.4 shows the radiation from the soil-structure system oscillation. Soil elasto-plasticity, foundation elasto-plasticity/damage, energy dissipation devices (seismic isolators), and the structure and its components disperse the remaining seismic energy. Most of the energy lost at the time of occurrence of significant earthquakes is probably due to the elasto-plastic deformation of the soil, foundation, and structure. The soil/rock, the foundation, and the building all exhibit this displacement-proportional dissipation, which is caused by the dissipation of plastic work. Ideally, before the incoming energy reaches the building, it would be dissipated in the soil/rock and, if present, seismic isolators. In particular, soil has quite high energy dissipation capacity than structure.

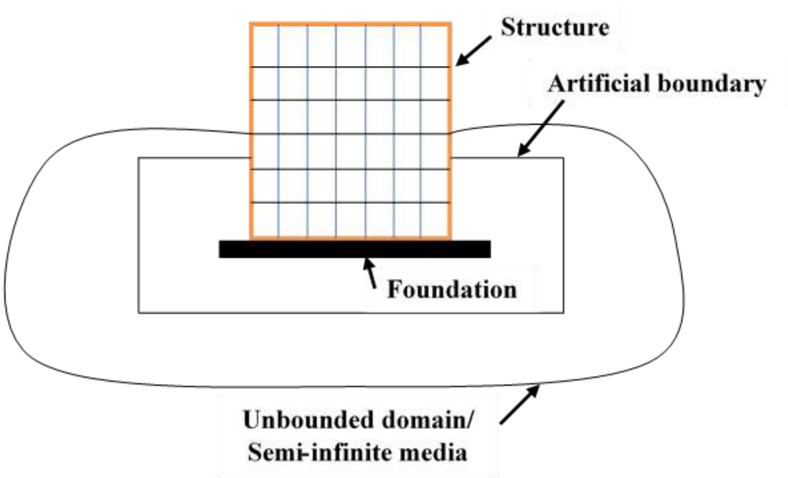

Figure 5: Interaction of unbounded soil with geo-structures

6.1.2. Idealized Soil Behavior

The complexity of in-situ soil behavior as a purely phenomenological characteristic has given rise to a number of idealized forms of soil behavior defined on classical elastic and plastic theories. The models are applied to research the problems of soil-foundation interaction. It has been indicated that under specific boundary conditions idealized models can possibly represent some part of the soil media, even though the generic stress- strain equations of soils do not even correspond to the bulk physical properties of a mass of soil. Particularly when solving complicated geotechnical engineering issues, the analytical rigor is reduced by the idealized soil behavior. Numerous elements, including but not limited to:

1. The soil kind.
2. The state of the soil.
3. What kind of base is used?
4. The external loading's characteristics.
5. The building processes.
6. The building's intended use, expected lifespan, and
7. All things related to money.

6.1.3. Wave Propagation

An unbounded or infinite medium (one that extends endlessly in the wave propagation directions) is the best starting point for understanding how stress waves propagate. An endlessly long rod or bar is a basic one-dimensional idealization of a limitless material. Equations 4.4 and 4.5 are known to be solutions to the one-dimensional wave equation (Kramer, 2008).

$$\frac{\partial_u^2}{\partial_t^2} = \frac{M}{\rho}\frac{\partial_u^2}{\partial_x^2} \quad \text{.....................} \text{(VI)}$$

OR

$$\frac{\partial_u^2}{\partial_t^2} = v_p^2\frac{\partial_u^2}{\partial_x^2} \quad \text{..................} \text{(VII)}$$

where,
v_p= Wave propagation velocity = √(M/ρ)
M = Constrained modulus = {(1-ν)/(1+ν) (1-2ν)} E
E = Modulus of elasticity of soil
One way to represent the solution using the wave number k is as follows:
$u(x,t) = A\cos(\overline{\omega}t - kx) + B\cos((\overline{\omega}t + kx)$ …………….. (VIII)
where,
$k = \frac{\overline{\omega}}{v}$ ………….. (IX)
The first phrase describes harmonic waves moving in the positive x-direction, whereas the second term describes harmonic waves moving in the negative x-direction. Similarly, in the case of the 3-D equation of motion,
$v_p = \sqrt{\frac{\lambda+2\mu}{\rho}}$ …………….. *(X)*
$v_p = \sqrt{\frac{2G(1-\nu)}{\rho(1-2\nu)}}$ ………….. (XI)
$v_s = \sqrt{\frac{G}{\rho}}$ …………….. (XII)
where, v_s = Shear wave velocity, λ, μ = Lame's constant, and *G* = Modulus of rigidity of soil.

6.1.4. Meshing in FE

It is a fundamental and critical step that directly influences the accuracy, stability, and convergence of numerical simulations in engineering analysis. It involves discretizing a complex geometric domain into smaller, manageable sub-domains called finite elements, which can be triangular, quadrilateral, tetrahedral, or hexahedral in shape, depending on the dimensionality and complexity of the structure. These elements are connected at nodes, which are calculated to have the main unknowns, such as displacement or temperature. A mesh is the process of converting a continuum into a discrete model so that a partial differential equation describing some physical phenomenon can be approximated numerically. The mesh properties such as element shape, size, skewness, and aspect ratio have a strong influence on the accuracy and the speed of FEM solution. The finer the mesh the more realistic the results are likely to be however it will consume a large number of computer resources. The finer the mesh is, the more accurate it becomes, but the more time it takes to perform the calculation. The trade-off between accuracy and processing efficiency is refined by re-meshing in high-gradient regions or regions of stress concentrations with advanced meshing technology, such as adaptive meshing. Structured meshes are commonly adopted in simple geometries because they are easy to generate and are regular. Unstructured or hybrid meshes are the favored approach, on the other hand, complex or irregular domains. Mesh generation tools like ABAQUS Meshing, Hyper-Mesh, G-msh, and COMSOL offer powerful capabilities to control element types, sizes, and refinement zones. An essential part of any study or industrial application based on finite element analysis, the mesh determines how successful the analysis will be.

7. Results:

The research takes its premises on a foundation width of 20 m and a foundation depth of 2 m. Parameters of soil, foundation, and the construction materials are indicated in Tables 5.1 and 5.2. The Mohr-Coulomb material simulation is applied to the research. We are assuming a damping factor of 15 percent for the soil and 5 percent for the foundation. We have approached the determination of acceleration and displacement of the system at different nodes (A, B, C) and compared such results with data at adjacent nodes (A, B, C). Turning to the Free-Field node F' of the system, additional reactions may be observed in the form of changes in the signal level and signal creation due to the synthesis of the signal absorption mode in stealth health, steps drastically reducing the receive rate of antitheft electronic equipment in the stealth sick or stealth behavioral health. The Northridge Earthquake (1994) with PGA 0.29g is applied at the system's base for 20 seconds to provide input motion. In Fig. 5.1, we can see the acceleration time history for 0.29g PGA.

Geo-structural issues have been analyzed using FEM over the last sixty years. If the soil is complex, it may classify each element according to a unique set of material properties. Furthermore, the domain might be subject to intricate boundary requirements. Additionally, pieces may have their sizes changed to suit specific needs. In order to analyze the DSSI phenomena of the soil-slope system under plane strain conditions, this research used a 2-dimensional finite element analysis using 8-noded quadrilateral elements.

The column and the beam were considered to be meshed with an Euler-Bernoulli beam element, which is a 3-node element with quadratic strain components of the beam operating on a plane strain situation. An 8-noded quadrilateral plane strain element was used to model the foundations that were simulated to be immersed in soil. The buildings were erected on top of the dirt.

To improve convergence and prevent elements from being distorted during analysis, consider using the sweeping meshing approach in specific areas and the adjacent plane region below the foundation's building mass in other areas. The quickest convergence cause for the realistic behavior of the seismic investigation was to use 8-noded quadrilateral plain strain components. Kumari and Kumari (2022a) found that these features helped identify the building's collected stresses and strains, which in turn helped forecast the slope mass's accumulated stress. Because of this, the failure zone in slope mass may be more accurately predicted.

Table 2: Material properties of soil

Properties of Soil	
Modulus of Elasticity	25x10^3 kN/m^2
Poisson's ratio	0.35
Unit weight of Soil	2050 kg/m^3
Damping in soil	15%
Rayleigh damping Coefficient α and β	0.2805 & 0.1212
Dilation angle	0.1
Shear Modulus	250 x 10^6 N/m^2
Cohesion	7 x 10^6 N/m^2
Friction angle	37^0

Table 3: Material properties of concrete

Properties of Concrete	
Modulus of Elasticity	25x10^6 kN/m^2
Poisson's ratio	0.25

Unit weight of Soil	2400 kg/m^3
Damping in soil	5%
Grade of Concrete	M 25

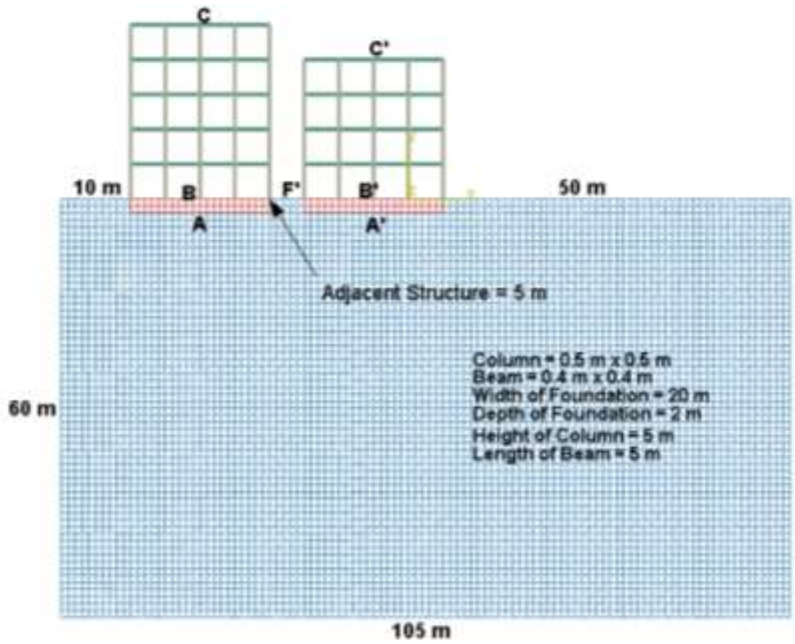

Figure 6: FE model for the adjacent building

7.1. Input Motion

In order to conduct the study, the model was treated as if it were not buried in the soil, and its reaction was contrasted with that of the identical model that was. The input motion is based on site-specific data from the Northridge earthquake (1994), which had a maximum acceleration of 0.29g. However, the ground cannot be directly used as an input motion for this acceleration time. As shown in Figure 7, deconvoluting the ground motion is necessary to get the input response at the base of the foundation soil or rock, which is 100 meters below ground level. See Figure 8 for the fundamental deconvolution needed.

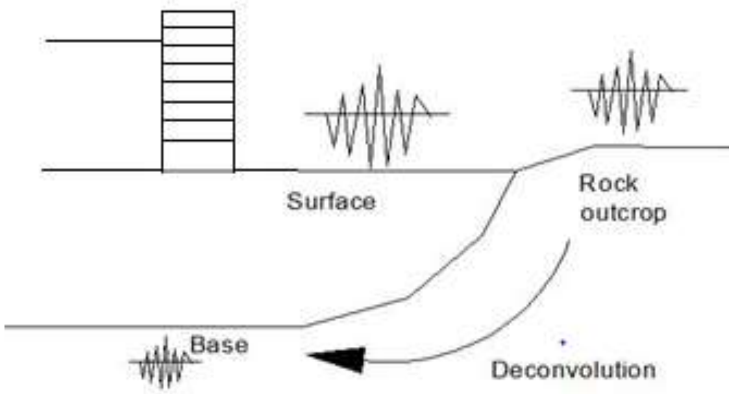

Figure 7: Deconvolution of seismic motion

By following these steps, you will quickly understand the deconvolution technique:

Motion at rock outcrop (time domain)

(Fast Fourier Transformation)

Motion at rock outcrop (Frequency domain)

(Compute transfer function in the frequency domain)

Motion at base of the foundation soil/rock (Frequency domain)

(Inverse Fast Fourier Transformation)

Desired motion at base of the foundation soil/rock (Time domain)

Figure 8: Deconvolution process for input motion

Then, the Peak Ground Acceleration (PGA) is assessed with Pro-sake software, and the deconvoluted PGA for the current location of study is calculated and shown in Fig. 9.

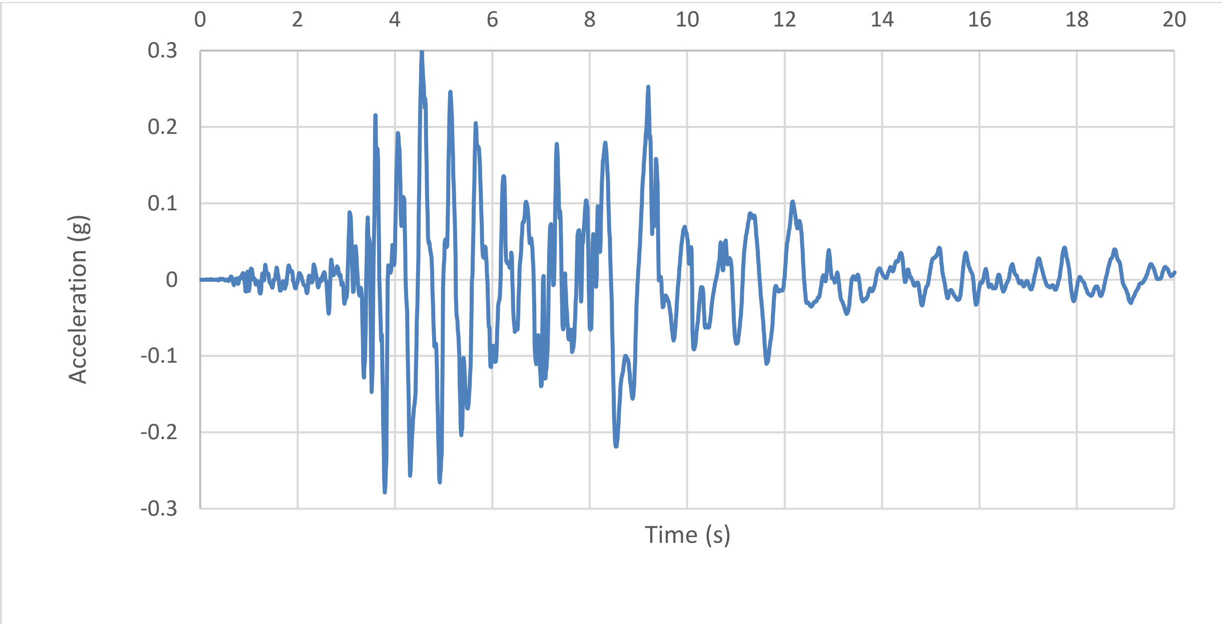

Figure 9: Acceleration-Time History of the 1994 Northridge Earthquake

7.2. Natural Frequency and Mode Shapes

Table 4 displays the computed system time for the first three modes. It is first believed that the building is located on the rock, which, due to its outstanding rigidity, will have a high natural frequency. The system becomes less rigid when the structure is placed on soft soil compared to the prior scenario. As a result, the system's frequency decreases somewhat, leading to an increase in the system's time. The duration of the system's three modes on a deformation scale factor of 10 is shown in Figures (5.5-5.7). As the structure becomes more rigid, the period decreases.

The soil and structure's deformation may be seen using the 10th deformation scale. The deformed shape clearly indicates that energy dissipation increases with higher modes. The frequency obtained in the first three mode shapes on soil was 0.873 cycles/sec., 0.823 cycles/sec. and 0.634 cycles/sec. It was found that the frequency of the system increases as the mode shape increases.

Table 4: Various mode shapes on structure response founded on soil and rock

Modes	Structure on Rock	Structure on Soil
1	0.531	0.873
2	0.216	0.823
3	0.191	0.634

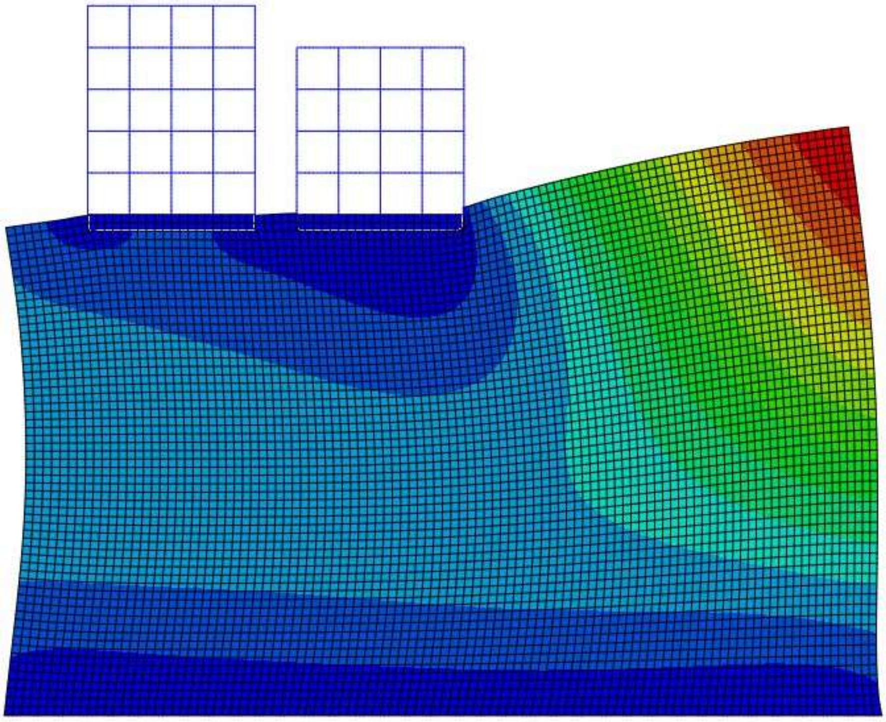

Figure 9(1st): mode shape

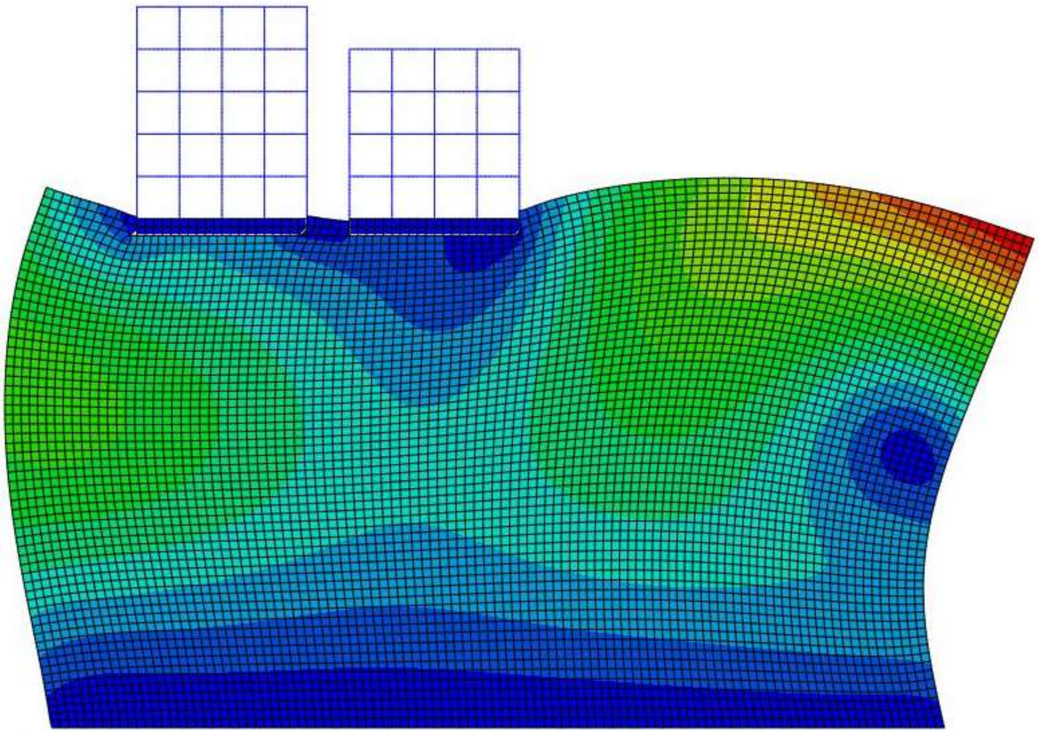

Figure 9(2nd): mode shape

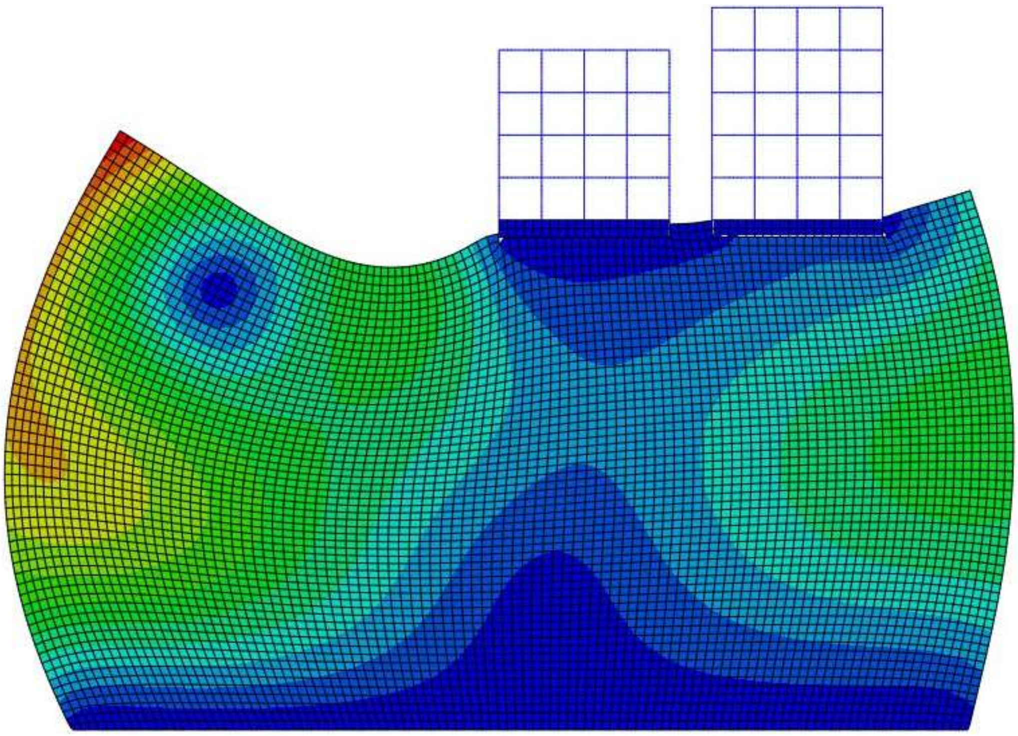

Figure 9(3rd): mode shape

7.3. Maximum Displacement and Acceleration Response

For each of the three foundation nodes, we have computed the response using one of three transmitting boundaries: BC-1 (L-K), BC-2 (N-M), and BC-3 (Bettess). Each PGA has its own unique set of boundary criteria. The displacement and acceleration response have been calculated and shown in Tables 5 and 6.

Table 5: Max displacement response of the system

Response points/ Boundaries Condition	**F'**	**A**	**B**	**C**	**A'**	**B'**	**C'**
	Maximum Displacement (cm)						
BC-1 (L-K)	11	8	14	27	7.5	13	21
BC-2 (N-M)	10	7	13	25	6.5	6	19.5
BC-3 (Bettess)	7	5	11	21	3	5	17

The result obtained from Table 6 can be assessed to overcome the pounding in the buildings. It is observed that as the boundary conditions change from viscous to infinite element boundaries, the response for the various nodes decreases. After careful consideration, it has been determined that the BC-3 is the superior choice for mitigating the impact within the structure. The effect of pounding decreases up to 30-40 % with infinite element boundaries.

Table 6: Max acceleration response of the system

Response points/ Boundaries Condition	**F'**	**A**	**B**	**C**	**A'**	**B'**	**C'**
	Maximum acceleration (g)						
BC-1 (L-K)	0.41	0.38	0.40	0.56	0.38	0.40	0.45
BC-2 (N-M)	0.39	0.35	0.37	0.48	0.36	0.38	0.43
BC-3 (Bettess)	0.35	0.31	0.33	0.41	0.33	0.34	0.36

The result obtained from Table 6 can be assessed to overcome the pounding in the buildings. It is observed that as boundaries condition changes to viscous to infinite element boundaries the response for the various nodes decreases. In order to lessen the impact of the hammering within the structure, the BC-3 was determined to be the superior choice. The effect of pounding on acceleration response decreases up to 15-20 % with infinite element boundaries. At node C, the system has shown its maximum responsiveness. Table 3 displays the appropriate answers for PGA of 0.29g. Due to the far-off radiation of energy, the system's acceleration and displacement responses are less with the infinite element boundary condition compared to the viscous and Novak and Mitwally boundary conditions.

7.4. Effect of Pounding

Pounding leads to a 30–50% increase in displacement. Height difference amplifies impact forces. A slight separation (<100 mm) is critical for a higher pounding risk.

Table 7: Effect of pounding on various parameters

Parameter	Without Pounding	With Pounding
Max Displacement (mm)	120	180
Max Inter-story Drift (%)	1.2	2.5
Pounding Force (kN)	0	95
Base Shear (kN)	3800	4200

8. Conclusion:

A study is conducted on the phenomenon of pounding on nearby buildings under SSI. The most significant part of pounding under seismic conditions is considered for the study. The displacement and acceleration response are assessed for the top of the building. The investigation also examined the effect of pounding. This research shows that dynamic SSI has a significant impact on structural pounding. Additionally, it was shown that inelastic analysis greatly amplifies the impact of hammering. A workable approach will be devised based on these impacts and results. Combining the effects of SSI with the inelastic behavior of the nearby structure is a viable approach to reducing structural pounding.

- The findings demonstrated a clear correlation between structural hammering and SSI and inelastic behavior, since these factors significantly amplified the impact. The following conclusions were obtained in the study:
- Because of the system's adaptability, the time rose when the soil-structure interaction impact was taken into account.
- Due to the far-off radiation of energy, the system's acceleration and displacement responses are less with the infinite element boundary condition compared to the viscous and Novak and Mitwally boundary conditions.
- With infinite element boundaries (BC-3), the impact of pounding on displacement response may be reduced by as much as 30–40%.
- With infinite element boundaries (BC-3), the impact of pounding on acceleration response may be reduced by as much as fifteen to twenty percent.
- Seismic damage was more severe in the neighboring higher structure since the reaction increases with height.
- Regarding safety and economy, taller structures respond with a higher side and are more susceptible to damage but not failure, because of the increased period.

9. Limitation of Findings:

The present research has the following limitations:

1. The study is limited to two adjacent buildings; however, the study is extended to the effect of pounding in the city.
2. The more generalized way of mapping can be done after studying the city effect.
3. The SSI effect is also considered for the various peak ground acceleration (PGA) effects on buildings.

The study's findings strongly suggest that, when doing seismic analysis and designing nearby buildings, engineers and engineering firms should simultaneously consider the effects of soil-structure interaction and structural pounding to guarantee the safety and integrity of the structures against earthquake action.

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