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Seismic Response of High-Rise Buildings on Soft and Hard Soils: Integrating Soil-Structure Interaction, Earthquake Frequency, and Foundation Effects

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Abstract: The objective of this study is to answer two questions, the first question is, whether the soft soil always increases the seismic response of structures regardless of the frequency content of an earthquake. The second is to check if response spectrum curves will be affected by the existence of superstructures of different heights. The study was conducted on representative strips of tall buildings ranging from twenty to eighty floors. Models were calibrated based on a study of dynamic analysis using soil structure interaction done by PLAXIS software. The study tried to optimize modeling by using a close to reality models that include both nonlinear structures and soils. Contrary to current guidelines, using earthquakes with different frequency domains shows that harder soil can magnify seismic response more than soft soil. The existence of superstructures in the study changes the induced response spectrum curves in an obvious way.
[Mohammed Naguib Abou El Saad, Mahmoud Al Sakkar, and Mohamed E. El Madawy. Seismic Response of High-Rise Buildings on Soft and Hard Soils: Integrating Soil-Structure Interaction, Earthquake Frequency, and Foundation Effects. *Nat Sci* 2025,23(2):31-44]. ISSN 1545-0740 (print); ISSN 2375-7167 (online). http://www.sciencepub.net/nature 05. doi:10.7537/marsnsj230225.05

Keywords: Dynamic soil-structure Interaction (SSI); soil-structure Interaction for seismic design; Soil effect on Tall-building; Soil Nonlinear time history Analysis; Foundation effect on soil-structure Interaction.

Introduction

The development of high-rise buildings is often considered an indicator of a nation's progress. Seismic forces are among the most critical loads to consider for these buildings. It is widely accepted that earthquakes do not directly cause human casualties; instead, fatalities occur when seismic loads impact buildings. Earthquakes are triggered by fault ruptures, which generate waves that travel through the rock beneath the structure and then propagate upward to the ground surface, reaching the building. In modern practice, seismic forces are applied to the floors of the structure, where they propagate downward to the fixed support at the base of the model. Typically, the bedrock earthquake magnitude is multiplied by a soil factor to account for the effects of the soil, with this factor being provided in the code and derived from previous site response studies.

This study had two primary objectives: first, to determine whether soft soil leads to greater response amplification compared to hard soil, regardless of the frequency content of different earthquakes, and second, to examine the response spectra curves at the ground surface when a superstructure is present. Ignoring the superstructure in geotechnical studies and considering it separately with a fixed base may increase the seismic loads on the superstructure, as this approach tends to underestimate the structure's period.

To enhance this study, previous research on soil-structure interaction was reviewed to adopt their strengths and avoid their shortcomings. Soil-structure interaction has been studied from various perspectives. In geotechnical research, specialized software or experimental models have typically been used to model the soil in depth, while the superstructure was often represented by generalized Single Degree of Freedom -SDOF- systems, Multi Degree of Freedom -MDOF- stick models, multi-bay and/or multi-level 2D frames, or simple 3D frames. On the other hand, structural research usually modeled the soil as a collection of springs, dashpots, and occasionally masses. Many prior studies did not model foundations in detail, especially deep foundations required for tall buildings, and would often represent only a small number of piles. Most earlier studies used the Mohr-Coulomb model for soil. However, the Mohr-Coulomb model lacks key features such as shear and compression hardening, stress-strain dependency, and dilatancy, which only activates once the shear surface is reached. Additionally, its loading and unloading paths coincide at the same point, meaning it does not account for hysteresis at the early stages of stresses. Furthermore, many studies modeled soil as a series of arbitrary layers, where changing the order of these layers could alter the results.

For seismic time history records, the El Centro time history and other records with their true magnitude were commonly used. Earlier studies generally employed a set of response spectrum curves to monitor the outcomes at various locations on the ground surface.

The disadvantages of previous studies are summarized in the following points, which are categorized into two main areas: disadvantages related to structure, foundations, and soil modeling, and those related to earthquake loads and the resulting data capture.

Tables 1 to 3 outline each disadvantage, specifying the relevant clause, and cite the previous research where these limitations were identified.

a) **For the structure:**

1. Studies that simplified the structure by disregarding higher modes, focusing only on the basic anticipated mode, and modeling the structure as a stick model with a single degree of freedom, uniform stiffness, and mass.
2. Research that considered both short and tall building extremes.
3. Studies that treated damping as a single modal damping ratio.
4. Research that neglected the structure's inelastic behavior, focusing solely on its elastic linear behavior.
5. Many studies did not model realistic buildings, particularly tall ones with shear walls.

b) **For foundations:**

1. Studies that did not consider footings at all.
2. Research that failed to account for the kinematic effects of the foundations.
3. Studies that overlooked the filtering effect of footings.
4. Research that considered only single pile models.
5. Studies that considered basic pilecaps with just three, four, or five piles.
6. Research that accounted for the mass of the footing.
7. Studies that neglected foundation damping.
8. Studies that did not consider the inelasticity of the footing.
9. One study examined the results of structural embedment using a basement in the soil.

c) **For the soil:**

1. Research that modeled the soil as a continuous spring and dashpot system.
2. Studies where soil layers were randomly chosen.
3. Research that did not account for the mass of the soil.
4. Studies that ignored radiation damping.
5. Research that did not adequately replicate soil nonlinearity.
6. Studies on nonlinearity that used an equivalent linear approach.
7. Research showing that soil nonlinearity behavior occurs at specific depths, depending on soil type and seismic excitation magnitude.
8. In experimental tests, the container used to hold the soil and define its boundary conditions may have affected the soil's overall behavior.
9. In small-scale prototypes (such as centrifugal tests), the size of soil particles, especially clay, is often too large to scale down and is treated as rocks and boulders by piles and foundations.
10. Earlier numerical models employed outdated soil models like Mohr-Coulomb and linear or nonlinear Hypoplastic models. It is recommended to use the newer hardening soil with small strain model for seismic analysis.
11. The concept of representing soil as a single macro-element for deep foundations was introduced in [9], [14], and [15].

d) **For excitation:**

1. Several studies used arbitrary seismic excitations, often the El Centro earthquake.
2. Studies with limited values of earthquake intensity.

e) **Analysis and findings:**

1. Studies where seismic loads were applied directly to the superstructure down to the soil, instead of applying them to the bedrock and allowing them to propagate upwards to the superstructure, as should be done.
2. Studies where the response was recorded at only a single point on the building.
3. Simple models were frequently used, while full numerical models were harder to manage. Some methods considered the substructure approach, while others used successive coupling, as seen in [3] and [6]. Other models simulated the nearby soil with the finite element method, while the distant soil was modeled with the boundary element method, as in [13].

Table 1. References for each clause from a-1 to b-9

Reference no	Clause no												
	a-1	a-2	a-3	a-4	b-1	b-2	b-3	b-4	b-5	b-6	b-7	b-8	b-9
Kramer, S.L. [1]	✓		✓	✓	✓		✓				✓	✓	
Kaynia, A.; Kausel, E [2]	✓		✓	✓			✓	✓	✓		✓	✓	
Maheshwari, B.K., et al. [3]	✓		✓	✓			✓	✓	✓		✓	✓	
Ghannad, M.A.; Jahankhah, H. [4]	✓	✓	✓			✓	✓			✓	✓	✓	
Nakhaei, M.; Ali Ghannad. [5]	✓		✓			✓				✓	✓	✓	
Cai, Y.X.; Gould, P.L , et al. [6]	✓		✓	✓	✓	✓	✓				✓	✓	
John P. wolf [7]				✓		✓	✓					✓	
Rosenblueth, N.M.N, et al. [8]				✓		✓	✓					✓	
PÉREZ-HERREROS, J. [9]						✓	✓					✓	
Wilson, E.L. [10]								✓			✓	✓	
Chiou, J.S.; Hung, W.Y, et al. [11]		✓							✓		✓	✓	
Baker, J.W. [12]													✓
Syed, N.M.; Maheshwari, B.K. [13]		✓						✓	✓				

Table 2. References for each clause from c-1 to c-10

Reference no	Clause no								
	c-1	c-2	c-3	c-4	c-5	c-6	c-7	c-8	c-10
Kramer, S.L. [1]	✓		✓	✓	✓				
Kaynia, A.; Kausel, E [2]	✓		✓	✓	✓				
Maheshwari, B.K., et al. [3]	✓	✓	✓	✓	✓				
Ghannad, M.A.; Jahankhah, H. [4]	✓		✓	✓	✓				
Nakhaei, M.; Ali Ghannad. [5]	✓		✓	✓		✓			
Cai, Y.X.; Gould, P.L , et al. [6]	✓		✓	✓	✓				
John P. wolf [7]	✓			✓	✓				
Rosenblueth, N.M.N, et al. [8]	✓			✓	✓				
PÉREZ-HERREROS, J. [9]	✓			✓	✓				
Wilson, E.L. [10]				✓	✓				
Chiou, J.S.; Hung, W.Y , et al. [11]		✓			✓				
Pérez-Herreros, J.; Cuira , et al. [14]									✓
Perez-Herreros, J. [15]									✓
Syed, N.M.; Maheshwari, B.K. [13]		✓					✓	✓	

Table 3. References for each clause from d-1 to e-3

Reference no	Clause no				
	d-1	d-2	e-1	e-2	e-3
Kramer, S.L. [1]			✓	✓	✓
Kaynia, A.; Kausel, E [2]			✓	✓	✓
Maheshwari, B.K., et al. [3]			✓	✓	✓
Ghannad, M.A.; Jahankhah, H. [4]	✓	✓	✓	✓	✓
Nakhaei, M.; Ali Ghannad. [5]	✓	✓	✓	✓	✓
Cai, Y.X.; Gould, P.L , et al. [6]			✓	✓	✓
Wilson, E.L. [10]				✓	✓
Syed, N.M.; Maheshwari, B.K. [13]	✓				

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This study integrates structural and geotechnical approaches to analyze a comprehensive 3-D strip, carefully selected to represent the system from deep rock to the soil surface, including a realistic tall building ranging from twenty to eighty floors. Due to limitations, it was not feasible to model these tall structures using full 3-D models. The deep foundations were represented using realistic pile distributions and lengths based on actual conditions. The soil was modeled using Schanz's advanced hardening soil with small strain model, which overcomes the limitations of the Mohr-Coulomb model and is more suitable for seismic analysis. To avoid complications in the selection of soil layer orders, two extreme types of soil—stiff and soft—were used in separate models, each represented by a large, uniform layer. The seismic records chosen for the study were based on various earthquakes with distinct frequency content that have significantly impacted earthquake engineering. These records were scaled to create two extreme seismic events, one weak and one strong. Time history and response spectrum curves were used to track results across a grid of points throughout the model.

The study shows that by addressing the limitations of previous research, new or different conclusions can be drawn. Notably, the Northridge earthquake, unlike the other records used, causes a stronger response in harder soils compared to softer ones. The response spectra measured at the ground surface also vary significantly when multiple towers are modeled.

2 Used Models and Selected Earthquake Records.

This research considered a range of tower heights, including 20, 40, 60, and 80-story structures. For the 20-story towers, two types of foundations were investigated: raft foundations and pile caps over piles. Using a raft foundation for taller structures is generally impractical and rarely implemented.

The towers were modeled on two extreme soil types: soft soil and hard soil. The hard soil was selected as very dense sand due to its superior strength and stiffness, while the soft soil was modeled as clay. Because of its substantial weight, the 80-story structure was modeled only on firm soil. The effect of groundwater was not included in this study.

2.1 Models' description

Nine three-dimensional PLAXIS simulations were conducted for the structures as outlined in Table 4. Following common practice, raft foundations are typically limited to medium-rise buildings, so they were only used for the 20-story structure.

Table 4 Models that were employed in the research.

Number of Floors	**20 floors**	**40 floors**	**60 floors**	**80 floors**
Type of soil	Hard/Weak	Hard/Weak	Hard/Weak	Hard
Type of Foundation	Raft/Pilecap	Pile cap	Pile cap	Pile cap

Solving a complete full model was not feasible at the time of the study due to the extensive computational requirements for running a nonlinear time history analysis of the entire soil-structure interaction. As a result, a slice model was selected to more accurately represent the structure. A five-meter slice was chosen for two reasons: first, the walls were spaced 5 meters apart, and second, there was a 2.5-meter gap between the piles. A 5-meter-wide section of the tower was extracted for modeling, with the tower's total length being 21 meters, as shown in Figure 1.

The slice contains two shear walls at its ends and another large internal shear wall that represents half of the core, as shown in Figure 1. The edge walls are 2.5 meters long, while the core wall is 5 meters long. The distance between the core wall and the adjacent edge walls is 5.5 meters. The internal core was modeled as a single shear wall with equivalent stiffness. The thickness of various structural elements in the different models is illustrated in Figure 2.

Table 5 Structural elements thickness for different models.

	Edge wall thick.	**The internal core is represented as an equivalent shear wall with thick.**	**Slab thick.**
20 floors	300 mm	700 mm	250 mm
40 floors	600 mm	1400 mm	250 mm
60 floors	900 mm	2100 mm	250 mm
80 floors	1200 mm	2800 mm	250 mm

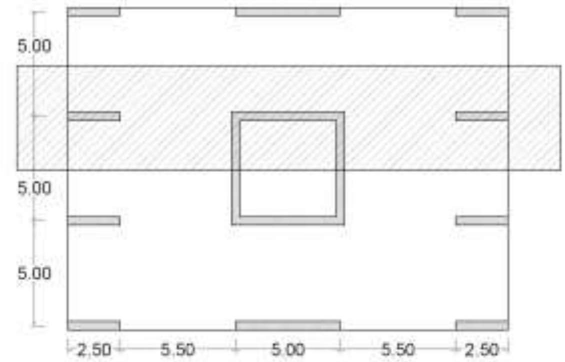

Figure 1 Plan of the used tower.

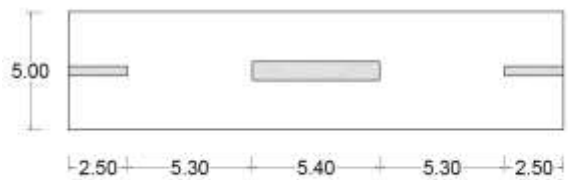

Figure 2 selected strip.

The soil block has the same width as the structure and extends 110 meters to both the left and right, resulting in a total width of 241 meters. The depth of the soil block in the model is 60 meters. These large soil dimensions were selected to satisfy the requirements for dynamic nonlinear soil analysis.

The piles were modeled as square sections with dimensions of 1 meter to simplify the meshing process and were spaced 2.5 meters apart. For the 20- and 40-story towers, the piles were designed to be 20 meters long, while for the 60- and 80-story towers, the pile length was set at 30 meters.

Three-dimensional models were used because plane-strain elements cannot accurately represent piles. Figure 3 illustrates the model of an 80-story skyscraper.

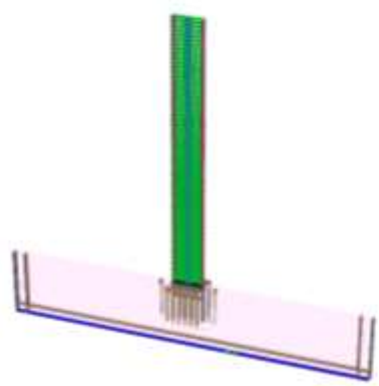
Figure 3 An eighty-floors piled foundation with hard soil PLAXIS model.

2.2 Soil Constitutive model

One of the key factors influencing dynamic analysis is the choice of the soil model. The Mohr-Coulomb model, shown in Figure 4, is a basic soil model that assumes the soil behaves as linearly elastic until it reaches the shear yield surface.

At this point, it transitions to perfectly plastic behavior without strain hardening or accounting for compression hardening. Since the Mohr-Coulomb model uses a single elastic modulus for both loading and unloading, it does not exhibit a hysteretic loop under cyclic loading. Dilatancy is only considered when the stress path reaches the yield surface.

The CAM-clay model, developed by the Cambridge team (Figure 5), combines shear yielding and compression yielding into a single surface. This model allows surface hardening, simulating both shear and compression hardening. Based on critical state theory, its failure surface intersects with the hardening surfaces. However, the CAM-clay model introduces inaccuracies at the pre-consolidation point along the hydrostatic pressure line because the strain vector includes a deviatoric component.

The Modified CAM-clay model addresses this limitation by transforming the yield surface into an elliptical shape (Figure 6), as shown with improved hardening behavior in Figure 7.

The Soft Soil and Soft Soil with Creep models (Figures 8 and 9) focus solely on compression hardening and assume a perfectly plastic shear yield surface without hardening.

The most advanced model used in this study is the Hardening Soil model with Small Strain stiffness (Figure 10), which incorporates both shear and compression hardening. In this model, the soil's modulus of elasticity varies based on the type of loading: shear, unloading, or compression loading. The stiffness is automatically stress-dependent, removing the need for manual assignment. Additionally, the model accounts for dilatancy before hardening occurs.

The differences between the Mohr-Coulomb and Hardening Soil models are illustrated in Figure 11, where triaxial test results highlight their distinct stress-strain relationships. As shown in Figure 12, hysteretic damping is captured by the difference between the initial soil modulus and the unloading/reloading modulus.

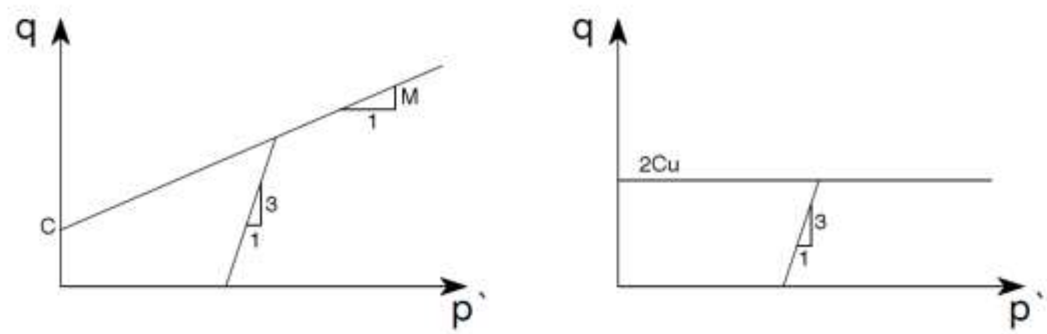

Figure 4 Mohr-Coulomb surface [16]

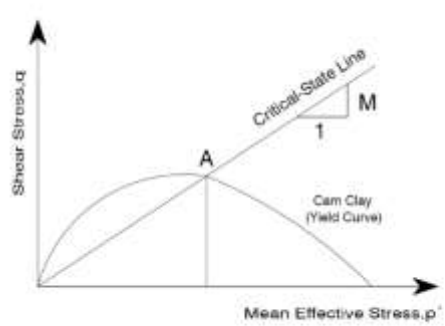

Figure 5 Relation between yield curve and critical state line [17]

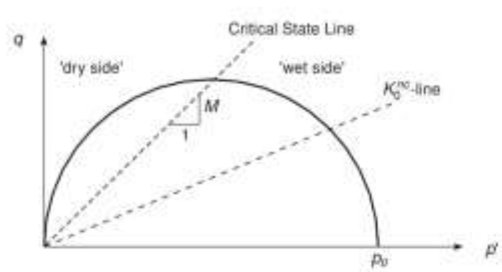

Figure 6 Modified Cam-clay model.[18]

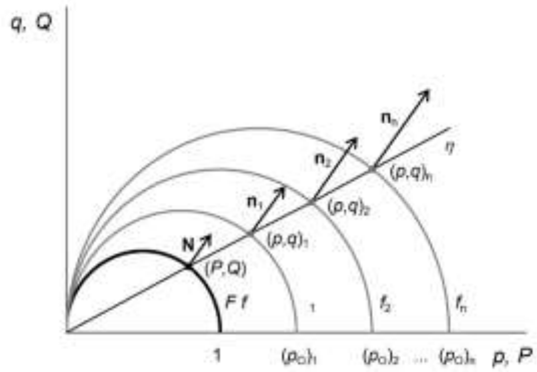

Figure7 Modified Cam-clay Hardening.[19]

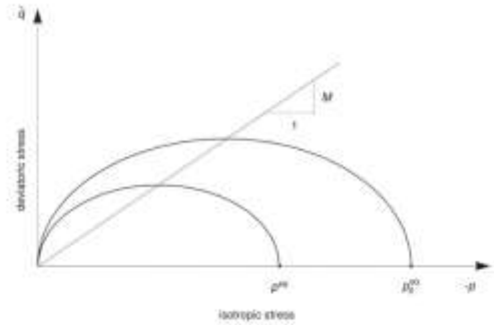

Figure 9 Soft soil with creep model. [18]

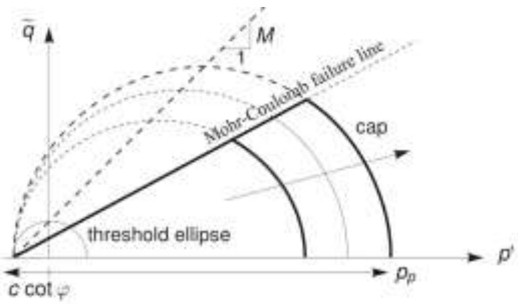

Figure 8 Soft soil model in p'-q plane. [18]

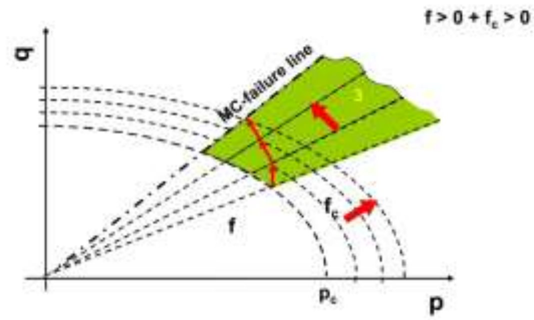

Figure 10 Shear and compression hardening. [17]

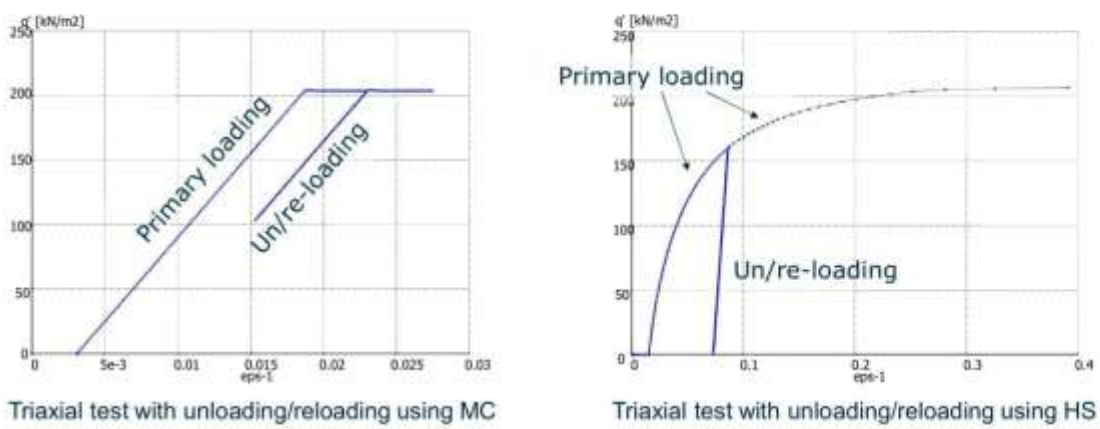

Figure 11 Triaxial test curve using both Mohr-Coulomb and Hardening soil model. [17].

2.3 Selection of an applied set of earthquake records.

The Imperial Valley earthquake (El Centro, California, 1940), the Loma Prieta earthquake (1989), and the Northridge earthquake (California, 1994) were selected for this study, as shown in Figure 13. To standardize the time histories, they were initially scaled to 0.15 g. Subsequently, the data were scaled down to 0.05 g for weak earthquakesand up to 0.3 g for strong ones. The frequency content of the three earthquakes is presented in Figure 14.

The parameters of two different soils for the Hardening soil with Small Strain model were chosen as given in

Table 6.

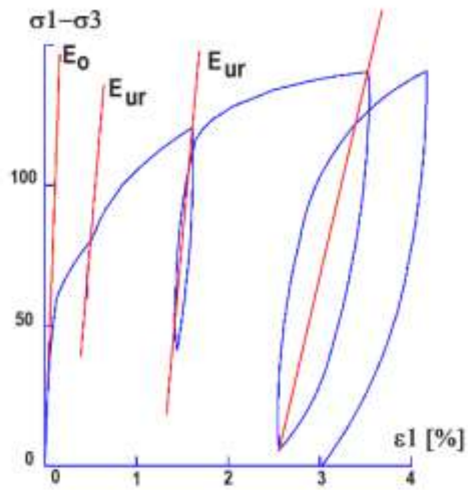

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Figure 12 E_0 and E_{UR} values [20]

Table 6 Soil Definitions as Required by Hardening Soil with Small Strain Model.

Soil Type	Hard Soil	Weak Soil
Soil Model	HS small model	HS small model
Unsaturated Soil Density KN/m3	20	14
Unsaturated Soil Density KN/m3	20	16
Rayleigh Damping Alpha Factor	0.09934	0.02457
Rayleigh Damping Beta Factor	0.8392E-3	0.2075E-3
Soil Secant Modulus of Elasticity at 50% of Ultimate Strength, E50 ref KN/m2	90,000	3000
Oedometer Soil Modulus of Elasticity, E oed ref KN/m2	65,000	3000
Unloading/Reloading Soil Modulus of Elasticity, E ur ref KN/m2	250,000	9000
Soil Cohesion, C' KN/m2	1	1
Soil angle of internal friction, Phi'	45	35
Soil angle of dilatancy, Psi	15	5
Gamma 0.7	0.10E-3	0.15E-3
Soil Initial Shear modulus, G0 ref KN/m2	300,000	9000
Poison Ratio for unloading and reloading, Neu' ur	0.2	0.2
R-Factor for Interface between Concrete and Soil Elements	0.7	0.7
Method to account for Initial Soil Stress	K0	K0

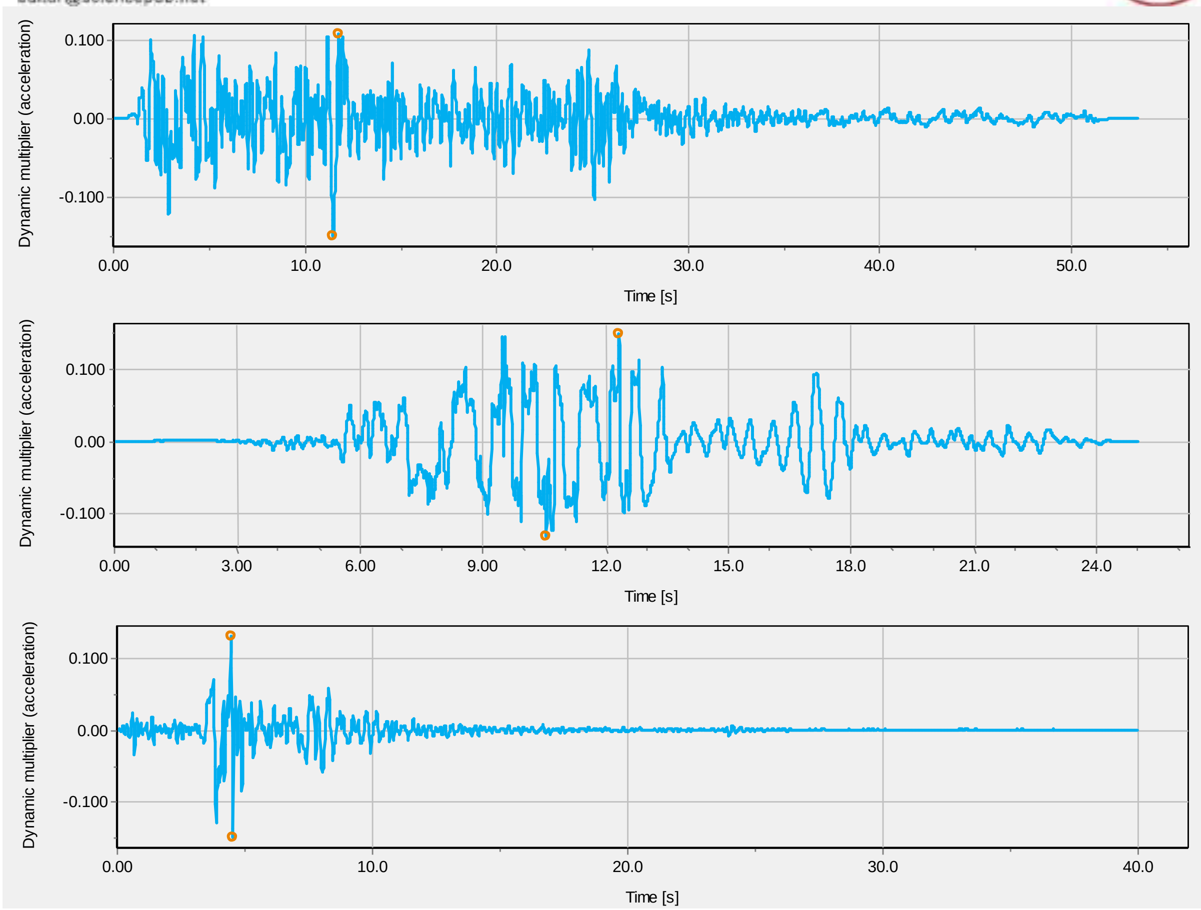
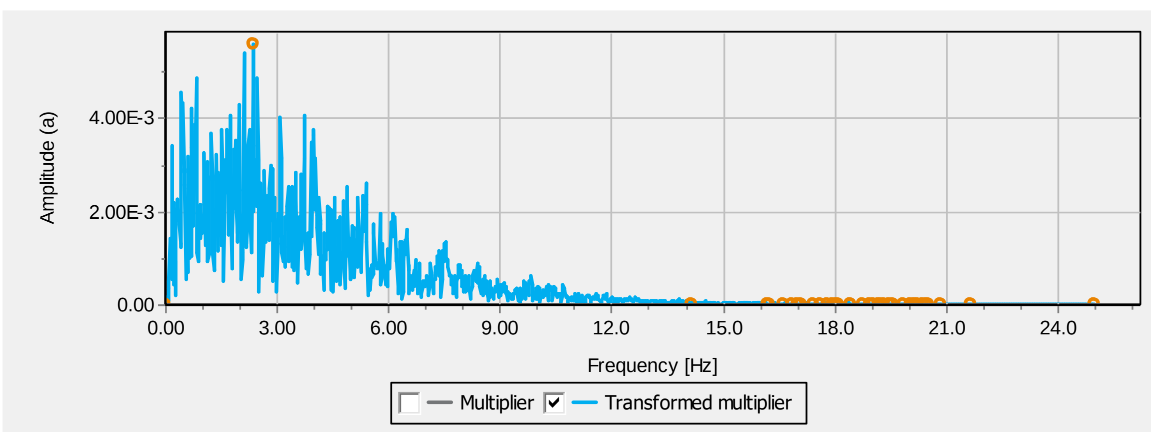


Figure 13 The Imperial Valley earthquake, the Loma Prieta earthquake, and the Northridge earthquake



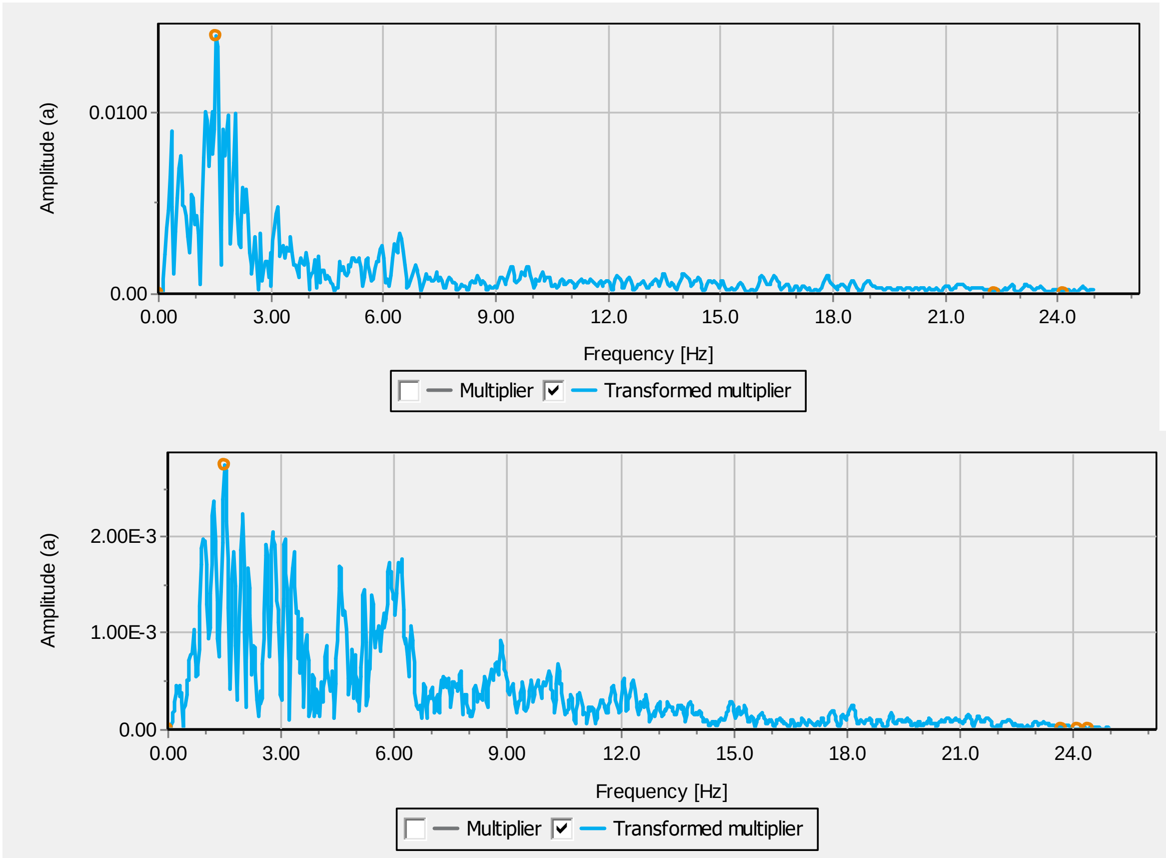


Figure 14 frequency content of The Imperial Valley earthquake, the Loma Prieta earthquake, and the Northridge earthquake

3 Results and Discussion

A three-dimensional numerical analysis was conducted for the described cases: free-field, sixty, forty, and twenty-floor buildings on piles, as well as twenty-floor buildings on a raft. The analysis was performed using PLAXIS 3D 2020. Response spectra curves for the applied time history at the model base, along with the corresponding response spectra curves measured at the top of the soil for both hard and soft soils, are presented in Figures 15 to 20.

In the following figures, the response spectrum curves are plotted for three selected earthquake events: Imperial Valley, Loma Prieta, and Northridge. For each earthquake, two levels of severity were considered: weak and strong.

The response spectrum curves were initially plotted at the base of the model, where the earthquake was applied, and labeled as follows: Imp Weak -60, Imp Strong -60, Loma Weak -60, Loma Strong -60, North Weak -60, and North Strong -60. These names represent the weak and strong intensities of the Imperial Valley, Loma Prieta, and Northridge earthquakes at a depth of 60 meters below ground.

The response spectrum curves were then plotted again at the soil surface for the same earthquake events, considering different building heights: 80, 60, 40, and 20 stories. These plots illustrate the response spectrum measured at the soil surface in the presence of towers with 80, 60, 40, and 20 floors.

Additionally, the response spectrum was measured at the soil surface without any building, referred to as the free-field response spectrum.

For the twenty-floor structure, the foundation was analyzed using two types: raft and piles, referred to as 20Raft and 20Piles, respectively.

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(A) (B)

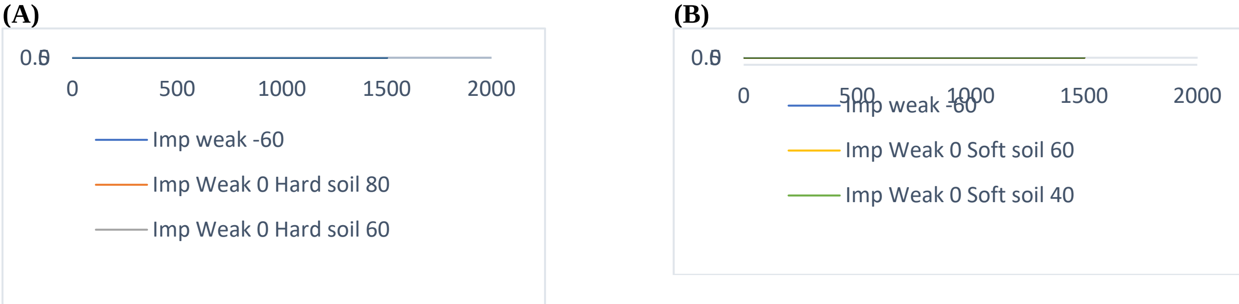

Figure 15 Input and output response spectra for El Centro earthquake with PGA of 0.05g. A) All towers based on hard soil. B) All towers based on soft soil.

Note: Horizontal axis is period in 10^-2 seconds and vertical axis is acceleration in m/sec^2.
Note: Imp stands for imperial valley, Loma for Loma Prieta, North for Northridge earthquakes, Weak and strong describe the earthquake magnitude, Soft and Hard describe the strength of soil 20,40,60 and 80 describes numbers of floors, Raft and piles describes type of foundations and Free field to describe the case of no super structures over the ground.

(A) (B)

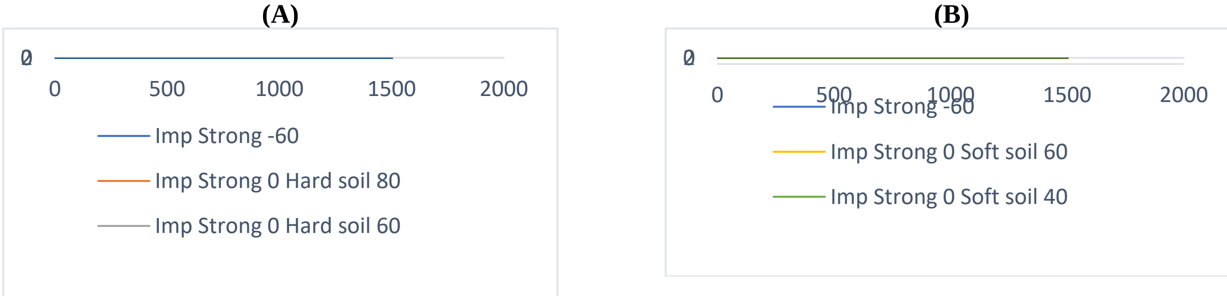

Figure 16 Input and output response spectra for El Centro earthquake with PGA of 0.3g.

(A) (B)

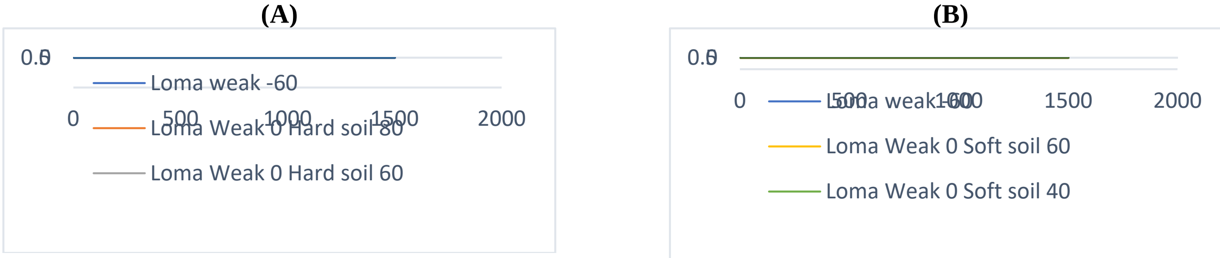

Figure 17 Input and output response spectra for Loma Prieta earthquake with PGA of 0.05g.

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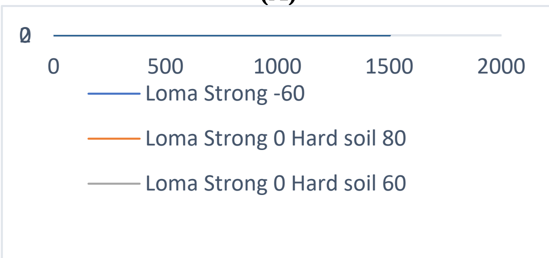
(A)



(B)

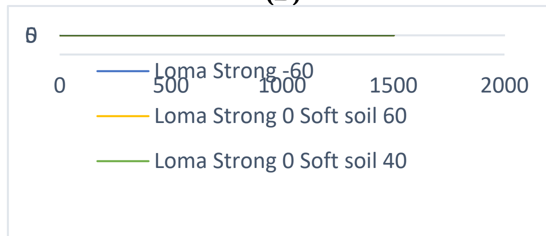
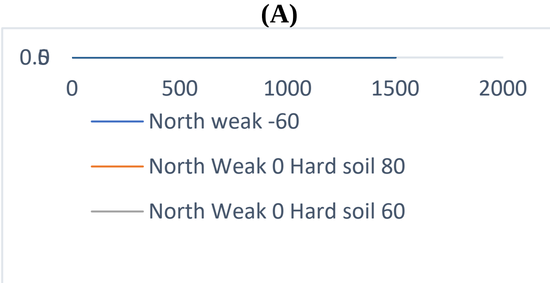


Figure 18 Input and output response spectra for Loma Prieta earthquake with PGA of 0.3g.

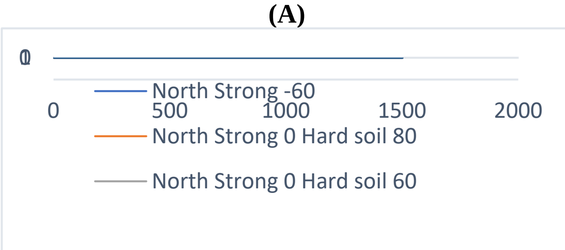
(A)



(B)

Figure 19 Input and output response spectra for Northridge earthquake with PGA of 0.05g.

(A)



(B)

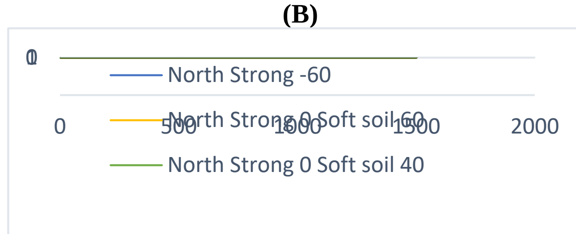


Figure 20. Input and output response spectra for Northridge earthquake with PGA of 0.3g.

4. Discussion

The following observations were noted:

a. For weak and strong Imperial Valley and Loma Prieta earthquakes:

1. **Soft soil models:**

The highest response was observed in the following order: free field, 60 floors, 40 floors, 20 floors with a raft foundation, and 20 floors with a pile foundation. The response of the 40-floor structure with piles was nearly the same as that of the 20-floor structure with a raft foundation.

2. **Hard soil models:**

The highest response was observed in the free field, followed by the 20-floor structure with a raft foundation, which showed a response nearly equal to that of the other towers.

In general, the response on soft soil was larger than on hard soil near the response spectrum periods, except for structures with a fundamental period between 1 and 1.5 seconds, where the response on hard soil was higher.The response of the 20-floor building with piles was found to be similar for both soft and hard soils under weak and strong Loma Prieta earthquakes.

b. For weak and strong Northridge earthquakes:

1. **Soft soil models:**

The highest response was observed in the following order: free field, 20 floors with a raft foundation, 20 floors with piles, 40 floors, and 60 floors.

2.

3. **Hard soil models:**

The highest response was observed in the free field, with almost identical responses for all towers. *In general*, the response on hard soil was slightly higher than on soft soil near the response spectrum periods, and it was significantly higher for structures with periods between 0 and 1.5 seconds.

c. General results (based on observations and response spectra curves):

1. **Site response variability:**

    The response of the same soil can either amplify or reduce depending on the earthquake record. The Northridge earthquake exhibited a different behavior compared to the Imperial Valley and Loma Prieta earthquakes, where hard soil produced a larger response than soft soil.

2. **Influence of soil stiffness:**

    Soil stiffness (soft vs. hard) affects the ground surface response spectrum. Soft soil amplifies the response more than hard soil for periods longer than 1 to 1.5 seconds in the Imperial Valley and Loma Prieta earthquakes. However, for the Northridge earthquake, hard soil amplifies the response similarly to soft soil for longer periods (greater than 1 to 1.5 seconds) and shows significantly higher amplification for shorter periods (less than 1 to 1.5 seconds).

3. **Effect of structure height:**

    The height of the structure influences the ground surface response. For all earthquakes, the free field condition produced the highest response. For the Imperial Valley and Loma Prieta earthquakes, taller towers exhibited higher responses at the ground level, whereas the Northridge earthquake showed the opposite trend.

4. **Impact of foundation type:**

    Foundation type significantly affects the superstructure response. The 20-floor structure with a raft foundation exhibited a response nearly equal to that of the 40-floor structure with piles. Additionally, the 20-floor structure with a raft foundation showed a significantly larger response than the 20-floor structure with a pile foundation for all the earthquakes studied.

5. Conclusions

Three-dimensional models of various tall buildings with raft foundations or raft on piles, constructed on hard and soft soils, were subjected to weak and strong ground motions from three different time history records. The models were analyzed using the Finite Element Method to evaluate the influence of these parameters on the ground surface response spectra. The key findings are as follows:

1. Contrary to international code predictions, certain earthquakes—such as the Northridge earthquake—exhibited larger responses on hard soil compared to soft soil.
2. The response spectra for soft and hard soils depend on the structure's period. An inflection point was observed in the response spectrum at a period of 1 to 1.5 seconds.
3. Free-field models consistently produced the maximum response compared to models with tall buildings.
4. For the Imperial Valley and Loma Prieta earthquakes, taller buildings resulted in larger ground-level response spectra. However, the opposite trend was observed for the Northridge earthquake.
5. The presence of piles improves soil response. For example, the response of a 20-floor structure with a raft foundation was comparable to that of a 40-floor structure with piles. This observation highlights a gap in current design codes, as they do not address this behavior.

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12/25/2025