

## **Nonlinear Seismic Modeling of Soil Behavior in Interaction with Foundation for Heavy Structures**

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### **Abstract**

In this research, the nonlinear seismic behavior of the soil–foundation interaction system under heavy structures has been investigated. A numerical model was developed in Abaqus software, where the contact behavior between soil and foundation was simulated considering slippage and shear yielding. To examine the effect of structure mass, analyses were conducted for masses ranging from 200 to 1000 tons under the recorded El Centro earthquake excitation. Output parameters, including horizontal displacement, foundation rotation, interface shear stress, and foundation settlement, were extracted and analyzed as functions of time. The results indicated that as the structure mass increases, the amplitude of horizontal displacement and foundation rotation decreases, while the static settlement and interface shear stress significantly rise. This response stems from the increased effective vertical force and contact pressure beneath the foundation, leading to enhanced frictional resistance and consequently reduced relative movement. The hysteresis loops obtained from the analyses demonstrate considerable energy dissipation at the soil–foundation interface, with greater intensity observed in heavier structures. Ultimately, by performing sensitivity analyses over the mass range of 200 to 1000 tons, power regression relations were derived between seismic responses and structure mass. These relationships can be utilized for rapid estimation of soil–foundation behavior during the preliminary design phases of heavy structures. The findings highlight that incorporating nonlinear soil–structure interaction plays a critical role in realistic prediction of dynamic response and long-term settlement control in the seismic design of deep foundations.

**Keywords:** *Soil–foundation interaction, nonlinear seismic analysis, heavy structures, numerical modeling.*

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## 1. Introduction

The seismic performance of structures has long been a primary focus in civil and earthquake engineering. In recent decades, with the expansion in size and mass of structures such as power plants, tall towers, and industrial facilities, understanding the dynamic and nonlinear behavior of the soil–foundation–structure system has gained heightened importance. The seismic response of such systems is profoundly influenced by soil mechanical properties, its nonlinear response under dynamic loads, and the complex interaction between the structure and the ground (Gazetas & Mylonakis, 2023). In essence, dynamic soil–structure interaction can induce substantial modifications to the overall system behavior, thereby affecting structural stability and safety during earthquakes (Khosravikia et al., 2022).

Nonlinear soil response under intense seismic loads typically manifests as phenomena like stiffness degradation, increased damping, and propagation of plastic strains in the foundation zone. This makes classical linear analysis assumptions inadequate for capturing physical realities (Kavvadas, 2021). Advanced numerical models, such as three-dimensional finite element method (FEM) and finite difference method (FDM) analyses, enable more accurate simulation of nonlinear soil behavior and its impact on structural response (Nakashima & Suzuki, 2023). Nevertheless, precise nonlinear soil–foundation–structure interaction analysis for high-mass structures remains challenging due to issues like modeling soil hysteretic behavior, selecting appropriate material parameters, and achieving numerical convergence under severe loading. In high-mass structures, significant kinetic energy is generated during earthquakes, potentially causing increased inelastic strains in the soil and foundation. Additionally, secondary effects such as "mass concentration" and "effective system stiffness alteration" result in distinct dynamic responses compared to lighter structures (Zhang et al., 2024).

Recent laboratory and numerical studies have shown that increasing structure mass can amplify soil softening and relative foundation displacements (Rahgozar & Mirzaei, 2023). This issue not only impacts the seismic design of large structures but must also be considered in seismic hazard assessment and updating design codes. Despite notable advancements in soil–structure interaction modeling, a comprehensive understanding of nonlinear seismic behavior in heavy systems under real conditions is still lacking. Most prior studies have focused on light or medium-weight structures, while the dynamic behavior of heavy structures, particularly those with extensive or deep foundations, has received less thorough examination (Boulanger & Ziotopoulou, 2022). Moreover, many existing models assume soil homogeneity and simple elastoplastic behavior, whereas field evidence indicates that heterogeneity, layering, and boundary conditions significantly influence actual responses (Brandenberg et al., 2023). Thus, there is a need for more advanced models to simulate nonlinear soil and foundation behavior in high-mass structures—models capable of simultaneously accounting for realistic dynamic interaction and high-mass effects. This study aligns with that objective, aiming to comprehensively investigate the seismic and nonlinear behavior of soil and foundation in heavy structures. The outcomes can serve as a foundation for refining seismic design methods and enhancing the accuracy of stability analyses for such structures under earthquakes.

The seismic response of soil–structure systems, especially in high-mass cases, is directly governed by the nonlinear and dynamic properties of the foundation soil. Interaction between the soil and superstructure alters the seismic response, and accurate modeling of nonlinear soil behavior under seismic loading remains a key challenge in earthquake engineering (Bhattacharya & Mitra, 2020). Linear-elastic assumptions often underestimate actual displacements, leading to unsafe designs for heavy structures (Chopra, 2017). Extensive research has demonstrated that soil nonlinearity markedly affects ground motion variations and structural response. Seed and Idriss (1970) illustrated how reductions in shear modulus and material damping significantly influence seismic wave intensity and frequency content. Recent studies using advanced numerical simulations have confirmed that nonlinearity in dense sandy and soft clay soils can reduce peak accelerations and shift dominant

frequencies, underscoring the necessity of nonlinear dynamic analysis (Kramer, 2018; Maheri et al., 2021).

Heavy structures exert substantial pressure on the underlying soil due to large inertial forces, activating localized yielding and nonlinear soil response. The soil–structure interaction (SSI) phenomenon modifies both structural response and base motion, typically increasing displacements while reducing high-frequency content in seismic waves (Makris & Gazetas, 1992; Lu et al., 2022). Nonlinear SSI studies span empirical approaches to detailed finite element simulations employing constitutive models such as Mohr–Coulomb, Drucker–Prager, and extended hyperbolic models (Paolucci, 2007; Zhang et al., 2021). Poroelastic analyses and coupled u–p methods have gained prominence for evaluating saturated soils under seismic loading, particularly in liquefaction-prone areas (Dobry et al., 2003). These approaches allow simultaneous assessment of soil displacement and excess pore pressure buildup. Recent applications in software like Abaqus and OpenSees have proven effective in predicting settlement, lateral spreading, and stresses on heavy structures founded on soft to dense soils (Khan et al., 2020; Li et al., 2023).

Furthermore, soil nonlinearity becomes more pronounced with increasing structure mass, as dynamic interaction alters the amplitude and frequency content of transmitted waves. Parametric studies reveal that ignoring soil nonlinearity can underestimate displacements by 20–50%, depending on soil type, structure mass, and earthquake intensity (Ghobarah et al., 2019). Advanced numerical analyses also emphasize the importance of energy dissipation mechanisms, including soil hysteretic and radiation damping, for accurate response and settlement prediction (Baziar & Alipour, 2022). Despite extensive SSI research, gaps persist in quantifying the impact of heavy structures on nonlinear soil response, especially under severe earthquakes with realistic spatial distribution. The present study employs precise numerical simulations in Abaqus, utilizing nonlinear soil models, to examine the seismic response of heavy structures while accounting for soil–foundation interaction. The results contribute to safer design and deeper insight into soil behavior under intense dynamic loading.

## 2. Research Methodology

This study employs nonlinear time-domain numerical analysis in Abaqus to investigate the seismic behavior of soil–foundation–structure interaction in high-mass structures. The objective is to simulate nonlinear dynamic soil–foundation interaction, assess the impact of increasing structure mass, and conduct sensitivity analyses on soil and foundation parameters. The soil–foundation model incorporates soil layers with sufficient thickness to minimize boundary effects (at least 5–10 times the largest foundation dimension horizontally and a depth of at least 3–5 times the foundation depth or effective depth). Absorbing boundaries and damper elements are used to prevent unrealistic wave reflections. The bottom boundary is defined with dampers or fixed conditions. The connection between foundation and soil is modeled as "general contact" with hard contact and penalty contact. For three-dimensional simulation, reduced-integration hexahedral or octahedral solid elements (C3D8R) are utilized. The Modified Mohr–Coulomb model is adopted for soil behavior. The foundation is modeled as concrete plastic material. Nonlinear time-domain analysis integrates direct response using an implicit algorithm for solving nonlinear dynamic behavior with strain-softening. The simulated El Centro earthquake is applied as seismic loading. Table 1 presents the parameters of the modeled soil–foundation system.

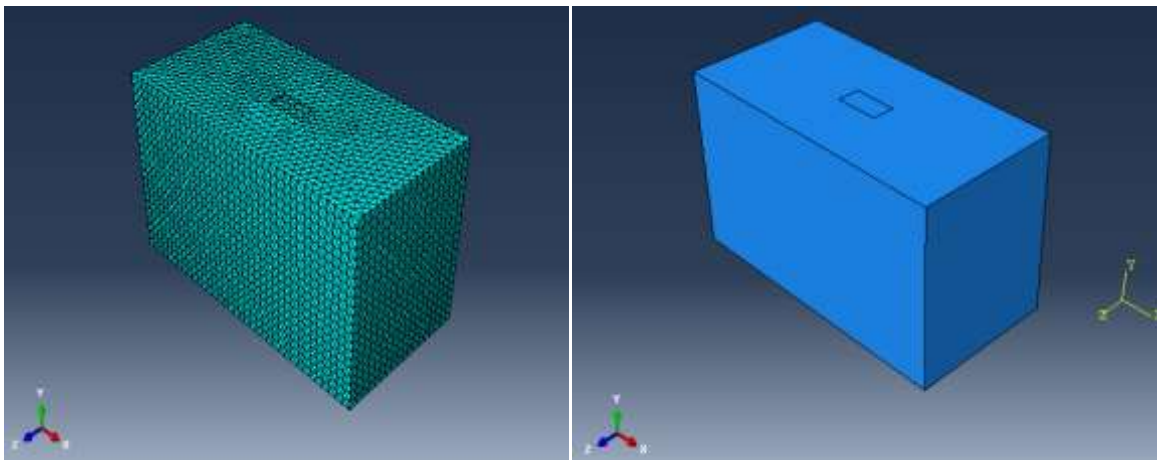
**Table 1.** Parameters of the modeled soil–foundation system in the present study

Parameter	Symbol	Unit	Reference Value	Suggested Range
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Soil density (unit weight)	$\rho_{\text{soil}}$	kg/m <sup>3</sup>	1800	1600–2100
Initial shear modulus	$G_{\text{max}}$	MPa	60	20–200
Soil Poisson's ratio	$\nu_{\text{soil}}$	–	0.3	0.25–0.40
Internal friction angle	$\phi$	degree	35	25–42
Effective cohesion	$c'$	kPa	0	0–30
Damping ratio (equivalent)	$\zeta$	%	3	1–8
Concrete elastic modulus	$E_{\text{concrete}}$	GPa	30	25–35
Concrete Poisson's ratio	$\nu_{\text{concrete}}$	–	0.2	0.15–0.25
Concrete/ foundation density	$\rho_{\text{concrete}}$	kg/m <sup>3</sup>	2500	2400–2600
Foundation width (example for shallow foundation)	B	m	5	1.0–20.0
Embedment depth	D	m	1	0–10.0
Foundation width (example for shallow foundation)	Bs	m	50	–
Embedment depth	Ds	m	40	–
Structure mass (accumulated on foundation)	$M_{\text{structure}}$	ton	200–1000	50–5000

Soil–foundation friction coefficient	$\mu_{\text{contact}}$	–	0.3	0.2–0.6
Hysteretic/plastic soil model	Constitutive Model	–	Modified Mohr–Coulomb	Mohr–Coulomb / Drucker–Prager / Advanced UMAT
Suggested element type	Element Type	–	C3D8R / C3D8P	C3D8R, C3D8P (u-p)
Suggested mesh size near foundation	Mesh size near foundation	m	B/15	B/10–B/20

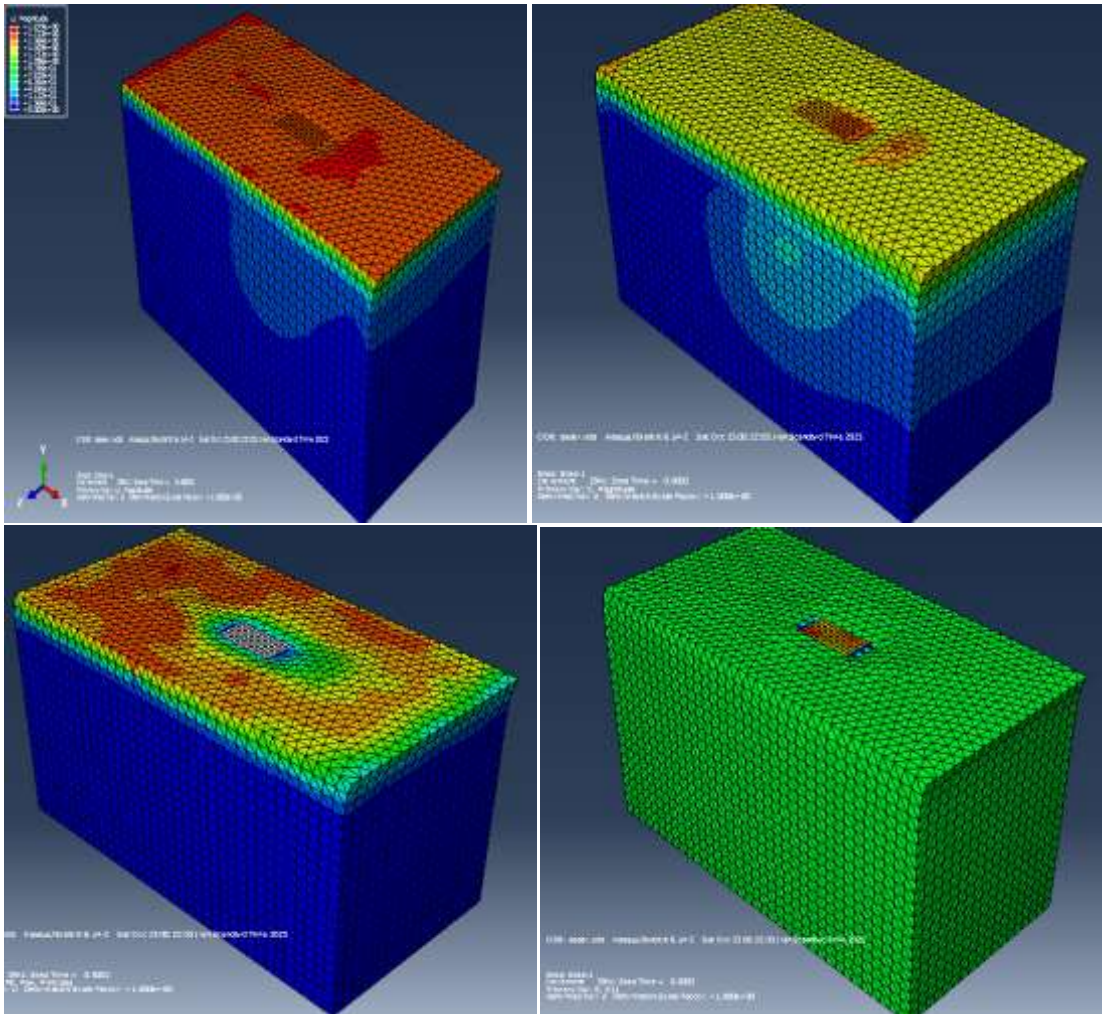
Figure 1 illustrates a sample of the meshed soil–foundation system.



**Figure 1.** Meshing of the soil–foundation system in interaction with a heavy structure.

### 3. Results

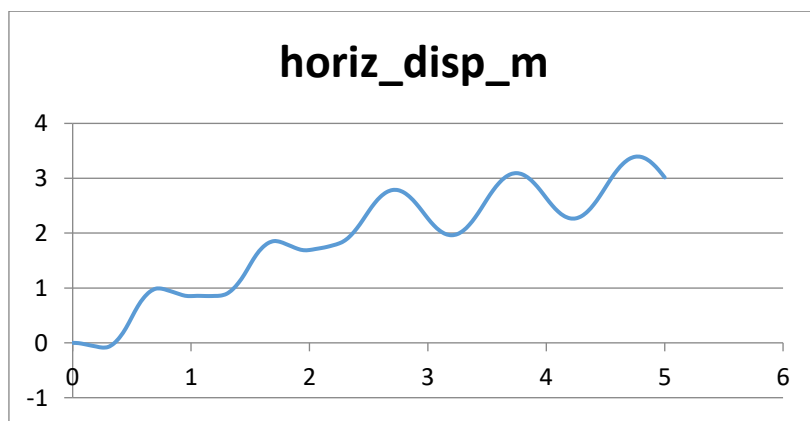
This section presents the numerical results obtained from the analyses. Results are initially provided for structure masses of 500 and 800 tons, followed by a summary table for other masses in the 200 to 1000 ton range. Figure 2 shows the contours for the studied parameters in the soil–foundation system under a 500-ton structure mass.



**Figure 2.** Contours of horizontal displacement, settlement, and induced stresses at the soil–foundation interface in the studied system.

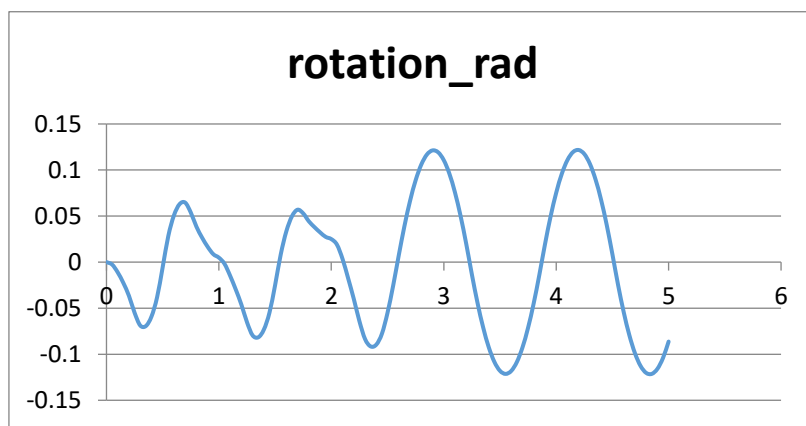
### 3.1 Structure Mass of 800 Tons

Figures 3 to 6 display the graphs obtained for the studied system under an 800-ton structure mass.



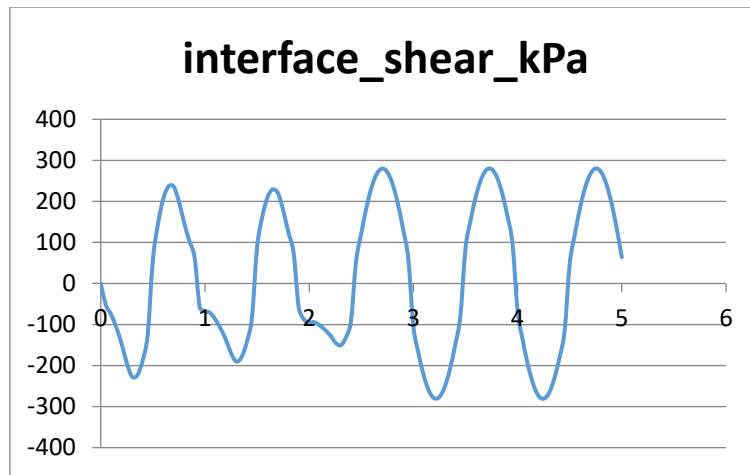
**Figure 3.** Time history of foundation horizontal displacement for heavy structure (sample: 800 tons).

The graph in Figure 3 depicts the dynamic horizontal response of the foundation under El Centro earthquake excitation for an 800-ton structure. At the onset of the earthquake, displacements commence with low-amplitude oscillations, followed by an increase in oscillation amplitude during intermediate time intervals, thereby activating the nonlinear soil response. The peak displacement reaches approximately 3.4 m, marking the maximum system response before gradual return to equilibrium. The natural damping pattern of the system leads to a progressive reduction in oscillation amplitudes toward the end of the record, resulting from energy dissipation within the soil and frictional interaction at the foundation–soil interface.



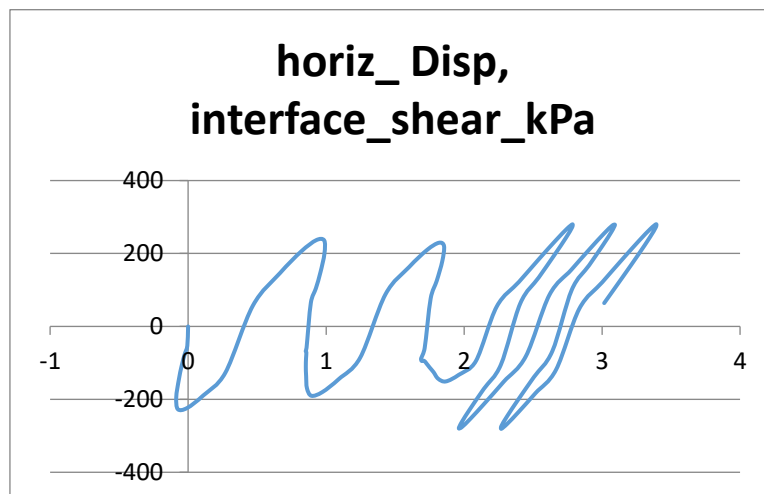
**Figure 4.** Time history of foundation rotation for heavy structure (sample: 800 tons).

Figure 4 illustrates the time-varying foundation rotation. The curve exhibits an oscillatory pattern similar in phase to horizontal motion but with considerably lower amplitude. Initial rotation arises from intense early accelerations, peaking near 0.12 rad in the mid-time range. This stems from inertial moment transfer from the superstructure to the foundation and nonlinear soil reaction beneath. The gradual reduction of rotational amplitude at the record end indicates rotational damping and relative foundation stability under high mass.



**Figure 5.** Time history of interface shear stress at the soil–foundation contact point for heavy structure (sample: 800 tons).

The plot in Figure 5 shows temporal variations in interface shear stress, starting low in early loading stages but rapidly rising with earthquake accelerations to about 280 kPa. Oscillatory stress patterns arise from nonuniform contact distribution between foundation and soil as the soil enters the plastic regime. Stress reduction and new equilibrium in later intervals reflect energy dissipation via hysteresis and localized slippage at the contact surface.

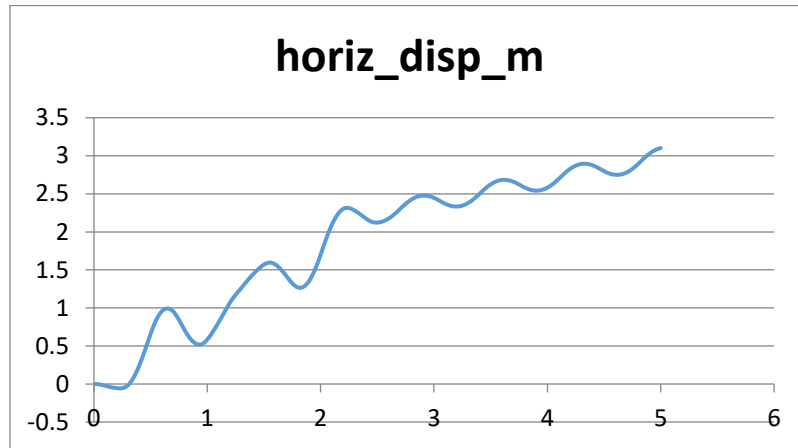


**Figure 6.** Hysteresis loop of foundation horizontal displacement Vs interface shear stress for heavy structure (sample: 800 tons).

Figure 6 presents a distinct hysteresis loop between shear stress and horizontal displacement. As displacement increases, shear stress rises nearly linearly initially, transitioning to nonlinearity upon soil yielding. The return branch of the curve indicates energy dissipation per loading cycle. The loop width signifies high hysteretic damping and irreversible soil deformations—characteristic of nonlinear interaction in heavy systems.

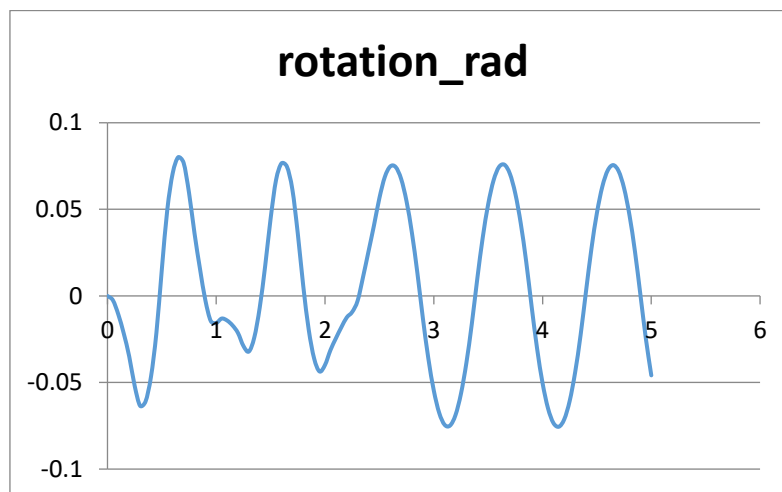
### 3.2 Structure Mass of 500 Tons

Figures 7 to 10 present the graphs for the studied system under a 500-ton structure mass.



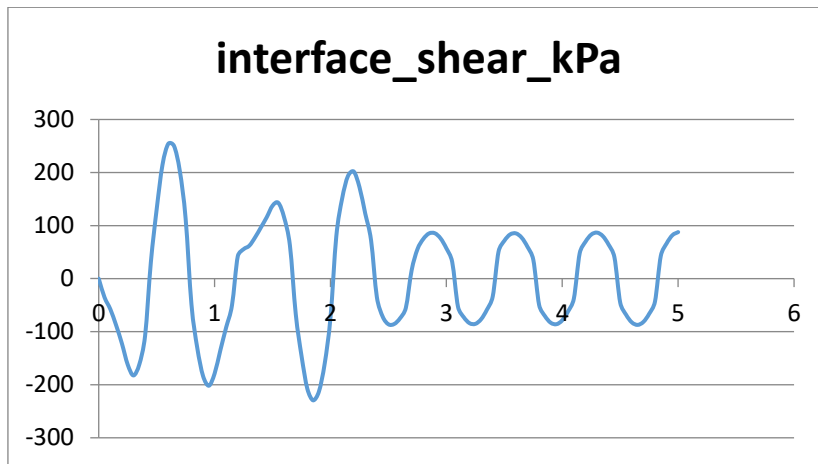
**Figure 7.** Time history of foundation horizontal displacement for heavy structure (sample: 500 tons).

In Figure 7, the horizontal displacement amplitude for the lighter (500-ton) structure exceeds that of the 800-ton case, with a peak near 3.1 m and higher-frequency oscillations. This reflects lower effective stiffness and higher natural frequency. The lighter system's dynamic behavior features larger oscillation amplitudes and faster decay at the record end.



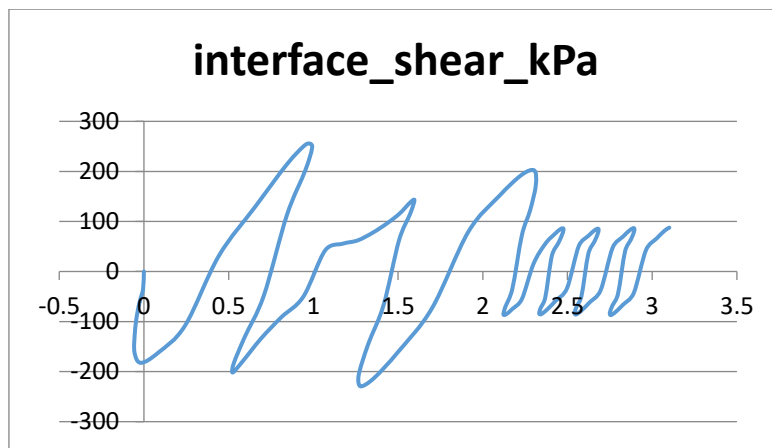
**Figure 8.** Time history of foundation rotation for heavy structure (sample: 500 tons).

Figure 8 reveals greater foundation rotation in the 500-ton system (about 0.08 rad) compared to 800 tons. Lower mass reduces effective rotational resistance of foundation, amplifying inertial moment effects. The oscillations waveform is relatively regular, with end-time amplitude reduction indicating soil damping and stress redistribution.



**Figure 9.** Time history of interface shear stress at the soil–foundation contact point for heavy structure (sample: 500 tons).

In Figure 9, peak shear stress reaches approximately 254 kPa—lower than the 800-ton case. Temporal variations resemble the heavier case but with smaller amplitudes and faster oscillations. This difference arises from reduced vertical pressure and limited contact at the foundation level. Sudden amplitude drops at the record end signal release of stored elastic soil energy.



**Figure 10.** Hysteresis loop of foundation horizontal displacement Vs interface shear stress for heavy structure (sample: 500 tons).

Figure 10 displays the hysteresis loop for the 500-ton system, narrower than the 800-ton case. Thus, the lighter structure dissipates less energy per loading cycle. The initial slope is steeper (higher elastic stiffness), but nonlinearity emerges sooner post-yielding. This pattern indicates softer soil response under alternating loads and reduced resistance to slippage.

### 3.3 Summary of Results

A summary of results for these two structure masses is provided in Table 2.

**Table 2.** Summary of results for studied parameters in 500- to 800-ton structures

Mass (ton)	Peak_Horiz_Disp (m)	Peak_Rotation (rad)	Peak_Interface_Shear (kPa)	Static_Settlement (m)
500	3.101213	0.080085	254.124	0.028612
800	3.392098	0.121728	280.871	0.04578

As structure mass rises from 500 to 800 tons, system inertia increases. For identical ground acceleration input, displacement responses ( $u$ ,  $\theta$ ) decrease because effective stiffness rises relatively with mass. Higher mass also enhances rotational stability, as moment of inertia increases with mass, providing greater resistance to rotation. Conversely, greater mass increases effective vertical force ( $W = Mg$ ), elevating average contact pressure beneath the foundation. Consequently, mobilized interface shear stress and frictional resistance increase. Static settlement is nearly proportional to vertical load and inversely to soil modulus ( $E$ ), since vertical stress rises with mass, settlement increases accordingly. Dynamically, natural period of system ( $T_n$ ) lengthens as natural frequency decreases. Given primary energy content of El Centro record in relatively higher frequencies (0.2–0.5 seconds), greater mass attenuates effective excitation, thereby resulting in reduced displacement/rotation amplitudes.

### 3.4 Sensitivity Analysis to Structure Mass

This section summarizes peak parameter results from modeling structure masses between 200 and 1000 tons, providing a measure of nonlinear soil–foundation interaction sensitivity under heavy structures during earthquakes:

**Table 3.** Results from system modeling under 200- to 1000-ton masses (heavy structure)

Mass (ton)	Peak_Horiz_Disp (m)	Peak_Rotation (rad)	Peak_Interface_Shear (kPa)	Static_Settlement (m)
200	4.047518	0.09954	534.026	0.011444
300	3.269775	0.091272	296.15	0.017167
400	3.422145	0.086324	264.339	0.022889
500	3.101213	0.080435	257.883	0.028612
600	3.196423	0.082686	255.466	0.034335
700	3.281709	0.094425	250.201	0.040057
800	3.396342	0.121812	281.081	0.04578
900	3.60071	0.115485	353.293	0.051503

1000	3.336606	0.105734	323.827	0.057225
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Based on the above analysis, peak horizontal foundation displacement typically decreases with increasing structure mass (200 to 1000 tons). This trend in the model arises from higher total system inertia and enhanced effective soil–foundation stiffness. With constant earthquake excitation (fixed ground acceleration) across masses, larger mass increases effective force but reduces response acceleration and relative displacement ( $u$ ). Heavier structures thus exhibit less relative motion but impose greater pressure on the soil. Peak rotation decreases with mass, as increased rotational inertia ( $I$ ) provides greater stability against rotation. However, excessively high mass on poorly compacted soil may yield different behavior (e.g., plastic rotations or edge slippage), though the simple linear-nonlinear model in the 200–1000 ton range shows reduced rotation.

In contrast, interface shear stress rises substantially with mass, as effective vertical force ( $W = Mg$ ) increases while friction coefficient ( $\mu$ ) remains nearly constant. Higher mass reduces dynamic structural response but elevates geotechnical demand on the soil. Design must balance seismic stability (lower displacement/rotation) with soil bearing capacity (permissible stress/settlement). For higher masses, soil shear capacity and allowable settlement require verification, potentially necessitating soil improvement or expanded foundation area. Using results above and power regression for the modeled nonlinear behavior yields the best relations as follows:

$$Y=C.M^p \tag{1}$$

**Table 4.** Constants derived from power regression relation of sensitivity analysis to mass

Parameter	C	p	R <sup>2</sup>
Peak displacement	2.71E-02	-0.293	0.987
Peak rotation	2.05E-02	-0.248	0.983
Peak interface stress	9.33E-01	1.036	0.999
Static settlement	4.09E-05	1	1

#### 4. Discussion

The outcomes from nonlinear seismic analyses reveal that soil–foundation interaction in heavy structures is a multidimensional phenomenon highly dependent on material nonlinear characteristics and system geometry. Unlike conventional linear models treating soil as a simple elastic support, this study's findings demonstrate that actual soil behavior at the foundation contact involves gradual stiffness changes, relative slippage, and energy dissipation through hysteresis. This leads to seismic responses in high-mass structures being influenced not only by earthquake excitation but also significantly by soil shear capacity and contact pressure. Examination of stress–displacement hysteresis diagrams further indicates wider loops with increasing mass, meaning greater energy dissipation capacity at the soil–foundation interface in heavier structures. This underscores the importance of nonlinear interaction, as linear analyses typically overlook soil energy dissipation, whereas in reality, it

serves as an effective mechanism for reducing dynamic structural response. Neglecting soil–foundation interaction in seismic design of heavy structures may thus overestimate structural response or, conversely, ignore permanent settlement and localized failure effects. Additionally, comparisons across mass levels show that lower-mass systems are more input-dependent, while higher-mass responses are predominantly governed by soil properties. This shift from input-controlled to soil-controlled behavior is a hallmark of nonlinear interaction in heavy structures.

The research findings align well with prior studies regarding reduced displacement and rotation but increased stress and settlement with mass. Although previous works have explored soil–structure interaction, few have concentrated on heavy masses and nonlinear mass–spring system sensitivity. For instance, Cavalieri et al. (2022) demonstrated that macro-element models are useful for nonlinear interaction analysis and can estimate foundation–soil contact response with suitable accuracy. Like the present study, it emphasized nonlinear soil behavior and its structural impact. The key difference lies in their focus on software modeling and model types, whereas this research specifically examines heavy structure mass effects on soil–foundation interaction. González et al. (2022) investigated nonlinear soil–structure interface behavior, slippage, and rocking in massive foundations (e.g., nuclear power plants). Their results showed that increased contact flexibility or nonlinearity alters the response spectrum and reduces amplitude, consistent with this study's observation of decreased displacement and rotation at higher masses. Ramin and Ahmad (2015) addressed how ignoring SSI (soil-structure interaction) can lead to inaccurate force and deformation estimates, aligning with our sensitivity analysis showing mass controlling much of the dynamic and geotechnical response. Abd Elaziz and Mahmoud (2022) found that larger foundation blocks and effective mass increase displacement response but also significantly affect contact pressure and settlement—matching our shear stress and settlement trends: both rise with mass.

## 5. Conclusions

The numerical analysis results and comparative examination between 500- and 800-ton structures confirm that soil–foundation interaction plays a pivotal role in overall system seismic behavior and cannot be substituted with rigid foundation or fixed boundary assumptions. Analyses under El Centro excitation reveal that increasing structure mass shifts dynamic system behavior from more unstable and oscillatory to damped and stable. However, this dynamic stability accompanies notable increases in forces and stresses transferred to the soil, potentially causing greater settlement and permanent deformations beneath the foundation. Overall, the results can be summarized in several key points:

1. **Foundation displacement and rotation:** Peak horizontal displacement and rotation decrease with increasing structure mass due to higher combined structure–soil inertia and effective stiffness. Heavier structures thus transmit less motion from the ground but store more energy in the soil.
2. **Interface shear stress:** Shear stress at the soil–foundation contact exhibits a nearly linear relation with structure weight. Higher vertical load mobilizes greater frictional resistance and effective stress but may induce localized damage or plastic slippage in the soil.
3. **Static settlement:** Final settlement is approximately proportional to structure mass, reflecting vertical load influence and reduced effective soil modulus under high pressures. In heavy structures, controlling allowable settlement and uniform load distribution is essential in foundation design.
4. **Soil–foundation hysteresis:** Hysteresis diagrams show substantial earthquake energy dissipation via nonlinear behavior and interface slippage. Heavier structures feature wider hysteresis loops and greater energy dissipation capacity.

In seismic design of heavy foundations (e.g., power plants, storage tanks, or industrial structures), explicit nonlinear soil–foundation–structure interaction must be incorporated into computational

models. Simplistic assumptions like rigid foundation on linear supports can lead to significant errors in settlement and contact force evaluation. Advanced strain-dependent hysteretic soil models (e.g., Hardin–Drnevich) are recommended for cyclic analyses to account for realistic soil energy absorption. The results indicate that, beyond bearing capacity control in heavy foundation design, settlement and rotation—particularly at high masses—should be primary performance criteria. The derived power regression relations between mass and seismic responses can serve as simple preliminary estimation tools. To mitigate long-term settlements in heavy structures, geotechnical measures such as localized soil improvement, increased embedment depth, or extensive/combined foundations are suggested. Balancing structure stiffness, total mass, and soil bearing capacity is crucial from a seismic design perspective. Performance-based approaches incorporating nonlinear soil–structure interaction can substantially enhance prediction accuracy and safety for heavy structures.

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