THE EFFECT OF BASE ISOLATION ON REDUCING THE UNCERTAINTY IN SEISMIC BEHAVIOR OF PILE FOUNDATIONS

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ABSTRACT

Conventional nuclear buildings are usually partially or fully embedded in the ground, with foundations extending to competent subgrade materials. In contrast, many advanced small modular reactors are significantly lighter and may need to be founded at ground elevation. Such designs can benefit from pile foundations, ideal for sites with weak or variable surface soils. These piles can transfer structural loads to deeper, more stable soil layers or bedrock.

Analyzing pile-founded structures requires careful consideration, as the dynamic impedance of piles is more uncertain compared to typical surface foundations, which have been more thoroughly studied from theoretical and experimental perspectives. Additional challenges include the high computational cost of modeling foundations and the difficulty of capturing the nonlinear p-y behavior of piles within an elastic analysis. These uncertainties are further amplified in certain soil conditions, such as non-uniform sites, which can reduce the reliability of pile-founded structure designs.

This study investigates the impact of base isolation on reducing uncertainties in pile foundation SSI through simplified case studies. The seismic performance of a base-isolated, pile-supported structure is evaluated in the frequency domain to assess the influence of base isolators on SSI behavior. Seismic responses are analyzed in terms of in-structure response spectra (ISRS) and seismic displacements at key locations, with comparisons between isolated and non-isolated structures to demonstrate the effectiveness of the isolation system. Different soil profiles are examined. The response quantities are computed below and above the base isolators, and the sensitivity of the response to soil and p-y spring properties is investigated. Findings indicate that while SSI effects remain prominent in pile foundations, the sensitivity of structural response to soil property variations is notably reduced by base isolation in pile-founded structures.

INTRODUCTION

Soil-structure interaction (SSI) models rely on assumptions and simplifications, such as treating soil as homogeneous or applying specific boundary conditions. These assumptions often fail to fully represent the system's actual behavior, leading to prediction inaccuracies. The presence of piles further complicates SSI due to the complexity of both pile behavior and the soil's response.

As load increases, the interaction between piles and soil can change significantly, with the soil's stiffness and strength properties evolving. Modeling the pile-soil interface is challenging because it involves friction, adhesion, and shear forces that vary with depth and load. The pile's resistance can differ depending on its material (e.g., concrete or steel) and the surrounding soil type (e.g., clay or sand). Additionally, the installation method (e.g., driving, drilling, or boring) can significantly impact the pile's behavior. The installation process may alter the surrounding soil, causing densification or displacement, which affects the pile's load-bearing capacity and its interaction with the soil. Over time, piles may undergo creep, consolidation, or material degradation, influencing the long-term pile-soil interaction. Predicting these

long-term effects is uncertain because they depend on factors like soil consolidation, water table fluctuations, and material degradation, which are difficult to forecast. The way pile-soil interaction is modeled, whether through spring constants or nonlinear contact elements, can introduce additional uncertainty.

On the other hand, base isolation reduces uncertainty in response prediction by decoupling the structure from ground motions during earthquakes or other dynamic loads. This method provides a more predictable and controlled way to manage the forces acting on the structure. The key advantage of base isolation is that it creates a separation between the natural frequencies of the building and the frequencies of expected seismic motions, which helps minimize resonance between the structure and the ground. Since resonance can amplify vibrations and increase response uncertainty, isolating the structure at different frequencies reduces this risk and makes the response more predictable. Moreover, many base isolation systems, such as spring and viscous dampers, have well-defined stiffness and damping characteristics. This allows engineers to predict their performance more confidently, enabling more accurate anticipation of the structure's response to dynamic loads. This level of predictability reduces uncertainty compared to traditional pile foundations, where the interaction between the soil and structure is often less understood.

Through simplified analyses, this study aims to show that the use of base isolators significantly reduces the variability of pile foundations' response and, therefore, provides additional confidence in the use of pile foundations in safety-related nuclear construction.

SEISMIC ANALYSES

The simplified models used in this study contain a single drilled pier, representing realistic drilled piers in a structure housing an advanced reactor design. Two primary configurations are developed (Figure 1): (I) a single pier foundation with superstructure mass, and (II) a single pier caisson foundation with the superstructure mass attached to the foundation via a base isolator. The single pier represents only a part of the foundation, which is supported by a single caisson. For this simplified study, this is a reasonable assumption given the expectation of a stiff pier cap diaphragm and reasonable mass distribution across individual piers. Comparing the responses of Systems I and II enables examination of the piles' combined kinematic-inertial interactions. The objective is to understand SSI effects by comparing seismic responses of two different soil-foundation systems. Note that Figure 1 schematics are conceptual and not shown to scale or with the number of layers used in the SSI analyses.
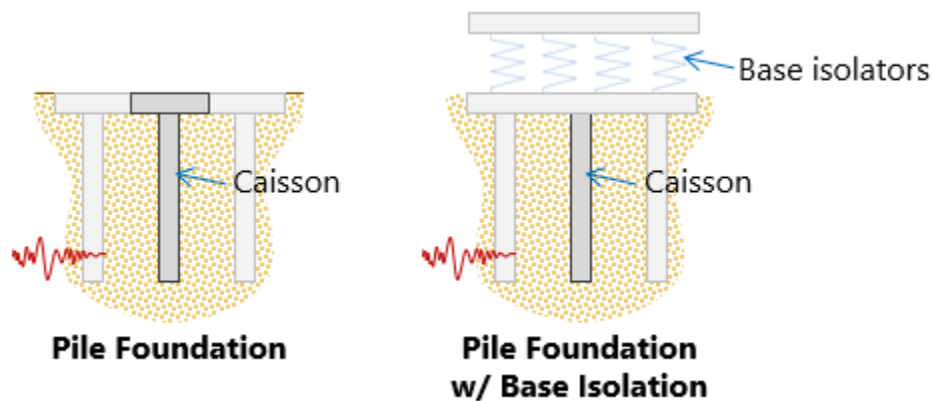

Figure 1. Considered soil-foundation systems for seismic analyses

Description of the Model and Input Data

The models are developed using SASSI computer program (Ostadan (2007)). In support of the analyses performed via SASSI, the computer program LPile (Wang et al. (2022)) is used to characterize the piles' near-field interaction with their surrounding medium. The examined piles are assumed to have fixed heads. Based on various literature, the interaction between the soil and the piles can be approximated by connecting the drilled pier nodes to the interaction nodes via p-y springs (Pecker (2015) and Roy et al. (2015)). The piles are modeled through a series of massless viscoelastic beam elements connected to the interaction nodes via viscoelastic p-y spring elements (Figure 2). The interaction nodes and spring elements are placed along the pile length at all soil/rock layer interfaces. While using the interaction nodes would suffice to capture the far-field response of the soil, the p-y spring elements between the beam elements and the interaction nodes are necessary to capture each caisson's near-field/local interaction with the soil/rock in its immediate vicinity. The model also contains i) two lumped masses representing the foundation mass and the building mass and ii) a spring element between the foundation mass and the building mass that represents the base isolators.
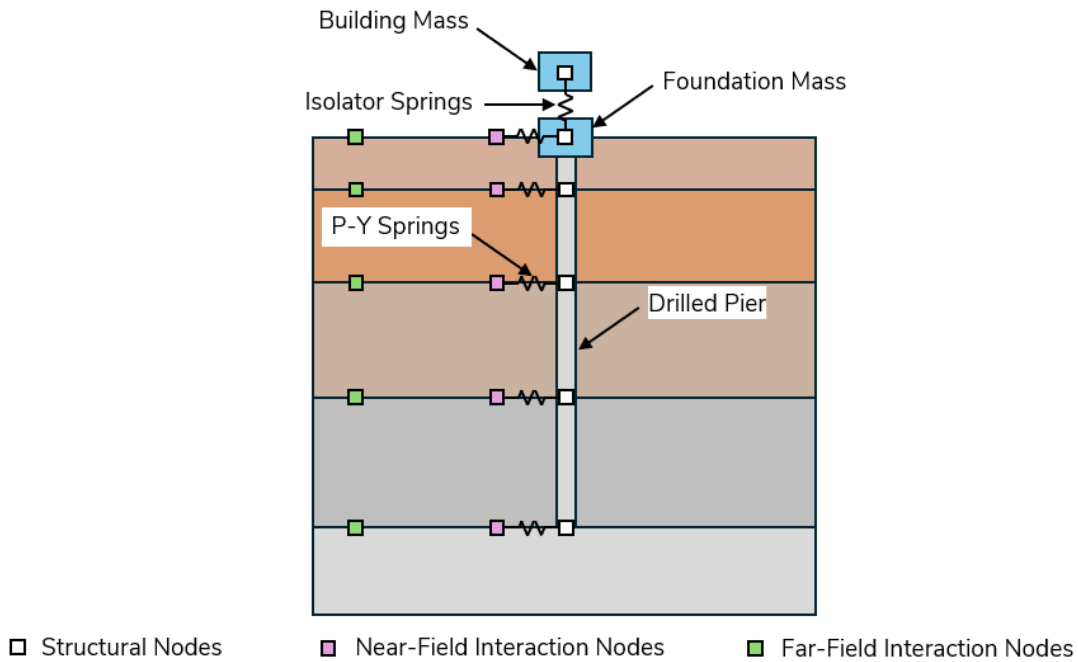

Figure 2. Schematic illustration of the model considered in this study

For this simplified single-pier study, the effects of soil layers above the pier head are neglected. The material and section properties of the drilled pier are given in Table 1 and Table 2, respectively. The isolator properties used in the SASSI model are given in Table 3. The weights of the lumped masses used to represent the foundation and building are 514 and 1294 kips, respectively.

Table 1. Material properties of the drilled pier modeled in SASSI

Material Properties	
Elastic Modulus (ksf)	635800
Poisson's Ratio	0.17
Unit Weight (kip/ft^3)	0.150
Damping Ratio	0.07

Table 2. Drilled Pier Section Properties

Section Type	Length (ft)	Diameter (in)	Longitudinal Reinforcement	Reinforcement Ratio
Round Shaft	30	72	36 #10 bars	1.12%

Table 3. Isolator Properties

Horizontal Stiffness (kip/ft)	Vertical Stiffness (kip/ft)	Horizontal Damping Ratio	Vertical Damping
1650	11170	40%	8%

Three soil cases, namely the best estimate (BE), upper bound (UB), and lower bond (LB), are considered in this study to account for a range of soil and p-y spring properties. The low-strain soil profiles corresponding to UB, LB, and BE properties are shown in Figure 3. P-y spring elements are defined by stiffnesses and damping ratios corresponding to three translational degrees of freedom. The damping ratio of each p-y spring element equals the strain-compatible damping ratio of the soil/rock layer immediately below it. The equivalent linear BE p-y properties corresponding to each spring depth in SASSI are obtained from LPile using an iterative approach described by Roy et al. (2015).

Table 4 lists the soil layer properties LPILE uses to obtain the p-y spring stiffnesses. Upper-bound (UB) and lower-bound (LB) p-y spring stiffnesses are computed by multiplying and dividing the BE stiffnesses by 2.0, respectively. Table 5 lists the equivalent linear p-y spring stiffnesses assigned to the models. In addition to UB and LB p-y springs, extreme cases where the p-y springs are rigid vs. soft are also considered. The rigid p-y springs neglect nonlinear behavior in pile-soil interaction, whereas the soft springs consider no interaction between the pile and its surrounding soil. Springs denoted as "rigid" are assigned a large stiffness value.
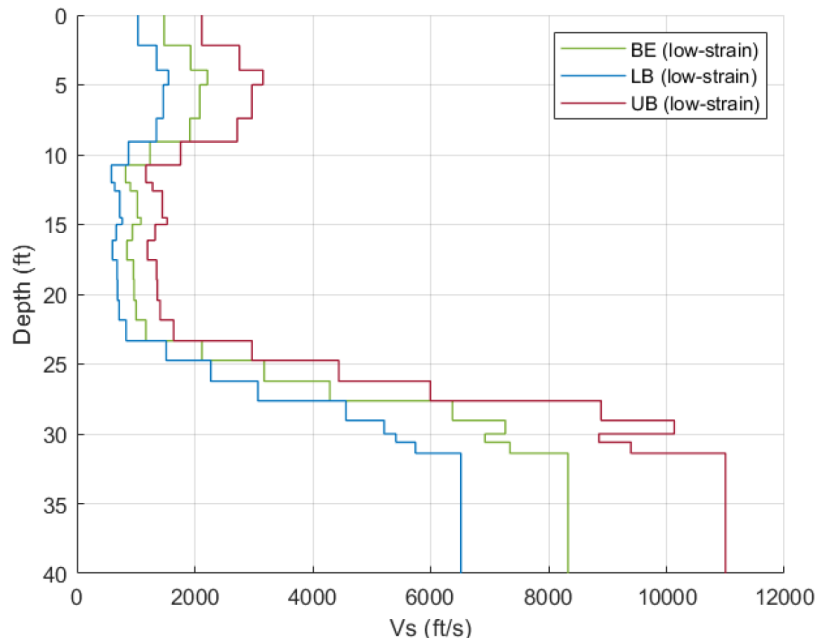

Figure 3. Low-strain soil properties

Table 4. Soil layer properties in the LPile model

Geologic Layer	Depth at Top (ft)	p-y Curve Model	Unit Weight (lb/ft^3)
Fill	0	Stiff Clay with Free Water	124
Residuum	2	Soft Clay	124
Epikarst	5	Stiff Clay with Free Water	133
Limestone	20	Massive Rock	165

Table 5. p-y spring Stiffness Values for BE, LB, and UB Cases

Depth (ft)	p-y spring Stiffness (kip/ft)		
	BE	UB (BE × 2)	LB (BE ÷ 2)
0	109.4	218.8	54.7
1.00	948.7	1897.5	474.4
2.00	1708.3	3416.6	854.1
3.50	1986.1	3972.2	993.0
5.00	6112.7	12225.3	3056.3
6.50	16509.4	33018.7	8254.7
8.00	27564.9	55129.8	13782.4
10.00	35710.8	71421.7	17855.4
12.00	28429.1	56858.2	14214.6
14.00	27761.2	55522.4	13880.6
16.00	29211.2	58422.4	14605.6
18.00	32358.3	64716.5	16179.1
20.00	177333.9	354667.8	88666.9
21.39	754084.2	1508168.5	377042.1
24.00	645720.5	1291441.1	322860.3
26.00	476382.6	952765.1	238191.3
28.00	451099.8	902199.6	225549.9
30.00	197342.0	394684.0	98671.0

The input motions are five sets of time histories matched to the design response spectra at a site in the eastern United States. The average results obtained from each input set are used to compare the behaviors between the two models.

Evaluation of the Results from Seismic Analyses

Maximum absolute displacements relative to the control point are computed at every p-y spring depth at the drilled pier nodes. The effect of increasing the soil and p-y spring stiffness is explored in Figure 4, which compares the relative displacements for various soil and p-y spring properties. As can be seen, the pier displacements are sensitive to the p-y spring stiffnesses.

Figure 5 shows the displacements above the isolators for various soil and p-y spring properties. As can be seen, despite the sensitivity of the pile displacements to the p-y spring properties, the displacements above the isolators are relatively insensitive to the soil and p-y spring properties. Similarly, Figure 6 shows the isolator shear forces indicating that the isolator demands are insensitive to the soil properties.
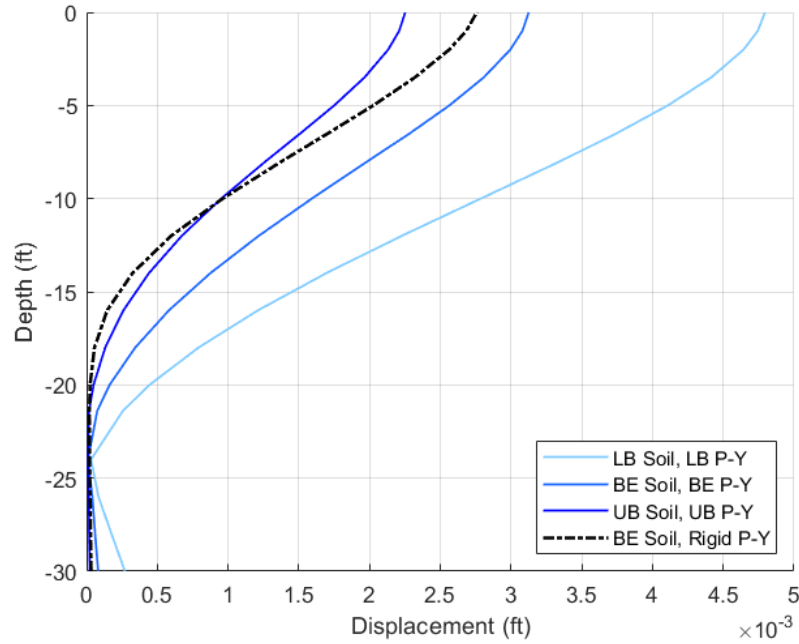
Figure 4. Maximum absolute displacements of drilled pier nodes and near-field nodes as p-y spring stiffness is increased
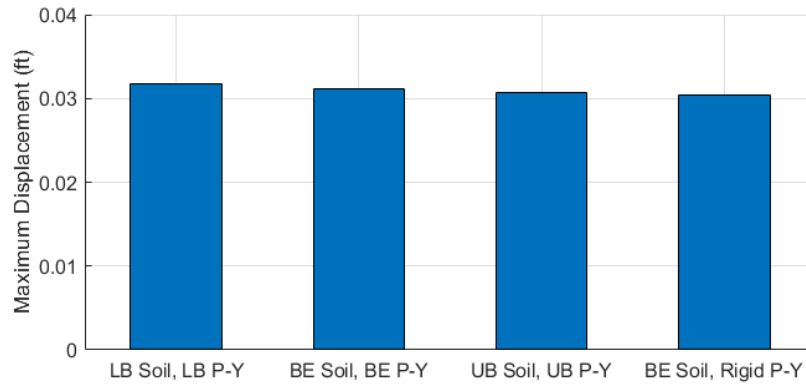

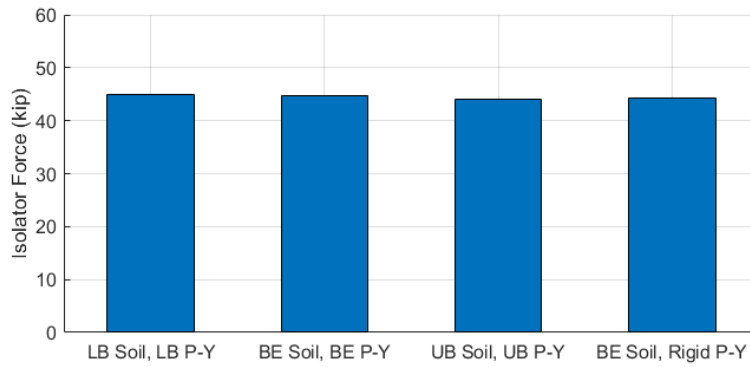Figure 5. Maximum displacements above the base isolators with various soil and p-y spring properties

Figure 6. Maximum shear demand in the isolators with various soil and p-y spring properties

The horizontal ISRS below and above the isolators are plotted in Figure 7. The peak spectral accelerations above the isolators are between 0.115g and 0.120g at 1.0 Hz, which is the natural frequency of the isolators. Inspecting Figure 7 reveals that relative to the Model with BE soil and BE p-y springs, changing the soil and the p-y springs to the LB case increases the peak spectral acceleration and decreases the peak frequency. Changing the soil and the p-y springs to the UB case reduces the peak spectral acceleration and increases the peak frequency. Changing just the p-y spring case and keeping the BE soil results in a smaller frequency shift and a smaller change in peak spectral acceleration than observed when changing the soil case in conjunction with the p-y spring case. Increasing the p-y spring stiffness to be effectively rigid causes a notable increase in the peak spectral acceleration and its corresponding frequency.

Figure 7 also shows that changes in the soil and p-y spring properties have minimal effect on the ISRS above the isolators. In all cases, the peak spectral acceleration occurs at the isolator frequency of 1.0 Hz, and it falls off at higher frequencies.

In summary, the ISRS results shown in Figure 7 indicate that, while the ISRS below the isolators are sensitive to soil and p-y spring stiffness properties, they are relatively insensitive to soil and p-y spring properties at frequencies below 25 Hz above the isolators. In other words, the base isolation reduces the uncertainty in the building response due to SSI.
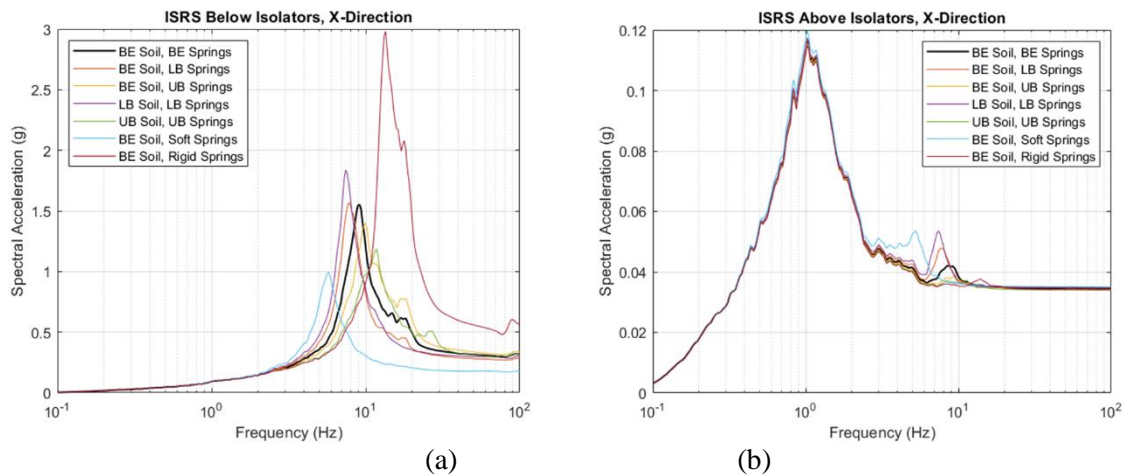

Figure 7. 5%-damped acceleration response spectra at (a) below the isolators and (b) above the isolators

CONCLUSIONS

This study evaluated base isolation's ability to reduce uncertainty in the seismic response and behavior of pile-founded structures. It involved comparing the seismic demands of a simplified single pile model with and without base isolation.

The results indicate that a pile foundation's response is sensitive to the modeling assumptions and properties of the soil and nonlinear springs representing the nonlinear interactions between the pile and soil. Varying the p-y spring stiffness between BE x0.5 and BE x2 resulted in moderate changes to the peak spectral acceleration and associated frequency at the pier heads below the isolators.

On the other hand, the study shows that the base-isolated structure demands above the isolators are independent of the soil properties. In particular, the displacement and ISRS above the base isolations are relatively similar, irrespective of the soil and p-y spring properties assigned to the soil. Similarly, the forces

in the isolators are relatively similar for the wide range of soil and p-y spring conditions considered in this study.

In summary, this study indicates that building isolation reduces the uncertainty of the building response due to SSI in a pile-founded building.

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