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AN EXPERIMENTAL INVESTIGATION INTO THE EFFECTS OF SOIL LAYERING ON SEISMIC SOIL-STRUCTURE INTERACTION

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Abstract

The seismic performance of structures is critically influenced by Soil-Structure Interaction (SSI), yet a significant knowledge gap persists regarding the effects of complex, multi-layered soil profiles commonly found in practice. This research addresses this gap through a series of controlled 1g scale model shake table tests. The experimental program utilized a flexible wall barrel container designed to mimic free-field soil response, a single-degree-of-freedom (SDOF) model structure representing a mid-rise building, and several meticulously prepared soil configurations. These configurations included homogeneous profiles of sand and clay, as well as multi-layered profiles combining sand, silt, and clay. The results demonstrate that soil layering is a first-order effect in SSI. Multi-layered soil profiles, particularly those with a stiff sand layer overlying a soft clay layer, exhibited a significant amplification of structural acceleration and a substantial increase in foundation settlement when compared to the homogeneous soil profiles. For instance, peak foundation settlement in a sand-over-clay profile was more than double that observed in a sand-only profile under the same seismic input. These findings carry a critical practical implication: simplified, single-layer soil models, often used in preliminary design, are insufficient and potentially unconservative for accurately predicting seismic demands on structures located at geologically complex sites. This underscores the necessity of detailed geotechnical characterization and appropriate modeling of soil stratification in seismic design.

1.0 Introduction

Traditional seismic analysis often relies on the assumption of a fixed-base structure, where the foundation is considered rigidly attached to non-deformable ground. However, for structures situated on flexible soils, this assumption can be dangerously unconservative, a point acknowledged in design codes such as IS 1893-2016. The dynamic interplay between a structure, its foundation, and the surrounding soil is a coupled phenomenon known as Soil-Structure Interaction (SSI). This interaction fundamentally alters the dynamic properties of the system and, consequently, the seismic demands imposed on the structure.

The process of SSI is driven by two primary mechanisms:

- **Kinematic Interaction:** This effect arises from the presence of stiff foundation elements (e.g., mat foundations, basements) within the soil. As seismic waves propagate upward, the foundation's stiffness and geometry prevent it from perfectly conforming to the free-field ground motion, resulting in a modified "input" motion at the structure's base.
- **Inertial Interaction:** This mechanism is driven by the structure's own vibration. The inertia of the vibrating superstructure generates a base shear and moment at the foundation level. These forces induce displacements and rotations of the foundation relative to the free-field ground, a process that dissipates energy through radiation and material damping in the soil.

While the importance of SSI is broadly acknowledged, there remains a significant lack of controlled, empirical data that quantifies its effects, especially in the context of multi-layered soil conditions which are far more common than homogeneous deposits. This research aims to address this critical knowledge gap through a systematic program of physical modeling. The primary objective of this study is to experimentally investigate and quantify the effects of different soil layering configurations on the seismic response of a representative shallow-foundation structure using 1g shake table testing. The current experimental work builds upon established physical modeling principles and previous research in the field to provide high-fidelity data on this complex phenomenon.

2.0 Experimental Program

To generate reliable empirical data under controlled and repeatable conditions, a comprehensive experimental program was designed. The program utilized a 1g one-dimensional (1-D) shake table, a scaled model structure, and meticulously prepared soil profiles to isolate the effects of soil layering on seismic performance.

2.1 Testing Facility and Soil Container

The experiments were conducted at Cal Poly's Parsons Earthquake Lab on a 1-D shake table. This facility has a 4500 kg payload capacity and, at maximum payload, can produce accelerations up to 1.0 g and operate within a frequency range of 0.1 to 50 Hz, specifications well-suited for the dynamic testing of scaled geotechnical models.

The soil was contained within a flexible wall barrel. As demonstrated by Meymand (1998) and Moss et al. (2010), this type of container, which uses a rubber membrane confined by Kevlar straps, is specifically designed to minimize boundary effects and simulate the shear deformation of a semi-infinite soil column. This setup provides a more realistic representation of free-field site response compared to rigid containers, which can reflect seismic waves and contaminate the results.

2.2 Model Structure and Foundation

A single-degree-of-freedom (SDOF) structural model was designed to mimic the fundamental seismic response of a narrow 3- to 5-story building. The model's design and components are based on the experimental setup detailed by Moss et al. (2011). It consists of a rigid mat foundation (a 46 cm x 46 cm steel plate), supported by 32 cm tall aluminum frame "basement" walls. A central threaded steel rod allowed for the adjustment of mass and height, enabling the tuning of the structure's fundamental period to represent the prototype scale.

2.3 Soil Profiles and Experimental Matrix

The prototype soil selected for this research program is San Francisco Young Bay Mud (YBM), a soft, high-plasticity clay known for its significant role in site amplification. To investigate the effect of layering, four distinct soil profiles were tested. The configurations, detailed in the table below, ranged from homogeneous sand and clay profiles to complex multi-layered systems.

Configuration	Top Layer	Middle Layer	Bottom Layer
Sand-only	Sand (400 mm)	-	-
Clay-only	Clay (400 mm)	-	-
Sand over Clay	Sand (200 mm)	-	Clay (200 mm)
Sand–Silt–Clay	Sand (150 mm)	Silt (100 mm)	Clay (150 mm)

2.4 Instrumentation and Input Motion

The dynamic response of the system was captured using a dense array of instrumentation. Following the methodology of Moss et al. (2011), two vertical arrays of accelerometers were installed: one in the free-field away from the structure and a second directly beneath the structure's foundation. This dual-array setup allows for the direct measurement of SSI effects by comparing the structural response to the free-field ground motion.

The results presented in this paper correspond to a sinusoidal input motion with a frequency of **2.5 Hz**, a peak acceleration of **0.20 g**, and a duration of **10 cycles**. This idealized motion was selected to provide a clear, fundamental assessment of the system's dynamic response across the different soil profiles. The described experimental program generated a comprehensive dataset allowing for a direct comparison of seismic performance across the different soil configurations.

3.0 Results and Analysis

The data collected from the instrumentation arrays facilitate a multi-faceted analysis of the system's dynamic response. This analysis focuses on key engineering demand parameters that are critical for seismic design, including acceleration, foundation settlement, and spectral amplification.

3.1 Acceleration Response

A primary indicator of structural demand is the acceleration experienced at the roof level. The experimental results show that acceleration amplification from the foundation to the roof increased significantly as the complexity of the soil layering increased. The maximum roof acceleration grew from 0.20 g in the Sand-only case to a substantially higher 0.29 g in the Sand-Silt-Clay configuration.

The 5% damped response spectrum for the "Sand over Clay" case further illustrates this phenomenon. The primary spectral peak at a period of approximately 0.4s corresponds to the fundamental period of the coupled soil-structure system, demonstrating the period lengthening effect characteristic of SSI on flexible soils. The peaks observed in the spectrum highlight the frequency-dependent amplification of the ground motion as it passes through the soil layers and interacts with the structure.

3.2 Foundation Settlement

Foundation settlement is a critical performance metric related to foundation damage and serviceability. The inclusion of a compliant clay layer in the soil profile was found to drastically increase both the peak (transient) and residual (permanent) settlement. The settlement-time history for the "Sand over Clay" case shows a clear pattern of progressive settlement accumulation during the cycles of shaking, followed by a permanent residual displacement after the motion ceases.

Quantitatively, the impact of layering is stark. The peak settlement for the "Sand over Clay" case was 3.07 mm, which is more than double the 1.34 mm observed for the "Sand-only" case under the same input motion. This demonstrates the critical role that underlying soft layers play in foundation performance, a factor that could be missed if only surface soils are considered.

3.3 Comparative Performance

The table below summarizes the key performance metrics across all four tested soil configurations, providing a clear comparison of their seismic response.

Configuration	Peak Settlement (mm)	Residual Settlement (mm)	Max Roof Acc (g)	Max Foundation Acc (g)	Roof/Base Spectral Ratio
Sand-only	1.34	0.97	0.20	0.14	1.44
Clay-only	2.12	1.78	0.22	0.13	1.69
Sand over Clay	3.07	2.53	0.26	0.14	1.85
Sand–Silt–Clay	3.92	3.21	0.29	0.13	2.00

The data synthesized in this table reveal an unambiguous trend: as the soil profile becomes more complex and incorporates softer, more compliant layers, both foundation settlement and superstructure acceleration amplification increase substantially. This trend is driven by the impedance contrast introduced by layering; the Roof/Base Spectral Ratio, a direct measure of structural amplification, increases from 1.44 in the uniform sand to 2.00 in the three-layer profile, a 39% increase directly attributable to trapped wave energy.

These results clearly demonstrate a strong relationship between soil stratification and seismic structural demands, which warrants a deeper interpretation.

4.0 Discussion

The experimental results provide clear, quantitative evidence of the profound impact of soil layering on SSI. This section interprets the physical mechanisms driving these observations and discusses their implications for seismic design practice.

The primary reason layering amplifies the seismic response is the impedance contrast between different soil strata. The interface between a relatively stiff layer (like sand) and a soft layer (like clay) can trap and reflect seismic wave energy. This phenomenon prevents energy from radiating away from the structure, leading to constructive interference and higher amplification of ground motion within the soil column, which is then transmitted to the structure. This energy trapping not only increases the peak amplitude but also alters the frequency content of the motion transmitted to the foundation, potentially exciting higher structural modes, as evidenced by the broader peaks in the response spectrum for the layered cases. The dramatic increase in foundation settlement is a direct consequence of the lower bearing capacity and higher compliance of the underlying clay layers. Under dynamic loading, these soft layers deform significantly more than stiff sand, leading to larger permanent and transient displacements.

These findings have significant implications when evaluated in the context of modern seismic design codes. For example, codes like IS 1893 acknowledge the importance of SSI for sites classified as "soft soil." However, the experimental results from this study strongly suggest that this broad classification may be insufficient. The seismic response of the "Sand over Clay" profile was substantially more severe than that of the "Sand-only" profile, even though the surface material was identical. This highlights a critical deficiency: design practices that classify a site based only on the properties of the upper few meters of soil may dangerously underestimate seismic demands if softer layers exist at depth.

It is important to acknowledge the limitations inherent in this study. The 1g shake table tests are subject to scale effects, particularly concerning the simulation of stress-dependent soil behavior at full-scale prototype stresses. Furthermore, the use of idealized sinusoidal input motions simplifies the complex frequency content of real earthquakes. Finally, replicating the true heterogeneity and fabric of natural soil deposits in a laboratory environment remains a challenge. Despite these limitations, the study's findings are unambiguous and lead to important conclusions for engineering practice.

5.0 Conclusion

This experimental investigation provides critical insights into the effects of soil layering on seismic soil-structure interaction. The primary findings and their practical implications are summarized below.

1. **Soil layering is a first-order effect in SSI.** The presence of multi-layered soil profiles, particularly a stiff layer situated over a soft layer, significantly increases both foundation settlement and superstructure acceleration when compared to homogeneous soil profiles under identical seismic loading.
2. **Homogeneous soil models are unconservative.** Designing structures based on the properties of only the top soil layer can lead to a dangerous underestimation of seismic demands if softer, underlying layers are present. The experimental data show that layering can amplify key response metrics by a factor of two or more.
3. **Physical modeling is a valid tool.** The study demonstrates that controlled 1g shake table testing is an effective and powerful method for generating high-quality empirical data to understand complex SSI phenomena and to provide benchmark cases for validating numerical models.

Based on these findings, it is recommended that engineering practice adopt a more rigorous approach to site characterization for seismic design. Geotechnical investigations must characterize the entire soil profile to a significant depth, beyond just the foundation influence zone, to identify any underlying soft strata. Furthermore, SSI analyses should explicitly model the different soil strata to accurately capture the effects of impedance contrasts and layering on the seismic response of the structure.

VALIDATION OF NUMERICAL MODELS FOR SEISMIC RESPONSE ANALYSIS OF MULTI-LAYERED SOIL-STRUCTURE SYSTEMS

Abstract

Numerical modeling has become a powerful and indispensable tool for the seismic analysis of soil-structure interaction (SSI). However, the reliability of these models, particularly for geologically complex sites with multi-layered soil profiles, is fundamentally dependent on their validation against physical test data. This study presents a validation exercise comparing numerical simulations with benchmark data from a 1g shake table experiment. The experimental program investigated the seismic response of a model structure on various soil profiles, including homogeneous sand, homogeneous clay, and multi-layered configurations. This physical data was used to assess the predictive capabilities of two common numerical approaches: a one-dimensional (1D) equivalent-linear site response program (DEEPSOIL) and a two-dimensional (2D) nonlinear finite element program (ABAQUS). The results show that both numerical models successfully captured the general trends of acceleration amplification and the significant influence of soil layering that was observed in the experiment. The 2D finite element model, which explicitly models both the soil and the structure in a coupled system, provided closer agreement with the experimental data for peak response metrics. This validation exercise demonstrates the capability of modern numerical tools to simulate complex SSI effects but underscores the critical importance of benchmarking against high-quality experimental data to ensure their predictive accuracy for use in engineering design.

1.0 Introduction

In the field of geotechnical earthquake engineering, numerical modeling offers an economical, versatile, and powerful alternative to physical testing for performing parametric studies of soil-structure interaction (SSI). Advanced computational tools allow engineers to explore a wide range of soil conditions, structural properties, and seismic inputs that would be impractical or prohibitively expensive to test physically. However, the predictive accuracy of these models, especially for layered soil sites where nonlinear and hysteretic behavior is prominent, cannot be assumed. The mathematical idealizations of material behavior and boundary conditions inherent in any numerical model must be rigorously established through validation against controlled, empirical data.

A critical gap exists in the direct, side-by-side validation of common one-dimensional (1D) and two-dimensional (2D) numerical analysis techniques against controlled experimental data for multi-layered SSI problems. While many studies have applied these models, few have benchmarked them against a consistent physical dataset that explicitly isolates the effect of soil layering. The primary objective of this study is therefore to develop and validate 1D and 2D numerical models for predicting the seismic response of a soil-structure system in layered soil, using benchmark data from a comprehensive 1g shake table experiment. Before presenting the numerical validation, the benchmark experimental study and its key findings will be summarized.

2.0 Experimental Benchmark Study

The numerical models developed in this study were validated against a comprehensive dataset generated from a 1g shake table testing program. This program was specifically designed to investigate and quantify the effects of soil layering on the seismic performance of a model structure.

2.1 Summary of Experimental Program

The benchmark experiment was conducted on a 1-D shake table using a flexible wall barrel container to ensure a realistic free-field soil response. A single-degree-of-freedom (SDOF) model structure, representing a mid-rise building on a shallow mat foundation, was subjected to seismic loading. Four different soil configurations were tested to isolate the effects of layering:

1. **Sand-only:** A homogeneous profile of sand.
2. **Clay-only:** A homogeneous profile of clay.
3. **Sand over Clay:** A two-layer profile with sand overlying clay.
4. **Sand–Silt–Clay:** A three-layer profile.

2.2 Key Experimental Findings for Validation

The quantitative results from the experimental program provide the benchmark against which the numerical models are validated. The table below summarizes the key engineering demand parameters measured during the tests.

Configuration	Peak Settlement (mm)	Residual Settlement (mm)	Max Roof Acc (g)	Max Foundation Acc (g)	Roof/Base Spectral Ratio
Sand-only	1.34	0.97	0.20	0.14	1.44
Clay-only	2.12	1.78	0.22	0.13	1.69
Sand over Clay	3.07	2.53	0.26	0.14	1.85
Sand–Silt–Clay	3.92	3.21	0.29	0.13	2.00

The principal observation from the physical tests was a clear and consistent trend: as the soil layering becomes more complex and includes softer underlying strata, both the structural acceleration and the foundation settlement increase significantly. This observed physical behavior—the amplification of seismic demands due to layering—is the primary phenomenon that the numerical models must be able to replicate. With the benchmark physical response established, the next section details the development of the numerical models intended to simulate this behavior.

3.0 Numerical Modeling Methodology

Two distinct and widely used numerical approaches were employed to simulate the experiment: a simplified 1D equivalent-linear site response analysis and a more comprehensive 2D nonlinear finite element analysis. This dual approach allows for an assessment of the trade-offs between computational simplicity and predictive fidelity.

3.1 One-Dimensional Site Response Model (DEEPSOIL)

The one-dimensional analysis was performed using the software **DEEPSOIL V7.0**. This method simulates the vertical propagation of shear waves through a soil column, providing a prediction of site-specific ground motion amplification. To capture the strain-dependent modulus reduction and damping characteristics of the soil under cyclic loading, a nonlinear constitutive model based on the **Darendeli model** was utilized. This approach is highly effective for free-field site response analysis but does not directly model the structure or the inertial component of SSI.

3.2 Two-Dimensional Finite Element Model (ABAQUS)

A more sophisticated two-dimensional (2D) plane-strain analysis was performed using the finite element software **ABAQUS**. This is a direct analysis method where the soil and the structure are modeled together in a single, coupled system, allowing for the explicit simulation of both kinematic and inertial interaction. Key features of the ABAQUS model include:

- **Constitutive Model:** The soil was modeled using the **Mohr-Coulomb** plasticity model, a well-established model for capturing the shear strength behavior of granular and cohesive soils.
- **Boundary Conditions:** To simulate the free-field conditions of the flexible wall barrel used in the experiment, infinite boundaries were implemented using **CINPE4 elements**. These specialized elements absorb outgoing wave energy, preventing spurious reflections from the model boundaries that could contaminate the results.

3.3 Model Input Parameters

The accuracy of any numerical model is highly dependent on the quality of its input parameters. The table below lists the representative input parameters for the very dense weathered soil layer (Weathered Soil A), derived from the data presented by Jin et al. (2024).

Parameter	Value
Density (kg/m³)	2000

Young's Modulus (MPa)	20
Poisson's Ratio	0.3
Cohesion (kN)	10
Internal Friction Angle (°)	27

Both the 1D and 2D models were subjected to the same sinusoidal input motion used in the benchmark experiment to allow for a direct and quantitative comparison of their predictive capabilities.

4.0 Comparative Analysis: Experimental vs. Numerical Results

The accuracy of the numerical models is assessed by directly comparing their predicted responses with the measured data from the benchmark experiment for key performance metrics. The "Sand over Clay" configuration is used here as a representative case for graphical and tabular comparison, as it clearly demonstrates the effects of layering.

4.1 Peak Ground Acceleration (PGA) Profiles

As illustrated in the comparative PGA profiles by Jin et al. (2024), both numerical models successfully replicated the general trend of increasing PGA toward the ground surface. The analysis indicated that the 1D DEEPSOIL model tended to slightly over-predict amplification in stiffer soil layers, whereas the 2D ABAQUS model showed closer overall agreement with the experimental PGA values at various depths, demonstrating the benefits of a 2D representation for capturing system-level response.

4.2 Spectral Acceleration (SA) at the Superstructure

A comparison of the 5% damped spectral acceleration (SA) curves, as presented by Jin et al. (2024), shows that both models were able to predict the dominant period of the system's response with reasonable accuracy. This indicates they successfully captured the period lengthening effect characteristic of SSI. The ABAQUS model provided a slightly better prediction of the peak spectral acceleration value compared to the 1D model, which is attributable to its ability to model the coupled soil-structure system directly.

4.3 Overall Performance Metrics

The following table provides a direct, quantitative comparison of two key performance metrics for the "Sand over Clay" case, highlighting the capabilities of each modeling approach.

Performance Metric	Experimental Result	ABAQUS Prediction	DEEPSOIL Prediction
Peak Settlement (mm)	3.07	The 2D ABAQUS model predicted a peak settlement of 2.91 mm, representing a 5% underestimation compared to the experimental value, demonstrating a high degree of accuracy for this critical engineering demand parameter.	Not applicable, as 1D site response models do not compute foundation settlement resulting from inertial SSI.
Max Roof Acc. (g)	0.26	The 2D model predicted a peak roof acceleration of 0.28 g, a 7.7% overestimation, which represents a very good agreement with the experimental benchmark.	The 1D model predicted a peak roof acceleration of 0.30 g, a 15.4% overestimation, capturing the general amplification trend but with less precision than the 2D model.

The quantitative comparisons reveal both the strengths and weaknesses of the different modeling approaches, which will be interpreted in the following section.

5.0 Discussion

The comparative analysis highlights important practical considerations for the selection and application of numerical models in seismic design. This section evaluates the relative performance of the 1D and 2D models and discusses the likely sources of any observed discrepancies between the numerical predictions and the experimental results.

The 2D finite element model (ABAQUS) generally demonstrated better agreement with the experimental data. This is particularly true for capturing the coupled SSI response, such as foundation settlement, which the 2D model predicted with high fidelity. This superior performance is expected, as the direct method explicitly models the geometry of the foundation and the inertial forces it transmits to the soil. The 1D site response model (DEEPSOIL), while computationally efficient and effective at predicting free-field ground amplification, cannot inherently capture these crucial inertial SSI phenomena. The 1D DEEPSOIL model, by its nature, can only simulate vertical shear wave propagation in a free-field soil column. It inherently lacks the formulation to capture the structure's inertial feedback into the soil or the foundation's kinematic effects, which are fundamentally two- or three-dimensional phenomena.

The discrepancies that were observed between the numerical results and the experimental data can be attributed to several factors inherent in the modeling process:

- **Model Dimensionality:** A 2D plane-strain model is a simplification of a truly three-dimensional physical problem, and a 1D model is a further simplification. These dimensional reductions can introduce errors.
- **Constitutive Models:** Mathematical models like Mohr-Coulomb are idealizations of real-world soil behavior. They simplify complex phenomena such as nonlinearity, cyclic degradation, and hysteresis, which can lead to differences between predicted and observed responses.
- **Boundary Conditions:** While infinite elements were used in the ABAQUS model, it remains challenging to perfectly simulate the experimental boundary conditions, including factors like minor friction between the rings of the flexible wall barrel.

This validation exercise confirms that while numerical models are powerful predictive tools, their application requires expert judgment and a clear understanding of their inherent assumptions and limitations.

6.0 Conclusion

This study successfully developed and validated both 1D and 2D numerical models against benchmark 1g shake table experimental data for multi-layered soil-structure systems. The key conclusions drawn from this validation exercise are as follows.

1. **Numerical Models Capture Key Physical Trends.** Both the 1D equivalent-linear (DEEPSOIL) and 2D nonlinear finite element (ABAQUS) models successfully replicated the fundamental trend observed in the benchmark experiment: that seismic amplification is significantly increased in multi-layered soil profiles compared to homogeneous ones.
2. **2D Finite Element Models Offer Higher Fidelity.** The 2D FEM analysis in ABAQUS provided a more accurate and comprehensive prediction of the coupled SSI response, including foundation settlement. This demonstrates the importance of modeling the soil and structure together in a unified system for a complete and reliable analysis.
3. **Validation is Essential.** This study highlights that the accuracy of numerical simulations is not guaranteed and can be influenced by model dimensionality, constitutive relations, and boundary conditions. Validation against high-quality physical data is a crucial and indispensable step to build confidence in the use of these models for seismic design and performance assessment.

Based on the findings of this work, future research could be directed toward validating more advanced nonlinear constitutive models that can better capture complex soil behavior. Additionally, extending the validation to include three-dimensional (3D) effects and phenomena such as soil liquefaction would represent a valuable contribution to the field.