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A Review of Seismic Behavior of Circular Shallow Foundations Using PLAXIS

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ABSTRACT

This This paper presents a comprehensive review of the seismic behavior of circular shallow foundations, with a focus on the role of soil-structure interaction (SSI) under earthquake loading. Both experimental and numerical studies are examined, including large-scale shaking table tests, advanced finite element simulations using PLAXIS, and analytical models. Special attention is given to the effects of dynamic loads, liquefaction, bearing capacity, settlement, foundation uplift, and nonlinear soil behavior. Geogrid-reinforced soils and their potential in improving seismic performance are also discussed. The review highlights recent developments in SSI modeling, parametric studies on soil and footing properties, and the influence of ground motion characteristics. Limitations in current modeling approaches and gaps in experimental data are identified, suggesting directions for future research. The findings aim to support improved design methodologies for safer and more resilient foundation systems in seismic regions.

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1. INTRODUCTION

In recent decades, the evaluation of the seismic response of shallow foundations has become increasingly important in geotechnical engineering. Earthquakes can induce strong local motion amplification, alter static soil conditions, and cause non-linear responses in soil, foundations, and structures. As a result, design procedures often require the use of numerical methods. Although a wide variety of commercial numerical codes are available today, they only partially meet these demands, as many are not fully suitable for geotechnical applications or require advanced programming skills to accurately model geotechnical behavior. Furthermore, there is a lack of numerical databases containing benchmark cases with known solutions, which would be useful for calibrating and validating numerical models (Faccioli et al., 2001) [1].

Circular Shallow Foundations (CSFs) are commonly used in practice due to their ease of construction and superior load distribution. However, their seismic behavior is not as well understood as that of rectangular foundations. Conducting prototype experiments on soil-footing interaction under arbitrary ground motions is often prohibitively expensive. Therefore, a PLAXIS-based numerical method has been developed to study the soil-footing interaction behavior of CSFs under earthquake excitations. A validation study using numerical models of large-scale shaking table tests on CSFs is first presented. Subsequently, parametric studies are conducted to examine the effects of soil and structural parameters on the seismic response of CSFs. Results indicate that the seismic responses of CSFs are influenced by both soil and footing parameters but are less affected by footing depth compared to rectangular foundations. Numerical pre-treatment methods for circular footings, such as radius ratio and flexural rigidity ratio, are recommended (Faccioli et al., 2001) [1].

The significant differences in the kinematic behavior between rectangular and circular foundations arise primarily from their varying rigidities, load distributions, and embedment depths. Although research on shallow foundations in the time domain has been limited, several studies have examined their numerical modeling in the frequency

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domain. These approaches can adequately estimate the 2D response of rectangular shallow foundations on horizontal or sloped beds subjected to seismic loading (Mirzaev, 2021) [2]. However, this area of study remains incomplete. The dynamic response of circular stiff or rigid foundations with different embedment depths has not been extensively explored. A three-dimensional finite element approach can account for soil-foundation-structure interaction, even under nonlinear conditions. Although this is one of the capabilities of such numerical codes, it remains a complex task. Numerical challenges, such as node compatibility along the soil-foundation interface and contact treatment of interface elements, can arise in large or deep models (Li et al., 2023; Zhou et al., 2023) [3][4].
The system input may change or be finalized at any time. In some cases, the structure does not perform as intended. Such discrepancies are often discovered after construction, especially during inspections, and can pose significant risks when the building is occupied. Eventually, existing structures may experience stronger vibrations, resulting in unexpected horizontal displacements and unforeseen three-dimensional rotational motions. Investigating the response of original foundations under seismic vibrations is crucial, and there is growing interest in the seismic analysis of existing structures. This process is essential for identifying any necessary retrofitting or upgrades. The foundation should be reassessed if soil properties or soil-structure interaction conditions change (Wu et al., 2022; Zhu et al., 2021) [5][6]. A review of the numerical analysis of soil-shallow foundation-fluid-structure interaction has been conducted, covering the current state-of-the-art numerical methods and capabilities. The review highlights various application techniques in both time-domain and frequency-domain analyses for soil-structure interaction under both seismic and non-seismic loading conditions. Studies on shallow foundation vibration behavior, particularly for circular shallow foundations subjected to horizontal earthquake vibrations, have also been conducted. One such study derived the foundation vibration spectrum ratio (FSVR) for a circular foundation resting on a soil layer above bedrock during earthquake excitation. The selected nonlinear soil model effectively captured the significant, irreversible deformations of soft clay under undrained conditions. A remarkable increase in FSVR was observed due to the presence of the circular shallow foundation across six analyzed cases. In the first case, a free horizontal boundary with no wave disturbance was considered, while the other cases involved fixed boundaries without load interaction with the foundation soil, resulting in unnecessary calculation time. Various modeling elements were utilized to address soil-structure interaction challenges, providing optimal mesh control with minimal accuracy loss. Two additional cases with identical soil properties but different structural configurations were analyzed; a raft foundation subjected to vertical and symmetrical horizontal loads on soil was modeled. All aspects of topology, loading, domain, and data handling were kept constant, and only the output results differed.

2 Seismic Analysis Fundamentals

The analysis of shallow foundations subject to seismic loading requires the seismic definition, the soil response analysis method, and the foundation transient response analysis. The seismic definition requires specification of the sites' seismic hazard, including the maximum earthquake expected over the service lifetime of the structure. The seismic hazard is subsequently transformed into the ground motion, which is analyzed by selecting a suitable ground motion model and adjusting its intensity to match the center frequency and the frequency content of the site design response spectrum (Gazetas et al., 2010 [7]). Ground motions and the structure-seismic ground system characterization are still being investigated by researchers, and this detection problem is generally difficult.

The procedure involved in the development of fully coupled models for site response analysis and shallow foundation transient response analysis is introduced. The concentration is given to the application of boundary-value problems associated with advanced soil models in the commercially available finite element code. Descriptions of site response analysis with validation against the analytical solution are presented first, followed by shallow foundation transient response analysis. The capability of the program for 2D boundary-value site and foundation response problems simulated with finite element models is demonstrated. Effectively developed numerical tools are expected to facilitate improved foundation seismic design practice and increase public safety (Faccioli et al., 2001 [1]).

The seismic design of shallow foundations has been based on empirical procedures or on simplified procedures with no deterministic formulation for the nonlinear behavior of soil and footings. These empirical and simplified procedures only yield first-order estimates of the response, which may be acceptable for buildings. However, foundations play a pivotal role in the structural-soil-system interaction and a more sophisticated approach is necessary for assessing their seismic robustness. This requires the resolution of transient dynamic equilibrium problems, involving time- and frequency-domain analyses, and necessitates an appropriate description of the soil and footing functional behavior (Mirzaev, 2021 [2])

2.1 Seismic Waves and Their Effects

The analysis of the seismic behaviour of shallow foundations due to seismic waves propagation and the relative motions of the superstructure, soil medium and the base has been a matter of intense theoretical-analytical and experimental investigation. These issues mainly stem from the consideration of the soil-foundation-structure interaction phenomenon, which plays a controlling role in most constructions for ground borne vibrations. On the one hand, immense computational resources allow the analysis to be carried out numerically for realistic models that result in a better understanding of the phenomenon. On the other hand, the way seismic waves propagate is still an area under investigation and requires millions of sensors to monitor ground accelerations and reconstruct the propagation of seismic wave trains (Faccioli et al., 2001 [8]).

The analysis of the seismic behaviour of shallow foundations due to seismic waves propagation and the relative motions of the superstructure, soil medium and the foundation has been a matter of great theoretical-analytical and experimental investigation. These issues mainly stem from the consideration of the soil-foundation-structure interaction phenomenon. An intensive research has been carried out to investigate this issue. The plethora of results obtained so far has contributed to the understanding of the interaction phenomenon and to the implementation of advanced methodologies for analysis and design, in particular for critical structures (Wu et al., 2022 [5]).

Efforts to better understand the seismic response of soil-structure interaction systems have turned to full scale and large scale experiments. The availability of large geotechnical centrifuges has allowed the performance of shaking table tests, closer to field conditions, and acting on foundations with dimensions in the order of meters. Nevertheless, modelling the seismic response of structures is still subjected to simplifications and uncertainties at the stages preceding experimentation and field monitoring. In sites of interest it is not always feasible to directly measure soil parameters since borehole invasiveness raises issues of contamination (Zhou et al., 2023 [4]).

2.2 Dynamic Soil Properties

The seismic analysis of structure-foundation interaction typically requires the use of advanced tools, such as commercially available finite element codes. Ground motion is usually represented using an elastic input motion. However, the fluid behaviour of the ground must be properly represented as well. A common practice is to laterally constrain the soil discretisation region, resorting to global failure criteria. This results in significant numerical costs, tends to misrepresent soil inertia and cannot take into account soil nonlinearity (Faccioli et al., 2001 [1]). An alternative viable option is available, based on the assumption of a lumped-mass rigid ground (infinitely stiff) that exploits Bernoulli-Euler beam theories. Proper beam solidity must be guaranteed, which usually translates into a high-order bending behaviour of the shallow foundation. However, it does not permit modelling the effective mass and stiffness interaction or the width of the excavation region, and therefore can be used only for deep foundation analysis. For shallow foundations this can be avoided by assuming a rigid frame. However, frame and beam codes cannot directly model a plane structure laid on a fluid foundation, and unless an effective staggered approach is considered, this requires a different representation of the soil. A reasonable compromise can be a three-dimensional model capable of predicting all effects with a moderate workload increase. This can be tested numerically by simulating a simplified example that requires full comparison between all approaches and generates a relevant benchmark for future research (Li et al., 2023 [3]).

Seismic response of shallow foundations is strongly dependent on the interaction between the structure and the ground. A completely coupled approach to study the interaction during seismic loading is possible with currently available numerical tools. Alternatively, two steps decoupled approaches can be used with sufficient approximations to the Boussinesq problem and to the rigid mass block assumption. PLAXIS is an available tool capable of implementing all necessary features with sufficient flexibility and computational efficiency. Finite elements are defined in PLAXIS 2D or PLAXIS 3D differential equation solvers. Several commercial codes use a different approach based on the direct solution of a differential equation boundary value problem. A time-domain formulation generates a state-space representation of the n-system and performs the resulting algebraic operations using a standard technique for large full or banded systems. A frequency-domain formulation applies the finite element method to derive a frequency-domain model of the n-system. Numerical computational costs are high since the high-order filtering necessary is highly sensitive to discretisation. Methods also confront computational limitations on the size of the system since it is not easy to implement the macromodels. On the other hand, this type of tool implements the essential numerical discipline for solving large order systems, and one shortcoming of tools currently employed is the lack of treatment in those prerequisites (Zhu et al., 2021 [6]).

2.3 Circular Shallow Foundations and Their Seismic Response

Circular shallow foundations on granular soils exhibit complex behaviors under seismic loading, including settlement, rotation, and sliding. These responses are significantly influenced by soil-structure interaction (SSI) mechanisms, which have been extensively investigated to improve seismic design methodologies.

E. Faccioli, R. Paolucci, and G. Vivero (2001) [1][8] conducted large-scale cyclic tests and developed analytical models to investigate the seismic behavior of shallow foundations. Their results demonstrated that under cyclic earthquake-like loading, significant permanent settlements and rocking occur, especially in low-density sands. Although the cyclic bearing capacity was found to be higher than pseudo-static predictions, large permanent deformations could still compromise structural safety. They also introduced a theoretical method for nonlinear dynamic SSI analyses, revealing possible reductions in spectral accelerations during strong earthquakes.

G. Gazetas, A. I. Panagiotidou, and N. Gerolymos (2010) [7] analyzed the pushover and inelastic-seismic response of shallow foundations supporting slender structures. They emphasized the importance of nonlinear soil behavior and foundation rocking, showing that controlled nonlinearities at the foundation level can effectively reduce seismic actions transmitted to superstructures.

R. Xu (2018) [9] proposed innovative geosynthetic-reinforced composite soil (GRCS) foundations and geotextile-reinforced cushioned pile foundations to address the challenges of excessive foundation settlement and rotation during earthquakes. Using three-dimensional numerical modeling that incorporates hysteretic soil damping, Xu demonstrated that these systems can significantly enhance seismic performance by reducing permanent displacements and rotations, provided that soil dynamic properties such as shear strength and plasticity index are accurately characterized.

Vicencio and Alexander (2022) [10] studied seismic structure-soil-structure interaction (SSSI) between pairs of buildings and highlighted the crucial influence of rotational ground motions on both displacement and acceleration responses. They warned that ignoring these rotational effects may lead to underestimations in seismic demand predictions.

Bapir, Abrahamczyk, and Wichtmann (2023) [11] provided a comprehensive review of SSI modeling techniques, discussing both their advantages and limitations. Their work offered guidance on selecting appropriate computational methods depending on structural configurations and site conditions.

Chen et al. (2024) [12] developed a discrete model for dynamic SSI systems with embedded foundations. Their model captured the complex interactions between structures and soils, particularly for embedded foundation systems, leading to more accurate predictions of seismic response.

Abdulaziz, Hamood, and Fattah (2023) [13] reviewed the seismic behavior of both individual and adjacent structures, considering SSI effects. They emphasized the necessity of incorporating interaction effects between neighboring buildings and their foundations to avoid unexpected damage during seismic events.

Homaei (2021) [14] focused on inelastic soil–foundation interface behavior and its effect on seismic demand. His study demonstrated that accounting for inelastic interface responses can significantly lower seismic demands on structures, highlighting the importance of considering nonlinear soil behavior in design.

Chorafa, Skrapalliou, and Katsimpini (2024) [15] investigated nonlinear behavior of composite structures under multiple seismic excitations, considering SSI effects. Their study showed that SSI can substantially affect inter story drifts, floor accelerations, and overall seismic performance, particularly for composite structural systems.

Collectively, these studies emphasize the critical importance of incorporating soil-structure interaction, nonlinear soil behavior, rotational ground motions, and interaction between adjacent structures in seismic analyses of circular shallow foundations. Advanced modeling techniques, such as finite element methods and macro-element approaches, as well as innovative foundation systems like geosynthetic-reinforced foundations, are essential tools to improve the seismic resilience of structures supported by circular shallow foundations.

3 Numerical Modeling and Analysis of Soil-Structure Interaction Using PLAXIS Software

The analysis of soil-structure interaction (SSI) under various loading conditions is a critical aspect of geotechnical engineering, particularly in the context of seismic performance, foundation stability, and deformation behavior. Numerical modeling provides a powerful tool for simulating complex geotechnical problems where analytical solutions are often not feasible. Among the available numerical tools, PLAXIS software has become widely recognized for its advanced capabilities in finite element analysis (FEA) of geotechnical structures. This section presents a comprehensive study that utilizes PLAXIS software for modelling, analysis, and evaluation of soil-structure interaction problems. The discussion begins with an overview of the PLAXIS software and its features, followed by a detailed description of the adopted methodology, and concludes with the presentation and interpretation of the obtained results.

3.1 PLAXIS Software Overview

According to Maheshwari et al. (2001) [16], PLAXIS software is a finite element program used for the analysis of deformation and stability of geotechnical structures. Its basic features include advanced soil models, easy 2D or 3D modeling, output control and access, custom plotting options, and a large library of applications. Sobhey et al. (2021) [17] stated that the PLAXIS approach covers a wide field of geotechnical engineering applications with a focus on simulation in soil-structure interaction, including the analysis of sheet pile walls, tunnels, excavations, embankments, slopes, foundations, and tunnels associated with excavation erosion. Hemeda (2024) [18] explained that from advanced finite element modeling of structures to the simulation of complex soil behavior, PLAXIS offers advanced capabilities to meet the needs of geotechnical engineers. Aligholi (2024) [19] noted that nonlinear soil models simulate the influence of definitive soil properties on deformation and stability, while the visualization of calculated results aids clear communication of the findings. Sanusi (2024) [20] emphasized that the geotechnical interface with easy 2D or 3D modeling of complex geometry ensures fast and efficient modeling, while the control center provides an overview of all essential settings. Chimdesa et al. (2023) [21] stated that all features are conveniently accessible via a single-access window. Badr and Shafiqu (2023) [22] mentioned that PLAXIS is available in two versions: PLAXIS 2D and PLAXIS 3D. The former performs 2D analysis of plane strain, general excavations, tunnels, sheet pile walls, or similar construction works, whereas the latter performs 3D analysis of tunnels, embankments, dumps, mounds, and structures with three-dimensional geometry. Sasmal and Behera (2024) [23] reported that both versions of PLAXIS include two-way coupled analysis of ground-water flow and soil deformation, large displacements and rotations of structures, liquid flow and consolidation in porous media, a diverse library of soil models varying from linear elastic to complex elastoplastic models, a user-defined soil model subroutine based on the programming language, dual mechanics formulation, nodal self-weight calculation of soil and structures similar to the hydrostatic pressure, various boundary conditions, the option to combine different codes/models in the same calculation, the three-stage calculation process numerical method, and output control options. Gupta et al. (2021) [24] discussed that the modeling of the cyclic loading soil-footing interaction problem in PLAXIS 2D is presented in the first part, where the selection of the proper model parameters is illustrated. Dhadse et al. (2021) [25] added that the refinement of the footing in a 2D PLAXIS model was created to investigate the seismic soil-footing interaction problem, considering various factors influencing footing performance, which were used for parametric investigations regarding the cyclic loading soil-footing interaction problem. Debnath et al. (2024) [26] presented analysis cases demonstrating differences of shallow and embedded footing performance under cyclic loading using PLAXIS 2D during an earthquake, providing new findings regarding moment development in the footing relative to soil displacement. El Hoseny et al. (2023) [27] indicated that a proper footing refinement in the PLAXIS 2D model was successfully created, and different configurations were examined using a 3D FEA code, with verification by powerful 3D results to understand specific behaviors. Jahed Orang and Motamed (2021) [28] extended the work discussing common modeling practices of rigid footings in the PLAXIS environment, including geometry, supports, loading, output choices, and additional modeling improvement suggestions. In the first series of analyses, two different models were built to examine the response of a shallow foundation in solid rock or in soft soil. In the second series, a fundamental frequency analysis was made on two models with equal parameters but with finite thickness bedrock bottoms, thus providing the features of the soil site-foundation-seat system. Lei et al. (2023) [29] described that the rock used in the model is Grey dolomites with a natural frequency of 100 Hz, density 2600 kg/m³, Young's modulus 70000 MPa, and Poisson's ratio 0.2. For the soil, in the first model, stiff firm clay was used with density 2200 kg/m³, Young's modulus 4000 MPa, and Poisson's ratio 0.4; in the second model, soft red clay was used with density 2100 kg/m³, Young's modulus 800 MPa, and Poisson's ratio 0.385. The foundation was a circular plate foundation with a diameter of 120 cm, height of 30 cm, density 2400 kg/m³, Young's modulus 19600 MPa, and Poisson's ratio 0.2, identical for both models. Li et al. (2021) [30] reported that model size and horizontal boundary conditions depended on the vertical or horizontal excitation frequency: for solid rock, 1100 cm for vertical and 800 cm for horizontal excitations were chosen; for relatively soft soil, models were 400 cm in height, with staggered boundary conditions applied. The tilt of the foundation was controlled with the angles of the case box, and with a tilting of 15°, the inclination was about 1/54 instead of 1/20 downwards. The four-degree of freedom

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excitation control forces were calculated in the simulation program, where all parameters (mass, stiffness, and damping matrices) were automatically included. The masses and axial inertances were added to the model. The model was built by regular input, only the stiffness and cross-coupling stiffness matrices were determined externally and inserted afterward.

3.2 Methodology

Shabani et al. (2022) [31] stated that quarterly reviews or inaccuracies in an article can affect the user's reliability, which may obscure the actual idea of the topic itself, especially in recent years when, through non-destructive testing, special attention has been paid to understanding how soil-structure interaction affects Belgian structures. Wyjadłowski et al. (2021) [32] explained that this fracture concern regarding the rebar beams of masonry structures, which dangerously suspend structures on far base pivot conditions, results from a lack of understanding of physics. Magliaro et al. (2022) [33] emphasized that the finite element program is one of the elastic simulation tools that can demonstrate how far something can move, how fast it moves, the frequency of ornamentation, and whether it returns, all before needing active non-destructive testing. Dai et al. (2022) [34] added that finite element net gravity simulations have already been done for vertical load under installed structures, and now motion simulations have started, with several static simulations regarding elastic displacement under seismic behavior completed, focusing on the effect of lateral stability on energy dissipation through hysteresis. Lu et al. (2016) [35] highlighted that for circular shallow foundations placed on cohesionless soil, 3D modeling seems promising for deepening the understanding of the foundation's movement. Yang et al. (2021) [36] noted that such modeling allows for simulating and comparing piles on cohesionless soil for bridge columns and roundabouts, while shallow rectangular and circular mat foundations require special attention due to large interaction effects on lateral motions from their flexibility and pronounced 3D effects. Fares et al. (2022) [37] stated that even though 3D modeling could theoretically run under parallel motion, that is not the current focus, while modeling deep foundations is also crucial due to their high moment capacity and the necessity to consider moment transfer into bridging piles on high footings on hydraulic sand. Zhang et al. (2022) [38] suggested that 3D non-linear finite element earthquake analyses of excavations are performed and validated against case histories with adequate records. Feng (2022) [39] indicated that the seismic response of shallow foundations is a significant concern, with structures represented by a rigid mass or massless hollow cylinder capable of rocking and translating, while Khezri et al. (2024) [40] explained that various analytical, FEM, empirical, and numerical methods are employed to study seismic response. Al-Arafat et al. (2024) [41] discussed that FEM analyses provide accurate solutions but face complications like defining proper mesh density, execution time, and instability. Pakdel and Chenari (2021) [42] mentioned that factors such as soil behavior models, model size, homogenization, foundation embedment, and non-linear soil properties complicate creating unique geometries for modeling shallow foundation behavior. Tavakoli et al. (2023) [43] observed that complex geometry benefits from re-meshing capabilities, while Kumar et al. (2023) [44] stated that open-source coding and GFEM in MATLAB have enabled new approaches to non-linear issues, with genetic programming and deep learning anticipated for future shallow foundation research. Intekhab et al. (2023) [45] emphasized that contiguous cast-in-place drilled shaft retaining walls are popular due to traffic limitations and surface ground restrictions, with excavations performed sequentially and particular concern for historic buildings. Soufi et al. (2021) [46] added that various types of shallow footings such as square, rectangular, continuous, trapezoidal, and circular are examined under static and dynamic conditions. Su et al. (2023) [47] detailed that static loading includes point, line, uniform, and corner loads, while dynamic loading includes harmonic, stepped, impulse, triangular, and earthquake loads. Izadi et al. (2022) [48] noted that test setups like fixed ring type load cells simplify static response analysis but applying static loads to full-scale footings is challenging, and seismic approach tests are fewer compared to static approaches. Tang et al. (2025) [49] explained that inertial forces during earthquakes equal horizontal accelerations, influencing inertia forces and bearing capacity failures. Del Toro Llorens and Kiendl (2021) [50] stated that seismic weight ratios and equivalent seismic load concepts help analyze shallow footings under complex loading, with dynamic bearing capacity factors and lateral earth pressures computed by combining dynamic and static conditions. Li (2022) [51] described analytical and numerical approaches for soil-structure interaction problems, using layered systems validated against closed solutions and applied to soft-strong site models, with 2D approaches extendable to 3D models. Spectral-ratio methods capture dynamic responses, with site-specific geologies tested under earthquakes, revealing amplitude differences between rock and soil, while layered models accommodate 3D geologies but present ill-conditioned inverse problems. Forward models are relatively easy to evaluate using sophisticated code, but inverse models require grid searches with fixed degrees of freedom to locate controlled responses amid random errors.

3.3 Results and Discussion

Faccioli et al. (2001) [8] explained that to better understand the main mechanisms involved in the seismic response of shallow foundations, several models have been conceived and tested: 1D models using flexural beams rotating about a hinge at the top of the wall or footing resting on the ground and defined with normal or non-linear rotational springs; 2D models made with beam elements representing inertia forces and the foundation, while the soil underneath was represented either with solid elements or in a multi-directional approach using rotational springs clamped on a beam element representing the footing, allowing rotation. They also performed dynamic analysis considering a beam-and-spring representation where the input acceleration is directly calculated at the top of the beam, determining the foundation-uplift by the slope translation and maximum rotation. The main mechanism is governed by thrust forces due to the overturning moment causing a net moment at the base, which affects the foundation's construction depending on its geometry and influences overall damage in the structure. Numerical simulations, particularly those based on FEM, were capable of modeling dynamic wave propagation and nonlinear soil behavior due to yielding and accumulated strain, demonstrating the essence of advanced models while acknowledging their complexity, as such analysis typically requires 10–15 hours to complete. Despite the power of such models, simpler approaches may lead to severe errors or modest design parameters unsuitable for certain conditions, potentially causing undisturbed ground failures and costly repairs often overlooked by engineers. Nath et al. (2024) [52] reported that to investigate the seismic response characteristics of circular shallow footings founded on soft and deep deposits, a detailed parametric study using PLAXIS 2D was conducted, analyzing the effects of foundation depth, soil properties, foundation embedment depth, and embedment angle. Ghosh and Prasad (2021) [53] and Kamal et al. (2021) [54] indicated that 93 cases were analyzed, including variations of the horizontal-to-vertical seismic motion ratio (HVSMR), dynamic load ratio (DLR), and ground motion type, contributing significantly to understanding soil nonlinear behavior under embankments of varying slopes. Gurbuz et al. (2025) [55] described a soil deposit consisting of silty clay, stiff clay, sand, and coarse gravel, with an overconsolidation ratio of 20 applied in soft clay for numerical stability. Wang et al. (2025) [56] explained that horizontal seismic waves were applied at the bedrock surface, with the footing embedded at 100 m depth and heights varying from 20 to 40 m, while slope angles ranged from 30° to 90°. Guan and Madabhushi (2025) [57] stated that sinusoidal waves with a frequency of 0.1 Hz and peak ground acceleration of 0.10–0.20g were used, with pseudo-static earth system models applied beneath the bedrock. Rohilla and Sebastian (2024) [58] explained that sliding stability was influenced by footing geometry, with smoother angles improving stability for continuous footings. Faccioli et al. (2001) [8] further modeled three large-scale seismic soil-footing interaction tests to verify PLAXIS software accuracy. The footing was a circular plate with a 1.0 m radius resting on sand with ~75% relative density. Two excitation levels, Low Density (LD) and High Density (HD), were tested with PGA values of 0.25g and 0.85g, corresponding to maximum horizontal forces of ~20,000 N and 80,000 N. The footing geometry and properties were identical to the experiments. The same nodal force and moment histories were applied, using a time increment of 0.01 s, damping ratios between 0.03 and 0.07, and a calculation duration of 82 s. σhx and Mz time histories predicted by PLAXIS models were compared to experimental data, showing good agreement though with a slight tendency to underestimate, particularly with no significant difference between LD and HD cases. The parametric study also examined transfer functions, maximum horizontal displacements, and response spectra as influenced by soil profile height, soil layers, decay parameters, and foundation width. The FE model from Section 5 provided insights into foundation contact and uplift during seismic excitation. Faccioli et al. (2001) [8] also investigated how soil elasticity, density, and foundation shape affect seismic response using innovative dynamic numerical models. Broader parameter ranges were tested, modeling conical bases on soft, medium, stiff soils, and floating foundations on soil with SPT N60 = 40. 3D FE models simulated full dynamic nonlinear elastic soil properties, rediscretizing foundation geometries and analyzing acceleration and displacement histories at FEM nodes. PLAXIS 3D models were adapted to create distorted foundation geometries, volume profiles, and contact assignments, varying elasticity moduli and densities across mesh groups. Soft soil basin models were developed to study wave propagation and the effect of basin height on soil-structure interaction, performing nonlinear 3D FE analyses of rocking or translational motions of shallow foundations atop the soil.

4 Advanced Case Studies of Seismic Soil-Structure Interaction

4.1 Numerical and Experimental Investigations

Faccioli et al. (2001) [8] emphasized that designing structures to resist seismic loads requires a detailed understanding of soil-structure interaction (SSI), which has become increasingly complex due to the nonlinear behavior of soil and dynamic wave propagation. In their large-scale cyclic tests, both 1D and 2D models were employed. The 1D models used flexural beams rotating about a hinge at the top of the wall or footing, incorporating normal or nonlinear rotational springs, while the 2D models combined beam elements with inertia forces and a foundation interacting with either solid elements or rotational springs clamped on the beam. Dynamic analysis also included beam-and-spring representations where acceleration inputs were directly applied to the top of the beam, which allowed evaluation of foundation uplift due to slope translation and rotation.

The primary seismic mechanism analyzed involves overturning moments producing thrust forces at the foundation base, directly influencing structural damage depending on the foundation's geometry. FEM-based numerical simulations captured dynamic wave propagation and nonlinear soil yielding, requiring significant computational effort but allowing improved understanding of strain accumulation and damage potential. Though highly sophisticated, such models remain time-consuming, taking approximately 10–15 hours to compute, and may sometimes underestimate certain parameters if simplifications are introduced.

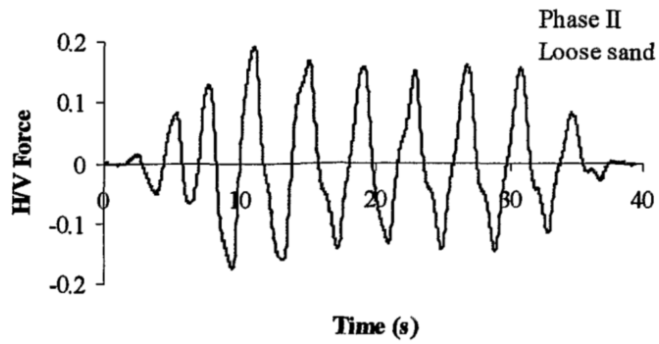

Figure 1 Experimental setup of large-scale cyclic loading tests (Faccioli et al., 2001)

4.2 Case Study A: Cyclic Loading and Wave Propagation

The first case study involved shallow foundations supporting slender structures subjected to cyclic lateral loading and shear wave propagation. The circular foundation was initially exposed to lateral loads inducing horizontal displacements, followed by shear waves initiated at the boundary of the numerical domain. The simulations revealed diverging behavior between two cases: in Case A, permanent displacements led to uplift termination, while in Case B, vertical contact forces between the soil and the foundation resulted in additional settlement and increased permanent lateral displacements. Foundation rotations were evaluated around three axes; rotations around the y-axis (longitudinal) were most significant, while transverse rotations remained minor. The loading frequency was gradually reduced to avoid resonance effects, with a standard 0.1 Hz used in later runs. Soil deformations below the foundation were also mapped, showing more pronounced displacement at deeper levels and during the initial stages before full propagation.

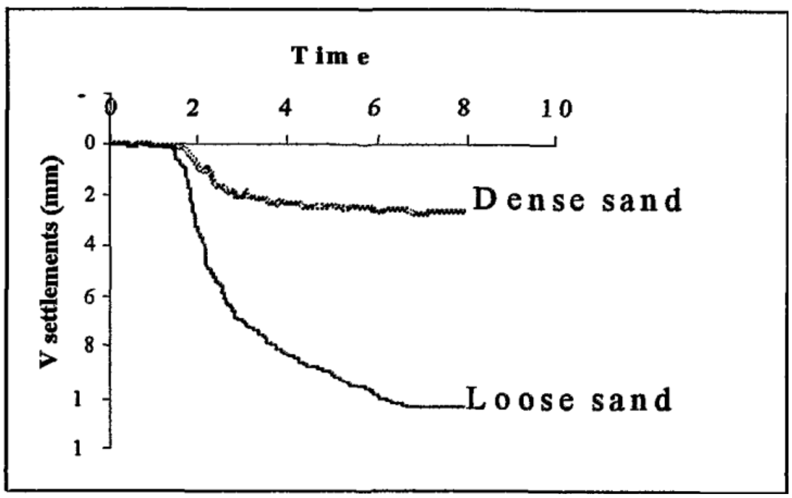

Figure 2 : Vertical foundation settlement under cyclic loading (Source: Faccioli et al., 2001)

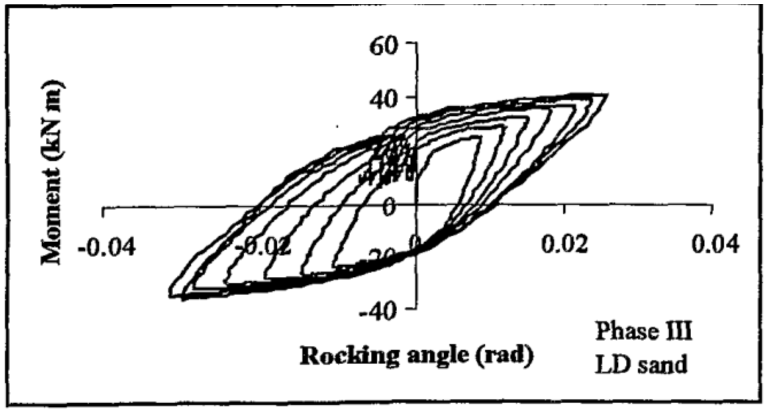

Figure 3 Overturning moment vs. rocking during failure stage (LD case)

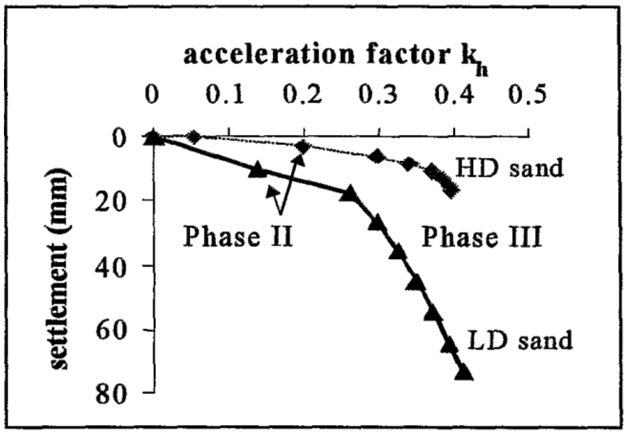

Figure 4 Foundation settlement vs. seismic coefficient

4.3 Case Study B: Water-Soil-Structure Interaction under Quasi-Static Conditions

In a second scenario, a stable plug formation was studied under quasi-static floating conditions, with the structure suspended in water. Here, lateral loads were reduced due to buoyancy, while water pressures balanced soil weights, allowing comparisons between submerged and dry conditions. The interaction between soil plasticity, void redistribution, and nonlinearity complicated stress transfer between the structure and soil. These nonlinear systems required advanced equilibrium solutions to accurately simulate cyclic and static conditions. The inclusion of cyclic loading emphasized the complexity of SSI, making deterministic analysis challenging and computationally intensive.

4.4 Case Study C: Seismic Amplification at Site C (Messina Urban Zone)

The third case study extended the investigation to urban seismic amplification. A sandy coastal site in Messina, Italy — characterized by tortonian flysch, quartzitic granitic layers, and sandy clays — was modeled to assess seismic site response amplification. Due to its rugged topography, the site is prone to seismic events, necessitating detailed SSI modeling. Both 1D equivalent analytical models and 2D pseudo-dynamic simulations were used to capture large displacements and nonlinear soil response. The soil exhibited high damping ratios for low-intensity harmonics, while synthetic near-field ground motions were generated at the base and portico levels. The 3D amplification effects showed spectral peaks at T = 0.38 s, suggesting the onset of secondary dynamic responses beyond the fundamental period of the soil column

5. Study Limitations, Future Research Directions, and Practical Implications

5.1. Limitations of the Study

Because of the nature of this study, which uses a numerical method, this analysis review has limitations. First, a bearing-capacity study has not yet been performed. A significant point for the model construction was the choice of the load number. Depending on the period of the earthquake, a significant difference in the response was observed. With a long period, it was expected that the condition would converge to a unique one, but this was not verified. A long-term simulation with a significant number of loading cycles could provide a better chance of identifying soil conditioning; a new analysis would be performed starting with a model already subjected to the earthquake, and this additional calculation would reveal future soil damage. A second limitation is the calibration of the soil model. The construction correctly reproduced common soil behavior in the area given its geological history, but there are no **in situ** data to back up the parameter assumptions. Although this work was already published, it is advisable to conduct a preliminary study using geotechnical methods to supply information for a more reliable assignment of the soil parameters. A third limitation is the exclusion of a local amplification study. In post-earthquake sedimentation and softening analysis, a significant increase in the amplitude and the duration of waves was observed, creating a second peak in the response. It is still unknown how the basal soil conditions affect the means of the foundation response. Finally, the basis of the study has so far centered on evaluating the conditions for a shallow foundation with an adequate time history. In this review, seismic responses with low frequency are presented for a frame supported on deep foundations or analyzed numerically by loading. This higher safety level ensures a more reliable response in case of earthquakes with a very low-frequency return period. A review of current methods used to derive the plastic rotation of deep foundations under seismic loading was published recently as part of an extensive research program, making it easy to set the frame for future work.

5.2. Future Research Directions.

In the past two decades, recent developments on the seismic response of shallow foundations have been presented. Research studies composed of both analytical and experimental works on seismic soil-foundation interaction are analyzed and presented. The infinite-element technique has been used to model the semi-infinite domain of the underlying soil in the frequency domain, taking into account the frequency-dependent behavior of both soil and structure. First, this methodology is validated through analyses on several rigid model footings interacting with homogeneous soil; the footing results with and without soil-structure interaction agree closely with published data. Second, parameters affecting the seismic response of shallow circular foundations founded on a multilayered soil are examined. Extensive numerical investigations are conducted in the time domain using PLAXIS; nonlinear soil behavior is introduced through a user material subroutine employing the hardening-soil model. The 2D axisymmetric results agree with RESTA software predictions. Accelerations and displacements of soil and footing generally decrease as the frequency of the bedrock motion increases, while increasing soil density slightly lengthens layered-soil periods at low frequencies only. Instead of one-dimensional equivalent-linear analyses, the peak spectral acceleration at the surface of the soil-foundation system is also obtained based on the frequencies of the input bedrock motion. In addition, computed dynamic stresses in the foundation should be checked to ensure undrained conditions in the soil strata and to avoid excessive excess pore-water pressure and possible liquefaction of coarser materials. Two numerical approaches remain important: a fully coupled dynamic approach—computationally costly because it solves bi-directional two-phase flow, instantaneous compression, and equilibrium simultaneously—and an effective-stress method, which considers ground motion and seepage on total and effective stresses but neglects dynamic ground survival effects on pore-pressure generation and on water-instrument response.

5.3. Practical Implications.

Innovative approaches have been applied in recent years to dissipate seismic energy at shallow foundations of large vibrating systems. A key example is the “kapacity design” philosophy at the Rion–Antirion Bridge near Patras, where material grading and reinforcement were controlled to ensure the foundation dissipates energy in sliding rather than overturning—far less harmful for tall structures. Most recent analytical methods for shallow footings are pseudo-static or simplified dynamic approaches. The pseudo-static procedures are based on horizontal seismic forces derived from the Newmark or Mononobe–Okabe formulas; simplified dynamic procedures rely on wave-propagation theory. Neither reproduces true seismic footing behavior because of simplifying assumptions. Large-scale cyclic tests in a handful of laboratories provide valid experimental insight into SSI effects during seismic loading; however, complexity and cost limit their widespread application, and academic researchers often neglect this important technique.

6. Conclusion:

Several numerical models predicting the seismic response of shallow foundations along with some comparisons with experimental data are presented in this paper. Due to practical limitations of modelling intensively instrumented laboratory tests, the choices of idealisation of the actual test and of the constitutive model were limited. In particular, to limit the number of parameters to be calibrated, the heterogeneous clay was modelled as homogeneous and the elastoplastic Mohr-Coulomb model related to a single reference point was used omitting the possible progressive plasticisation of the clay. Furthermore, the stress path accessible to the foundational footing neighbouring the wetting front in the softer clay was incorporated in a simplistic way in the numerical models, omitting other possible sources of stress concentration. Therefore, the excess pore pressure generated, which had only a small effect on the dynamic behaviour of the foundations during the large shaking tests, was neglected in the models. Although these simplifications and omissions introduce inaccuracies and uncertainty in calculating stress, strain and pore pressure, they are compensated with increased flexibility of modelling other scenarios, discounting at least part of the effects of site specific boundary and soil issues.

Neglecting boundary conditions taking into account either the total stress state or both stress and pore pressure is common in numerical modelling of shallow foundations. Additionally to reflecting experimental boundary conditions, pressure boundaries are employed to decrease the computational time needed for spin-up of the clay. Several numerical models for shallow foundations have been refined and then developed to cover other load conditions neglecting factors enhancing uncertainties of modelling or generating boundary problems in modelling other soil fields not tested yet. These models could be of interest in terms of their applicational flexibility and for modelling the seismic response of shallow foundations due to questions regarding other sites, loading conditions, loading order effects or other configurations not covered by laboratory tests.

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