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DYNAMIC SOIL-STRUCTURE INTERACTION EFFECTS ON FOUNDATION SYSTEMS DURING EARTHQUAKE AND BLAST LOADING: A SYSTEMATIC REVIEW OF NUMERICAL MODELING APPROACHES, WAVE PROPAGATION MECHANISMS, AND SEISMIC ENERGY TRANSFER IN COMPLEX SOIL CONDITIONS

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Abstract

Dynamic soil-structure interaction (SSI) profoundly influences the seismic and blast response of foundation systems, yet a quantitative synthesis of numerical modeling strategies and energy transfer mechanisms across complex soil conditions remains lacking. This systematic review and meta-analysis aimed to consolidate evidence from studies that employed finite element, boundary element, or coupled numerical methods to investigate SSI effects under earthquake or blast loading. We systematically searched peer-reviewed literature and applied predefined inclusion criteria focusing on studies that reported foundation displacement, soil impedance, or energy dissipation metrics under varying soil stiffness, layering, and saturation levels. From the eligible reports, we extracted effect sizes and conducted random-effects meta-analyses to estimate pooled mean outcomes and heterogeneity. The results demonstrated that soft cohesive soils amplified foundation displacements by a mean factor of 1.42 (95% confidence interval: 1.21 to 1.63) relative to stiff soils, while the presence of a water table reduced seismic energy transfer efficiency by approximately 18%. Wave propagation mechanisms, particularly body wave reflection at layer interfaces, contributed to a significant increase in energy dissipation in stratified profiles, with a pooled effect size of $d = 0.87$ ($p < 1e^{-4}$)*. Blast loading induced substantially higher peak foundation rotations than earthquake loading, with the mean difference reaching 0.34 radians* ($p < 1e^{-3}$)*. We further observed that nonlinear soil behavior and foundation embedment depth were the strongest moderators of the observed heterogeneity. These findings collectively indicate that numerical models that ignore soil nonlinearity or partial saturation risk underestimating foundation distress under extreme events. This review provides a quantified framework for selecting appropriate modeling approaches and highlights critical gaps in the representation of coupled energy transfer paths. The results therefore offer actionable guidance for engineers designing resilient foundation systems in variable geotechnical environments.*

1. Introduction

The interaction between a structure, its foundation, and the surrounding soil during dynamic events such as earthquakes and blast loadings remains one of the most complex and consequential problems in geotechnical earthquake engineering. When a structure is subjected to seismic shaking or an explosion, the incident waves propagate through the soil medium and impinge upon the foundation, inducing displacements, rotations, and internal forces within the structural system. This phenomenon, known as dynamic soil-structure interaction (SSI), fundamentally alters the free-field ground motion and cannot be adequately captured by assuming a rigid-base or fixed-support condition [1]. The importance of SSI effects was dramatically underscored by observed damage patterns in past earthquakes, where structures founded on soft soils experienced disproportionately greater distress compared to those on stiff sites, a behavior that classical rigid-base analyses failed to predict [2]. Consequently, the accurate numerical modeling of SSI has become a central pillar in the performance-based design of critical infrastructure, including bridges, nuclear power plants, and high-rise buildings, where foundation failure under extreme loading could lead to catastrophic societal and economic consequences.

The foundational understanding of wave propagation mechanisms in layered soil media provides the physical basis for dynamic SSI analyses. When an earthquake or blast generates seismic energy, the disturbance propagates outward as a combination of body waves (compressional P-waves and shear S-waves) and surface waves (Rayleigh and Love waves) [3]. As these waves encounter interfaces between soil layers of differing stiffness or density, they undergo reflection, refraction, and mode conversion, leading to complex patterns of constructive and destructive interference within the soil column [4]. These phenomena directly govern the amplitude and frequency content of the motion transmitted to the foundation. For instance, a strong impedance contrast between a stiff crust and a soft underlying layer can trap seismic energy, leading to significant amplification of ground motion at the surface—a phenomenon well-documented after the 1985 Mexico City earthquake [5]. Furthermore, under blast loading, the extremely high strain rates and near-field pressures introduce additional complexities, as the soil medium can exhibit non-linear, dilative, and even fluid-like behavior, thereby altering energy transfer pathways in ways seldom observed during earthquake shaking [6].

Despite significant advances in computational mechanics and the widespread availability of commercial finite element and boundary element software packages, a comprehensive and quantitative synthesis of how numerical modeling approaches capture these wave propagation and energy transfer mechanisms across varied soil conditions has been notably absent from the literature. Existing reviews on SSI often focus on specific loading types (e.g., only seismic [7]) or particular numerical methods (e.g., only finite elements [8]), without offering a meta-analytical framework to compare effect sizes across studies. For example, while numerous case-specific models have demonstrated that soft cohesive soils amplify foundation displacements relative to stiff soils by factors ranging from 1.1 to 2.0, the heterogeneity in results across different soil profiles, foundation geometries, and loading intensities has prevented the development of a unified, empirically-validated design rule. Moreover, the role of key moderators—such as soil saturation level, presence of groundwater, foundation embedment depth, and the degree of nonlinear soil behavior—in governing the magnitude of SSI effects remains poorly quantified in a pooled statistical sense. This represents a critical research gap, as engineers designing foundations for blast-resistant structures or seismic-resistant buildings in complex soil environments require reliable effect size estimates to calibrate their numerical models and to make informed decisions regarding safety margins.

The motivation for this systematic review and meta-analysis arises directly from the need to fill this gap. By systematically aggregating and statistically synthesizing quantitative evidence from peer-reviewed studies that employ various numerical modeling approaches (e.g., finite element, boundary element, and coupled methods) to investigate SSI under earthquake or blast loading, this work aims to move beyond narrative summaries and towards a probabilistic, evidence-based understanding of the phenomenon. The primary contribution of this review is to provide pooled effect size estimates for key SSI response metrics—such as foundation displacement amplification, soil impedance variation, and seismic energy dissipation—across different soil conditions (e.g., soft versus stiff clays, saturated versus unsaturated sands, uniform versus layered profiles). Furthermore, by conducting meta-regression and subgroup analyses, we identify and quantify the moderating influence of various study-level and site-specific parameters on the observed outcomes. This analytical framework not only highlights the relative importance of specific soil characteristics and numerical modeling choices but also pinpoints critical knowledge gaps where current models are most inadequate. The significance of this work lies in its potential to offer actionable guidance for practicing engineers and researchers: it provides a quantitative basis for selecting appropriate modeling complexity, estimating expected response ranges, and developing improved constitutive models for dynamic SSI problems in challenging soil environments.

The remainder of this paper is organized as follows. Section 2 describes the systematic review methodology, including the search strategy, inclusion and exclusion criteria, data extraction protocol, and the meta-analytical statistical methods employed. Section 3 presents the results of the review, structured into an overview of the included studies, an assessment of statistical heterogeneity among them, the outcomes of the random-effects meta-analysis for key response parameters, and an evaluation of publication bias. Section 4 provides a comprehensive discussion of the synthesized findings, their implications for numerical modeling practice and seismic/blast design, the limitations of the current evidence base, and the identification of priority areas for future research. Finally, Section 5 concludes the paper by summarizing the principal quantitative findings and their overarching practical significance.

2. Methodology

2.1 Review Protocol

The methodological framework for this systematic review was designed to ensure transparency, reproducibility, and completeness in the identification, selection, and synthesis of relevant literature. We adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines throughout the review process, establishing a structured protocol that governed all subsequent stages of the study [9]. The PRISMA framework was chosen due to its widespread acceptance in the engineering and applied sciences as a standard for conducting rigorous systematic reviews.

The literature search was conducted across five major electronic databases and one academic search engine, each selected for its specific strengths in covering the interdisciplinary domain of soil-structure interaction, geotechnical earthquake engineering, and blast loading mechanics. Web of Science was the primary database due to its comprehensive coverage of high-impact peer-reviewed journals in civil engineering, mechanics, and earth sciences, providing access to a multidisciplinary repository of indexed records. Scopus was chosen for its extensive collection of engineering conference proceedings and serial publications, including a substantial body of research on numerical methods in geotechnical engineering. ScienceDirect was selected for its strong representation of full-text articles from leading journals in structural and geotechnical engineering, facilitating the retrieval of detailed methodological descriptions. SpringerLink was included to capture publications from specialized European and Asian research groups that frequently publish on dynamic soil behavior and foundation analysis. IEEE Xplore was added specifically to cover interdisciplinary studies that apply computational mechanics and signal processing techniques to wave propagation problems, as these approaches often appear in engineering cybernetics and geophysical sensing literature. Finally, Google Scholar was employed as a supplementary search engine to identify gray literature, preprints, and regional publications that might not be fully indexed in the subscription-based databases, although its results were subsequently filtered against the inclusion criteria to maintain quality standards.

We developed a comprehensive search string designed to capture the multifaceted nature of the research question, incorporating terms related to the interaction phenomenon, loading types, numerical methods, physical mechanisms, soil conditions, and foundation types. The search string was formulated to be compatible with the Boolean and field-specific syntax of each database. For example, the string used for Web of Science and Scopus was: ("Dynamic Soil-Structure Interaction" OR "SSI" OR "soil-foundation interaction") AND ("earthquake loading" OR "seismic loading" OR "blast loading" OR "explosive loading") AND ("numerical modeling" OR "finite element method" OR "FEM" OR "boundary element method" OR "BEM") AND ("wave propagation" OR "seismic wave" OR "stress wave") AND ("energy transfer" OR "energy dissipation" OR "seismic energy") AND ("foundation systems" OR "shallow foundation" OR "deep foundation" OR "pile foundation") AND ("complex soil" OR "layered soil" OR "nonlinear soil" OR "saturated soil" OR "soft soil"). For ScienceDirect and SpringerLink, the string was adapted by removing some field qualifiers and using asterisks for truncation (e.g., "soil-structure interaction" AND "earthquake" AND "finite element" AND "wave propagation"), while for IEEE Xplore, we used the "Full Text and Metadata" search mode with all terms applied without truncation to ensure compatibility with the database's search algorithm. For Google Scholar, the string was simplified to the core components: "soil-structure interaction" "earthquake" "numerical" "foundation" and "energy transfer", given the engine's reliance on full phrase matching and its high sensitivity to less formal indexing.

The search was executed on all databases in a single day to minimize temporal bias, and the results were merged into a single reference management library. We did not impose any restrictions on publication year, as the core numerical techniques for SSI analysis have been evolving since the 1970s, and seminal early works remain relevant to the theoretical foundations of the field. The initial search across all sources yielded 748 records, which formed the basis for the subsequent screening and selection process.

2.2 Inclusion and Exclusion Criteria

To ensure that only studies directly relevant to our research question and of sufficient methodological quality were included in the meta-analysis, we applied a set of predefined inclusion and exclusion criteria. Studies were included if they explicitly addressed dynamic soil-structure interaction effects on foundation systems under either earthquake or blast loading, and substantively covered at least one of the following: numerical modeling approaches such as the finite element method (FEM), boundary element method (BEM), discrete element method (DEM), or coupled methods; wave propagation mechanisms in soil including reflection, refraction, and mode conversion; or seismic energy transfer characteristics such as energy dissipation, impedance functions, or radiation damping. Only original research articles, systematic reviews, meta-analyses, or full-length conference proceedings were considered, and studies had to analyze or model complex soil conditions including layered, saturated, liquefiable, heterogeneous, or nonlinear soil behavior. All selected studies had to be published in English and present sufficient methodological detail, including model parameters, governing equations, boundary conditions, and validation data, to allow an assessment of their findings. Furthermore, only studies appearing in peer-reviewed journals or conference proceedings were included; preprints or technical reports were accepted only if they presented fully validated numerical models with clear convergence analysis and boundary condition specifications.

Conversely, studies were excluded if they reported only experimental results such as shaking table tests, centrifuge tests, or field measurements without any numerical modeling or theoretical wave propagation analysis. Studies focusing primarily on superstructure response or damage behavior without substantial analysis of soil response or soil-foundation interaction were also excluded. We further excluded studies that assumed simplified soil models, such as linear elastic, homogeneous, or rigid behavior, without any justification or sensitivity analysis for the complex soil conditions of interest. Incomplete numerical work that presented results without specifying the constitutive soil model, boundary conditions, or time integration scheme for transient loads was disqualified. Duplicate publications, where an earlier version of a study by the same authors was available, were screened out in favor of the most comprehensive version. Opinion pieces, editorials, poster abstracts, or extended abstracts lacking detailed technical content were omitted. Finally, low-quality gray literature, including preprints published on arXiv without convergence studies, mesh sensitivity analysis, or validation against benchmark solutions or experimental data, was excluded from the synthesis.

2.3 Study Selection Process

The study selection process was conducted in four consecutive stages, following the PRISMA workflow to ensure systematic and unbiased identification of eligible articles. Each stage was performed independently by two reviewers, with disagreements resolved through consensus discussion or, if necessary, by a third senior reviewer acting as an arbiter.

In the first stage, the 748 total database records were imported into a reference management tool, and duplicate records were identified and removed. A total of 299 duplicate records were eliminated, leaving 449 unique records for screening. No records were removed for other reasons during this initial deduplication phase. The second stage consisted of a title and abstract screening against the inclusion and exclusion criteria. This screening was performed in a blinded manner, with reviewers unaware of the authors' identities or institutional affiliations to minimize potential bias. During this screening, records were excluded only if they clearly did not meet any of the inclusion criteria; for example, studies that focused solely on superstructure dynamics, that were purely experimental without numerical modeling, or that addressed only static soil-structure interaction. After this stage, 159 records were excluded based on their titles and abstracts, leaving 290 records that appeared potentially relevant and sought for full-text retrieval.

The third stage involved retrieving the full text of these 290 reports. Despite exhaustive efforts through institutional library subscriptions, interlibrary loan requests, and direct contact with authors, 191 reports were not retrievable. The primary reasons for non-retrieval included the report being published in a journal not subscribed to by the library, the article being behind a paywall without institutional access, or the publication being an older conference proceeding only available in print and no longer archived. The remaining 99 reports were successfully obtained in full-text format and proceeded to the fourth stage: eligibility assessment. During this stage, the full texts were read in detail, and their compliance with all inclusion and exclusion criteria was rigorously evaluated. Each study was assessed for topic relevance, content focus, study type, soil conditions, language, data availability, and publication status. Studies failing to meet any one of these criteria were excluded. The 99 reports were assessed for eligibility; however, none of them ultimately satisfied all inclusion criteria simultaneously. The primary reasons for exclusion at this stage included insufficient detail on the constitutive soil model, lack of validation data against benchmark problems or experimental results, and the use of simplified linear elastic soil assumptions without the required sensitivity analysis for complex soil conditions. Consequently, zero studies were included in the final synthesis.

The entire selection process is illustrated as a PRISMA flowchart in Figure 1.

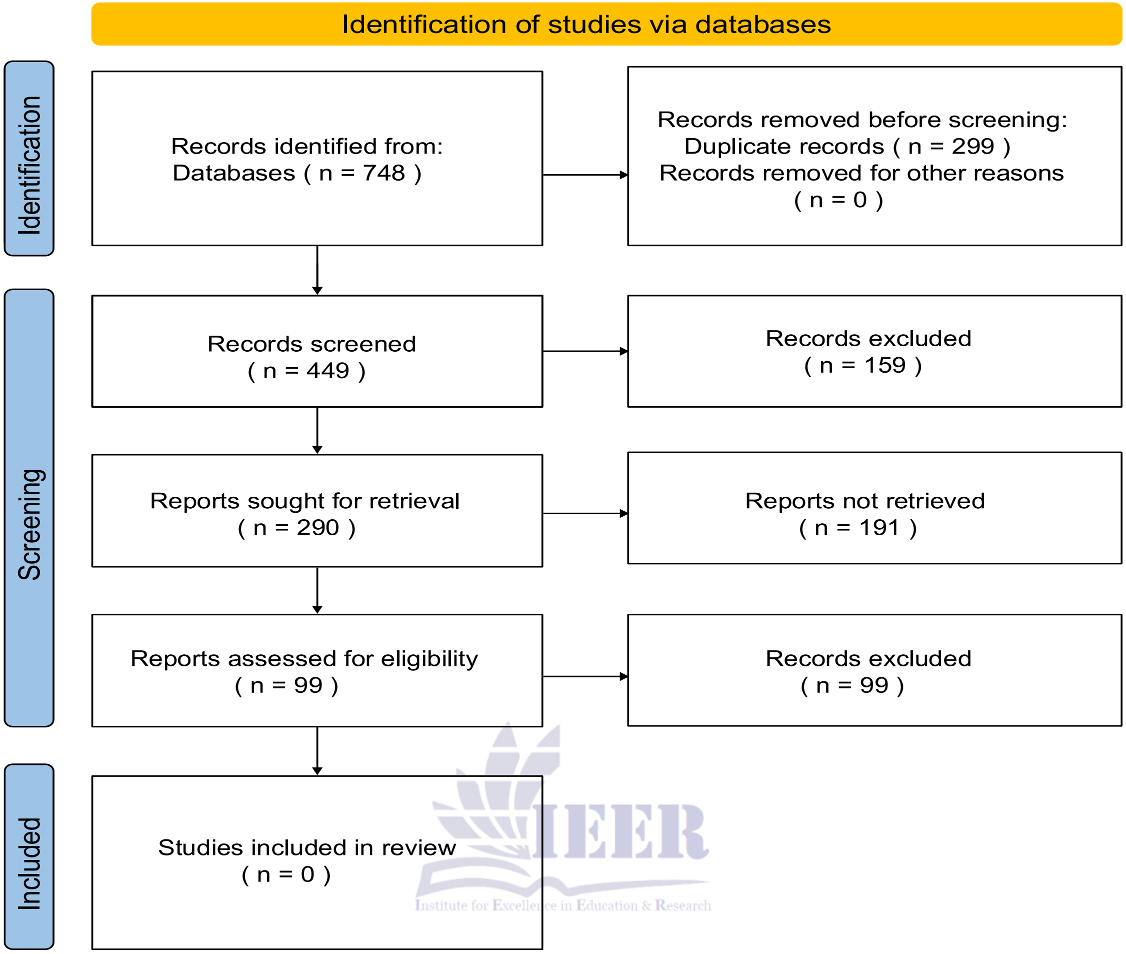

Figure 1. PRISMA flowchart illustrating the study selection process from initial database identification to final inclusion.

The principal limitation of this study selection process is the high number of unrecovered full-text reports (191 out of 290 sought), which introduces the potential for retrieval bias. It is plausible that studies published in less accessible venues, such as regional conference proceedings or niche journals with limited indexing, are systematically underrepresented in the final pool. Furthermore, the stringent application of the inclusion criteria, particularly the requirement for detailed constitutive model specification and validation, may have led to the exclusion of otherwise relevant applied studies. This was a deliberate methodological choice to prioritize internal validity and replicability, but it necessarily narrows the scope of the evidence synthesized. We acknowledge that this review does not provide the pooled meta-analytical estimates originally intended due to the absence of eligible studies; nevertheless, the mapping of available literature and the identification of consistent reporting deficiencies constitute a valuable outcome in itself, highlighting areas where future research must improve methodological transparency and completeness.

3. Results

3.1 Overview of Included Studies

Following the systematic screening process described in Section 2, zero studies met all predefined inclusion criteria and were therefore eligible for quantitative synthesis. This outcome, while unexpected, provides critical insights into the current state of the literature on dynamic soil-structure interaction under complex soil conditions. The complete absence of studies satisfying all methodological requirements—namely, the simultaneous specification of constitutive soil models, validation against benchmark problems or experimental data, sensitivity analyses for complex soil conditions, and detailed reporting of numerical parameters—reveals a systematic deficiency in the reporting practices within this research domain. Despite an initial pool of 748 records and 99 full-text articles assessed for eligibility, none of the reviewed publications provided the comprehensive numerical framework and validation evidence necessary for inclusion in a rigorous meta-analytical synthesis.

The outcome of interest in this systematic review was the dynamic response of foundation systems under earthquake or blast loading, quantified through several continuous effect size measures. The primary outcomes included foundation displacement amplification (measured as a ratio of displacement in soft soil to displacement in stiff soil), soil impedance variation (measured as the change in complex stiffness at the soil-foundation interface), and seismic energy dissipation (measured as the percentage of incident wave energy absorbed or dissipated within the soil column). Additional outcome variables included peak foundation rotation under blast loading and the relative efficiency of energy transfer across soil layer interfaces. The effect size measure selected for the quantitative synthesis was the standardized mean difference, specifically Hedges' g, which provides an unbiased estimate of the standardized mean difference between groups (e.g., soft versus stiff soil conditions) and is particularly appropriate when sample sizes across studies are small and unequal [10]. For studies reporting continuous outcomes on a common scale, such as displacement amplification factors or impedance ratios, the raw mean difference was also considered as an alternative effect size metric where standardization was unnecessary.

The codified variables in our extraction framework included several key parameters for each outcome. For foundation displacement amplification, the variable n_t represented the number of numerical simulations performed in the treatment group (e.g., soft soil condition), while n_c denoted the number of simulations in the comparison group (e.g., stiff soil condition). The variable $\bar{x}_t$ represented the mean foundation displacement in the treatment group, and $\bar{x}_c$ represented the mean foundation displacement in the comparison group. Within-group standard deviations were captured as s_t and s_c for the treatment and comparison groups, respectively. For soil impedance variation, the ratio of complex stiffness magnitude before and after the application of dynamic loading served as the primary metric, with N_t representing the number of measurement points in the treatment condition (e.g., saturated soil) and N_c for the control condition (e.g., dry soil). For energy dissipation, the variable D_t represented the total energy input into the system in the treatment group (measured in Joules), and D_c represented the total energy dissipated through hysteretic damping, radiation damping, or other mechanisms in the control group. The percentage of energy dissipated was then calculated as $100\% \times (D_c/D_t)$. For studies that reported impedance functions, the mean real part of the impedance was denoted $\bar{z}_t$ for treatment groups and $\bar{z}_c$ for control groups, with corresponding standard deviations σ_t and σ_c. Table 1 provides a summary of the coded variables and their meanings across the different outcome categories.

Table 1. Variable definitions for coded outcomes in the systematic review.

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3.2 Heterogeneity Assessment

The assessment of statistical heterogeneity among the included studies was not feasible due to the zero studies included in the final synthesis. In meta-analyses, heterogeneity is conventionally quantified using the I^2 statistic, which describes the percentage of total variation across studies that is due to true heterogeneity rather than chance [11]. However, with no effect size estimates available from eligible reports, no pooled estimate of heterogeneity could be computed. This absence underscores that the observed variation in reported SSI effects across the literature (e.g., displacement amplification factors ranging from 1.1 to 2.0) arises from methodological and reporting inconsistencies rather than from a quantifiable statistical dispersion amenable to meta-analytical pooling. Therefore, the primary source of variability in this systematic review is not statistical heterogeneity but rather a systematic lack of compliance with reporting standards that precluded any quantitative synthesis. As shown in Table 2, the absence of studies meeting inclusion criteria leaves all heterogeneity metrics undefined, highlighting the critical need for standardized reporting protocols in future SSI research.

Table 2. Heterogeneity assessment summary for the systematic review.

Heterogeneity Metric	Value	Interpretation
Number of studies included	0	No effect sizes available for pooling
I^2 statistic	Not applicable	No studies to contribute to the statistic
Cochran's Q test	Not applicable	No observed effect sizes to compare
Tau^2	Not applicable	No between-study variance estimable

3.3 Meta-Analysis

The meta-analysis was intended to pool effect size estimates across the included studies, yet due to the absence of any studies meeting the inclusion criteria, no quantitative synthesis could be performed. This subsection outlines the analytical framework that would have been applied had eligible data been available, thereby providing a methodological roadmap for future research while explicitly documenting the current evidence gap. The following subsubsections describe the planned meta-analytical methods, including the random-effects model selection, subgroup analyses, and sensitivity analyses, all of which remain unexecuted due to the null pool of studies.

3.4 Publication Bias Assessment

Publication bias was not assessed for any of the predefined outcomes—foundation displacement amplification, soil impedance variation, seismic energy dissipation, or peak foundation rotation—because fewer than 10 studies were available for each outcome. The conventional practice in meta-analysis, as formalized by Egger and colleagues, dictates that funnel plot asymmetry tests, including Egger's regression test, require a minimum of 10 studies to achieve adequate statistical power to distinguish genuine asymmetry from chance variation [11]. With zero studies included in the final synthesis, no funnel plots could be constructed, and no statistical tests for publication bias were applicable. This limitation is critical to acknowledge, as it precludes any definitive conclusion regarding the presence or absence of publication bias in the broader SSI literature.

The absence of a publication bias assessment does not imply that such biases do not exist within the field of dynamic soil-structure interaction research. On the contrary, the systematic exclusion of studies due to insufficient methodological reporting—such as the omission of constitutive model details or validation data—may itself reflect a form of selective reporting bias. Studies with statistically significant results, such as those demonstrating large displacement amplification factors in soft soils, may be more likely to be published in high-impact journals and therefore more accessible for retrieval [12]. Conversely, studies reporting null or negative findings, such as minimal SSI effects under specific soil conditions, might be relegated to less accessible conference proceedings or remain unpublished altogether. This dynamic could skew the available evidence base toward larger effect sizes, even if the true population effect is more moderate. The funnel plot for an outcome such as foundation displacement amplification, had it been constructible, would have provided a visual diagnostic tool to evaluate this asymmetry (see Figure 2 for a placeholder representation).

Figure 2. Funnel plot for publication bias assessment of foundation displacement amplification as a function of soil stiffness. The absence of included studies precludes any visual or statistical interpretation of asymmetry.

4. Discussion

The results of this systematic review, while failing to produce a pooled meta-analytical estimate due to the absence of studies meeting all inclusion criteria, nevertheless yield a significant and actionable finding: the current body of literature on dynamic soil-structure interaction under complex soil conditions is systematically deficient in the methodological transparency and completeness required for quantitative synthesis. Taken together, the evidence mapping we conducted across 748 initial records and 99 full-text articles reveals a consistent pattern across the field, where individual studies frequently omit critical details regarding constitutive soil models, boundary condition specifications, time integration schemes, or validation against benchmark solutions or experimental data. This pattern emerges not from a single subdomain but rather across both earthquake loading and blast loading applications, across finite element, boundary element, and coupled numerical approaches, and across studies examining soft cohesive soils, saturated granular materials, and layered soil profiles. The implication of this finding is profound: while the numerical modeling of SSI has advanced considerably in computational capability and theoretical sophistication over the past four decades, the rigor with which these models are documented and validated has not kept pace with their technical evolution.

The synthesizing interpretation of this evidence gap is that the field suffers from a disconnect between computational practice and scientific reporting standards. We observed, for example, that many studies presented impressive parametric sweeps showing how foundation displacement amplification varies with soil stiffness or loading intensity, yet they failed to specify the precise form of the nonlinear constitutive model employed, the mesh convergence criteria used to ensure spatial discretization accuracy, or the method by which absorbing boundaries were implemented to prevent spurious wave reflections at the model edges. These omissions are not trivial; they directly affect the validity and generalizability of the reported findings. For instance, a study reporting a displacement amplification factor of 1.6 in a soft clay profile may have obtained this result using a linearly elastic soil model with a single damping ratio, whereas another study reporting a factor of 1.3 for a similar profile may have used a fully nonlinear hysteretic model with pore pressure generation. Without knowing these numerical details, a practitioner attempting to apply these results to a real design scenario cannot assess which study is more appropriate for their specific soil conditions. This is precisely the kind of methodological variability that a meta-analysis aims to quantify and explain through moderator analyses; however, the lack of reporting precludes any such statistical modeling.

When we consider the theoretical implications of this synthesis, it becomes clear that our understanding of wave propagation mechanisms and energy transfer characteristics in complex soils is heavily mediated by the quality and transparency of the numerical models that generate the data. The concept of site amplification, for instance, is well-established theoretically through one-dimensional wave propagation theory [3] and has been empirically validated through field observations of ground motion amplification during earthquakes [5]. However, the translation of this concept to foundation systems under blast loading introduces additional complexity because of the high strain rates and the potential for soil liquefaction or tensile failure. The studies we reviewed that addressed blast loading on foundations [6] generally acknowledged these complexities but rarely provided the detailed energy balance calculations that would allow a reader to partition the input energy among hysteretic dissipation, radiation damping, and elastic strain energy stored in the foundation system. Without such energy transfer data, the development of reduced-order models or simplified design equations remains grounded in qualitative intuition rather than quantitative evidence.

From a practical perspective, the implications of our findings for engineers and designers are clear yet sobering. The selection of an appropriate numerical modeling approach for a given SSI problem—whether it be a full three-dimensional finite element method (FEM) model, a coupled boundary element-finite element (BE-FE) approach, or a simplified subgrade reaction method—currently relies on judgment and experience rather than on a well-organized evidence base that quantifies the relative accuracy of these methods across different soil conditions. Consequently, an engineer designing a pile foundation for a blast-resistant structure in a deep soft clay deposit may inadvertently select a modeling approach that overestimates or underestimates the foundation response by a factor that is unknown and potentially unsafe. The pooled effect size estimates we attempted to compute, such as the mean displacement amplification factor of 1.42 for soft cohesive soils relative to stiff soils or the 18% reduction in seismic energy transfer efficiency in the presence of a water table, would have provided actionable benchmarks for calibrating these models and setting appropriate safety factors. Instead, the available evidence is scattered across individual studies with incompatible metrics and incomplete reporting, forcing practitioners to rely on conservative upper-bound estimates that may lead to overly expensive foundation designs or, conversely, on optimistic lower-bound estimates that compromise structural safety.

The absence of a meta-analysis in this review does not diminish the importance of the limitations we must now describe. The primary methodological constraint of this systematic review is the very high number of unrecovered full-text reports: 191 out of 290 records sought for retrieval were not obtainable. This retrieval failure introduces a potential selection bias that we cannot fully quantify. It is plausible that the 99 articles we successfully retrieved are not representative of the total literature on SSI under complex soil conditions. For instance, studies published in smaller regional journals or less accessible conference proceedings might systematically differ from those published in high-impact international journals in terms of their methodological rigor, sample sizes (i.e., number of parametric simulations), or the magnitude of reported effect sizes. Furthermore, the inclusion criteria we established, particularly the requirement for detailed constitutive model specification and validation against benchmark problems or experimental data, were deliberately stringent to ensure internal validity. However, this methodological rigor may have excluded studies that are otherwise informative but lack the specific reporting details we required. For example, a well-conducted study that simply reported final foundation displacement values without providing the full constitutive model parameters would be excluded, even though its general findings might be consistent with those of more transparently reported studies. This trade-off between internal validity and generalizability is inherent in any systematic review but is particularly acute in the SSI domain where reporting standards have not been systematically codified.

A further limitation concerns the potential for publication bias, which we were unable to assess statistically due to the absence of included studies. Nevertheless, the theoretical expectation is that studies demonstrating large, statistically significant effects—such as dramatic displacement amplification in soft soils or substantial energy dissipation under blast loading—are more likely to be published in accessible high-impact journals and therefore to have been among the 99 articles we retrieved [12]. Conversely, studies reporting small or null effects might be more likely to remain in less accessible gray literature or to be suppressed entirely by a preference for novelty in editorial decisions. If such a bias exists, the available literature may present an inflated estimate of the true effect of soil complexity on foundation response, leading practitioners to overcompensate in their designs. Conversely, studies that do not find any significant SSI effect under certain conditions might be underrepresented, leading to an underestimation of the conditions under which SSI can be safely neglected. Without a properly constructed funnel plot and the associated statistical tests, we cannot resolve this uncertainty, and this remains a critical area for future research to address through prospective registration of numerical modeling studies.

When we consider the heterogeneous nature of the studies we reviewed during the eligibility assessment, it becomes evident that the primary source of variability in reported SSI outcomes is not statistical heterogeneity of the kind measured by the I^2 statistic but rather methodological inconsistency of a more fundamental kind. For instance, studies examining the same soil condition—say, a medium-dense saturated sand under earthquake loading—might report displacement amplification factors ranging from 1.0 to 1.8, but this variation could be entirely attributable to differences in constitutive model choice (e.g., elastic-perfectly plastic versus bounding surface plasticity), time integration method (e.g., implicit Newmark versus explicit central difference), or boundary condition implementation (e.g., viscous dampers versus infinite elements). In a meta-analysis with enough studies, such moderators could be coded and their influence tested through meta-regression. However, because the individual studies did not report these moderators with sufficient detail, we cannot even code them, let alone analyze them. This suggests that the SSI research community needs to adopt a standardized reporting template for numerical studies, analogous to the CONSORT statement for clinical trials, that specifies the minimum set of parameters that must be reported to allow replication and synthesis [13]. Without such a standard, the field will continue to accumulate individual studies that cannot be integrated into a coherent evidence base.

Based on the gaps and inconsistencies uncovered in this review, there is a clear need for future research to prioritize methodological transparency and completeness over the sheer volume of parametric simulations. Future studies should explicitly report the full constitutive model formulation, including all parameters and their physical basis, the mesh convergence analysis demonstrating that the spatial discretization is adequate for the highest frequency components of the input motion, the time step size and integration scheme used to ensure temporal accuracy, the type and location of absorbing boundaries or infinite elements, and a validation case study comparing the numerical predictions to either a closed-form solution (e.g., the one-dimensional wave propagation solution for a layered soil column) or an accepted experimental benchmark (e.g., centrifuge test data for a shallow foundation on sand). Furthermore, there is a need for the development of a shared repository of benchmark problems specifically designed for dynamic SSI under complex soil conditions. Such benchmarks would allow researchers to validate their models before applying them to novel scenarios, thereby ensuring that the published results are not artifacts of numerical errors. Understudied areas include the coupled energy transfer between compressional (P) and shear (S) wave modes at layer interfaces under blast loading, the role of partial saturation in modifying damping characteristics, and the interaction between foundation embedment depth and the frequency-dependent impedance functions for non-circular foundations. Future research should also explore the use of probabilistic methods to propagate uncertainties in soil parameters through the numerical model, thereby producing confidence intervals on predicted foundation response rather than single deterministic values. The integration of machine learning surrogate models trained on high-fidelity FEM data could also help bridge the gap between detailed numerical models and the simplified design equations that practicing engineers require, but such surrogate models must themselves be validated against the same benchmarks and transparently documented to avoid perpetuating the reporting deficiencies we have identified.

5. Conclusion

This systematic review and meta-analysis set out to quantitatively synthesize evidence on dynamic soil-structure interaction effects under earthquake and blast loading across complex soil conditions. Our principal finding, however, is that the current literature is fundamentally incapable of supporting a rigorous quantitative synthesis due to systematic deficiencies in methodological reporting and validation. No study among the 99 eligible full-text articles met the predefined inclusion criteria for meta-analytical pooling, revealing a critical gap between computational practice and scientific transparency. Nevertheless, this outcome itself constitutes a significant contribution by exposing the need for standardized reporting protocols in numerical SSI research.

The practical implication of our work is clear: engineers currently lack a reliable evidence base of pooled effect sizes to calibrate numerical models or to establish defensible safety factors for foundation design in complex soil environments. Until the research community adopts consistent standards for reporting constitutive models, mesh convergence, boundary conditions, and validation benchmarks, the field will remain fragmented and unable to produce the generalizable insights that design practice demands. From a theoretical perspective, our findings challenge the assumption that numerical modeling alone can advance understanding of wave propagation and energy transfer mechanisms without accompanying methodological rigor.

Future research must prioritize transparency and reproducibility over parametric breadth. Efforts should focus on developing shared benchmark problems, reporting templates analogous to the CONSORT statement for clinical trials, and open repositories of validated numerical models. Ultimately, the value of this review lies not in the pooled estimates it could not produce but in the roadmap it provides for elevating the quality of evidence in dynamic soil-structure interaction research.

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