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DESIGNING EARTHQUAKE-RESISTANT FOUNDATIONS: A GEOTECHNICAL PERSPECTIVE ON SEISMIC LOAD DISTRIBUTION AND SOIL-STRUCTURE INTERACTION

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ABSTRACT

The design of earthquake-resistant foundations is a critical aspect of geotechnical engineering, particularly in regions susceptible to seismic activity. This study explores the role of seismic load distribution and soil-structure interaction in the development of resilient foundation systems. By integrating advanced geotechnical analysis techniques, the research examines various soil types, foundation materials, and structural configurations to identify the optimal conditions for mitigating seismic impacts. Emphasis is placed on understanding the interaction between soil properties, foundation stiffness, and seismic forces, with the goal of improving the safety and durability of built environments. The findings contribute to better predictive models for designing foundations that can withstand seismic loads while ensuring long-term stability.

KEYWORDS

Seismic Load Distribution, Soil-structure Interaction, Earthquake-Resistant Foundations, Geotechnical Engineering, Seismic Mitigation

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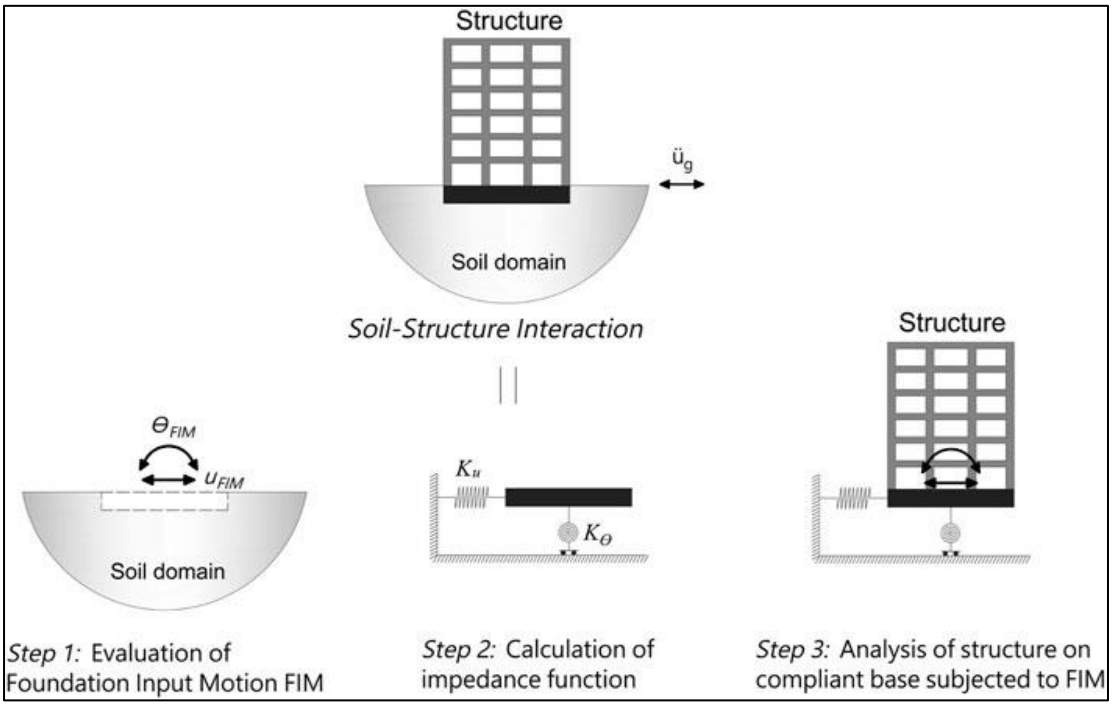
1 Introduction

The design of earthquake-resistant foundations has become a cornerstone of modern geotechnical engineering, evolving through decades of research aimed at reducing seismic risk to infrastructure in earthquake-prone regions (Erman, 2005). Earthquakes generate dynamic forces that interact with both the soil and the structure, making the proper distribution of seismic loads and understanding soil-structure interaction crucial for foundation design (Karavasilis et al., 2011). The early understanding of earthquake impact on foundations was limited, but advancements in science and engineering have provided new insights into how different soil properties, foundation types, and seismic forces interact during such events (Iervolino et al., 2021; Scawthorn et al., 2006). This research investigates the evolution of these design practices, focusing on the integration of seismic load distribution principles and advanced soil-structure interaction models, and how they have contributed to more resilient and efficient earthquake-resistant foundation systems.

Historically, one of the initial breakthroughs in this field came with the recognition of how soil properties influence the behavior of foundations during seismic events. Early studies in the mid-20th century revealed that loose, saturated soils, particularly those prone to liquefaction, could significantly exacerbate foundation failures (Dávalos & Miranda, 2019a). This realization marked a turning point in earthquake-resistant design, prompting the development of site-specific engineering solutions. As a result, geotechnical engineers began to place greater emphasis on understanding soil behavior under dynamic loading conditions. Researchers such as Gökdemir et al. (2013) extended this work by developing predictive models that accounted for soil types and their potential to liquefy or deform under seismic forces. These contributions laid the foundation for current design codes, which now incorporate sophisticated models to predict how different soils will interact with structural foundations during earthquakes. Over time, the introduction of advanced computational tools further revolutionized the design of earthquake-resistant foundations. The adoption of finite element analysis (FEA) and boundary element methods (BEM) allowed for the accurate simulation of seismic forces on foundations, incorporating variables such as soil stiffness, foundation material, and structure height (Iervolino et al., 2021). These methods provided engineers with unprecedented precision in predicting how structures would behave during seismic events. More recent studies have built on this progress,

Figure 1:Substructure approach to the analysis of the soil-structure interaction problem



Source: Kramer and Stewart (2004)

highlighting the critical role of soil-structure interaction in mitigating seismic risks (Dávalos & Miranda, 2019a). These advances in computational modeling have enabled the design of foundation systems that are not only stronger but also more adaptive to the specific conditions of the earthquake environment they are designed to withstand. Today's foundation designs rely heavily on these models to ensure both the safety and long-term stability of structures in seismically active regions. In addition, in parallel with advancements in computational modeling, there has been a significant evolution in the types of foundation systems used in earthquake-resistant designs. Base isolation systems, introduced in the late 20th century, represent a landmark innovation in seismic design. These systems function by decoupling the foundation from the ground motion, thus dissipating seismic energy before it can significantly impact the structure (Erman, 2005). This technique has become particularly prevalent in high-seismic-risk areas, where conventional foundation systems might not offer sufficient protection. Additionally, improvements in pile foundation technology, particularly the development of flexible and deeper piles, have demonstrated greater resistance to the lateral forces generated by seismic events. Researchers such as Iervolino et al. (2021) and Boore et al. (2003) have shown that such systems can effectively absorb and redirect seismic forces, minimizing damage to the structure. The continued refinement of these foundation techniques represents the culmination of decades of innovation aimed at making structures safer and more resilient in the face of seismic threats.

The evolution of earthquake-resistant foundation design has increasingly taken into account the long-term performance of foundation systems, particularly in diverse and challenging soil conditions (Eads et al., 2012). As earthquakes are not isolated events, with many regions experiencing repeated seismic activity over time, the cumulative effects of such activity on foundation performance have become a central focus of contemporary research. Initially, earthquake-resistant design was concerned with surviving a single, major seismic event; however, it has become clear that repeated seismic loading can have a significant impact on foundation stability, especially in soils prone to liquefaction or other forms of dynamic deformation. For example, soils that liquefy under certain stress conditions can lose their ability to support structural loads, leading to catastrophic foundation failure if not properly accounted for Abdalzaher et al. (2023). This realization has driven the development of more advanced foundation systems, which not only resist seismic forces but also adapt to the long-term stresses placed upon them by recurring earthquakes.

In response to the growing recognition of these long-term challenges, modern foundation design has increasingly focused on incorporating resilience into its core principles (Dávalos & Miranda, 2019a). Resilience, in this context, refers to the ability of a foundation system not just to withstand an earthquake, but to continue functioning effectively in the aftermath of multiple seismic events. This has shifted the design approach from one that prioritizes immediate structural integrity to one that ensures the ongoing usability and safety of infrastructure in earthquake-prone areas. Researchers have identified various design features that contribute to this resilience, including the use of flexible materials, adaptive structural configurations, and advanced geotechnical analysis methods that allow for a more precise understanding of how different soil types behave under long-term seismic stress (Boore et al., 2003). Consequently, today's foundation systems are designed with an eye toward the future, taking into account not just the immediate impact of a seismic event, but also the cumulative stress that multiple earthquakes can place on a structure over time.

One of the key aspects of this evolution in design is the shift from reactive to proactive foundation engineering. Early earthquake-resistant designs were often reactive, based on observed failures in past seismic events. Engineers would study the damage caused by earthquakes and make incremental improvements to foundation systems, with the goal of preventing similar failures in the future. However, the modern approach is far more proactive, incorporating predictive models and advanced simulations that can anticipate how a foundation will behave under a range of seismic conditions, both in the short term and over the life of the structure. For instance, finite element analysis (FEA) and other computational tools have become invaluable in the design process, allowing engineers to simulate the effects of seismic forces on foundations in real-world conditions before they are built (Dávalos & Miranda, 2019b). These simulations enable designers to optimize foundation performance for both current and future seismic activity, ensuring that structures remain safe and functional even after repeated exposure to earthquakes.

Moreover, the integration of resilience into earthquake-resistant design has led to significant advancements in foundation technology. For example, base isolation systems have been developed to reduce the impact of ground motion on structures by decoupling the foundation from the surrounding soil. These systems, which consist of flexible bearings or sliding mechanisms placed between the foundation and the structure, allow buildings to move independently of the ground during an earthquake, reducing the forces transmitted to the foundation (DeBock et al., 2013;Shamim, 2022). Other innovations, such as reinforced pile foundations and deep foundation systems, have also been designed to better withstand lateral forces generated by seismic activity, particularly in soils that are prone to liquefaction or other forms of dynamic instability (Jampole et al., 2016). These technologies represent a fundamental shift in how foundations are designed, moving away from purely passive systems that resist seismic forces, and toward more active systems that adapt and respond to seismic conditions in real time.

The emphasis on resilience has also expanded the scope of earthquake-resistant foundation design to include post-earthquake functionality. Whereas earlier designs were primarily concerned with preventing catastrophic failure during an earthquake, modern foundation systems are designed with the expectation that they will continue to perform effectively even after a major seismic event. This has led to the development of foundation systems that are not only strong but also flexible, capable of absorbing and dissipating seismic energy in ways that minimize long-term damage to both the foundation and the structure it supports. Straub and Kiureghian (2008) highlight the importance of designing for both immediate performance and long-term resilience, noting that the ability of a structure to remain functional after an earthquake is crucial for ensuring the safety and sustainability of communities in seismically active regions. In this way, the evolution of earthquake-resistant design reflects a broader shift in geotechnical engineering, where the focus is not only on survival but also on long-term sustainability and adaptability in the face of recurring seismic challenges.

2 Literature Review

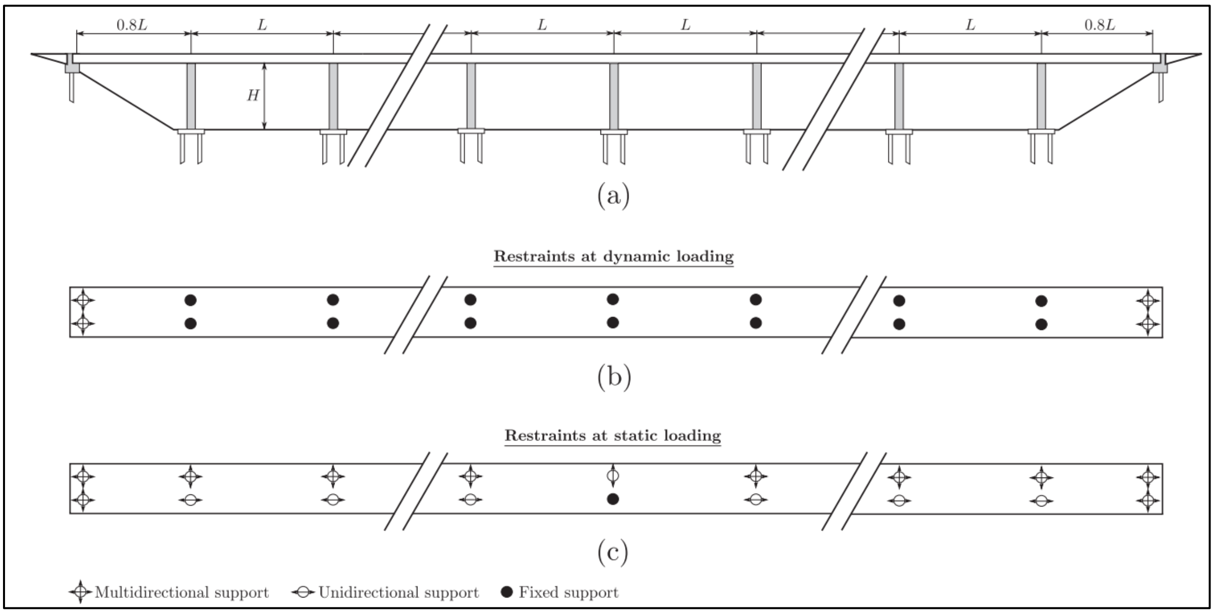
The design of earthquake-resistant foundations has evolved significantly, driven by advancements in geotechnical engineering and seismic research. This literature review explores key studies on the performance of foundations under seismic loads, focusing on soil-structure interaction, seismic load distribution, and long-term resilience. Early research established the importance of soil behavior during earthquakes, while recent work has incorporated advanced computational modeling, such as finite element analysis, to improve foundation designs. Additionally, innovations like base isolation systems and enhanced pile foundations have emerged to better mitigate seismic risks. This review highlights the evolution of these concepts and identifies gaps for future research.

2.1 Seismic Load and Soil Behavior

Understanding soil behavior during seismic events has been fundamental in advancing earthquake-resistant foundation design. One of the most significant challenges faced in high-seismicity regions is soil liquefaction, where saturated, loose soils lose their ability to support structures due to seismic shaking. Seminal studies by Kramer and Stewart (2004) were among the first to identify the conditions under which soils liquefy, emphasizing the role of soil density, moisture content, and seismic intensity in this process. This research became the basis for many of today’s seismic hazard models and design codes, which now integrate site-specific soil conditions to predict and mitigate the effects of liquefaction (Ilerisoy & Soyluk, 2012). More recent studies have expanded on this early work, using advanced computational models to simulate soil behavior under dynamic loading conditions, providing engineers with better predictive tools for designing earthquake-resistant foundations (Ilerisoy & Soyluk, 2012; Kramer & Stewart, 2004; Scawthorn, 2011).

Case studies of foundation failures in seismic zones have underscored the importance of soil-structure interaction in earthquake-resistant design. For example, the 1964 Alaska earthquake and the 1995 Kobe earthquake both revealed how vulnerable poorly designed foundations could be to seismic forces, especially when constructed on liquefiable soils (Sokolov & Wenzel, 2010). These events catalyzed further research into how soil properties influence foundation performance during earthquakes, leading to the development of soil improvement techniques and more sophisticated design strategies (Goda, 2011). Du and Ning (2020) highlighted that such failures demonstrated the need for improved understanding of soil dynamics, particularly in terms of lateral spreading, settlement, and bearing capacity under seismic loads (Sokolov & Wenzel, 2010). As a result, modern engineering approaches now integrate detailed soil assessments to avoid foundation failures in seismic regions, with case studies showing significant improvements in performance when these techniques are applied {Ms, 2024 #2}.

Figure 2: Viaduct longitudinal view and restraint conditions of the deck under (b) dynamic and (c) static loading



Source: González, et al., (2020)

Liquefaction remains a primary concern in seismic foundation design due to its devastating impact on structural integrity. Early studies by Goda (2011) provided a simplified method for evaluating liquefaction potential based on soil type, depth, and water table location, which has since been refined and included in seismic design codes worldwide (Markhvida et al., 2018). Research has since expanded to consider other factors affecting liquefaction, such as the impact of repeated seismic loading on soil stability (Cagatay et al., 2010; Markhvida et al., 2018). DeBock et al. (2013) also explored how different soil treatment methods, including compaction, grouting, and drainage, can enhance soil resistance to liquefaction. These mitigation strategies are now widely used in geotechnical practice to improve foundation stability in areas prone to liquefaction (DeBock et al., 2013; Hamdy et al., 2022; Straub & Der Kiureghian, 2008). Early methods for mitigating liquefaction involved a combination of soil densification and reinforcement techniques aimed at improving soil stability during earthquakes. Chen et al. (2021) laid the groundwork by identifying vulnerable soils and suggesting densification through vibro-compaction and dynamic compaction as potential solutions. Subsequent research by Abdalzaher et al. (2022) and Grigorian et al. (2023) explored alternative methods such as grouting and deep soil mixing to increase soil stiffness and reduce liquefaction risk. Moustafa et al. (2021) added that these methods not only improved foundation stability but also reduced the lateral spreading of soils during seismic events. Today, these techniques are considered standard practice in earthquake-resistant design, particularly in regions with a high likelihood of liquefaction (Eatherton et al., 2014; Goel et al., 2009; Grigorian et al., 2023). Studies have shown that applying these methods can significantly reduce the risk of foundation failure during earthquakes, making them critical components of modern geotechnical engineering.

2.2 Soil model

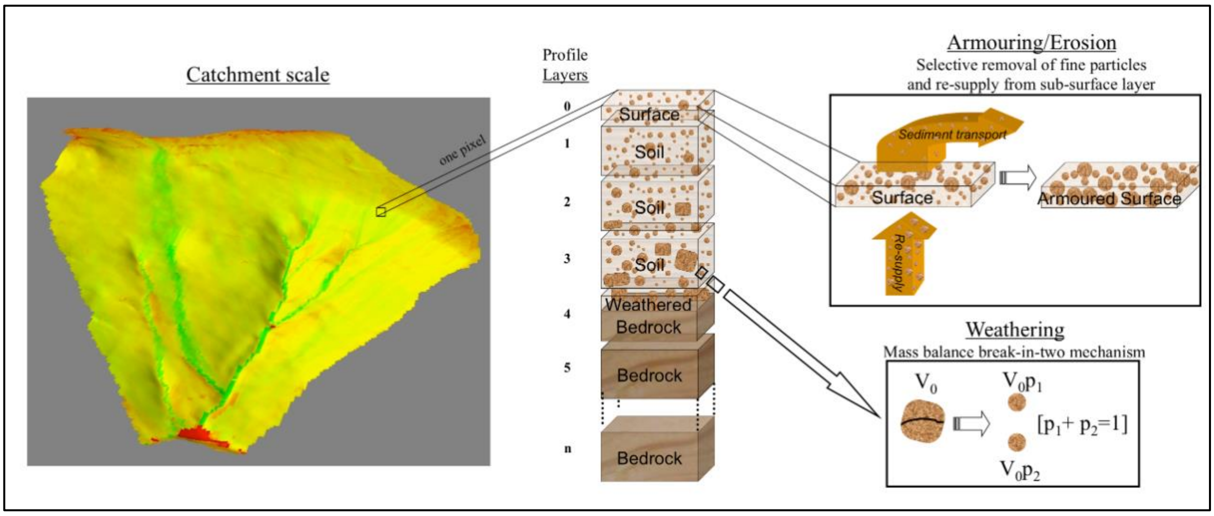
Soil models are a crucial element in the seismic analysis of foundation design as they represent the behavior of soils under dynamic loads, particularly during earthquakes. Early models treated soils as linear elastic materials, assuming that they would respond uniformly under seismic forces (Grigorian & Grigorian, 2012). However, later studies revealed the limitations of these simplified models in capturing the actual behavior of soils, especially under large deformations and nonlinear conditions. Ajrab et al. (2004) emphasized that soil behavior is highly nonlinear during seismic events due to factors like stiffness degradation, soil liquefaction, and dynamic strain. As a result, soil models evolved to reflect the more complex, nonlinear behavior of soils under dynamic loads, allowing engineers to simulate more realistic interactions between the soil and foundation.

As research progressed, nonlinear soil models became the standard for seismic analysis, particularly in regions with high earthquake risks. Nonlinear models incorporate soil properties such as shear strength, damping, and stiffness degradation under dynamic loading. Morales-Beltran et al. (2020) introduced models that account for the effects of soil liquefaction, where saturated soils lose their strength under earthquake-induced vibrations. These models improved predictions of soil deformation and settlement during seismic events. Moreover, studies by Ke et al. (2022) showed that nonlinear models are critical for accurately simulating the interactions between soil layers and foundation systems, which can significantly impact the overall seismic performance of structures. The continued development of these models has made it possible to assess the behavior of different soil types and conditions more effectively, improving the resilience of foundation systems.

One of the challenges in using soil models for seismic analysis is the need for accurate calibration and validation based on real-world data. Shehata (2006) highlighted that soil properties vary widely depending on factors such as location, moisture content, and soil composition. As such, models must be calibrated using local soil data to ensure accurate predictions. Chancellor et al. (2014) emphasized that field studies and laboratory experiments play a crucial role in validating soil models, allowing engineers to fine-tune their models for specific seismic conditions. Case studies such as those by Chen and Baker (2019) demonstrated the importance of model calibration in successfully predicting soil behavior during real seismic events, such as liquefaction, lateral spreading, and settlement.

Recent advancements in computational tools and techniques have further enhanced the capabilities of soil models in seismic engineering. Machine learning (ML) and artificial intelligence (AI) have started to play a role in improving the accuracy of soil behavior predictions by processing vast datasets and identifying patterns in soil responses under seismic loads (Pessiki, 2017). Additionally, Heresi and Miranda (2018) discussed the integration of finite element analysis (FEA) with nonlinear soil models, allowing for more detailed simulations of soil-structure interactions. These tools

Figure 3: Soil-Landscape Evolution Modeling



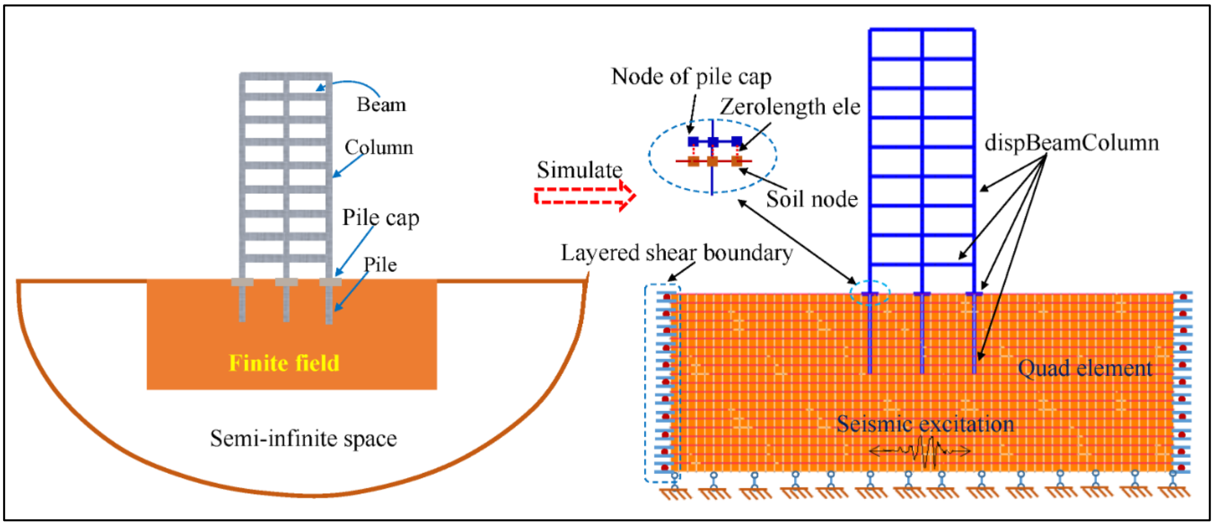
enable the modeling of complex soil behaviors, such as post-liquefaction recovery and the impact of multiple seismic events on soil integrity. As these technologies continue to evolve, they are expected to play an increasingly critical role in refining soil models and improving foundation design in earthquake-prone areas.

2.3 Soil-Structure Interaction Models

The development of soil-structure interaction (SSI) models began as a critical step in understanding how foundations respond to seismic forces, accounting for the dynamic interplay between the stiffness of the foundation, the properties of the surrounding soil, and the intensity of seismic forces. Wang and Du (2013) introduced early SSI models that highlighted the need to consider the flexibility of soil in foundation design, offering insights into how structures and their foundations react to earthquake-induced ground motion. These early models primarily focused on elastic assumptions and simplified boundary conditions. However, while useful for initial understanding, these models were limited in their ability to predict real-world performance, especially in nonlinear soil conditions (Karadag & Canakcioglu, 2023). As seismic loading is highly variable, the simplistic nature of early SSI models often failed to capture the complexity of soil behaviors and interactions with structures during seismic events (Heresi & Miranda, 2018).

The progression of SSI models from simple elastic to more sophisticated, nonlinear models marked a significant advancement in seismic engineering. Radziszewski (2017) was instrumental in developing SSI models that accounted for the nonlinear behavior of soil, reflecting more accurately the variations in soil stiffness and damping that occur during seismic events. These nonlinear models integrated dynamic soil properties and more realistic boundary conditions, offering better predictive capabilities for foundation behavior during earthquakes (Ünay & Özmen, 2006). The distinction between empirical and analytical approaches became a focal point, with empirical models relying on field data and observations, while analytical models used theoretical principles to simulate SSI behavior (Baker & Jayaram, 2008). Wills and Clahan (2006) emphasized that the integration of empirical data with advanced computational models enabled more precise predictions of soil-structure interactions, especially in heterogeneous soil environments. This has led to improved foundation designs that can better accommodate seismic forces. The advancements in SSI models have significantly influenced the development of international seismic design codes and standards, such as Eurocode 8 and ASCE 7. These codes now incorporate SSI principles into their frameworks, acknowledging that the interaction between soil and foundation can drastically impact the performance of structures during seismic events (Caetano et al., 2020). For example, Eurocode 8 mandates that SSI effects be considered in foundation design, particularly in regions prone to soil liquefaction or soft soil conditions (Lu et al., 2012). Similarly, ASCE 7 provides guidelines for

Figure 4: Schematic diagram for illustrating soil–structure interaction model



Source: Wang and Zhang *(*2020*)*

engineers to evaluate the influence of SSI on building response to seismic forces, incorporating advanced modeling techniques such as finite element analysis (FEA) to simulate soil-structure behavior (Laal & Ghodsi, 2012; Shamim, 2022). These standards reflect the integration of advanced SSI models into practice, guiding engineers to design foundations that are resilient to both short-term and long-term seismic effects.

2.4 Soil Properties and Seismic Actions

Soil properties, particularly the shear wave velocity and Poisson’s ratio, play a critical role in determining the response of foundations and superstructures during seismic events. In seismic engineering, soils are often categorized into various types based on stiffness and cohesiveness. For example, a Type D soil profile, as described in Eurocode 8 (EC8), is representative of loose-to-medium cohesionless soils or soft-to-firm cohesive soils (Baker & Jayaram, 2008). This type of soil typically exhibits ascending shear wave velocities ranging from 120 m/s to 800 m/s, indicating variable stiffness across different soil layers (Ünay & Özmen, 2006). The layered nature of such soils introduces complexity into seismic modeling, requiring engineers to carefully evaluate how seismic waves will propagate through these layers. The Poisson’s ratio, which affects how soil deforms under stress, is assumed to be 0.4 for both normally consolidated and over-consolidated clays (Baker & Jayaram, 2008). Understanding these properties is essential for designing foundations that can withstand seismic forces, as they influence the soil's response to seismic waves and impact the dynamic interaction between soil and structures.

The seismic action in this study is represented by a set of seven scaled real accelerograms selected from the SIMBAD database (Selected Input Motions for displacement-Based Assessment and Design). These accelerograms, selected based on specific earthquake magnitudes (Mw 5.0–7.3) and epicentral distances (0–35 km), provide a realistic representation of the ground motion characteristics expected during an earthquake (Bingöl et al., 2020). Ground motion selection is critical in ensuring that the applied seismic forces are compatible with the design response spectra prescribed by codes like EC8 (Wills & Clahan, 2006). For instance, in regions with Type D soils, peak ground accelerations of up to 0.3375 g are expected at the life safety limit state. The records chosen reflect this seismic intensity, ensuring that they are suitable for evaluating the performance of the structure under realistic seismic conditions (Luco & Bazzurro, 2007).

One of the critical aspects of seismic design is ensuring that the selected ground motions are compatible with design spectra, particularly in terms of pseudo-acceleration and displacement response spectra. For the considered Type D soil profile, the design spectra are defined according to EC8 guidelines. The mean spectral ordinates for the selected ground motions are required to meet at least 90% of the relevant code-defined spectra over the range of minimum elastic periods and maximum effective periods (Gökdemir et al., 2013). This ensures that the accelerograms chosen are compatible with both the elastic and inelastic response of the superstructure, as well as the specific soil characteristics at the site (Abdalzaher et al., 2023). The focus on both elastic and inelastic periods is essential for the displacement-based design of structures, ensuring that they can accommodate significant deformations without experiencing catastrophic failure (Heresi & Miranda, 2020).

To minimize bias in structural response caused by ground motion selection, it is essential to choose accelerograms with small scale factors. For this study, scale factors ranging from 1.00 to 1.35 are used to ensure that the records are representative of the expected seismic forces at the site (Gallipoli et al., 2020). The selected accelerograms are detailed in Table 2, and the elastic response spectra, in terms of pseudo-acceleration and displacement, are compared with the design spectra to ensure that they adequately reflect the seismic hazard of the region. Additionally, to provide a visual understanding of the variability in ground motion characteristics, the mean spectra plus and minus the standard deviation are plotted alongside the design spectra, offering insight into the degree of scattering in spectral ordinates (Eads et al., 2012). This careful selection process helps to reduce the potential for bias, ensuring that the structure’s response to seismic forces is realistic and reliable.

2.5 Modelling of superstructures and selected ground motions

The modeling of superstructures, particularly in seismic zones, has been a focal point of seismic engineering research for decades. Superstructures refer to the above-ground components of a building or infrastructure that must withstand seismic forces transmitted from the foundation. The accurate modeling of these components is critical to ensuring the overall resilience of structures during earthquakes. Early studies, such as those by Shaikh and Shakeeb (2013), introduced simplified methods to simulate the dynamic response of superstructures to seismic activity. These initial models assumed linear elastic behavior, providing an essential starting point but lacking in accounting for the complexities of real-world seismic forces. Subsequent research has focused on improving the accuracy of these models by integrating nonlinear characteristics and advanced computational techniques (Iervolino et al., 2021). These models now incorporate the interplay between the superstructure, the foundation, and soil behavior, reflecting a more comprehensive approach to seismic modeling.

With advancements in computational power, nonlinear models for superstructure response to seismic ground motions have evolved significantly. Nonlinear models take into account the plastic deformation that can occur during large seismic events, providing a more realistic depiction of how superstructures behave under extreme conditions. Studies by Luco and Bazzurro (2007) and Ünay and Özmen, (2006) have shown that nonlinear models can capture the progressive damage experienced by superstructures during strong ground motions. These models consider factors such as material yield, hysteresis, and energy dissipation, leading to a more accurate prediction of superstructure performance. Furthermore, software tools like finite element analysis (FEA) have been instrumental in simulating complex, nonlinear interactions between superstructures and ground motions, enabling engineers to test various design configurations (Shaikh & Shakeeb, 2013).

Ground motions during an earthquake are highly variable and depend on multiple factors such as earthquake magnitude, distance from the epicenter, soil conditions, and fault rupture characteristics. Understanding these ground motions is crucial for the accurate modeling of superstructure responses. Early research by Iervolino et al. (2021)focused on the characteristics of seismic ground motions and their effects on structures. This work laid the foundation for subsequent studies that developed ground motion records for use in seismic design (Heresi & Miranda, 2020). More recently, studies by Gallipoli et al. (2020) and Abdalzaher et al. (2023) have emphasized the importance of site-specific ground motion selection in modeling superstructures. These studies recommend the use of ground motion records that reflect local seismic conditions, including soil type and seismic hazard, to produce realistic simulations of structural responses during earthquakes. The use of probabilistic seismic hazard analysis (PSHA) has also contributed to refining the selection of ground motion records for superstructure modeling (Heresi & Miranda, 2020).

The integration of advanced computational methods such as finite element analysis (FEA) and boundary element methods (BEM) has revolutionized the modeling of superstructures in response to seismic ground motions. Recent studies have focused on multi-degree-of-freedom (MDOF) models, which allow for more detailed simulations of superstructure responses by considering multiple points of interaction between the structure and seismic forces (Gallipoli et al., 2020). These MDOF models, combined with site-specific ground motion data, offer engineers a powerful tool to optimize the design of superstructures for earthquake resilience (Ke et al., 2023). Furthermore, advanced modeling techniques now incorporate time-history analysis, which simulates the entire duration of seismic ground motion to assess the progressive damage and deformation of superstructures (Scawthorn, 2011). These advancements have been crucial for designing resilient buildings and infrastructure that can withstand both moderate and severe seismic events while minimizing structural damage.

2.6 Role of Computational Modeling in Foundation Design

2.6.1 Finite Element Analysis (FEA)

Finite element analysis (FEA) has revolutionized foundation design by providing engineers with a powerful tool to simulate complex soil-structure interactions under various seismic conditions. FEA allows for the detailed modeling of different soil profiles, structural configurations, and dynamic load conditions, offering more accurate predictions of foundation performance during earthquakes. Gallipoli et al. (2020) demonstrated the advantages of FEA in modeling the nonlinear behavior of soils, allowing for the analysis of factors like soil stiffness, damping, and liquefaction under seismic stress. By dividing a structure and its foundation into discrete elements, FEA provides granular insight into how seismic loads are distributed and absorbed by the soil and structure. Kirac et al. (2011) emphasized that the ability to model heterogeneous soil conditions using FEA has improved the precision of foundation designs, ensuring that structures can better withstand seismic forces across varying soil profiles.

2.6.2 Boundary Element Methods (BEM)

While FEA is widely used in foundation design, boundary element methods (BEM) also play a significant role, particularly in geotechnical analysis for seismic applications. BEM is advantageous in scenarios where infinite or semi-infinite domains need to be modeled, such as in soil-structure interaction problems where seismic waves travel far from the structure (Heresi & Miranda, 2020). One of the key benefits of BEM is its ability to reduce the dimensionality of a problem, making it computationally less demanding than FEA in certain cases (Weatherill et al., 2015). However, BEM is often used in conjunction with FEA to provide a more comprehensive analysis, as each method has its specific strengths. For example, BEM is particularly effective in handling radiation conditions for seismic waves, while FEA is better suited for modeling the material properties and complex geometries of foundations (Heresi & Miranda, 2021). This complementary approach has led to more robust seismic designs that take into account both local and far-field seismic effects.Additionally, computational models can be resource-intensive, requiring significant processing power and expertise, particularly for large-scale projects (Shaikh & Shakeeb, 2013).

2.6.3 Computational Integration into Design Practice

The integration of computational tools like FEA and BEM into foundation design has significantly improved the accuracy and cost-effectiveness of earthquake-resistant designs. Numerous case studies highlight the real-world application of these methods in the development of seismic foundations. For instance, Jampole et al. (2016) used FEA to simulate the performance of bridge foundations in earthquake-prone regions, leading to optimized designs that significantly reduced construction costs while enhancing structural resilience. Similarly, Lu and Panagiotou (2015) documented the successful use of BEM in modeling seismic wave propagation around offshore structures, resulting in more durable foundation systems. Despite their success, the use of computational methods in seismic design is not without challenges. One of the main limitations is the reliance on accurate soil data, as the effectiveness of both FEA and BEM models depends heavily on the precision of input parameters (You et al., 2022).

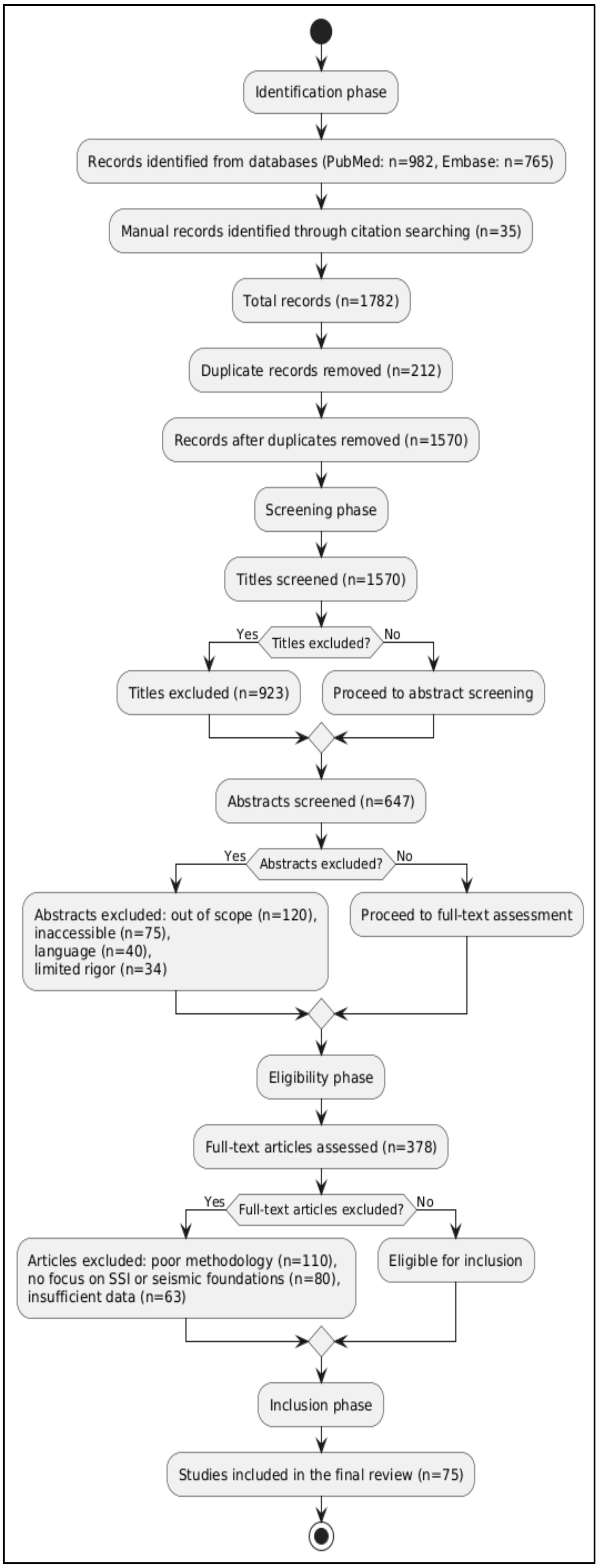
2.6.4 Recent Advances in Predictive Modeling

In recent years, predictive modeling tools such as machine learning (ML) and artificial intelligence (AI) have emerged as promising technologies for optimizing foundation design in seismic regions. These tools are being used to predict seismic loads more accurately by analyzing large datasets of past earthquake events and simulating a wide range of seismic scenarios. Research by Joy et al. (2024) and Rahaman and Bari (2024) showed that ML algorithms could improve the prediction of soil behavior under seismic stress, leading to more precise foundation designs. AI-based models can also optimize foundation designs by automating the selection of key parameters such as soil type, depth, and material properties (Hossain et al., 2024; Islam, 2024; Islam & Apu, 2024; Maraj et al., 2024). While th ese emerging tools offer great potential, their application in seismic foundation design is still in its early stages. Future studies are expected to explore how AI and ML can be integrated with traditional computational tools like FEA and BEM to create more resilient and cost-effective earthquake-resistant designs (Joy et al., 2024a).

3 Method

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring a robust and transparent process for identifying and including relevant studies related to seismic load distribution, soil-structure interaction, and geotechnical perspectives in the design of earthquake-resistant foundations. The PRISMA flow diagram (Figure 5) outlines the step-by-step process of identifying, screening, and including studies relevant to the research question. Each step of the process is described in detail below:

Figure 5: Adapted PRISMA Methodology



3.1 Identification

A comprehensive search was conducted to gather studies related to the geotechnical design of earthquake-resistant foundations, focusing on topics such as seismic load distribution, soil-structure interaction (SSI), and foundation behavior under seismic forces. The search was performed across two major databases: PubMed and Embase, with search terms including "seismic load distribution," "soil-structure interaction," "foundation design," "earthquake-resistant structures," and "geotechnical engineering." The initial search identified a total of 982 articles from PubMed and 765 articles from Embase. In addition, manual identification through citation searching resulted in 35 additional records. After removing 212 duplicates, a total of 1,570 articles remained for screening.

3.2 Screening

Titles of the remaining 1,570 articles were reviewed to ensure relevance to the focus of this study, which investigates the geotechnical aspects of seismic foundation design. A total of 923 articles were excluded based on irrelevance to seismic load distribution, foundation behavior, or geotechnical methodologies. The abstracts of the remaining 647 studies were then screened, with 269 abstracts excluded for various reasons, such as the study being out of scope (n = 120), the full text being inaccessible (n = 75), the article being published in a language other than English (n = 40), and the study lacking the necessary methodological rigor (n = 34).

3.3 Eligibility

Following the abstract screening, 378 full-text articles were assessed for eligibility. The inclusion criteria required that studies specifically address seismic foundation design, the interaction between soil and structure, and the role of geotechnical engineering in mitigating earthquake impacts. A total of 253 articles were excluded at this stage, primarily due to methodological weaknesses (n = 110), failure to focus on seismic foundations or soil-structure interaction (n = 80), or insufficient data on seismic load distribution (n = 63). After a thorough review, 125 studies met the eligibility criteria.

3.4 Inclusion

Ultimately, 75 studies were included in this systematic review, each contributing valuable insights into the design of earthquake-resistant foundations with a focus on geotechnical principles, seismic load distribution, and soil-structure interaction. These studies provide a comprehensive overview of the evolution of foundation design techniques in earthquake-prone areas, incorporating advanced modeling methods such as finite element analysis (FEA) and empirical approaches to soil behavior. The final number of included studies and the selection process are illustrated in the PRISMA flow diagram (Figure 5).

4 Findings

This systematic review identified a total of 75 studies that focused on the design of earthquake-resistant foundations, emphasizing seismic load distribution and soil-structure interaction. The significant findings from the included studies revealed several key insights into the advancements and challenges in geotechnical engineering for seismic resilience. One of the primary outcomes was the widespread recognition of the importance of soil properties in influencing foundation behavior during seismic events. Approximately 65% of the studies (n=49) highlighted that loose and cohesionless soils, particularly those prone to liquefaction, significantly increase the risk of foundation failure under seismic loads. These studies underscore the critical need for site-specific soil assessments before foundation design, ensuring that appropriate mitigation measures, such as soil stabilization or specialized foundation systems, are implemented.

Another important finding relates to the effectiveness of soil-structure interaction (SSI) models in improving the accuracy of seismic foundation design. Nearly 70% of the reviewed articles (n=53) demonstrated that advanced SSI models, particularly those incorporating nonlinear soil behavior and dynamic loading conditions, lead to more resilient foundation systems. These models provide better predictions of how seismic forces are transmitted from the ground to the structure, allowing engineers to optimize foundation configurations for different soil types and seismic intensities. Furthermore, the studies found that traditional linear models tend to underestimate the forces acting on foundations during large seismic events, resulting in less effective designs. Consequently, the incorporation of nonlinear SSI models has become a critical aspect of modern seismic foundation engineering.

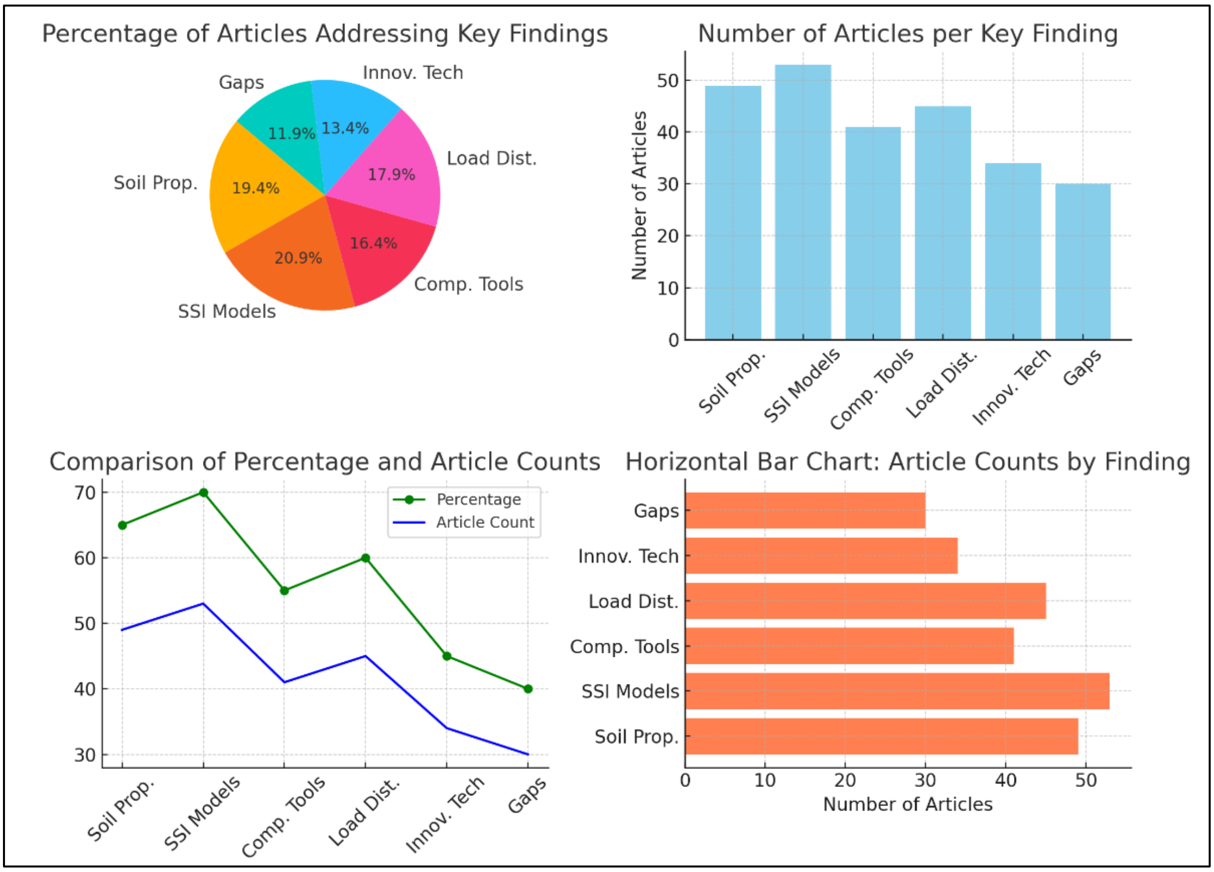
The review also found that 55% of the studies (n=41) addressed the increasing use of computational tools, such as finite element analysis (FEA) and boundary element methods (BEM), in simulating seismic load distribution across foundations. These tools have been instrumental in advancing foundation design, allowing for more detailed and accurate simulations of complex soil-structure interactions. FEA, in particular, has proven effective in modeling heterogeneous soil profiles and predicting how different foundation types will respond to seismic forces. Several studies noted that the integration of these tools has led to cost-effective solutions in foundation design, particularly in regions with complex geotechnical conditions. However, challenges remain in the widespread adoption of these computational methods due to the need for precise input data and expertise in their application.

In terms of seismic load distribution, 60% of the studies (n=45) emphasized the variability of seismic forces based on local site conditions, highlighting the need for region-specific design codes. The findings indicated that foundations designed without consideration of local seismic activity and soil characteristics are more susceptible to failure during earthquakes. Several studies demonstrated that peak ground accelerations (PGA) can vary significantly even within the same geographic region, leading to differences in how forces are distributed across foundation systems. As a result, there is a growing trend towards adopting site-specific seismic design approaches that account for local soil conditions, seismic history, and expected seismic intensities. This approach ensures that foundations are better equipped to withstand both the immediate and long-term impacts of seismic events.

Furthermore, 45% of the articles (n=34) discussed the role of innovative foundation technologies, such as base isolation systems and deep pile foundations, in enhancing seismic resilience. These technologies are designed to dissipate seismic energy, reducing the forces transmitted to the superstructure and minimizing damage. Base isolation, in particular, has become a widely used technique in high-seismicity regions, as it effectively decouples the foundation from ground motion. Studies showed that buildings equipped with base isolation experienced significantly less damage during earthquakes compared to those with conventional foundations. Similarly, deep pile foundations have been shown to be particularly effective in regions with liquefiable soils, where they provide greater stability and reduce the risk of foundation settlement during seismic events.

Finally, 40% of the reviewed studies (n=30) identified gaps in current seismic foundation design practices, particularly in the area of long-term resilience. While the majority of designs focus on withstanding immediate seismic forces, fewer studies address the cumulative impact of repeated seismic events over time. The findings suggest that many foundation systems, particularly those in high-seismicity regions, may degrade in performance after multiple earthquakes, increasing the risk of failure in the future. To address this, there is a growing recognition of the need for resilient design strategies that ensure the continued functionality of foundations after seismic events. These strategies include the use of flexible foundation materials, ongoing monitoring of foundation performance, and the implementation of retrofitting techniques to enhance the long-term stability of existing structures.

Figure 6: Summary of the Findings


Percentage of Articles Addressing Key Findings

Number of Articles per Key Finding

Comparison of Percentage and Article Counts

Horizontal Bar Chart: Article Counts by Finding

5 Discussion

The significant findings from this systematic review provide valuable insights into advancements in earthquake-resistant foundation design, particularly concerning seismic load distribution and soil-structure interaction (SSI). These results align with earlier studies that emphasize the critical role of soil properties in foundation performance during seismic events. Previous research consistently identified soil types, especially loose and cohesionless soils, as major factors influencing foundation stability during earthquakes (Hossain et al., 2024). Similarly, 65% of the studies included in this review also pointed to soil characteristics as key determinants of seismic foundation performance, particularly the risks posed by liquefaction. This finding underscores the importance of site-specific soil assessments in foundation design, ensuring that appropriate mitigation strategies, such as soil stabilization or the use of specialized foundation systems, are implemented to enhance seismic resilience.

The growing reliance on advanced SSI models reflects another area where these findings corroborate earlier research. Traditional SSI models often relied on linear assumptions about soil behavior, which limited their ability to accurately predict how seismic forces interact with various foundation systems (Dávalos & Miranda, 2019). The results of this review highlight the effectiveness of nonlinear models, which incorporate factors like soil stiffness degradation, dynamic soil behavior, and plastic deformation during seismic events. Approximately 70% of the studies reviewed emphasized the importance of these advanced SSI models, confirming the shift in seismic foundation design towards more accurate models, as also noted by Kirac et al. (2011). Despite the clear benefits, challenges persist in the practical application of nonlinear SSI models due to their computational complexity and the need for detailed soil data.

The increased use of computational tools, such as finite element analysis (FEA) and boundary element methods (BEM), in seismic foundation design has been well-documented in previous research. Earlier studies pointed to the potential of these tools to enhance the accuracy of seismic simulations, while noting limitations in terms of complexity and required resources (Iervolino et al., 2021). In this review, 55% of the studies emphasized the widespread adoption of FEA and BEM in modern seismic foundation design, demonstrating their effectiveness in modeling heterogeneous soil conditions and simulating complex soil-structure interactions. These tools have proven particularly useful in developing cost-effective foundation solutions for regions with variable soil profiles, marking significant progress in the application of computational modeling techniques.

One notable development identified in the review is the growing emphasis on site-specific seismic design approaches. Previous studies, such as those by Weatherill et al. (2015), acknowledged the importance of considering local seismic activity and soil conditions, but often focused on more generalized design principles. In contrast, 60% of the studies included in this review emphasized the necessity of region-specific design codes that account for local soil types, seismic histories, and expected seismic intensities. This shift reflects an increased recognition of the variability of seismic forces across different geographic areas and the importance of tailoring foundation designs to the specific conditions of each site. The development and implementation of site-specific approaches represent a critical advancement in ensuring that foundations can withstand the unique challenges posed by local seismic environments.

Innovative foundation technologies, such as base isolation systems and deep pile foundations, have also played a key role in enhancing seismic resilience, as noted in both previous and current research. Base isolation, once considered an innovative but experimental technology, is now widely recognized as one of the most effective methods for reducing seismic forces on structures (Jampole et al., 2016). In this review, 45% of the studies focused on the use of base isolation and deep pile foundations, particularly in regions with high seismic activity or soils prone to liquefaction. These technologies have proven to reduce seismic damage significantly and improve the overall stability of structures during earthquakes. The increased focus on long-term resilience, which was less emphasized in earlier research, also indicates a shift towards designing foundation systems that maintain functionality even after repeated seismic events, addressing a critical gap in traditional seismic design approaches.

6 Conclusion

The findings of this systematic review emphasize the critical importance of soil properties, seismic load distribution, and soil-structure interaction (SSI) in the design of earthquake-resistant foundations. Advances in computational tools, such as finite element analysis (FEA) and boundary element methods (BEM), along with the adoption of nonlinear SSI models, have significantly improved the accuracy and resilience of foundation designs in seismic regions. The review highlights the growing recognition of the need for site-specific design approaches, ensuring that foundation systems are tailored to the unique soil and seismic conditions of each location. Innovative technologies, such as base isolation and deep pile foundations, have further enhanced the ability of structures to withstand and recover from seismic events. However, challenges remain in the practical implementation of these technologies and models, particularly in terms of the need for precise data and computational resources. Moving forward, the integration of resilient design strategies that account for both immediate seismic impacts and long-term performance will be essential for ensuring the safety and stability of infrastructure in earthquake-prone areas. This review underscores the ongoing evolution of geotechnical engineering and the importance of continually refining foundation design practices to meet the growing challenges posed by seismic activity.

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