Tikrit Journal of Engineering Sciences (2025); 32(2): 1953
DOI: http://doi.org/10.25130/tjes.32.2.33

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Seismic Response of Piled Foundations: A State-of-the-Art Review

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Keywords:
Numerical modeling; Pile groups; Seismic response; Shaking table test; Soil-pile interaction.

Highlights:

- *Static pile foundation behavior is well-understood, but dynamic scenarios lack sufficient research.*
- *Report analyzes seismic responses of pile groups, summarizing key findings from multiple studies.*
- *Covers pile groups' seismic dynamics, factors influencing their behavior, and soil-structure interaction.*
- *Study insights help build foundations resistant to seismic dynamic challenges.*

ARTICLE INFO

Article history:

Received	30 Dec. 2023
Received in revised form	16 May 2024
Accepted	22 June 2024
Final Proofreading	04 Mar. 2025
Available online	31 May 2025

Citation: Al-Jeznawi D, Al-Janabi MAQ, Imran H, Bernardo LFA, Henedy SN. **Seismic Response of Piled Foundations: A State-of-the-Art Review**. *Tikrit Journal of Engineering Sciences* 2025; **32**(2): 1953.
http://doi.org/10.25130/tjes.32.2.33

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Abstract: The foundations of buildings and other structures must support static and seismic loads in areas where seismic activity is common. To avoid bearing capacity failures, increase the dynamic stiffness of the structural system, and minimize dynamic oscillations during earthquakes, a transition from shallow to deep foundations is required. Although much information is available regarding pile foundations' structural response to static loads, much less is known about how they behave under dynamic loads. The present paper summarizes key findings from numerous research projects to give an extensive overview of the reaction of piling groups subjected to seismic loads. The paper covers a wide range of pile group behavior topics, such as how they dynamically respond to seismic loadings, what influences their performance, and how soil-structure interaction affects them. This research offers significant insight into the seismic reaction patterns of pile groups, which can be used to improve the dynamic performance of foundation systems. This work underscores that understanding the behavior of pile groups' underground motion is pivotal for informing and refining the design of pile foundations. By optimizing designs for improved seismic resilience and overall performance, engineers and researchers can further enhance the safety and stability of structures in seismically susceptible places.

السلوك الزلزالي لأسس الركائز: مراجعة

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الخلاصة

يجب أن تدعم أسس المباني والهياكل الأخرى كل من الأحمال الثابتة والزلزالية في المناطق التي يعتبر النشاط الزلزالي فيها شائعًا. لتجنب فشل قدرة التحمل، وزيادة صلابة النظام الإنشائي، وتقليل التذبذبات الديناميكية أثناء الزلازل، يتطلب التحول من الأساسات الضحلة إلى العميقة. على الرغم من توفر الكثير من المعلومات بشأن استجابة أساسات الركائز للأحمال الثابتة، إلا أن القليل جدًا معروف عن كيفية سلوكها تحت الأحمال الديناميكية. تلخص هذه الورقة البحثية النتائج الرئيسية للعديد من الابحاث لتقديم نظرة شاملة عن استجابة مجموعات الركائز للأحمال الزلزالية. تغطي الدراسة مجموعة واسعة من مواضيع سلوك مجموعات الركائز، مثل كيفية استجابتها بشكل ديناميكي للأحمال الزلزالية، وما يؤثر في أدائها، وكيفية تأثير تفاعل التربة - الهيكل عليها. يقدم هذا البحث رؤية هامة حول أنماط الاستجابة الزلزالية لمجموعات الركائز، والتي يمكن استخدامها لتحسين الأداء الديناميكي لأنظمة الأساسات. تؤكد هذه الدراسة على أن فهم سلوك مجموعات الركائز تحت حركة التربة أمر بالغ الأهمية لإغناء وتحديث تصميم اسس الركائز. من خلال تحسين التصميم لتعزيز المرونة الزلزالية والأداء العام، يمكن للمهندسين والباحثين تعزيز الأمان والاستقرار للهياكل في الأماكن المعرضة للزلازل.

الكلمات الدالة: السلوك الزلزالي، مجموعة ركائز، اختبار طاولة الهز، نمذجة عددية، تفاعل التربة -الركيزة.

1.INTRODUCTION

A pile foundation is a structural component embedded in the ground and utilized to transfer loads from the superstructure to the soil below. Pile systems are frequently used to control and reduce settlement and fluctuations in settlement, besides their function of shifting the weight of structures to the supporting strata below [1]. The difficulties in attaining exact vertical alignment and guaranteeing that the foundation is exactly centered over a column or wall usually prevent using of a single pile beneath them. This issue is vital because any deviation can lead to eccentric loading, potentially causing the connection between the pile and the column to rupture and subjecting the pile to structural failure due to bending stresses [2]. In practical scenarios, structural loads are sustained through multiple piles functioning collectively as a group. Consequently, the settlement experienced by the group tends to exceed that of a single pile, often referred to as the "efficiency" or "settlement ratio" of pile groups. In geotechnical and structural engineering, pile group configuration and stress dispersion patterns are essential concepts [3]. Figure 1 presents the typical pile group configurations and how the stress is distributed within the ground under a single and a group of closely spaced piles. They dictate how piles are arranged and loads are distributed within the group, directly impacting the stability and efficiency of the foundation. The group settlement tends to be significant in size due to the greater depth of the pressure bulb associated with the group compared to an individual pile (Fig. 1). Engineers employ various analytical tools to optimize designs, considering factors like pile number, spacing, properties, and soil characteristics to ensure structural integrity and prevent settlement issues [2].

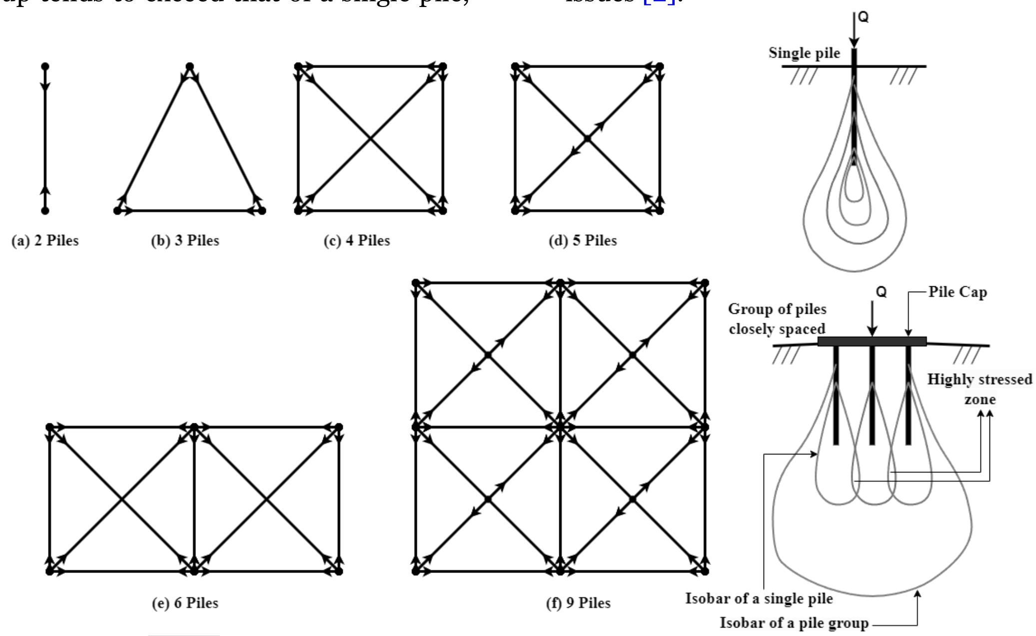


Fig. 1 Pile Group Configuration and Stress Dispersion Pattern.

Pile foundations are classified into different types based on their shape (as presented in Table 1). Choosing the pile shape depends on the specific engineering requirements of the project, the soil conditions at the construction site, and other logistical considerations. Piles are essential for supporting heavy structures by transferring their weight to the ground. They are used in critical structures like bridges and tall buildings. However, in earthquake-prone areas, piles in loose, liquefiable soil can fail during tremors despite existing building codes trying to account for this risk. Piles are seldom used in isolation; more commonly, they are employed in groups connected to a common foundation block referred to as a pile cap. Over the years, there has been a significant increase in research works on pile group foundations. Earlier research primarily concentrated on two main aspects: the behavior of pile groups under vertical loads, [1] focused on assessing bearing capacities and settlement; and the response of pile groups to lateral loads. Studies [2-9] are dedicated to evaluating bending moments and lateral deflections. However, it is worth noting that studying the isolated effects of vertical and lateral loads may not accurately represent the actual response of pile groups in real-world field conditions. This limitation has been acknowledged by researchers [10]. Very few studies have explored how pile groups respond when they experience vertical and lateral loads at the same time, as demonstrated by [10]. Furthermore, scholars studied pile groups facing combined eccentric lateral and torsional loads [11-14]. The later investigations, as conducted by [11, 12, 14], evaluate twist angles, shear forces, and bending moments using various approaches, such as centrifugal model tests, analytical methods, and numerical analysis. Geotechnical and structural engineers have long considered the seismic response of pile groups to be an essential subject. In areas where earthquakes are common, pile foundations are vital for giving various constructions stability and load-bearing capacity. Designing strong and secure networks requires understanding how pile groups react to seismic stresses [15]. Pile foundations are prone to severe damage during strong earthquakes in areas where seismic activity poses a considerable threat, collapsing the structures they support catastrophically. These issues have been brought up in several studies [16–19]. In addition, sites with loose, saturated sand layers are more likely to experience liquefaction due to the accumulation of pore water pressure (PWP). This phenomenon has led to a lot of research to understand the complex behavior of soil-pile-structure interaction (SPSI) in liquefiable soil. Research findings [20–23] have emphasized that the liquefaction of loose sand deposits is one of the major factors responsible for the extensive damage that pile foundations in buildings, bridges, and waterfront structures sustain during different major earthquakes. Additionally, when soil layers have a slope, lateral ground movement may occur, resulting in lateral spreading that applies extra lateral forces on piles [24-28]. Recent earthquake events, such as the 1989 Loma Prieta, 1995 Kobe, and 1999 Chi-Chi earthquakes, have emphasized the critical need for a deeper understanding and assessment of seismic SPSI effects, as evidenced by failures of pile foundations and superstructures [29-32].

Table 1 Pile Classification Based on Shape with their Descriptions.

No.	Pile classification based on its shape	Description
1	Cylindrical piles	Also known as round piles, they feature a circular cross-sectional shape (Fig. 2 (a, b)). These piles are commonly constructed using materials such as concrete or steel. Cylindrical piles are favored for their ease of manufacturing and installation, making them suitable for a diverse array of construction applications. Several researchers have designed and analyzed cylindrical pile foundations, including the works by [23,24,26,33-41] and others.
2	Square or rectangular piles	Featuring a square cross-section, they are commonly used in construction (refer to Fig. 2 (c)). They provide stability and are particularly well-suited for transferring heavy loads. Numerous researchers designed and analyzed square and rectangular pile foundations. Some notable contributions in this field include the works by [42-47], among others.
3	Octagonal piles	Characterized by their eight-sided structure (Fig. 2 (c)), they represent a middle ground between the simplicity of circular piles and the load-bearing capacity of square piles. They find application in scenarios where stability and ease of installation are vital considerations. Despite their potential advantages, there is a noticeable scarcity of research concerning octagonal pile foundations (e.g.,[48-51]) compared to more conventional shapes, such as square and cylindrical piles. The lack of research can be linked to established shape traditions and the inherent complexity of designing octagonal piles.
4	H-piles	They have an "H" shape when viewed in cross-section (Fig. 2 (c)). They are often made of steel and commonly used in marine and waterfront construction due to their ability to resist lateral forces. Extensive research has been undertaken regarding this pile type, including studies by [52-61] and others.
5	Tapered piles	Featuring a varying cross-section (Fig. 2 (d)), with one end more significant than the other, they allow optimal load-bearing capacity with reduced material usage. Several researchers have explored this pile type, including studies by [62-72] and others.
6	Spiral piles	They have a spiral or helical shape along their length, similar to a corkscrew (Fig. 2 (e)). They are often used in softer soils and can be twisted or screwed into the ground. Numerous researchers have investigated this type of pile [73-78].

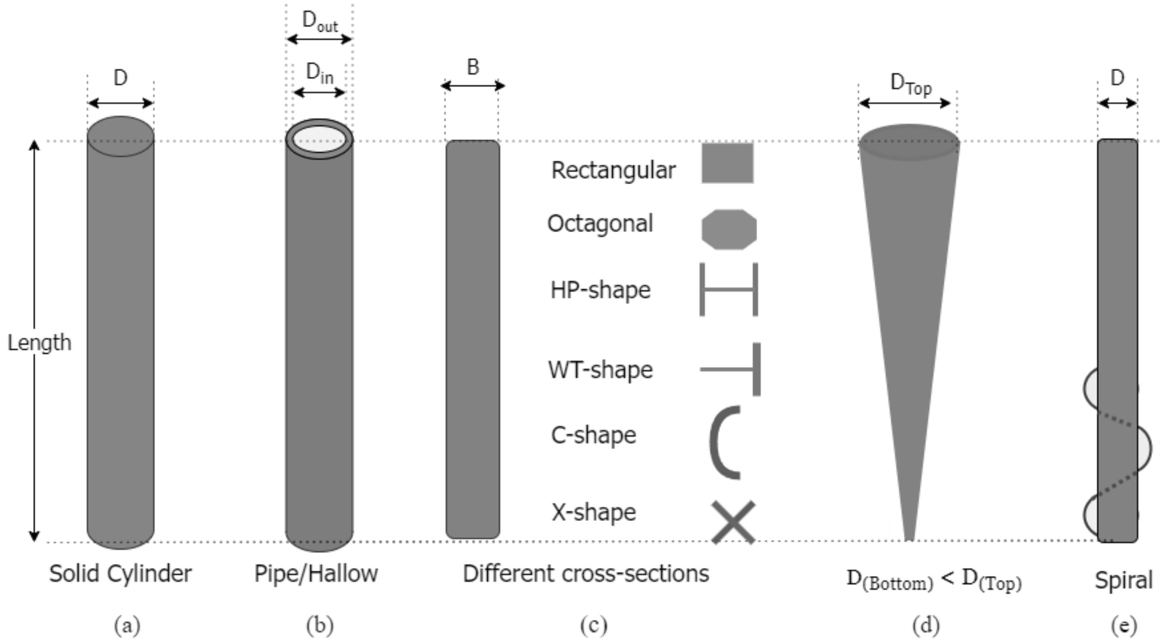
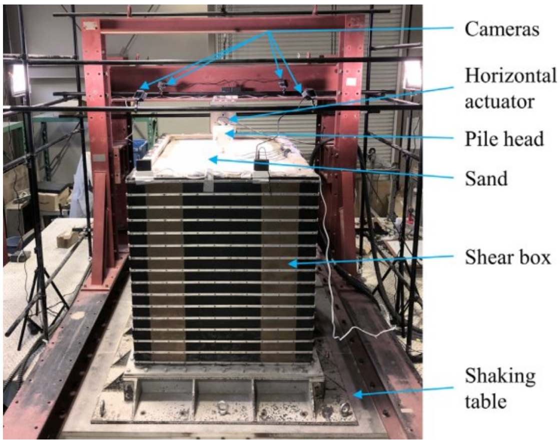


Fig. 2 Common Pile Foundation Shapes.

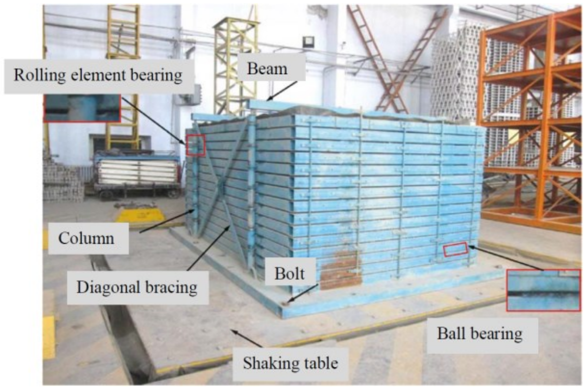
Analyzing the interaction between pile foundations and soil under seismic excitation is considered one of the intricate challenges in geotechnical earthquake engineering. In specific situations, pile foundations are preferred over shallow foundations, particularly the case in areas where the near-surface soil layers exhibit significant weakness, to the extent that the soil properties fail to meet the necessary strength requirements, or where the settling and/or movements of a shallow footing on such ground would be considered unacceptable. The primary aim of this study is to offer a comprehensive understanding of the seismic response patterns observed in pile groups, thereby providing valuable insights into the dynamic behavior of deep foundation systems. The present research contributes to the knowledge base by shedding light on how pile groups react to seismic forces and enhances the understanding of their performance during earthquakes, which is crucial for designing more resilient structures in earthquake-prone regions.

2.SHAKING TABLE TESTS ON PILE GROUPS

Dynamic testing of pile foundations has been conducted using various approaches, including experiments with real-scale models (as illustrated in [79,80]), laboratory-scale models, which include shaking table models (as demonstrated by [81,82]), and centrifuge models (as explored in [83,84]). As highlighted by [85], this testing method is considered less cost-effective and less time-consuming than conducting full-scale foundation tests, making it a common choice for studying soil-pile interaction, simulating various soil conditions, pile types, and replicating real seismic forces. The laboratory testing method involves using a specialized platform known as a shaking table, which is capable of simulating various types and intensities of ground motions, including earthquakes [85]. Understanding how piles and the soil they are embedded in react to fluctuations in load, especially motions caused by earthquakes, is the main goal of these tests [86]. These tests are used by researchers to evaluate pile foundation performance, stability, and safety in seismically active areas. A big mechanical apparatus called a shaking table is used to simulate earthquakes brought on by earthquakes or other dynamic forces [87]. As seen in Fig. 3, it is composed of a horizontal platform able to move in several directions (up, down, left, right, and back and forth) to replicate the intricate motions of the ground during an earthquake. On top of the shaking table, piles are placed in a test chamber or specifically made soil container. To replicate actual soil conditions, the sand inside the chamber is typically prepared and compacted. Depending on the research goals, the pile group layout can change, including the number and arrangement of heaps. By applying regulated accelerations and displacements to the test specimen, the shaking table is designed to produce seismic excitations [88]. The motion's frequency, amplitude, and duration can be changed to more closely resemble actual earthquakes. To measure essential characteristics during the test, various sensors and devices are placed on and around the pile group. These could incorporate strain gauges on the piles to measure deformation, pressure cells to track soil pressures surrounding the piles, and accelerometers to record ground motion. To get information on how the pile group reacts to the simulated earthquake, researchers closely observe the test in real-time. After that, this data is examined to evaluate elements, including shear forces, axial load distribution, bending moments, pile deflection, and settlement. Shaking table testing has become more critical in analyzing soil-pile interactions as dynamic structural evaluation technologies, and the idea of model similitude has developed, as [89] has shown. Similitude principles are crucial when evaluating soil-pile systems on a shaking table. Specialized parts, including laminar boxes, wing-equipped box walls, and stiff inner linings, are intended to be used in conjunction with the shaking table to regulate wave reflection from the boundaries. To investigate the effects of seismic forces on piles, Tokimatsu et al. [90] conducted comprehensive shaking table experiments on dry and saturated soils, paying particular attention to the kinematic and inertial forces. Their results demonstrated that pile stress was significantly impacted by inertial and kinematic elements when the superstructure's natural period exceeds that of the underlying soil. Full-scale piles were built for large-scale shaking table tests in horizontal and sloping terrains in a different study [91]. Their analysis showed that, in horizontal ground, the interface between the pile and the foundation and, in sloped terrain, the movement caused by liquefaction affected the behavior of the piles. Additionally, Ebeido et al. [26] performed four large-scale shaking table tests using a 3% inclined layer of sand with a relative density ranging from 40% to 50%. These tests aimed to investigate the behavior of single steel pipe piles, as well as pile groups under conditions of liquefaction-induced differential settlement. It is well-established that reproducing precise dynamic signals, such as earthquake ground motions, using shaking tables is a challenging task, which has been acknowledged in [92-94]. The distortion of signals that occurs during reproduction is primarily influenced by the inherent dynamic characteristics of the various subsystems within the shaking table system, including mechanical, hydraulic, and electronic components, as well as their interactions. Over the last decade, significant efforts have been dedicated to two main research areas. Firstly, there has been a focus on evaluating the actual performance of existing shaking table facilities, as demonstrated in [95-98]. Secondly, there has been a concerted effort to develop advanced control algorithms, including real-time adaptive techniques, to enhance the accuracy of reproducing time history signals, as discussed by [99]. Therefore, shaking table tests on pile groups provide valuable insights into pile foundations' dynamic behavior and performance under seismic conditions. They help validate and refine mathematical models and numerical simulations used in earthquake engineering and geotechnical analysis. The results of these tests can inform the design and construction of safer and more resilient pile foundations in earthquake-prone areas.



(a) Shrestha et al. [100].



(b) Dong et al. [101].

Fig. 3 Shaking Table Devices.

3.NUMERICAL APPROACHES AND MODELING FOR ANALYZING THE SEISMIC RESPONSE OF PILE GROUPS

Numerical techniques for analyzing pile groups can be broadly categorized into two main groups: a) approaches based on a continuum model and b) approaches that rely on load-transfer methods, often known as subgrade reaction approaches. In the latter category, based on the concept of the Winkler spring idealization of the soil, load transfer functions are used to describe the relationship between the load applied at various points along the pile and the resulting deformation of the surrounding soil at those points [11]. This semi-empirical method is commonly employed to analyze and design individual piles, especially in cases where the soil exhibits nonlinear behavior, and the soil composition is complex, as in the "p-y" curve analysis method. Notable computer programs falling into this category include PILGPI [102], FIPIER [103], and GROUP [104]. However, it is essential to note that this approach has certain limitations, which can be summarized as follows:

1- The modulus of subgrade reaction is not an inherent property of the soil itself but rather reflects how the soil is perceived by a pile at a specific depth. Consequently, its value depends not only on soil characteristics but also on pile properties and loading conditions. Consequently, no direct tests are available to establish force-displacement relationships for a specific pile and soil combination type. To create these relationships, engineers typically rely on data collected from field tests conducted with an instrumented pile. However, such tests are rarely justifiable for onshore applications due to their high costs. As a result, engineers often resort to using standard load-transfer curves in practical situations. This approach requires significant engineering judgment when adapting these curves to site conditions that differ significantly from the recorded field test data. Murchison and O'Neill [105] conducted a study in which they compared four commonly used procedures for selecting p-y curves with data from field tests. Their findings revealed that errors in predicting pile-head deflections could be as high as 75%. Additionally, Huang et al. [106] attempted to analyze laterally loaded piles using several sets of p-y curves derived from data from the dilatometer test (DMT). However, none of these p-y curves accurately predicted the measured pile deflections.

2- The load-deformation relationship along a pile is represented using discrete, independent springs, and the analysis does not provide any information about how deformation occurs around the pile. This lack of consideration for soil continuity makes it challenging to quantitatively assess the interaction effects between piles in a group using a rational approach. As a result, when evaluating the impact of pile groups, engineers typically resort to an entirely empirical procedure. This procedure involves adjusting the load-transfer curves for individual piles based on data from small-scale and full-scale experiments conducted on pile groups in various soil types. While Reese et al. [104] reported some successful analyses using this method for pile groups subjected to lateral loading, there are persisting uncertainties regarding the widespread application of this approach in routine design, as noted by Rollins et al. [107] and Huang et al. [106].

3- The influence of pile-head fixity on p-y curves remains uncertain. This aspect has received relatively little attention in research, even though Reese et al. [108] demonstrated that pile-head fixity impacted p-y relationships. Understanding the relevance of this factor is critical, especially when using p-y curves derived from single pile tests to make predictions for pile groups where the pile heads are constrained or fixed by a cap.

These limitations can be overcome by employing soil continuum-based solutions, typically based on the Finite Element Method (FEM), as demonstrated by Ottavianin [109], or the Boundary Element Method (BEM), as shown by Butterfield and Banerjee [110]. These approaches offer a more effective way to account for the essential aspects of pile interaction within the soil continuum, resulting in a more realistic representation of the problem. Additionally, the mechanical properties introduced into these models have a clear physical significance and can be directly measured. While finite element analyses are valuable for understanding how loads are transferred from piles to the surrounding soil, especially in the case of pile groups, they are not easily applicable to practical engineering problems. The substantial effort required for data preparation and the high computational costs, particularly when dealing with nonlinear soil behavior, make these techniques less suitable for routine design. As an example of the computational resources needed, consider the nonlinear FEM analysis of a laterally loaded 9-pile group by Kimura and Adachi [111], who reported a CPU time of 85 hours on a SPARC II workstation. Nowadays, numerical simulation has become widely used to study pile foundation behavior. FEM is one of many computational modeling techniques frequently used to manage complicated connections in pile foundations. An extensive review of numerical modeling in geotechnical engineering has been provided by Schweiger et al. [112]. It is critical to include an appropriate constitutive model that considers large-strain responses, such as irrecoverable deformations, and small-strain effects, such as hysteretic damping, after precisely representing the soil components. FEMs become instrumental in validating the soil profile and the established numerical model when the appropriate soil-pile interface elements are applied along with suitable boundary conditions, as highlighted by [113]. Aghayarzadeh et al. [114] emphasized that when a simplified constitutive model is used to represent ground conditions under dynamic loads, it may be necessary to adjust or recalibrate the model parameters to ensure that the numerical simulations align closely with laboratory measurements of load-displacement curves. The precision offered by numerical modeling in geotechnical engineering brings several advantages. It enables the representation of coupled phenomena and the accurate simulation of the nonlinear behavior of diverse materials. This capability becomes especially valuable when dealing with natural materials in geotechnical engineering, which differ significantly from materials like concrete that adhere to predefined specifications. Natural materials are inherently heterogeneous, posing computational challenges when modeling their mechanical and hydraulic properties. Moreover, the choice of pile installation methods (e.g., mix-in-place concrete, bored, and driven) has a pronounced impact on stress distribution in the soil, making realistic replication through simulation a complex task. Consequently, even with thorough field investigations, considerable uncertainties persist in the soil profile [112]. Hence, geotechnical engineering modeling poses a significant challenge, involving a multitude of geological and geotechnical factors with complex interrelationships. Geomaterials exhibit highly nonlinear behaviors that distinguish them from other engineering materials. Such challenges lack available closed-form theoretical solutions. Al-Jeznawi et al. [33] investigated the response of pile groups subjected to vertical, eccentric lateral, and seismic loads within dense sand. To accomplish this goal, they utilized an extensive 3D nonlinear finite element model, which underwent thorough validation and refinements to support further analysis. The research involved a detailed investigation of two different configurations of pile groups exposed to various loading scenarios, with the dynamic analysis based on data recorded during the El Centro earthquake. Fansuri et al. [115] introduced a proficient method based on Bhattacharya's deterministic approach to calculate pile buckling instability. This technique was verified and validated using 3D finite-element simulations conducted with OpenSees software. In a recent study by [75], the impact of model scale on the seismic behavior of real helical pile groups was investigated. They employed a finite element modeling approach, which was corroborated by outcomes from shaking table experiments conducted on isolated piles installed in dry and saturated sands. To configure the full-scale shaking tests, the researchers relied on insights from the smaller-scale model shake table tests, ensuring consistency with established similarity and dimensional principles. Fayez et al. [116] conducted a significant study using large-scale shake table tests to analyze the seismic behavior of single and grouped helical piles. They considered earthquake characteristics, like intensity and frequency, and studied how pile groups interact, including their vertical and lateral stiffness contributions. The later study also explored the impact of pile head connections (fixed or pinned) on group response and compared single piles to those within groups. Al-Jeznawi et al. [113] introduced 2D and 3D finite element analyses that utilize the strength reduction technique to investigate how slopes, when stabilized with piles, respond to seismic excitation. Several other studies have focused on the seismic response of pile groups (Table 2).

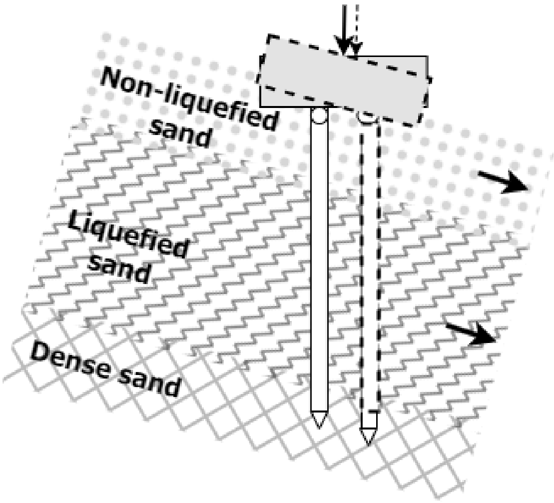
Table 2 Numerical Studies on Seismic Response of Pile Groups.

No.	Reference	Software	Parameters
1	Al-Jeznawi et al. [33]	MIDAS GTS NX (2022R1)	Scaling effect, number of piles, layouts of pile groups, and loading scenarios and intensities
2	Fansuri et al. [115]	OpenSees platform	Pile characteristics, loading scenarios and intensities, ground inclination, and pile spacing
3	Hussein and El Naggar [75]	OpenSees platform	Soil conditions, scaling effect, and ground motion intensities
4	Fayez et al. [116]	Ensoft Inc. LPILE v6.0	Ground motion intensities and pile head connection to the pile cap (fixed or pinned)
5	Jawad and Albusoda [117]	PLAXIS 3D	Pile length, slenderness ratio, pile spacing, and ground motion intensities
6	Al-Jeznawi et al. [113]	MIDAS GTS NX (2022R1)	Pile spacing, pile length, scaling effect, number of piles, and layouts of pile groups
7	Hussein and El Naggar [15]	OpenSees platform	Soil conditions, ground motion intensities, kinematic and inertial effects, and pile characteristics
8	Tang et al. [23]	OpenSees platform	Pile spacing, pile stiffness (EI), superstructure mass, sand permeability, and ground motion intensities
9	Chehade et al. [118]	FLAC3D	Ground motion intensities, ground conditions, and piles inclination
10	Hokmabadi et al. [119]	FLAC3D	Ground motion intensities and type of foundations
11	Eslami et al. [120]	ABAQUS (6.10)	With/without raft footing and loading conditions
12	Chu and Truman [121]	ABAQUS (6.10)	Layouts of pile groups, number of piles, pile spacing, and ground conditions

4.PILE GROUP BEHAVIOR SUBJECTED TO GROUND MOTIONS

Ground motion intensity can vary significantly during an earthquake or due to other dynamic events. Researchers investigate how these variations affect pile deflection, bending moments, and axial loads. The failure mechanisms of piles under seismic loads are influenced by several factors, including soil conditions, pile design, and seismic intensity [33]. Table 3 presents significant previous studies on the seismic response of pile groups. Common failure modes include liquefaction-induced settlement, which is especially pronounced in loose or saturated soils. During seismic events, these soils temporarily lose strength, behaving like a liquid and potentially causing significant settlement and pile tilting [75]. Excessive axial loads, primarily in the vertical direction, may result from seismic forces exceeding pile capacity and material strength, leading to pile buckling or crushing. Additionally, horizontal ground movements, such as lateral spreading and seismic shaking, can subject piles to lateral forces, causing tilting, bending, or failure, particularly if not designed for lateral loads. Soil-structure interaction is critical, as seismic forces can activate lateral soil resistance, effectiveness varying with soil characteristics [15]. Inadequate lateral resistance can lead to excessive lateral displacement or pile failure. Weaknesses also exist at pile-to-structure connections, where seismic forces may induce bending or shear stresses, potentially resulting in failure [23]. Seismic shaking can generate dynamic force amplification, causing forces experienced by the pile to exceed static levels due to ground motion characteristics. Additionally, seismic loading can induce uneven foundation soil settlement, potentially causing differential pile settlement and structural damage if not addressed in the design [122]. A case of pile group failure caused by seismic activity can be illustrated by the significant damage sustained by a wharf structure, wherein the pile foundations supporting the wharf sank into liquefied soil. This occurrence is depicted in Fig. 4 (a) [122], which displays the development of plastic hinges at the pile heads. Madabhushi et al. [122] had previously predicted this type of failure mechanism through a series of centrifuge tests to comprehend how piles settle into liquefied sand overlying dense sand layers. Upon comparing Figs. 5 (a) and (b), it can be inferred that the failure mechanism observed in piles groups within liquefied soils during dynamic centrifuge tests was corroborated by post-earthquake.

(a) Madabhushi et al. [122].



(b)

Fig. 4 Hinging Failure Mechanism, with (a) Hinging of Piles Supporting a Wharf Structure and (b) the Failure Mechanism Caused by Pile Settlements.

The buckling failure of slender piles could be attributed to the impact of excessive axial loading when there is a reduction in effective stress and shear strength in the surrounding soil due to liquefaction, as discussed by [123, 41, 115], which stated that when a pile is inserted into the soil, it results in the compression of the adjacent soil, leading to the application of lateral stress on the pile shaft. The force and deformation characteristics of structural piles during seismic vibrations are illustrated in Fig. 6 [115]. A simplified approach involving one-dimensional (1D) or two-dimensional (2D) numerical simulations has demonstrated the possibility of predicting the pile's maximum lateral displacement and maximum bending moment. However, it is important to note that this approach relies on several assumptions, as highlighted by [36, 124, 125]. In contrast, more recent research has explored the capacity of computer-based analysis methods through three-dimensional (3D) numerical simulations, providing valuable insights into the interaction between piles and liquefiable ground. Nonetheless, this analysis method has certain limitations, such as its inability to directly simulate pore pressure generation and considering the reduction in shear strength resulting from soil shear deformation. These limitations have been discussed by [126, 127]. To address the challenges posed by liquefaction conditions, various models involving beams on soil springs have been proposed for design purposes. These models come with a range of recommendations concerning parameter selection and loading details, as outlined in [25, 128-131]. Recent advancements in designing piles for seismic conditions have focused on assessing the bending moment experienced by piles due to lateral forces, like inertial forces resulting from ground movement, such as lateral spreading [113]. Consequently, seismic pile and drilled shaft design also consider factors like elastic settlement, consolidation settlement (for pile groups), shear forces, pile deflection, top lateral deflection, soil reaction, and more. Lateral spreading refers to the flow and dragging of liquefied soil layers with any non-liquefied layers above due to a loss of shear strength. It is important to note that beam bending and column buckling are treated differently. Pile buckling occurs when the strength and stiffness of liquefied layers are significantly reduced [132]. In such cases, the soil may not provide adequate stabilizing support for slender piles through thick liquefied layers, as discussed by [133]. Bending failure is widely recognized as a possible mode of failure following a strong earthquake. Despite its significance, there is still limited understanding of pile buckling instability in liquefiable soil and how it affects the behavior of the soil around the pile. Various mechanisms for buckling instability in liquefiable soil have been proposed [134-136]. During liquefaction, piles can experience a significant loss of lateral support in the liquefied zone. Therefore, if the axial load on the pile approaches its critical buckling load, buckling instability may occur, especially when subjected to lateral loading or material limitations.

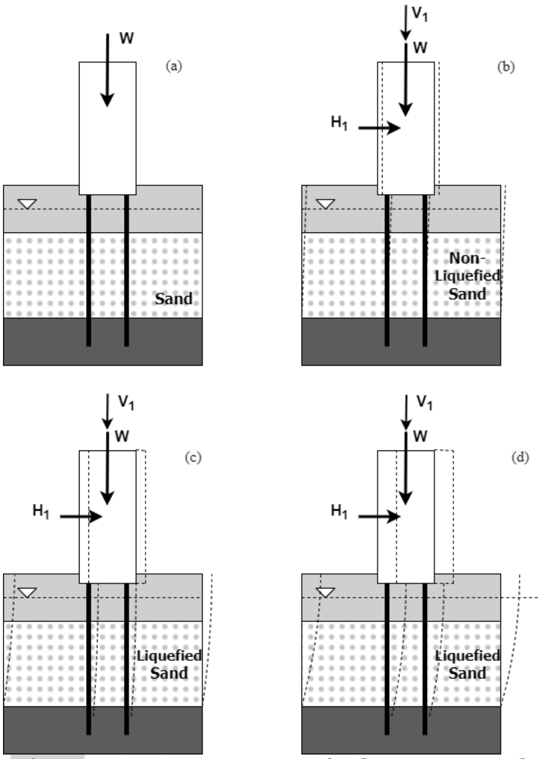


Fig. 5 Seismic Response of Pile Groups under Different Shaking Intensities: (a) Before Shaking; (b) During Low Seismic Intensity; (c) During High Seismic Intensity and Soil Liquefaction; and (d) During High Seismic Intensity, Soil Liquefaction, and Lateral Deformation.

Table 3 Previous Works on Seismic Response of Pile Group.

No.	Reference	Type of piles	Type of investigation	Investigating factors
1	Yoo et al. [137]	Cylindrical pipe piles	Experimental work	Ground inclination and ground motion intensities
2	Jia et al. [138]	Cylindrical	Experimental work	Ground motion intensities and with/without bridges
3	Al-Jeznawi et al. [33]	Cylindrical pipe piles	Numerical modeling	Scaling effect, number of piles, layouts of pile groups, and loading scenarios and intensities
4	Al-Jeznawi et al. [133]	Cylindrical pipe piles	Numerical modeling	Scaling effect, number of piles, layouts of pile groups, and loading scenarios and intensities
5	Fansuri et al. [115]	Cylindrical	Numerical modeling	Pile characteristics, loading scenarios and intensities, ground inclination, and pile spacing
6	Hussein and El Naggar [75]	Helical	Numerical modeling	Soil conditions, scaling effect, and ground motion intensities
7	Fayez et al. [116]	Helical	Numerical modeling	Ground motion intensities and pile head connection to the pile cap (fixed or pinned)
8	Zhang et al. [41]	Rectangular	Experimental work	Pile characteristics
9	Hussein and El Naggar [15]	Cylindrical and H	Experimental work, numerical modeling	Soil conditions, ground motion intensities, kinematic/inertial effects, and pile characteristics
10	Huang et al. [139]	Square	Theoretical study	Soil-structure interaction, natural frequency, and loading time
11	Ebeido et al. [26]	Cylindrical pipe piles	Experimental work	Number of piles, ground profiles and conditions, layouts of pile groups, and loading scenarios and intensities
12	Tang et al. [23]	Cylindrical	Experimental work, numerical modeling	Pile spacing, pile stiffness (EI), superstructure mass, sand permeability, and ground motion intensities

13	Chehade et al. [118]	Cylindrical	Numerical modeling	Ground motion intensities, ground conditions, and piles inclination
14	Haeri et al. [86]	Cylindrical	Experimental work	Case study of a specific pile group
16	Hokmabadi et al. [119]	Cylindrical pipe piles	Experimental work, numerical modeling	Ground motion intensities and type of foundations
17	Eslami et al. [120]	Square piles	Numerical modeling	With/without raft footing and loading conditions
18	Dash et al. [20]	Cylindrical pipe piles	Theoretical study	Different analytical methods
19	Knappett and Madabhushi [135]	Cylindrical	Experimental work	Layouts of pile groups, ground motion intensities, and pile head connection to pile cap
20	Ghazavi [140]	Tapered	Theoretical study	Taper angle
21	Liyanapathirana and Poulos [36]	Cylindrical	Theoretical study	Pile length and diameter and loading scenarios and intensities
22	Chu and Truman [121]	Square	Numerical modeling	Layouts of pile groups, number of piles, pile spacing, and ground conditions
23	Abdoun and Dobry [24]	Cylindrical	Experimental work	Number of piles, ground profiles and conditions, layouts of pile groups, and loading scenarios and intensities
24	Meymand [141]	Cylindrical	Field investigation, experimental work	Scaling effect, flexible base frequencies, damping factors, and ground motion intensities

5.DESIGN CONSIDERATIONS FOR SEISMIC-RESISTANT PILE GROUPS

- Designing seismic-resistant pile groups involves assessing seismic hazards, understanding soil-structure interaction, analyzing vertical and lateral loads, optimizing pile configuration and design, considering energy dissipation devices, accounting for foundation stiffness, ensuring quality construction, and adhering to local building codes. Ongoing monitoring and maintenance are also essential for long-term performance and safety.
- While reviewing the code of practice, it was found that Sarkar et al. [142] pointed out that the Japanese Highway Code of Practice (JRA) delineates two specific loading conditions for assessment. These conditions involve: a) the inertial force generated by the oscillation of the superstructure, as depicted in Fig. 5 (a), and (b) the kinematic load arising from the lateral pressure exerted by the liquefied layer and any non-liquefied crust on top of the liquefied deposit, as illustrated in Fig. 5 (d). Moreover, the code indicated that the evaluation of the susceptibility to bending failure resulting from kinematic and inertial forces should be conducted separately.
- Eurocode 8 [143] recommends that pile design should account for bending resulting from inertial and kinematic forces generated by soil deformation. In situations involving liquefaction, Eurocode 8 [143] further proposes that the resistance from soil layers prone to liquefaction or significant strength reduction should be disregarded.
- NEHRP code [144] and Indian Code [145] also focus on how piles can bend. These codes basically treat piles as beams that can bend when subjected to lateral loads caused by inertia and soil movement. Therefore, histories of pile failures during seismic events have been documented, even though current codes of practice address the seismic design of piles.
- Indian Code [145] provides a formula for the load-carrying capacity of an individual pile under various soil conditions, offering valuable insights for designing bored piles, driven piles, and pile caps within a pile group. Pile spacing, the response of the pile within the group, and reinforcement specifications conform to the code recommendations. The code's methodology is also utilized to determine the lateral resistance of a single pile, and the bearing capacity is derived from the same code.
- Since negative skin friction arises when soil settlement exceeds pile movement, Bowles [146] introduced a concept that examines the relationship between pile movement rates and soil settlement to study negative skin friction.
- According to Francis [147], it is essential to acknowledge that pile failures actually result from complex combinations of mechanisms, such as bending, shear, or buckling. Failures of piles and structures supported by piles can arise from various complex combinations, encompassing structural pile failures, like shear, bending, and buckling, as well as soil-related failures, such as settlement.

Consequently, it is imperative for codes of practice to incorporate these interconnected failure mechanisms, ensuring a conservative approach when addressing liquefaction scenarios.

6.FUTURE RESEARCH NEEDS

investigating how pile groups respond to seismic forces is a critical research domain in geotechnical and structural engineering, with profound implications for the stability and integrity of various structures, including buildings, bridges, and offshore platforms. While substantial progress has been made in understanding the behavior of pile groups under seismic loads, several key areas for future research must be addressed, including modifying seismic design guidelines, further exploration of soil-structure interaction, the development of innovative pile group configurations, research into retrofitting techniques for existing structures, deploying of instrumentation for on-site testing during seismic, and considering environmental factors, including the potential impact of climate change on seismic activity. Advancing knowledge in these areas is crucial for enhancing the resilience and safety of infrastructure in earthquake-prone regions. Future research on the seismic response of pile groups should prioritize the development of advanced soil-structure interaction models that can accurately represent nonlinear soil behavior. Additionally, investigating the impacts of pile spacing and arrangement to optimize design, understanding dynamic soil properties during seismic events, and refining region-specific seismic hazard assessments are essential. Innovations in pile design and materials, comprehensive field testing and monitoring during seismic events, and exploring effective seismic mitigation strategies are critical areas of study. Real-world case examples should be examined to draw practical insights, and design guidelines must be updated to incorporate the latest findings.

7.CONCLUSIONS

The present research offers a comprehensive analysis of the response of pile groups to seismic loadings. It has condensed the key conclusions from numerous research investigations into a brief synopsis. Several components of pile group behavior have been reviewed in the paper, such as their dynamic behaviors to seismic occurrences, the variables influencing their performance, and the interactions between the soil and the structure that affect how they behave. The design of pile foundations is greatly influenced by the results of research on pile group behavior in underground motion. To study this connection, scientists employ lab tests, field testing, and numerical modeling. With this knowledge, engineers may choose the proper pile depth, spacing, and reinforcement to ensure that structures can resist the anticipated ground motions. Developing an efficient pile cap for load transmission to soil strata, characterizing soil properties for the necessary soil-structure interaction analysis, assessing column-induced forces on the foundation, and choosing the appropriate pile type for transferring applied loads to the soil layers are all crucial steps in the design of a pile foundation system. In conclusion, designing seismic-resistant pile groups requires a thorough evaluation of multiple factors, ongoing maintenance for long-term safety, and incorporating interconnected failure modes from various codes to address liquefaction risks conservatively.

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