



Behavior of Combined Vertical-Lateral Loaded Group Pile in Sand: A Review

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ABSTRACT

This review summarizes recent understanding of pile group behavior in sand under combined vertical and lateral loading, with emphasis on load–displacement response, capacity, stiffness degradation, and settlement. The surveyed studies show that pile performance under coupled loading differs from single-load assumptions because vertical load alters confinement and stress level around the pile, changing the mobilization of soil resistance and the p–y response. In sand, moderate pre-applied vertical compression often improves lateral capacity and reduces lateral deflection and bending demand, while the magnitude of this benefit depends on pile geometry (L/D), head fixity, and soil density. For pile groups, interaction effects govern behavior; pile spacing strongly controls group efficiency and settlement through overlapping stress zones and load sharing, and overly close spacing can increase settlement and reduce efficiency. The review also highlights the roles of pile diameter and length in increasing stiffness and mobilizable resistance, and compares common analysis approaches including Winkler/p–y methods, finite element soil–structure interaction modeling, and emerging data-driven tools. Overall, reliable design of laterally loaded pile groups in sand should explicitly consider combined-load level and sequence, group interaction, and nonlinear soil response, supported by validated numerical analysis and appropriate testing.

1. Introduction

Deep foundations are widely used to transfer structural loads through weak or compressible surface soils to deeper, more competent layers, providing adequate bearing capacity and limiting settlement. Among these systems, pile foundations resist loads through end-bearing support, side friction, or a combination of both, making them essential for structures such as bridges, towers, and high-rise buildings. In sandy soils, pile performance becomes strongly influenced by soil–pile interaction under real loading conditions, where vertical loads (capacity and settlement) often act simultaneously with lateral loads

(deflection and bending) from wind, waves, traffic, or seismic effects. For pile groups, these combined vertical–lateral actions are further complicated by group interaction and load sharing, which can reduce stiffness and capacity compared with single piles[1].

Deep foundations now include driven and bored piles in all soil and rock formations, with diameters up to about 4 m and depths ≥ 150 m, enabled by modern rotary drilling, casings, slurry support and heavy driving equipment[2]

Innovative geometries and materials (T-shaped modular piles, piles with “pockets”, low-carbon composite piles, energy piles) aim to enhance side friction, reduce cost and carbon

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footprint, and improve seismic or thermal–mechanical performance[3-5].

By the 1960s it was recognized that advanced construction cannot guarantee defect-free piles, prompting systematic integrity testing[6].

Stress-wave theory, from early one-dimensional wave mechanics and wave-equation programs in the 1940s, enabled dynamic pile driving analysis and capacity prediction; modern practice was consolidated by work at Case Western Reserve University and the Michigan pile tests around 1960[7].

Quantitative analysis of pile behavior is essential for designing piles subjected to inclined loads, whether in compression or tension. In pile foundation engineering, reliable numerical estimates are required to ensure that piles meet the performance demands imposed by inclined compressive or uplift forces[8].

Current non-destructive methods include low-strain PIT, cross-hole sonic logging and ultrasonic tests for integrity, and high-strain dynamic tests (PDA, DLT) for both capacity and integrity, interpreted via wave-equation and signal-matching analyses[7, 9].

Machine learning and AI are increasingly used for interpreting stress-wave data and predicting capacity or defect patterns[10].

2. Previous studies of researchers

the literature on pile foundations has progressively shifted from single-action loading assumptions to coupled loading interpretations, driven by larger structures and construction on weaker or more deformable ground. The reviewed sources emphasize that realistic design must capture side (shaft) friction mobilization, overturning resistance, and overall stability, particularly when vertical and lateral actions occur together.

2.1 Pile with vertical Loaded

Zhao et al., 2023 reported that vertically loaded piles resist axial loads through a combination of shaft friction along the pile surface and end bearing at the pile base, both governed by the mechanical properties and

stress state of the surrounding soil [11]. Their work further illustrates the progressive mobilization of resistance along the pile length, showing how axial force decreases with depth as shaft resistance develops before the remaining load is transferred to the pile toe shown in figure (1).

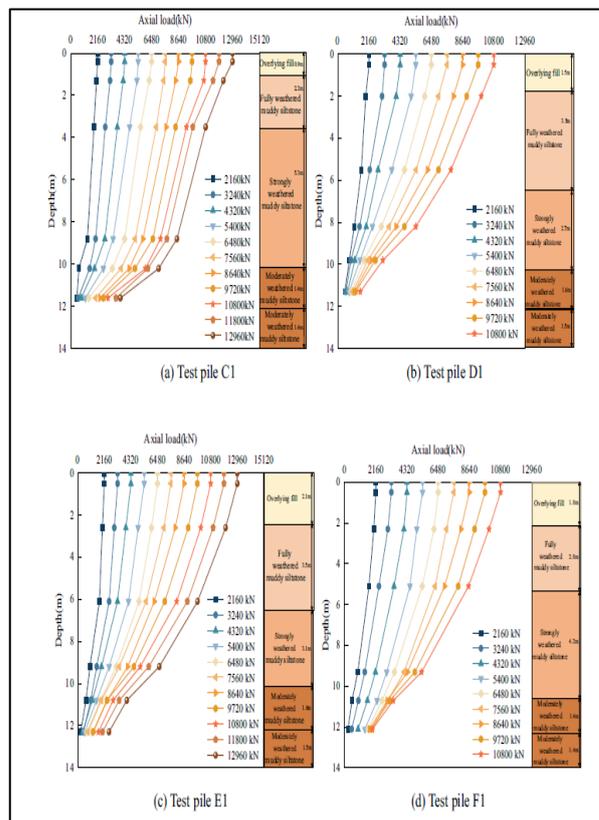


Figure 1. Axial force distribution along the test pile with depth[11].

Liu et al., 2025 and Wen et al., 2023 studies the pile transfers the applied vertical load from the superstructure to the soil by mobilizing shear stresses along the pile–soil interface and compressive stresses beneath the pile toe, so that the ultimate load capacity can be expressed as the sum of side resistance and base resistance [12, 13]. **Kumar et al., 2025** examined the axial load-bearing capacity of vertically loaded piles under the combined effects of soil type, construction quality (including installation method, rock cavity drilling, and cementing soil improvement), and loading direction and rate. These interacting factors affect both the magnitude and distribution of vertical friction and the terminal

load resistance at each pile depth, making accurate capacity prediction challenging under site conditions.[14].

2.2 Pile with Laterally Loaded

In terms of the lateral loads that the pile may be exposed to, two basic criteria become clear to us: the first is to reach final failure safely, and the second is that the deflection resulting from the effect of the normal operational load remains within the permissible limits. Quantitative estimates of the piles must be obtained to meet the pressure and pull requirements resulting from the effect of lateral loads [15]. According to figure (2), we can observe the mechanism of the effect of lateral loads on the pile, whether with or without a cap. We notice from this figure that the pile is divided into two sections: the upper section, which moves in the direction of the load, is the passive section, which is the upper section, while the lower section, or what is called the active section, is transferred from the pile towards the surrounding soil, as this soil moves from the previous equilibrium state to a new equilibrium state that differs from the initial state.

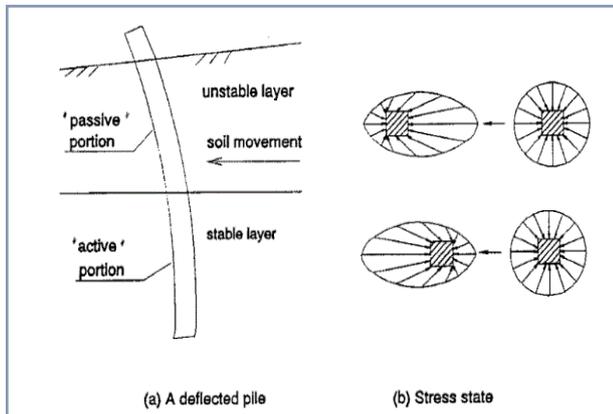


Figure 2. Pile subjected to soil movement [15]

the pile footing experiences deformation, rotation, bending moment or translation because of the lateral load applied to it. The specific type of response (deflection, rotation, bending moments or translation) depends on the pile's geometry and boundary conditions, as shown in figure (3). If the rotational deformation of the pile head is minimal, the

piles are likely to shift horizontally primarily after installation [16].

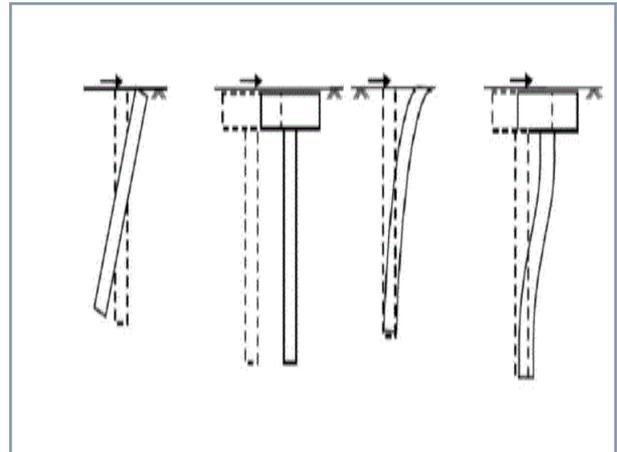


Figure 3. Response of an individual pile to lateral load

In order to evaluate the lateral load of piles, there were many strategies used in the analytical process, based on several assumptions to simulate the behavior of the pile and soil, such as the lateral earth pressure hypothesis, which is used to test the behavior of lateral forces on pile foundations [17]. There are other hypotheses, such as the existence of a relationship between the resistance of the foundation and the linear properties of the spring, which represents the behavior of the soil resistance [18]. There are also those who considered the pile and soil as elastic materials and developed a model to analyze the behavior of the lateral load and used the finite difference method in that [19]. The (P-Y) method is the most common method and has been widely used, as this method considers the piles as beams and represents the soil through separate spring elements located at different depths. The stiffness of this spring is determined by the critical variables, which are the soil resistance, which is usually concentrated in P, and the lateral deformation of the soil, which is symbolized by Y. The relationship between them is affected by the properties of the soil, the type of substrate, interactions between the soil and the substrate, and groundwater. Therefore, we may obtain several categories of relationships along the depth of the soil. Figure (4) shows the response of the soil and the corresponding P-Y curve [20].

The pile is classified into two types: long or short, depending on the distribution of bending and moment along its length. It is flexible when the moment and bending are limited to the upper part of the pile, and the total depth does not have a significant effect on the pile's reaction [21].

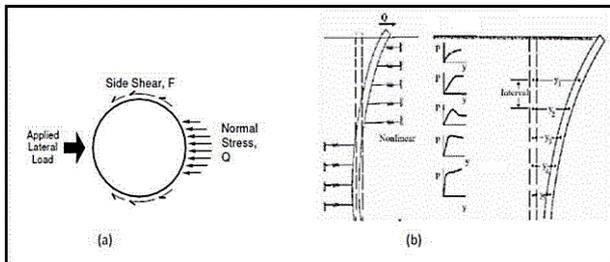


Figure 4. (a) Schematic of soil response around a pile cross-section under lateral loading (normal stress Q and side shear F). (b) Idealized p - y representation used to model lateral pile-soil interaction[22]

There are several methods for measuring the horizontal capacity of individual piles. Collapse or failure occurs for two reasons: the first is the failure of the lateral soil bearing capacity, which occurs due to the soil losing its hardness over time, and the second is the formation of a joint in the pile, i.e. the occurrence of a breaking point due to its inability to bear lateral loads [21]. Through the figure (5), we can observe the development and formation of the joint stresses.

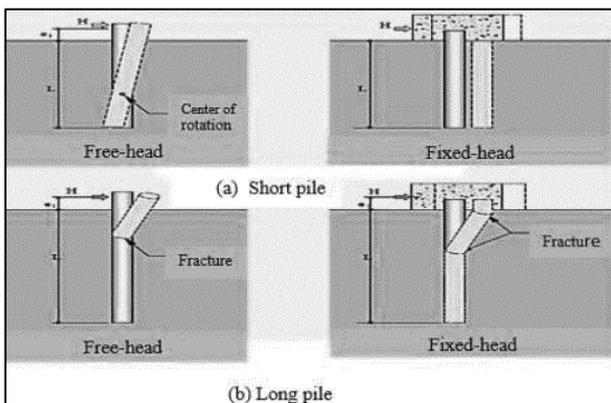


Figure 5. Failure forms of piles under horizontal loads [21]

According to **Heidari et al., 2021** pile-soil interaction under lateral loads results in the pile being divided into an upper passive section that moves with the applied load and a lower active section that transfers forces to the surrounding soil. This process causes the soil

to transition from its initial equilibrium to a new state.[23].

Thangavel and Rathod 2024 stated that laterally loaded piles must satisfy two key criteria: they should safely reach ultimate failure without collapse, and deflections under normal operational loads must remain within permissible limits to ensure structural integrity[24]. **Thangavel et al., 2024** discovered that the response of the substrate deflection, rotation, bending moments, or displacement depends on the geometry and boundary conditions; usually, a minimal rotational deformation at the head of the substrate results in a dominant horizontal displacement, as illustrated in figure (6) [25].

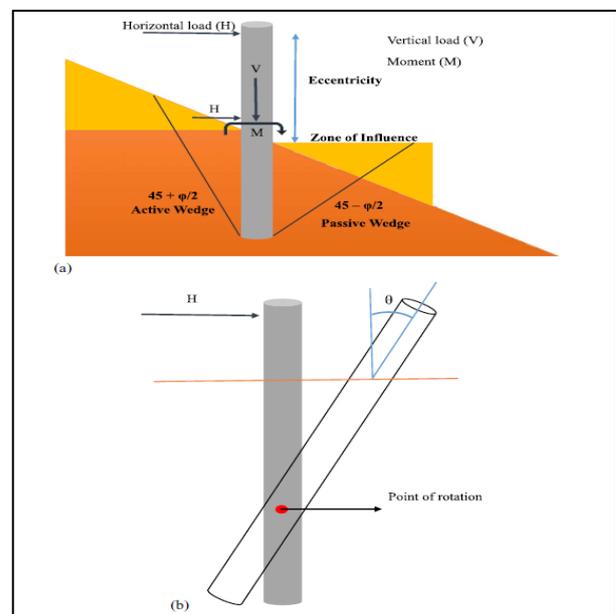


Figure 6. (a) Pile placed on sloping ground; and (b) Rotation of pile[25]

In accordance with **Zheng et al., 2024** analytical methods for evaluating lateral pile behavior include the widely used p - y method. This approach models the pile as a beam supported by nonlinear soil springs, with spring stiffness varying according to depth and soil properties. The method effectively captures the relationship between soil resistance and pile deformation.[26].

2.3 Combination piles with vertically and laterally loaded

Based on finding, **Al-Baghdadi et al., 2017; Hussien et al 2014; Karthigeyan et al., 2007** The interaction between vertical and lateral loads on piles significantly influences their behavior, yet the existing literature presents mixed findings on how these loads interact. Some model tests indicate that vertical loads can enhance the lateral capacity of piles, particularly under vertical compression, by increasing soil confinement and lateral resistance. Understanding these interactions is essential for effective pile design and analysis[27-29]. **Hazzar et al., 2017** found that, in contrast to previous findings, vertical loads may reduce the lateral bearing capacity of soils, particularly in clay soils, by altering soil stress distribution and diminishing lateral resistance[30]. **Hazzar et al., 2017** Numerical analyses further show that the effect of vertical loads depends on soil type and pile configuration; for example, vertical loads tend to increase lateral capacity in sandy soils but decrease it in clays, with layered soil conditions adding complexity to this interaction[31]. **Song et al., 2024; Zhang et al., 2024** demonstrated that the redistribution of bending moments and lateral displacements along the pile under combined loading underscores the need to rigorously consider vertical load effects in the design process[32, 33]. **Zang et al., 2021** emphasize that accurately understanding the superposition of vertical and lateral loads necessitates detailed experimental and numerical studies tailored to specific soil and pile conditions, since generalizations are limited[34].

Stalin et al. (2021) [35] examined the response of piles under different lateral and vertical stress conditions concerning diverse soil strata. The study involved implementing pile load tests in a controlled model tank environment, where sand, clay and a clay–sand mixture were utilised to investigate the response and characteristics of individual piles and pile groups subjected to vertical and lateral force. Single piles and pile groups consisting of two piles arranged in a 2×2 configuration was subjected to vertical compressive loads and horizontal loads. These tests were conducted using various types of soil mediums, various

combinations of loading, different numbers of piles and changing (L/D) ratios. The findings demonstrated that the vertical load capacity of a pile was positively correlated with the (L/D) ratio and the number of piles for a specific settlement. However, the vertical capacity of sand medium consistently surpassed that of clay or clay–sand medium. A comparable pattern was evident in the lateral load capacity as well. At the specified deflection, the lateral capacity had a positive correlation with the (L/D) ratio and the number of piles, particularly in the case of a sand medium. However, this relationship was less pronounced in clay and clay–sand beds.

2.4 Transferring Mechanism Single Pile

Fattah et al., 2020 describe single-pile load transfer as a progressive process in which the pile head load is first transmitted downward as the pile deforms, initially mobilizing shaft (skin) friction, and subsequently reaching the toe end-bearing. The allowable load is defined as the total resistance divided by a safety factor. Their results shown in figure (7), indicate that, at early loading stages, approximately 70% of the load is supported by shaft resistance and 30% by tip resistance[36].

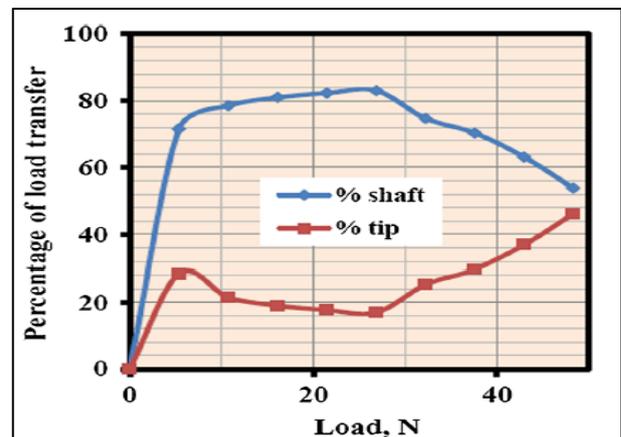


Figure 7. Distribution of load transfer from a single pile head to the shaft and tip in saturated soil conditions ($\gamma_d=15 \text{ kN/m}^3$) [36]

According to **Wang et al., 2025** the relative contributions of lateral friction and end bearing depend on soil type. For instance, sandy soils typically mobilize greater skin friction, whereas rocky or dense soils rely more on end bearing[37].

Fattah et al., 2024 report that during the initial stages of loading, the column supports approximately 70% of the load. As loading continues and settlement occurs in the piles, the load distribution shifts, increasing column resistance through the soil-pile cohesion[38]. Depending upon **Liu et al., 2025**, advanced analytical frameworks now couple load-transfer methods ($t-z$ / $q-z$) with Disturbed State Concept (DSC)-based interface constitutive modeling to represent the nonlinear mobilization and softening of shaft friction and pile-base resistance, which improves the realism and accuracy of predicted load-settlement curves. This coupling is commonly implemented using discretized pile elements connected to nonlinear springs, as illustrated by the elastoplastic Winkler representation and its transfer functions in Figure (8)[39].

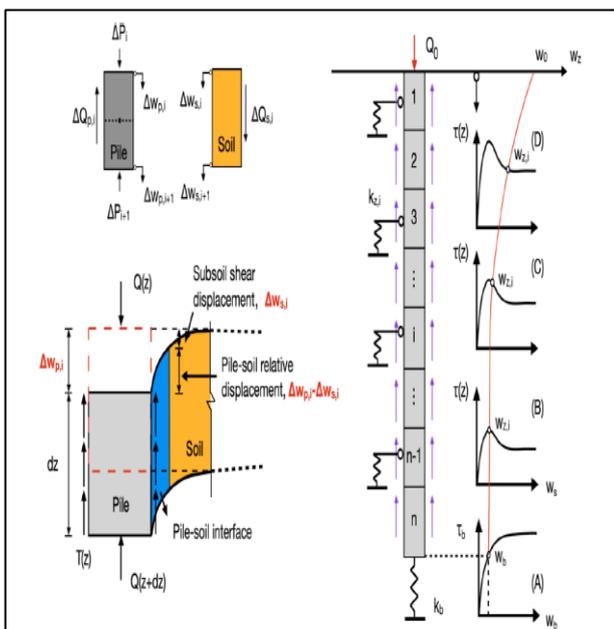


Figure 8. The elastoplastic Winkler model demonstrates (A) the pile base load transfer function and (B-D) the pile-soil interface transfer function [39]

Fenghao et al., 2025 furthermore, pile surface characteristics, including roughness and threading, significantly influence lateral friction and overall load transfer. Screw piles exhibit greater side resistance and lower stress concentration at the tip compared to smooth cylindrical piles[40].

2.5 Failure Under Lateral Loading

Keawsawasvong and Ukritchon (2020) state that failure of laterally loaded piles occurs when the applied lateral load–moment demand reaches the soil–pile limit state. At this point, the soil can no longer provide adequate resistance, leading to the development of a failure mechanism. Their findings demonstrate this behavior using a normalized lateral load–moment failure envelope, indicating that capacity is governed by the combined action of lateral load and moment, rather than by lateral load alone, as illustrated in Figure (9)[41].

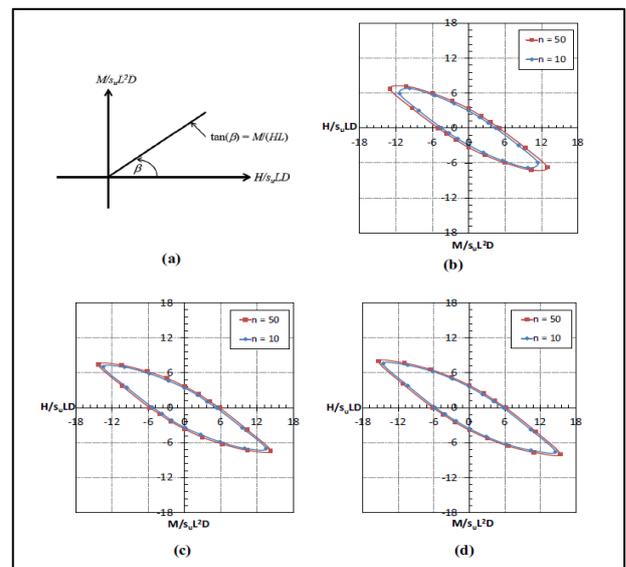


Figure 9. Failure envelopes of piles subjected to lateral loading under combined horizontal force and moment: (a) definition of the failure envelope; (b) $L/D = 10$; (c) $L/D = 40$; (d) $L/D = 60$ [41]

Kunasegaram and Takemura (2022) state that the lateral response of a pile is determined by its relative stiffness compared to the surrounding ground. Short, stiff (rigid) piles primarily deform through rotation near the base or embedded region. In contrast, long, flexible piles mobilize resistance via distributed bending along a greater length of the shaft, resulting in a more gradual soil–pile deformation pattern. This distinction is evident in the breakdown of displacement components for short and long socketed piles[42]. According to **Guangwei et al., 2023** large-diameter monopiles can trigger additional rotational soil-flow mechanisms, thereby modifying the governing failure mechanisms and associated bearing capacity. The study emphasizes that base shear and bending

moments are key contributors to lateral load resistance and overall response[43].**Hong et al., 2017** showed that, under one-way cyclic lateral loading in soft clay, a semi-rigid pile can shift from flexure-dominated (flexible) behavior to rotation-dominated (rigid) behavior as cyclic degradation reduces pile–soil stiffness. This transition changes the soil-flow mechanism from wedge/full-flow patterns to a pronounced rotational soil flow near the lower pile region, as illustrated in Figure (10)[44].

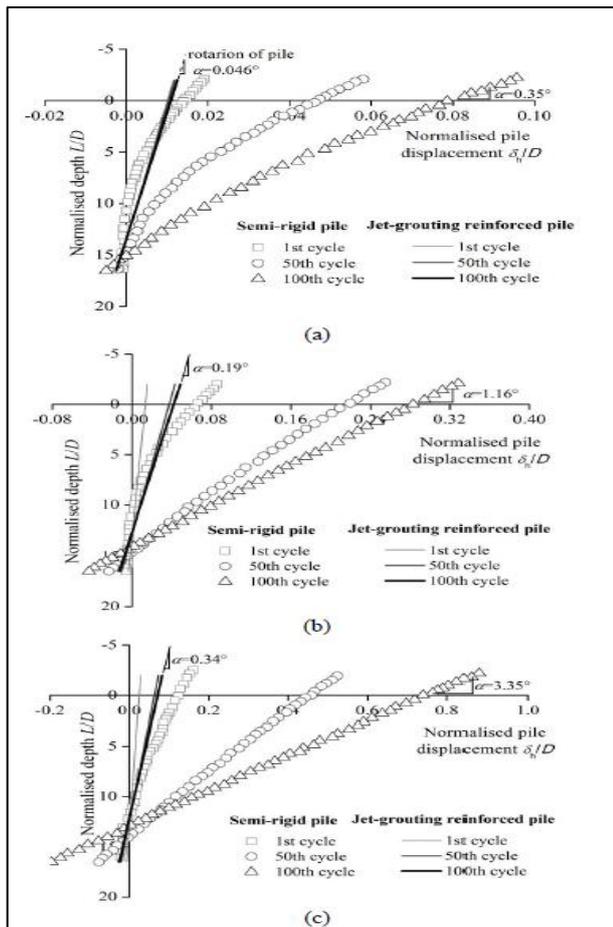


Figure 10. Measured lateral deformation responses of the semi-rigid pile and the jet-grouting-reinforced pile for: (a) the first cycling stage; (b) the second cycling stage; and (c) the third cycling stage [44]

Lichen et al., 2025 demonstrate that advanced numerical models and centrifuge tests reveal that failure mechanisms frequently involve excessive pile rotation in conjunction with wedge-shaped soil failure near the surface. Soil type, pile embedment depth, and pile geometry are identified as significant factors influencing these processes[45]. **Islam et al., 2024** found that pile-group lateral response is strongly controlled by spacing and cement-improved

soil (CIS). Adding or thickening CIS around the piles reduces bending demand and protects against tensile damage. They reported reductions in bending moment and head displacement for group piles. This reduction is evident in the group bending-moment profiles shown in Figure (11). Increasing CIS thickness and widening spacing lowers the maximum positive bending moment compared with groups without CIS[46].

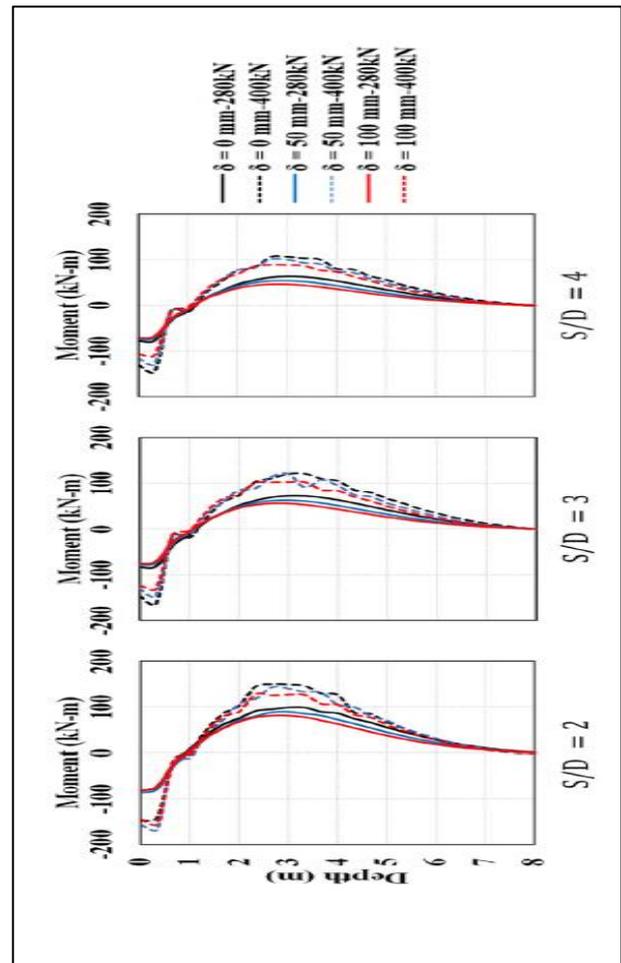


Figure 11. Depth-dependent sectional bending moment responses of grouped piles under 280 kN and 400 kN loading ($L/D = 30$), with emphasis on the roles of the CIS layer and pile spacing[46]

2.6 Analysis of Laterally Loaded Piles

According to **Moussa & Christou (2017)**, laterally loaded pile analysis is essential for capturing pile response to horizontal actions such as wind and earthquakes, where design focuses on lateral deflection and the distribution of soil reaction along the shaft. In the classical subgrade-reaction (Winkler) approach, the pile is idealized as a beam on an

elastic foundation represented by independent springs, and the soil reaction at a point is assumed to be proportional to the lateral displacement at that point. This idealization and its pile-spring representation are commonly illustrated using the laterally loaded pile model and associated p - y springs as shown in figure (12) [46].

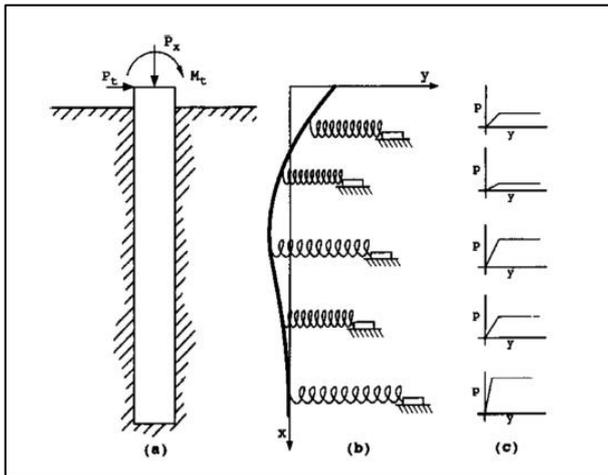


Figure 12. Conceptual model of a pile under lateral loading: (a) elevation view; (b) elastic-line idealization; (c) p - y curve formulation [47]

Ouyang et al., 2024 observe that numerical soil-structure interaction (SSI) analyses, such as finite element method (FEM) implementations, are particularly effective for laterally loaded piles. These analyses more accurately capture nonlinear soil response by discretizing the surrounding ground into multiple interacting elements or springs, rather than relying on linear soil behavior assumptions as shown in figure (13). This increased modeling fidelity enables detailed predictions of pile deflection and internal forces along the embedment. However, it requires extensive meshing and iterative computation[48].

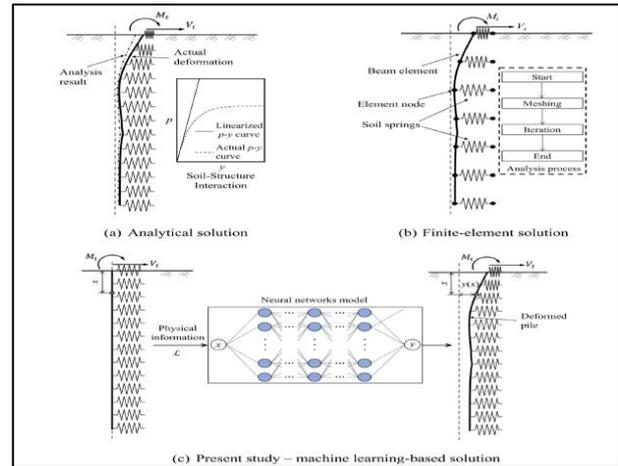


Figure 13. Analytical and numerical solutions for soil-structure interaction in laterally loaded piles[48]

(Mu et.al. 2017) [49] conducted a sequence of model experiments to examine the influence of vertical loads on the lateral response of monopiles in sandy soil. The study involved the examination of a smooth aluminium pipe pile model with dimension of 48mm in diameter and 400 mm in length implanted within a dry sandy soil. The introduction of vertical loads exhibited a linear enhancement in the lateral bearing capacity of monopiles in the sand, provided that the vertical load was applied before the horizontal load. The inclusion of the vertical load concurrently diminished the maximum bending moment and the lateral deformation experienced by the monopile when subjected to a designated lateral load mainly because placing a vertical load on the pile augmented the p - y curves adjacent to the pile, which was mostly due to the heightened stress levels induced in the soil.

Wyjadłowski (2025) states that semi-empirical, or semi-experimental, design methods, such as the Broms method, estimate ultimate lateral pile capacity. These methods integrate simplified mechanics with assumptions calibrated to experimental data. In this methodology, soil at failure is represented by an ultimate lateral pressure distribution corresponding to the plastic or passive state. The method differentiates between short (rigid) and long (flexible) piles by applying different failure and rotation assumptions. Figure (14) shows typical ultimate pressure distributions used in design[50].

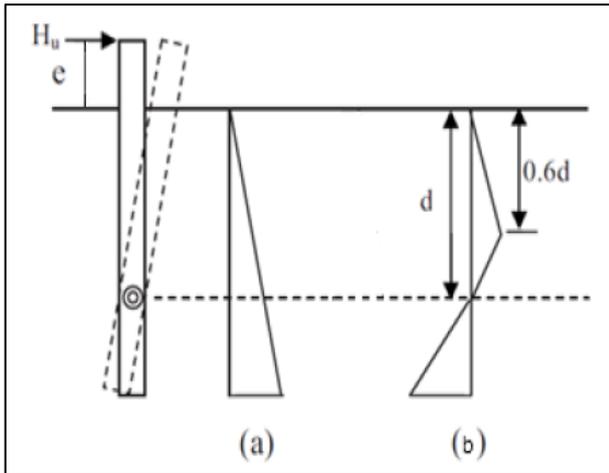


Figure 14. Lateral soil pressure distribution at ultimate capacity: (a) Broms method; (b) Petrasovits method [50]

Zhang et al., 2021 describe the p–y curve method as a practical soil–pile interaction approach that represents the soil response at each depth using a nonlinear relationship between lateral soil resistance P and pile deflection y . Because this point-based constitutive representation is simple and shows good agreement with field-test behavior in sand, it is widely adopted for iterative evaluation of pile response; a typical expression is $P = \eta P_u \frac{y}{y+y_0}$.

The loading framework commonly used with this approach (including lateral load, soil resistance, and related effects) is illustrated in figure (15) [34].

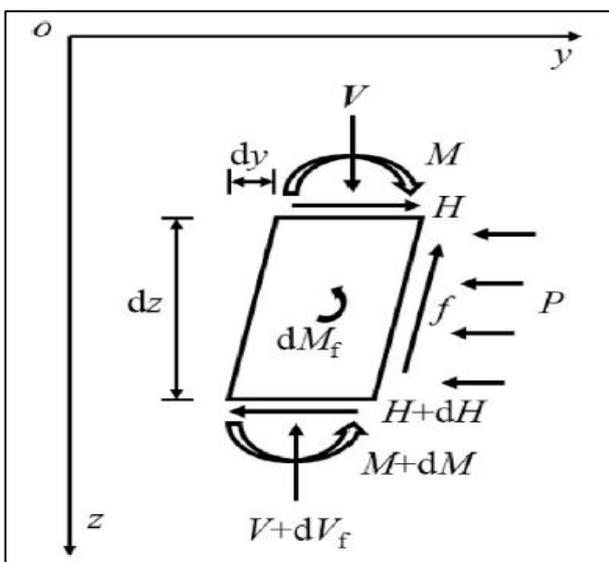


Figure 15. Stress analysis of the pile section[34]

Zheng et al., 2024 report that recent advances include the application of machine learning techniques, such as physics-informed neural networks, for efficient soil-structure interaction modeling. Additionally, the development of refined analytical models for floating piles has improved both prediction accuracy and computational efficiency in lateral load analysis[26].

2.7 Factor Effect on Load Capacity

2.7.1 Effects of Spacing on Load Capacity

Several studies have indicated that the spacing between piles directly impacts the load capacity of the group. According to **Duncan and Seed (1986)** [51], closer spacing can lead to increased group efficiency due to reduced soil failure mechanisms around the piles. However, **Mu et al. (2017)**[52] found that excessive closeness (spacing less than 3 times the pile diameter) can cause negative interactions that may reduce overall capacity. The distribution of load intensity beneath pile groups is influenced by both pile load and pile spacing, according to more recent studies that use finite element modeling (**Wang et al., 2018)** [53]. In order to balance construction costs and structural performance, these studies place a strong emphasis on optimizing pile spacing. The interaction of stresses as shown in figure (16) according to **Elshehawy (2019)** [54].

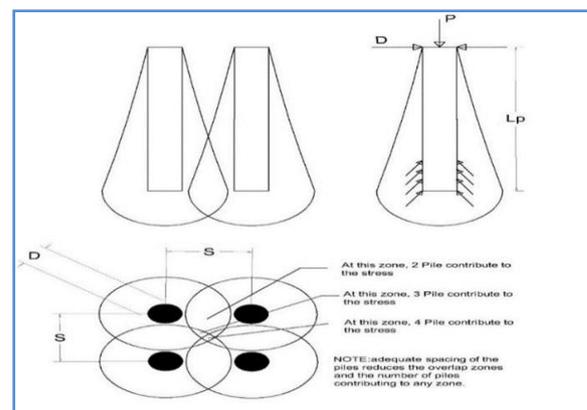


Figure 16. Interaction stresses zones of a pile group and the stresses around a friction pile [54]

According to **Elshehawy and Altharany (2020)** [55], the recommendation of distance between pile are listed in Table 1.

Table 1: Recommendation distance

Type	Recommended center-to-center spacing
Friction piles in cohesive or medium-density soils	3D
End Bearing	2.5*2.5D<
Friction and End bearing Type	2.5to 3.5D
Large spacing pegs	3D until 5D
economically maximum	5D<

2.7.2 Effects of Diameter and Length Pile

The diameter and length of piles significantly influence their load-bearing capacity, settlement behavior, and overall performance. Larger diameter piles tend to have reduced settlement under the same load due to increased stiffness and soil-pile interaction (**Tomlinson and Woodward, 2008**)[56]. Increasing pile diameter generally increases the cross-sectional area and the surface area in contact with soil, enhancing both end-bearing and skin friction capacity (**Das, 2010**) [57]. Frictional resistance increased with soil depth, with different degrees of abrupt changes due to soil layers' properties. Increasing pile length and diameter can reduce foundation settlement, with 25.7% reduction in 65-75 m piles and 35.9% reduction in 1.5-2.0 m piles. Sedimentary soils in coastal areas are mostly sandy and soft, so increasing pile spacing can minimize settlement **Nguyen et al. (2014)** [58], this details are shown in figures (17) and (18)

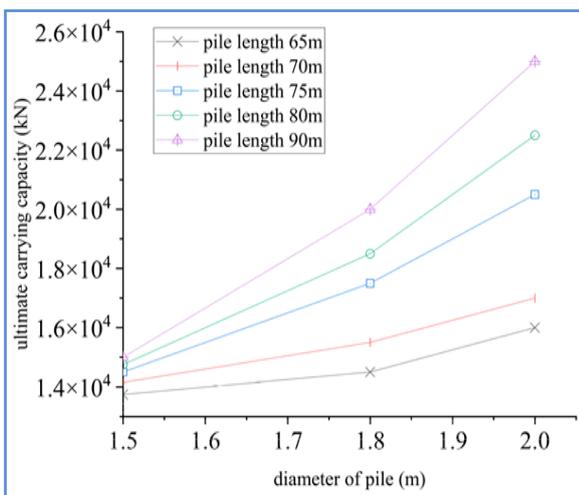


Figure 17. Bearing capacity variation rule with pile diameter [58]

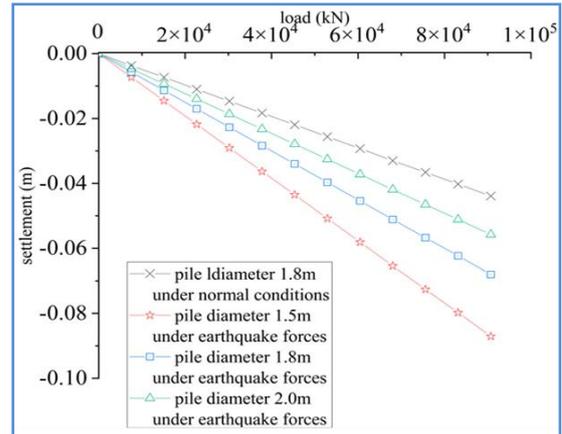


Figure 18. Influence of the pile diameter on the settlement of the pile group foundation [58]

2.7.3 Influence of Soil Type

The performance of bi-directional loading piles is significantly influenced by soil characteristics. Studies have shown that soil type, cohesion, friction angle, and density impact the load-bearing capacity and lateral resistance of piles.

Cohesive Soils: Research by **Zhang et al. (2016)** [59] indicates that bi-directional loading piles exhibit different behavior in cohesive soils compared to granular soils. In cohesive soils, the mobilization of shear strength plays a critical role in resisting lateral loads. Granular Soils: In granular soils, the inter-particle friction and density influence the lateral resistance. **Wang and Huang (2019)** [60] found that the effective stress principle is crucial in understanding pile behavior under lateral loading in these soils.

2.7.4 Settlement Behavior

The piles' entire bearing capacity may be utilized when they are employed as settlement reducers. To deploy the shaft pile's whole bearing capacity, relatively little soil settlement is required **Elshehawey et al. (2019)** [54]. When piles are spaced too closely, there can be a significant increase in total settlement due to the overlapping stress zones in the soil. Conversely, optimal spacing can

3. Conclusions

Deep foundations in sand often carry combined vertical and lateral loads, so behavior can differ from single-load assumptions. Response

depends on soil–pile interaction, pile geometry, loading sequence, and (for groups) pile–pile interaction.

- Axial resistance mobilizes via shaft friction + toe bearing as settlement develops.
- Lateral response depends on L/D, head fixity, and nonlinear soil reaction (p–y/Winkler; FEM for complex cases).
- Vertical load can change lateral capacity: often increases it in sand (higher confinement), but may decrease it in clay/layered soils.
- Group performance is highly spacing-dependent; very close spacing can increase settlement due to overlapping stress zones.
- Larger diameter/length generally improves stiffness and capacity, but cost and group interaction must be considered.
- Design should include combined-load effects, loading sequence, and validated nonlinear group analysis.

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