Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 3, Issue 5, 2025

BEHAVIOR OF A LATERALLY LOADED PILE IN A PILE GROUP: A SIMPLIFIED ANALYTICAL STUDY

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DOI: https://doi.org/

Keywords
Single pile, pile group, lateral load, Simplified procedure

Article History
Received on 22 April 2025
Accepted on 22 May 2025
Published on 29 May 2025

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Abstract
Pile foundations are widely used to support superstructures where surface soils are weak or compressible. While vertical loads have traditionally been the main focus, piles also encounter substantial lateral loads in bridges, high-rise buildings, berthing structures, and offshore platforms. This study investigates the behavior of laterally loaded piles both as isolated single piles and as components of a pile group with varying center-to-center spacing. A comparative analysis is conducted using Allpile software to evaluate the bending moment response under lateral loading. The results demonstrate the significant influence of pile spacing on group interaction effects. At closer spacing (e.g., 3D), lateral moments increase due to load redistribution and shadowing effects. As spacing increases (up to 8D), the group effect diminishes and the pile behavior approaches that of a single isolated pile. This study provides practical insights into optimal pile group configurations and validates the importance of considering pile-soil-pile interaction in lateral load analysis.

INTRODUCTION

A pile is a long, slender foundation element, typically constructed from concrete, steel, or timber, designed to transfer structural loads to deeper, more competent soil layers. When used as construction foundation elements, the piles effectively transfer the structure's loads to the earth (Toprak, 2018). In cases where shallow foundations are unsuitable due to weak soil strata, piles serve to improve load-carrying capacity and offer resistance against both axial and lateral forces.

Traditionally, vertical piles were primarily used for axial load resistance, with batter piles preferred for lateral resistance. However, modern research has established that vertical piles also provide substantial lateral load capacity, making them viable for a wide range of structures subjected to lateral forces.

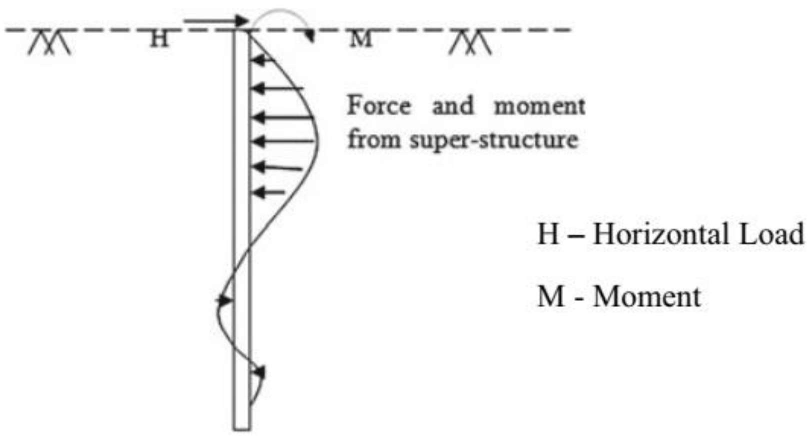
Piles serve as vertical or slightly slanted columns that transfer weights to a deeper, more capable soil layer from the superstructure (such as a building or bridge). Additionally, they can increase the soil's carrying capacity by offering deeper-level support. Moreover, Piles can serve as retaining elements or fenders by withstanding lateral loads. Because piles can also resist lateral loads not only axial loads. The piled raft foundation consists of three bearing elements: piles, raft, and subsoil. The function of the piles is to reduce settlements by transferring the load deep into the soil (Katzenbach, R., et al., 1998).

The pile group foundation, a geotechnical composite design made up of three components piles, pile cap, and soil—is being used more and more for tall building foundations. Complex interaction effects between the elements affect the behavior of the foundation system, and a trustworthy design requires an understanding of these effects. Pile groups, rather than single piles, are typically used in practice. In a pile group, the behavior of each individual pile is influenced by the surrounding piles due to soil deformation, load redistribution, and group interaction effects. Therefore, understanding how pile spacing influences lateral performance is critical in the design of deep foundations.

1. Literature Review

The piles are capable of bearing lateral loads as well as a combination of lateral and vertical loads in addition to supporting vertical loads. However, piles' lateral and vertical responses are frequently assessed independently without taking into account any potential interactions (Hazzar et al., 2017). According to Rollins et al. (2006), piles are usually built in groups, and their placement within the group has a direct impact on their performance, particularly on their lateral behavior. The lateral load resistance of the piling foundation of these structures is critical to their design under lateral loads from soil movements, wind, waves and earthquakes (Ahmed et al., 2009).

In earlier practices, vertical piles were considered effective only for resisting axial loads, while batter piles were preferred for handling lateral forces. However, subsequent research and field experience have demonstrated that vertical piles also possess significant lateral load-carrying capacity. The deflection of the pile creates strains in the soil. To maintain equilibrium, the soil must react along the pile's length to balance the applied loads and moments (Budhu, M., 2011). As a result, they are now commonly utilized in high-rise buildings, bridges, berthing facilities, and offshore structures that are subjected to substantial lateral forces as shown in (Sivapriya, 2022).



Figures.1: mechanism for the pile's load transmission from the superstructure to the soil

Many constructions often experience lateral loads due to ground pressure, wave action, earthquakes, wind, and ship collision. Although piles are usually used in groups, most studies focused on the behavior of single, laterally loaded piles. In order to better understand the critical elements that affect the response of laterally loaded pile groups (2 x 2 and 3 x 3 pile configurations), such as sand relative density, pile spacing (s = 2.5 D, 5 D, and 8 D), and pile location within the group, three-dimensional finite element Plaxis modeling is employed in this study. It is shown that under the same lateral pressure, piles positioned adjacent to one another deflect more than a single pile due to the group effect. The load deflection response of piles in groups is softer than that of a single pile load deflection curve. The shadowing effect decreases with increasing pile separation, making the difference less obvious. For a given displacement, the middle and rear rows of a pile group with a fixed head bear less weight than the front row, which bears the maximum weight (Elhakim et al., 2016).

Mechanism of Pile Under Lateral Load:

Pile foundations for marine constructions, offshore platforms, and bridge piers must be able to withstand both lateral dynamic loading and static loading. It is common for pile foundations to experience both lateral and vertical loads. The pile design is done independently for vertical and lateral loads since current design standards believe that the effects of these two loads are independent of one another (Karthigeyan, S., 2006). A common method for connecting pile deflections to nonlinear soil reactions is to employ static p-y curves. By comparing the load transfer curves of a group of piles to those of a single pile, the p-multiplier idea is utilized to account for the group effect.

A cylindrical pile under lateral stress Qh is sketched in Figure.2-a, with a thin soil slice visible at depth z1. Figure.2-b and c show the identical scenario below the ground line. For a pile that has been installed without bending, the consistent distribution of stresses normal to the pile wall in Figure.2-d is valid. The distribution of the stresses would resemble that in Figure.2-e if the pile were to deflect a distance y1, which is inflated in the sketch for clarity. The pile's active zone, or back side, will experience less stress, while the passive zone, or front side, will experience more (García et al., 2022).

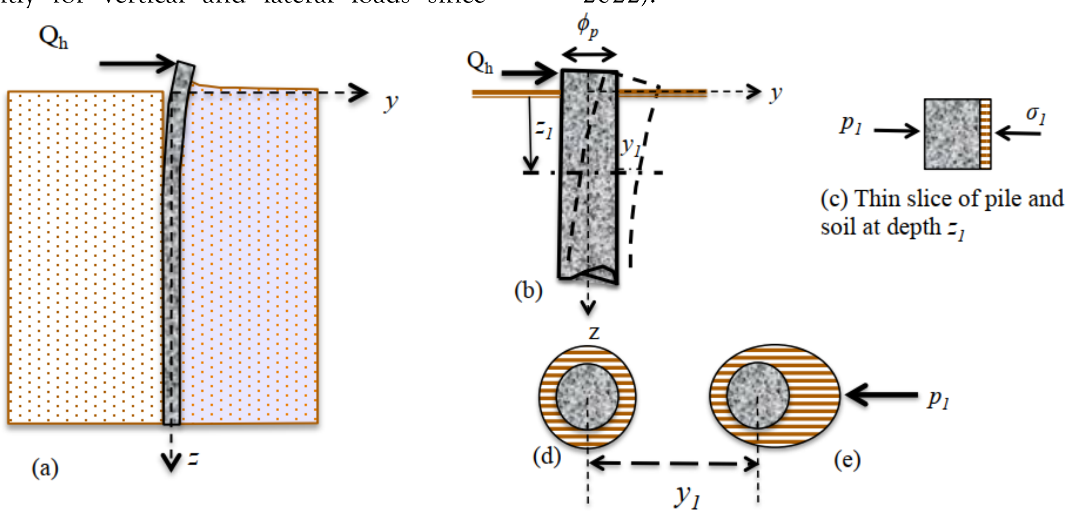


Figure.2: Pile Under Lateral Load

Shafts with a single drill can support extremely high lateral stresses. Bhushan et al. (1978) presented test findings showing that drilled shafts with a high diameter in hard clay may support lateral stresses up to 400 kips (Meyer & Reese, n.d.).

According to Brown et al. (1988), one of the most popular techniques for taking into account the group reduction effects is to use a P-multiplier to alter the single pile p-y curve. Reese and Matlock (1974) introduced the p–y curve method to simulate nonlinear soil resistance under lateral pile loading, laying the foundation for most modern lateral pile analyses. Hazzar et al. (2017) investigated combined vertical and lateral loading in pile groups and demonstrated the influence of pile group spacing on lateral stiffness (Hazzar et al., 2017). Rollins et al. (2006) reported significant reductions in lateral capacity due to group effects and emphasized the role of pile spacing.

Sivapriya (2022) reviewed studies on laterally loaded vertical piles and highlighted the importance of considering load interaction in sloping and horizontal grounds. García et al. (2022) evaluated defective piles in group configurations, underscoring the complexity introduced by load sharing and interaction. These studies collectively emphasize the need for spacing optimization in pile group design to balance performance and cost. With increase in spacing and number of piles in agroup, the lateral load capacity increases (Sivapriya & Muttharam, 2019).

3. Objective

- To compare the lateral behavior of a single pile versus piles in a group configuration.
- To assess the effect of pile spacing (3D, 4D, 5D, 7D, and 8D) on lateral bending moments.
- To analyze results using simplified analytical methods through Allpile software.

2.Methodology

The study uses Allpile software, which implements the FHWA's p–y curve approach for lateral load analysis. A single pile and several 3×3 pile groups are modeled. The center-to-center spacing between piles in group configurations is varied: 3D, 4D, 5D, 7D, and 8D, where D is the pile diameter.

- **Pile Diameter:** 2 ft
- **Pile Length:** 60 ft
- **Load:** Combined lateral and vertical loads (values held constant across models)

Each model is analyzed to extract the bending moment experienced by the pile under lateral loading. Comparative results are plotted and discussed to evaluate the effect of spacing on group interaction.

3. Results and Discussion

The moment on a single pile is 235 kip-ft, as shown in Figure.3.

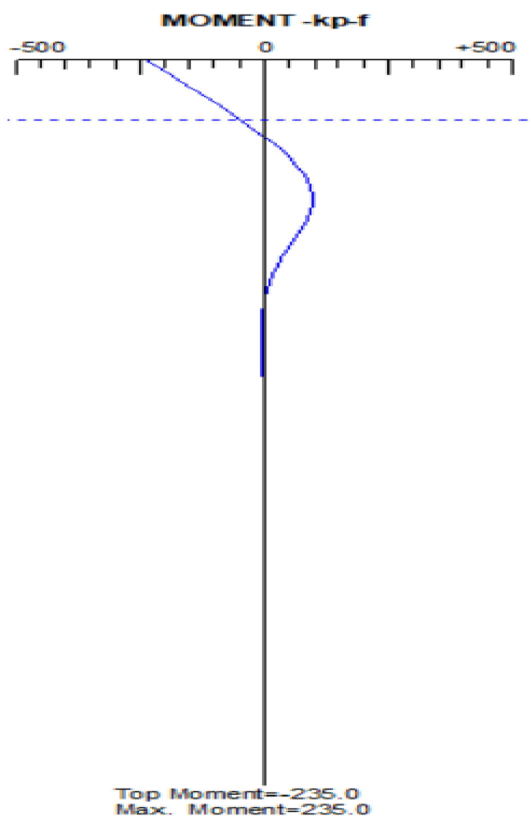


Figure.3: Single Pile Moment

Group Pile of 3d Spacing:

The moment on a pile in a pile group is 249.2 kip-ft, as shown in Figure.4.

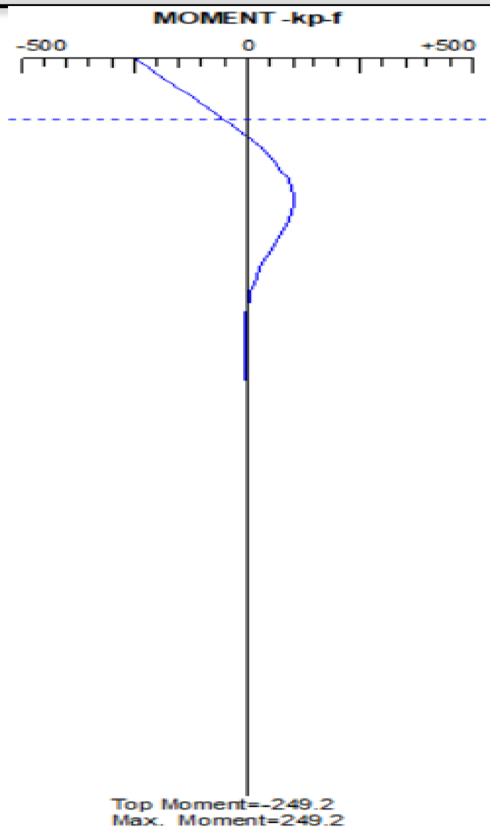


Figure.4: Moment on a pile in a pile group

Group Pile of 4d Spacing:

The moment on a pile in a pile group of spacing 4d is 239.2 kip-ft, as shown in Figure.5

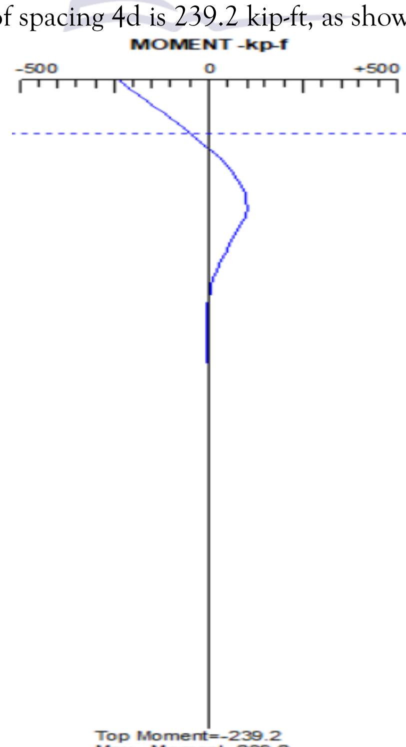


Figure.5: Moment on a pile in a pile group

Group Pile of 5d Spacing:

The moment on a pile in a pile group of spacing 5d is 235kip-ft, as shown in Figure.6.

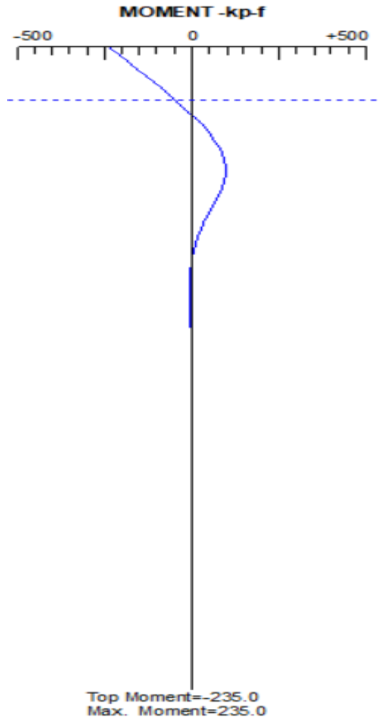


Figure.6: Moment on a pile in a pile group

Group Pile of 7d Spacing:

The moment on a pile in a pile group of spacing 7d is 233.3 kip-ft as shown in Figure.7.

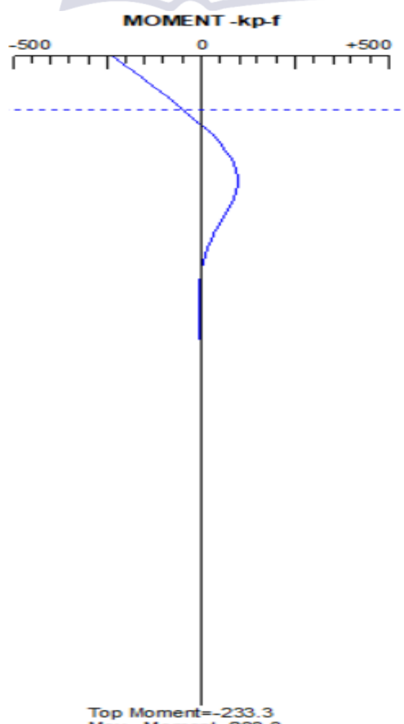


Figure.7: Moment on a pile in a pile group

Group Pile of 8d Spacing:

The moment on a pile in a pile group of spacing 8d is 232.5 kip-ft as shown in Figure.8.

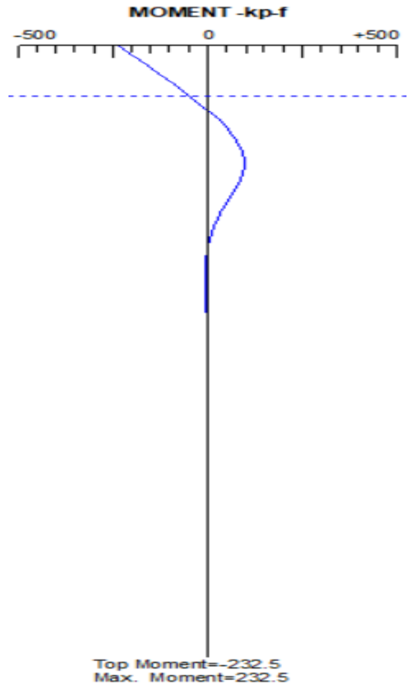


Figure.8: Moment on a pile in a pile group

In tabulated form.

Table.1: Maximum Bending Moment

Configuration	Bending Moment (kip-ft)
Single Pile	235.0
Group Pile (3D spacing)	249.2
Group Pile (4D spacing)	239.2
Group Pile (5D spacing)	235.0
Group Pile (7D spacing)	233.3
Group Pile (8D spacing)	232.5

As shown in the Table.1, the maximum bending moment occurs in the 3D group configuration, indicating strong group interaction and load amplification due to reduced spacing. The moment decreases as spacing increases, approaching the value for the single pile at 5D spacing.

Interestingly, the results also indicate that at 7D and 8D spacing, the bending moment was slightly lower than that of the single pile. While this may appear counterintuitive, it is likely due to simplified soil behavior modeling within the software, boundary condition effects, or slight load redistribution among piles in the group configuration. Additionally, the p–y curve softening in cohesive soils may allow slightly more efficient resistance distribution in wider spacing scenarios. These findings emphasize the importance of validating simplified models against field or advanced numerical results and recognizing the limitations inherent in empirical methods.

6. Conclusion

This study confirms the influence of pile group spacing on lateral behavior. At close spacing (3D–4D), pile-to-pile interaction increases lateral demand due to overlapping stress zones and load sharing. At wider spacing (7D–8D), each pile behaves independently, and the group effect becomes negligible.

Engineers must consider group interaction in preliminary and detailed designs, especially when spacing is below 5D. Simplified tools like Allpile are effective for capturing general trends and are particularly useful for preliminary designs. For critical structures or highly irregular configurations, 3D numerical modeling is recommended for greater accuracy.

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