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Numerical evaluation of load transfer between adjacent piles under varying load conditions

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Abstract
Most facilities and tall buildings require deep foundations to transfer structural loads to stronger underlying soil layers. In many cases, only part of a facility may be loaded while adjacent areas remain unloaded. Therefore, accurately evaluating the load transfer between neighboring piles is crucial for ensuring structural integrity. This study employs a numerical approach using ABAQUS 2020 software to analyze the magnitude of load transfer between two adjacent piles, focusing on their interaction with the surrounding soil. The piles modeled are steel pipes filled with concrete and embedded in clay soil, subjected to various loading scenarios. The effect of pile spacing on load transfer behavior was investigated by considering three different distances between piles: 2.5D, 4D, and 6D. Four loading scenarios were analyzed: Horizontal load applied to pile 1, with pile 2 unloaded; Torsional load applied to pile 1, with pile 2 unloaded; Horizontal load on pile 1 and vertical load on pile 2; Torsional load on pile 1 and vertical load on pile 2. The results highlight that the interaction between neighboring piles significantly influences geotechnical performance. A smaller pile spacing leads to higher load transfer. The transferred load notably affects shear forces and bending moments in the adjacent pile, regardless of whether it is loaded. The shear force transfer ratio was found to range from 11% to 28%, while the bending moment ranged from 19% to 31%. Based on the results, a spacing of 2.5D is recommended as optimal for effective load transfer, aligning with the guidelines of ACI-2019 and IS-2011 codes.

Keywords
Load transfer, Adjacent piles, Pile spacing, Numerical simulation, ABAQUS, Geotechnical engineering.

1.Introduction
Single piles and piles groups are widely used to transfer loads to a strong stratum. Therefore, this deep foundation has been used in the construction of tall buildings, towers, offshore structures, bridges, and any structure that requires this deep foundation [1]. The design of a pile or pile group is crucial in geotechnical engineering and depends on the magnitude of the load transferred along the pile, which directly impacts the stability of the structures built above them [2, 3]. The transfer of applied loads from a building to the soil depends on several factors, including the type and number of piles, their distribution method, soil properties, soil-pile interaction, and the type of load on the pile head [4].

Predicting load transfer—whether from a pile to the soil, between individual piles, or within a pile group—relies on accurate modeling of their physical behavior [5–10]. Several numerical methods have been developed to determine load transfer, including those proposed by [11–13]. However, some of these methods rely on impractical systematic calculations, necessitating the development of new, applicable methodologies for pile design. Al-jeznawi et al. [14] proposed a load transfer method based on the relationship between applied load and recorded settlement, offering a simple approach with direct results.

Traditional methods, based on mathematical calculations, have been used to evaluate the maximum load-bearing capacity of vertical piles, as

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demonstrated in studies [15, 16]. The interaction between pile and soil or a group of piles with the soil is a difficult problem for the design of the pile due to the excavation or driving the pile which leads to movement of the soil surrounding the pile and loosening of the soil properties [17–22]. The ABAQUS program relies on a set of methods to represent the interaction between the soil and piles by giving accurate specifications for the soil surrounding the pile [23, 24]. The current research applies a simplified strategy to model soil–pile interaction, assuming a fully bonded connection between the two.

Estimating the magnitude of load transfer between piles is a critical challenge in structural pile design, particularly when calculating shear forces and bending moments at their peak values. Therefore, this study contributes to addressing these challenges by calculating the magnitude of loads based on the type of load applied to piles made of concrete-filled steel tubes submerged in clay soil.

Section 1 outlines the significance of deep foundation design and explores the various methods used to calculate load magnitudes on piles. Section 2 provides a summary of recent key studies related to load calculation techniques. Section 3 describes the problem formulation, material properties, ABAQUS modeling procedures, and the adopted solution approach. Section 4 presents and discusses the simulation results in detail, including an analysis of the study's limitations and corresponding recommendations. Section 5 concludes the study, highlighting the key findings.

2.Literature review

This section reviews the topic of load transfer between supports within a single structure or across multiple structures.

Song et al. (2024) employed analytical methods to assess the effect of vertical loading on the behavior of piles subjected to lateral dynamic loads. Additionally, the obtained results were compared with the available techniques [25]. Fuentes and Ledezma (2024) investigated the structural dynamic behavior of vertical piles in a port platform under wave loading, taking into account soil–pile interaction. The displacement and bending moment of the deck on the piles were assessed for a set of geotechnical, hydraulic, and structural variables. The results indicated that resonance impacts associated with dynamic loading and the superposition of short-period waves significantly affect the response to irregular wave cases [26]. Ma et al. (2024) conducted a study on the behavior of a bearing pile subjected to time-harmonic torsional loading. The pile was embedded in unsaturated, homogeneous, transversely isotropic soil to examine its torsional dynamic behavior. The governing equations related to soil were derived in cylindrical coordinates, and a one-dimensional elastic theory was used to model the piles [27]. Barbieri et al. (2024) developed a stochastic model for the pile's dynamic response to harmonic loading, considering on the uncertainty for the pile and the soil mechanical parameters respectively. The impact of pile diameter(D) and its uncertainty properties, along with mean soil stiffness and the selection of distribution models for random variables, were assessed [28]. Yang and Jia (2023) adopted a coupling method to investigate the behavior of pile groups located adjacent to a surcharge load. The equations of pile group's dynamic response have been derived by adopting the coupled method finite element method-boundary element method (FEM-BEM). The location of the maximum pile displacement response is seen to shift from the middle of the soft soil layer to the top of the pile as the surcharge load increases. The influence of the surcharge load is not significant when the distance between the groups and the applied load is greater than twice the soft soil layer thickness. The center of the soft soil layer and the interface between the soil layers exhibit comparatively large bending moments [29]. Wu et al. (2023) analytically investigated the dynamic impedance of pile groups. The accumulation of hydrodynamic pressure and secondary ground waves is considered in the solution. The pile was modeled using the Euler-Bernoulli beam theory, which was employed to determine the hydrodynamic pressure. Also, the saturated soil surrounding the pile was described by Biot's dynamic poroelastic theory [30]. Gu et al. (2022) studied the offshore structures pile foundation dynamic stability to ship impacts and wave loads. Also, the study dealt with the impact of soil properties, pile length, and stiffness on the performance of piles [31]. Baqi et al. (2022) conducted a numerical analysis to investigate the nonlinear behavior of a hollow steel single pile with a concrete pile cap subjected to combined lateral and axial loads. The response is expressed in terms of horizontal and vertical displacement as well as the stresses that are developed in both pile and soil [32]. Luan et al. (2020) calculated by a new analytical model the pile group dynamic horizontal impedance. The solution included pile to pile interaction influence, by adopting the secondary wave which is generated by vibration [33]. Also, Luan et al. (2020) calculated by an analytical model the pile group dynamic impedance. The solution included the ground wave owing to pile vibration in both vertical and horizontal planes respectively. The study also considered the impact of the actual pile section geometry on the reaction from the surrounding soil [34]. Huissen and Albusoda (2021) used FLAC 2D software to conduct a numerical investigation on a single pile subjected to combined loading (lateral and axial loads) under various earthquake motions. Several variables were analyzed, including pile head vertical deflection, pore water pressure, and lateral displacement of the soil surface along the pile depth [35]. Abbas and Mahmood (2021) studied experimentally the piles group performance adopting piles shape and axial load when the group was under cyclic loading. In addition, the study examined the influence of pile spacing on lateral displacement under pure and combined loading [36]. Qasim and Hasan (2020) used the finite element method, implemented in ABAQUS software, to reveal the response of piles supporting the offshore platform to dynamic ship impact load. The pile response has been expressed in terms of lateral deflection, twist angle, shear force and bending moment [37]. Khalil et al. (2019) evaluated numerically in three dimensions the dynamic response of pile-soil interaction between neighboring piles in the same group. The results from the numerical simulation have been compared with those from a selected study to verify their accuracy [38]. Ismael and, Ahmed [39] used the finite element method and Plaxis 3D program to study the response of piles in slope soil under the influence of earthquake loads and the modality of loads transferred between the pile group. It was observed that the settlement of the piles increases as the intensity of the earthquakes increases. The type of earthquake affects the amount of settlement of the piles, and the pile cap plays a key role in distributing the load on the piles. Using the plane-tension theory, Zhong and Meng [40] studied the effect of soil-pile vibration on several models of piles. The study considered the effect of the passive scuttle of piles under the action of waves and the effect of load transmission through the pile. The study found that the slenderness of the pile has a significant adverse effect on the oscillations transmitted between the piles and the soil. These frequencies decrease with increasing slenderness, and stiffer piles given the greater interaction factor.

The study was conducted on single piles and pile groups. The aim of this study is to evaluate the magnitude of load (horizontal or torsional) transferred from one loaded pile to another (unloaded or loaded pile) through soil-pile interaction and to analyze the pile response in terms of shear forces, bending moments, soil reaction, and pile displacement.

3.Materials and methods

The problem methodology comprises the following parts.

3.1Problem description

The current work focuses on calculating the magnitude of lateral or torsional load transferred from one pile to another through soil-pile interaction. *Figure 1* clearly illustrates the problem, where piles P1 and P2 have a length of 30 m, a diameter of 500 mm, and a thickness of 12.7 mm. These piles are surrounded by cohesive soil and protrude 1 m above ground level. The distance between the two piles varies and is expressed in terms of pile diameter. Three different distances are considered in this study: 2.5D, 4D, and 6D, where D represents the pile diameter. For the soil domain, the distance from the pile center to any domain side is 10D, which is also the distance from the pile base to the bottom of the domain. The bond between the pile and the surrounding soil, as well as the bond between the steel pipe wall and the concrete core, is assumed to be fully developed.

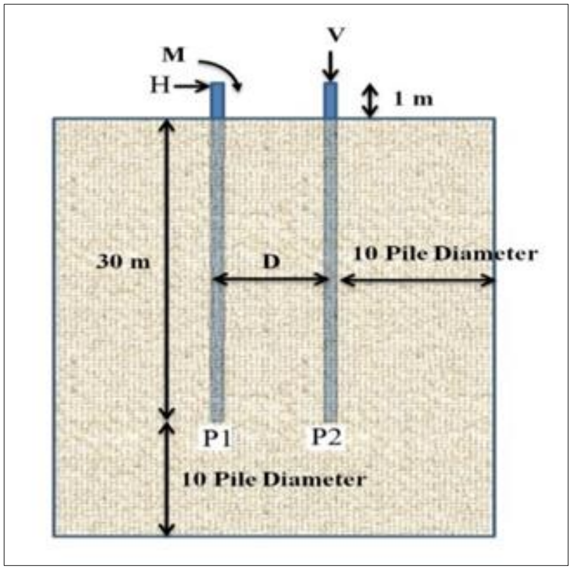


Figure 1 Problem description

3.2Materials descriptions

Basically, three materials are used in this study: steel and concrete for piles and clay for the soil surrounding of two piles. All these materials are in an elastic- plastic state, where clay is described by the Coulomb model as shown in *Table 1*. *Table 2* shows the specifications of the steel material that makes up the pile in an elastic- plastic state. The concrete material used in the tube pile, as shown in *Table 3*, is also in an elastic-plastic state. The ABAQUS program contains many models of the materials used in their different states (plastic, flexible, and elastic) [41–46]. The ABAQUS software adopts the quasi-Newton method to calculate the nonlinearity of materials and calculate the convergence through the amount of increase.

Table 1 Soil material properties based on the Mohr–Coulomb model

Variable	Unit	Value	
Mass Density γ	kg/m^3	1700	
Young's Modulus E	MPa	8.6	
Poisson's Ratio ν			0.4
Cohesion C		kPa	20

Table 2 Mechanical properties of steel

Variable	Unit	Value
Mass Density γ	kg/m3	7850
Young's Modulus E	MPa	2E9
Poisson's Ratio ν		0.3
Yield stress σ	MPa	550
Strian ε		0.003

Table 3 Mechanical properties of concrete material

Variable	Unit	Value
Elastic properties		
Mass Density γ	kg/m3	2400
Young's Modulus E	MPa	30
Poisson's Ratio ν		0.2
Plastic properties		
Dilation angle ø		38
Eccentricity *e*		0.1
The ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress (Fb0/fc0)		1.12
The ratio of the second stress invariant on the tensile meridian (k)		0.666
Viscosity μ		0.002

3.3Boundary conditions

The domain based has been adopted full fixed while, the domain sides that are parallel to the x-direction allow to move in y-direction and the domain sides that are parallel to y-direction allow to move in x-direction [47–49].

3.4Loading conditions

The current investigation depends on four various loading conditions and these conditions are shown below:

1. A lateral load of 30 tons is applied at the head of pile P1, while no load is applied at the head of pile P2.
2. A torsional load of 30 ton·m is applied at the head of pile P1, with no load applied at the head of pile P2.
3. A lateral load of 30 tons is applied at the head of pile P1, and a vertical load of 30 tons is applied at the head of pile P2.
4. A torsional load of 30 ton·m is applied at the head of pile P1, and a vertical load of 30 tons is applied at the head of pile P2.

The applied torsional and lateral loads follow the loading profile shown in *Figure 2*, whereas the vertical load is applied statically.

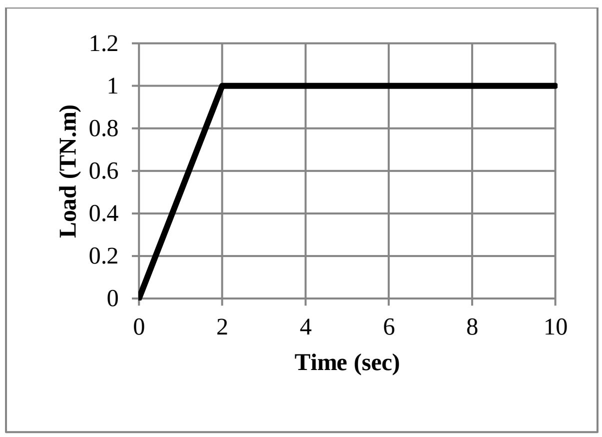


Figure 2 Time-dependent loading profile for torsional and lateral loads

3.5Numerical simulation

ABAQUS 2020 has been used to perform the required numerical simulation in three dimensions. The brick element with 20-nodes (C3D20R) has been employed to model pile and soil as shown in *Figure 3*. Here, the pile consists of two different materials (steel and concrete). The modelling of soil includes 243130 while the modelling of pile includes 1739 elements. Dynamic Model load has been used to achieve the required analysis and obtain the results [50, 51]. The implicit analysis is done by ABAQUS program with increment size 1×10^{-5}.

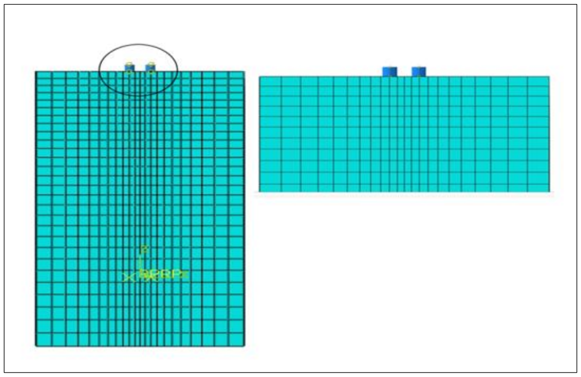


Figure 3 Problem mesh

Mohamedzein et al. [52] conducted a laboratory experiment on a reinforced concrete pile with a diameter of 50 mm and L/d = 10 subjected to a lateral load and immersed in a clayey soil. The soil specifications in elastic and plastic states were tested, and calculated P-Y curves and the concrete and reinforcement steel properties were tested, too. The piles were fixed to the soil using the drilling method. Then, the load was applied with an increase of 0.045 to 0.1 kN until failure occurred. All materials, methods, and pile loading were used in the ABAQUS program, and the pile response was studied through bending moments and load curves. The results showed a convergence between the numerical analysis using the program and the laboratory values of the pile, as shown in *Figures 4(a)* and *4(b).*

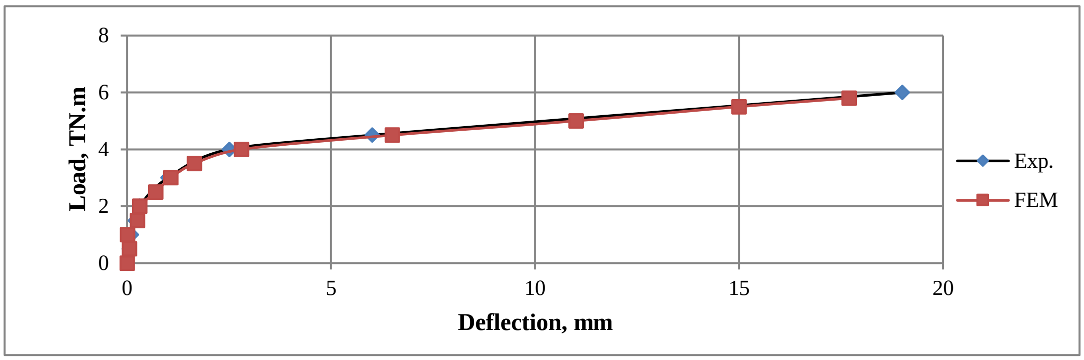


Figure 4 (a) Load Deflection curve for experimental and finite element analysis (FEM)

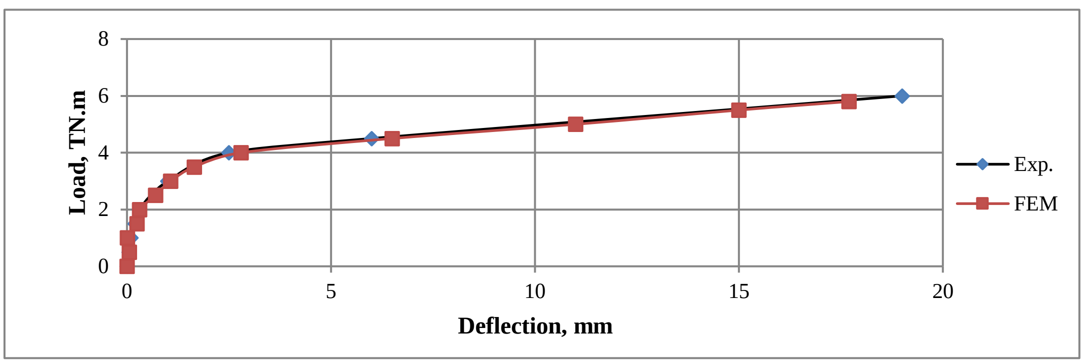


Figure 4(b) Bending moment along pile length for experimental and FEM

4.Results and discussion

The magnitude of load transferred from one pile to another is assessed by calculating the shear forces and bending moments in the neighboring pile. Additionally, the displacement profile along the pile was computed to analyze the response of both the loaded and unloaded piles to the transferred load. The soil reaction along the pile length was also evaluated to understand the influence of soil properties on load distribution.

The notation 2.5D P1 indicates that the second pile (P2) is placed at a distance of 2.5 times the pile diameter (D) from the first pile (P1). Similarly, 4D P1 and 6D P1 signify that P2 is located at distances of 4D and 6D from P1, respectively.

4.1Shear force

The variation of shear forces along the pile length for the four loading cases is illustrated in *Figure 4.* The black curve represents the shear force distribution in the loaded pile (P1), while the colored curves depict the response of the second pile (P2)—either unloaded (*Figures 5(a)* and *5(b)* or loaded with a vertical force (*Figures 5(c)* and *5d*).

The results show that the shear force in P1 reaches 217 kN when P2 is unloaded, and increases to 262 kN when P2 is loaded with a 30 kN vertical load, representing a 20% increase. For the torsional loading case, this increase drops to 11%, indicating that the type of load significantly affects the magnitude of transferred forces.

The distance between the two piles also influences the transferred load. When P2 is placed 2.5D from P1:

- In lateral load cases (Cases 1 and 3), the shear forces in P2 are 140 kN and 160 kN, respectively.
- In torsional load cases (Cases 2 and 4), the values are 45 kN and 52 kN, respectively.

At greater pile spacings (4D and 6D), the shear force transferred to P2 becomes minimal, and the type of load—lateral or torsional—has negligible influence. The inflection point of the shear force diagram is crucial in understanding the pile response. This point depends on the pile and soil properties, as well as the nature of the applied load. In lateral load cases (Cases 1 and 3), the inflection point occurs at a depth of 8 meters, while in torsional load cases (Cases 2 and 4), it shifts deeper to around 12 meters, consistently across all pile spacings.

The depth at which shear forces reduce to zero is also load-dependent. It occurs at approximately 18 meters in lateral load cases and at 23 meters in torsional load cases. These observations demonstrate that torsional loads have a greater influence on the inflection and zero-shear points, whereas lateral loads result in a more significant transferred shear force.

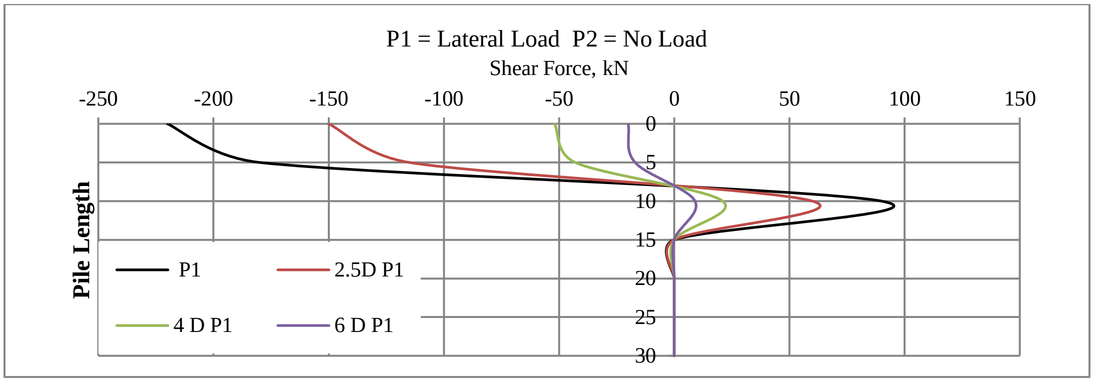


Figure 5(a) Shear force distribution for Pile 1 subjected to a horizontal load and Pile 2 with no applied load

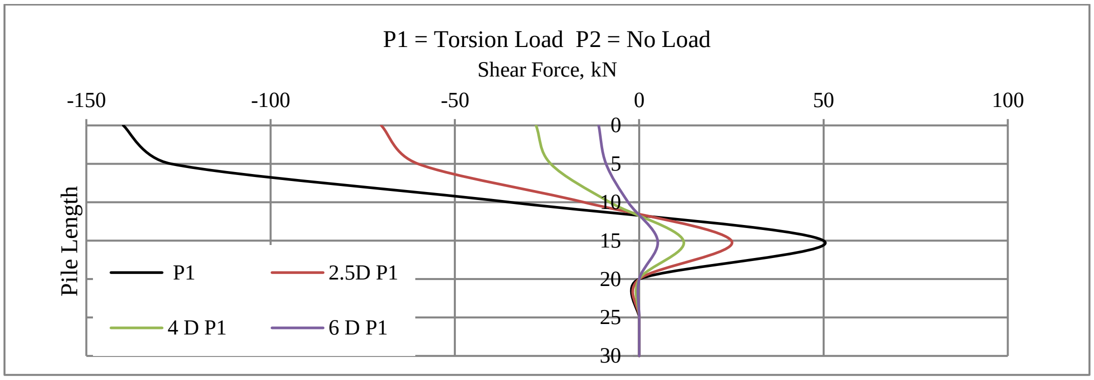


Figure 5(b) Shear force distribution for Pile 1 subjected to a torsional load and Pile 2 with no applied load

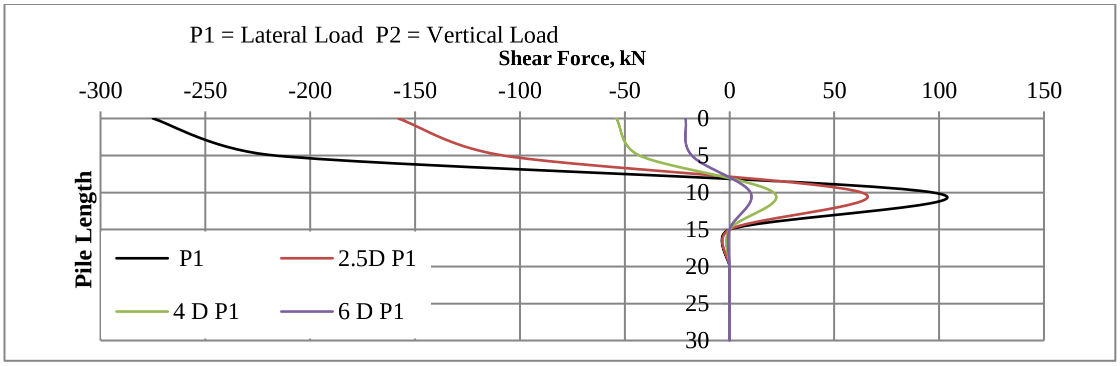


Figure 5(c) Shear force for pile 1 Horizontal load and pile two vertical loads

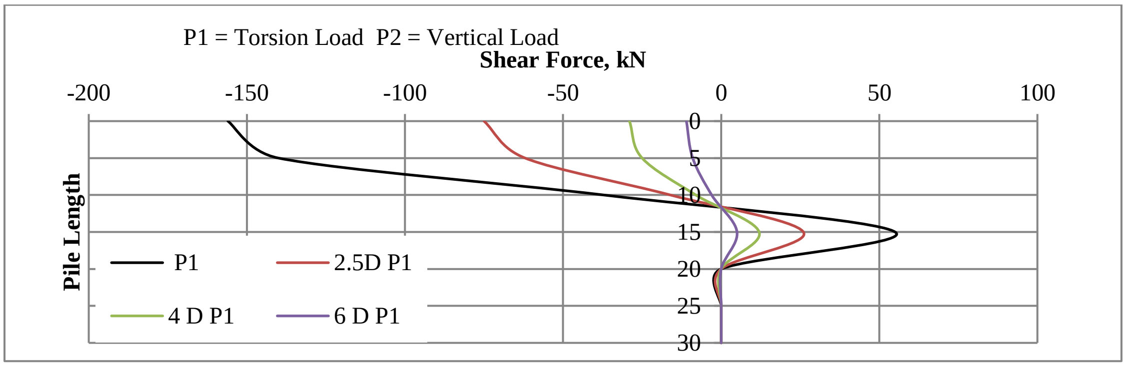


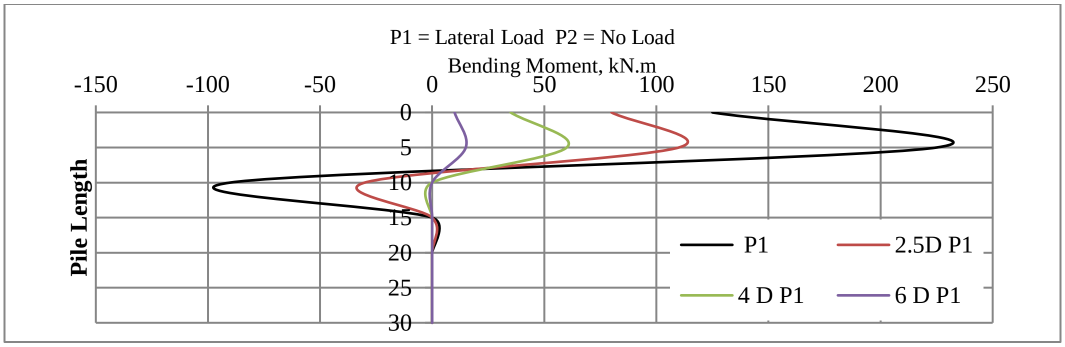
Figure 5(d) Shear force for pile 1 Torsion load and pile two vertical loads
Figure 5 shear force variation along piles depth for various loading

4.2Bending moment

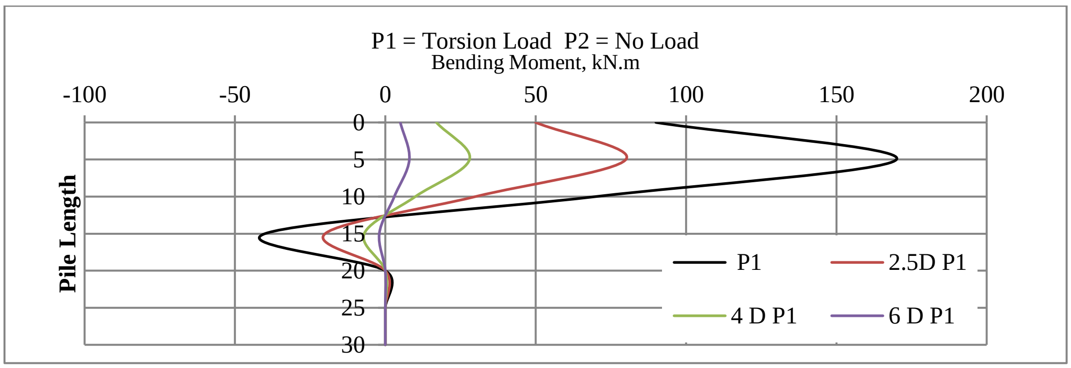
The second variable used to quantify the load transferred between two neighboring piles is the magnitude of the bending moment transferred from a loaded pile to the adjacent pile (either loaded or unloaded). *Figure 6* illustrates the variation of bending moment along the depth of the piles. The black curve represents the bending moment in the loaded pile (P1), while the other colored curves correspond to the second pile—unloaded in *Figures 6(a)* and *6(b),* and loaded with a vertical force in *Figures 6(c)* and *6(d).*

The bending moment typically initiates at a certain value, increases due to the soil reaction, reaches a peak, and then gradually decreases with depth. This pattern is evident in the figure. Additionally, it is observed that the inflection point of the bending moment occurs at a depth of approximately 8 meters in the lateral load cases (Cases 1 and 3), whereas in the torsional load cases (Cases 2 and 4), it shifts to a depth of around 12 meters, regardless of the spacing between piles. This behavior is consistent with the corresponding shear force diagrams.

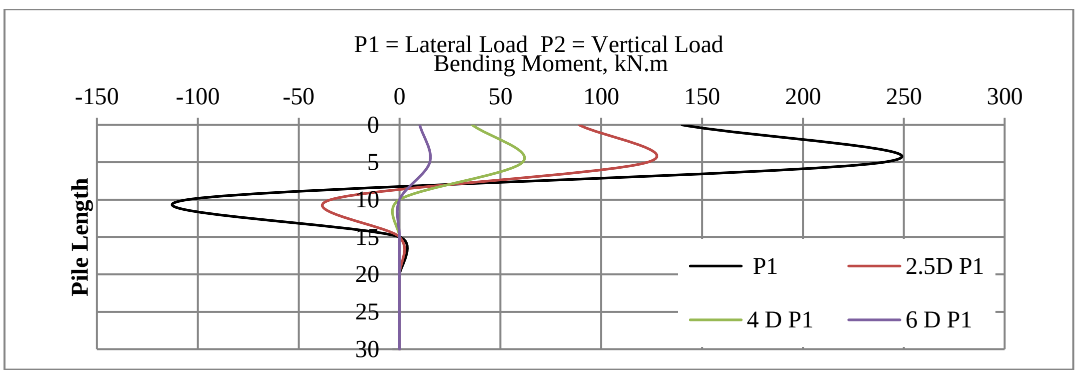
Figure 6(a) shows that the percentage of bending moment transferred from the first pile (P1), subjected to a lateral load, to the second pile (P2), which is unloaded, is 23% at a spacing of 2.5D, 5% at 4D, and 3% at 6D. *Figure 6(b)* presents the case where P1 is torsionally loaded and P2 is unloaded. The transmitted bending moment is 19% at 2.5D, 4.5% at 4D, and 3% at 6D. In *Figure 6(c),* with P1 laterally loaded and P2 vertically loaded, the bending moment transferred is 31% at 2.5D, 4.8% at 4D, and 3% at 6D. *Figure 6(d)* illustrates the case of a torsional load on P1 and a vertical load on P2, with the transferred bending moment recorded as 27% at 2.5D, 4.2% at 4D, and 3% at 6D. This variation in the magnitude of transmitted bending moments follows the same trend observed in shear force transmission, primarily due to the effect of pile-soil-pile interaction. The fixity depth-defined as the depth at which the bending moment becomes constant—is observed at approximately 18 meters in the lateral load cases (*Figures 6(a)*and *6(c)),* and 20 meters in the torsional load cases (*Figures 6(b)* and *6(d).*



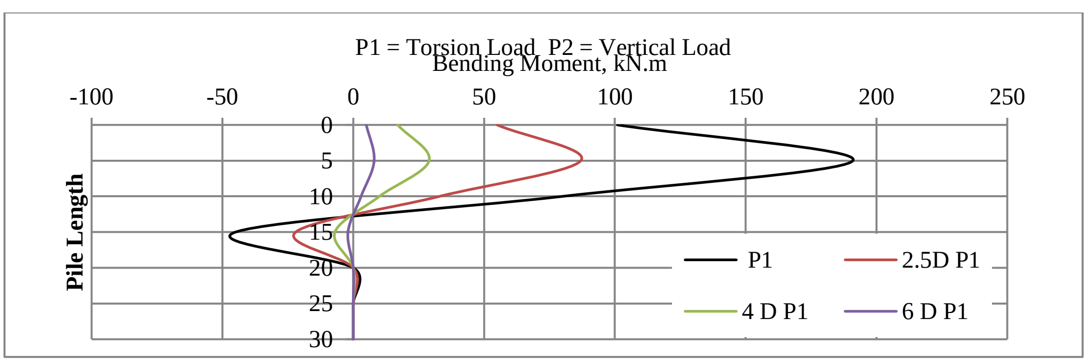
(a) Bending moment distribution for Pile 1 subjected to a horizontal load and Pile 2 with no applied load



(b) Bending moment distribution for Pile 1 subjected to a torsional load and Pile 2 with no applied load



(c) Bending moment distribution for Pile 1 subjected to a horizontal load and Pile 2 subjected to a vertical load



(d) Bending moment distribution for Pile 1 subjected to a torsional load and Pile 2 subjected to a vertical load

Figure 6 Bending moment variation along piles depth for various loading

4.3Displacement

Calculating the magnitude of displacement along the pile is very important to study the response of the first pile P1 (loaded pile) and the second pile P2 (unloaded or loaded pile) according to the type of load (lateral load or torsional load). *Figures 7(a), 7(b), 7(c) and 7(d)* show the change value of displacement along the pile's length. The black colour represents the magnitude of the displacement in the loaded pile P1, while the other colours represent the second pile P2 in all figures.

The displacement in the first pile P1 is 1.3 cm when the second pile P2 is unloaded and 0.6 cm when the second pile P2 is loaded with a vertical load of 30 kN at lateral load, this mean that adding a vertical load to the second pile P2 made it more stable than without a load, despite the equal distances between the two pile *Figure 7(a) and 7(c).* But at the torsion, we notice the same difference, The displacement in the first pile P1 is 0.2 cm when the second pile P2 is unloaded and 0.14 cm when the second pile P2 is loaded with vertical load 30 kN at lateral load, *Figure 7(b) and 7(d).*

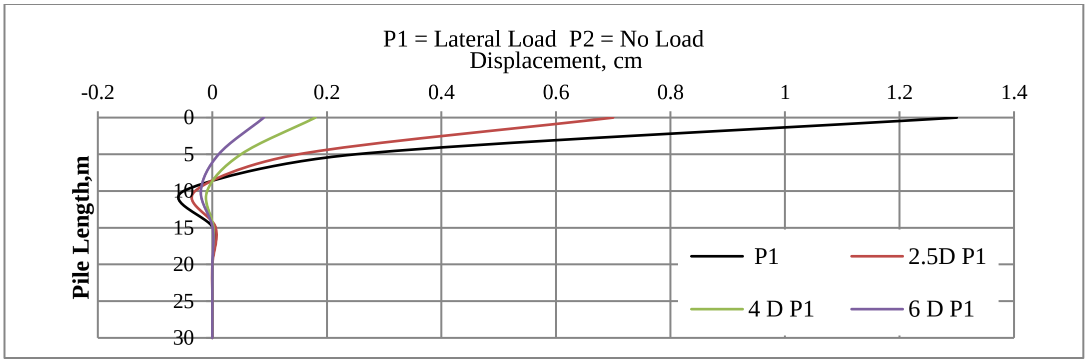
The displacement ratio between the first pile P1 and the second pile P2 at a distance of 2.5D equal to 23%, at a distance of 4D equal to 4 %, and at a distance of 6D equal to 1.6% as a result of the transferred loads when the load on the first pile P1 is lateral and the second pile P2 is unloaded *Figure 7(a).*

The displacement ratio between the first pile P1 and the second pile P2 at a distance of 2.5D equal to 25%, at a distance of 4D equal to 5 %, and at a distance of 6D equal to 2.2 % as a result of the transferred loads when the load on the first pile P1 is torsional and the second pile P2 is unloaded *Figure 7(b).* The displacement ratio between the first pile P1 and the second pile P2 at a distance of 2.5D equal to 20%, at a distance of 4D equal to 3 %, and at a distance of 6D equal to 1.2 % as a result of the transferred loads when the load on the first pile P1 is lateral and the second pile P2 is loaded with 30 kN vertical load *Figure 7(c).* The displacement ratio between the first pile P1 and the second pile P2 at a distance of 2.5D equal to 16 %, at a distance of 4D equal to 3 %, and at a distance of 6D equal to 1.3 % as a result of the transferred loads when the load on the first pile P1 is torsional and the second pile P2 is loaded with 30 kN vertical load *Figure 7(d).* The displacement is zero along the pile at a distance of 18 m below the ground level in the case of lateral load and 20 m below the ground level in the case of torsional load Due to the different type of imposed load.

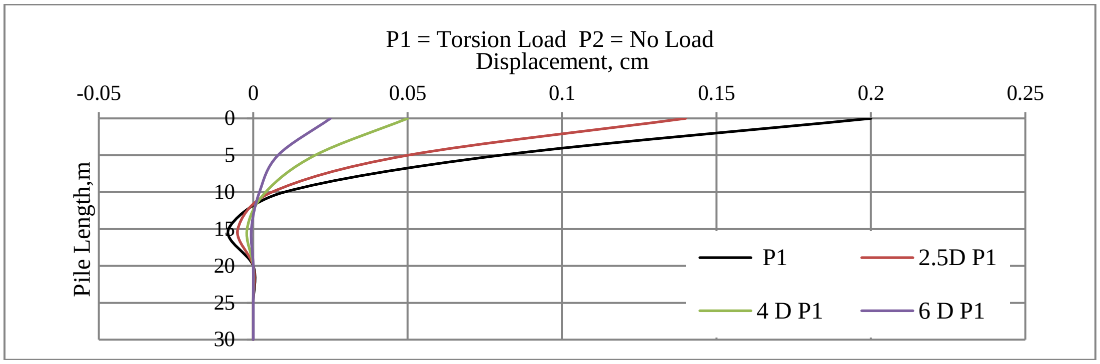
4.4Soil reaction

Soil reaction is very important to know the variation in soil stresses along pile length and the transfer load behaviour between soil particles. *Figures 8(a), 8(b), 8(c) and 8(d)* show the value of reaction along the length of the pile for the four loading cases. The magnitude of the soil reaction starts from zero (the normal value) and increases rapidly to a depth of 5 m (when the load is lateral) and 7 m (when the load is torsional) on the first pile P1. From the figures below for the soil reaction, it is noted that when the load is lateral on the first pile P1, the response value is large even after the inflection point, unlike the torsional load, the response value is relatively less than the lateral load even after the inflection point, but it disappears quickly.

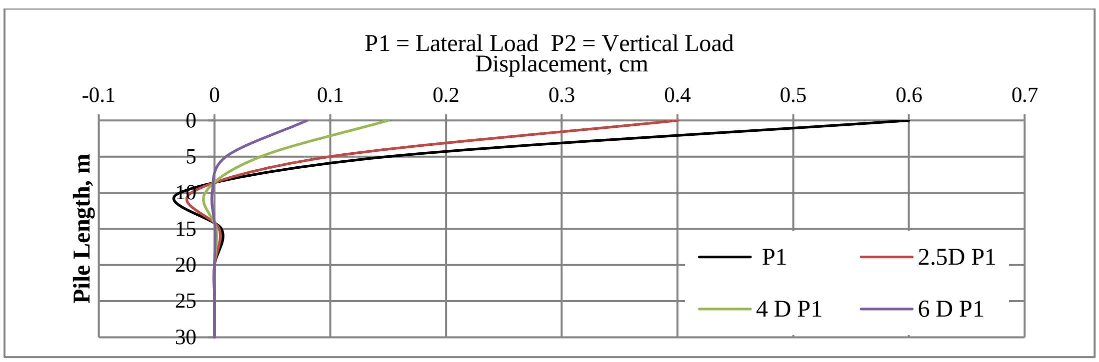
The magnitude of the soil reaction continues to the last point in the pile, but its value is close to zero at a depth of 25 meters. The black colour indicates the magnitude of the soil reaction in the loaded pile P1, while the other colours represent the second pile P2 (whether it is unloaded in *Figure 8(a) and 8(b)* or loaded with a vertical load in *Figure 8(c) and 8(d)*. When the load is lateral, the soil reaction rate from the first pile P1 (loaded) to the second pile P2 at the distance of 2.5 D (unloaded) is 24%, and this rate increases when the second pile P2 is (loaded) to become 27% as a result of the Pile-Soil interaction, for the other distances, the reaction is relatively small, less than 5% when the distance is 4D and 2% when the distance is 6D. at torsion load, the soil reaction rate from the first pile P1 (loaded) to the second pile P2 at the distance of 2.5 D (unloaded) is 22%, and this rate increases when the second pile P2 is (loaded) to become 24 % as a result of the Pile-Soil interaction, for the other distances, the reaction is relatively small, less than 5% when the distance is 4D and 2% when the distance is 6D.



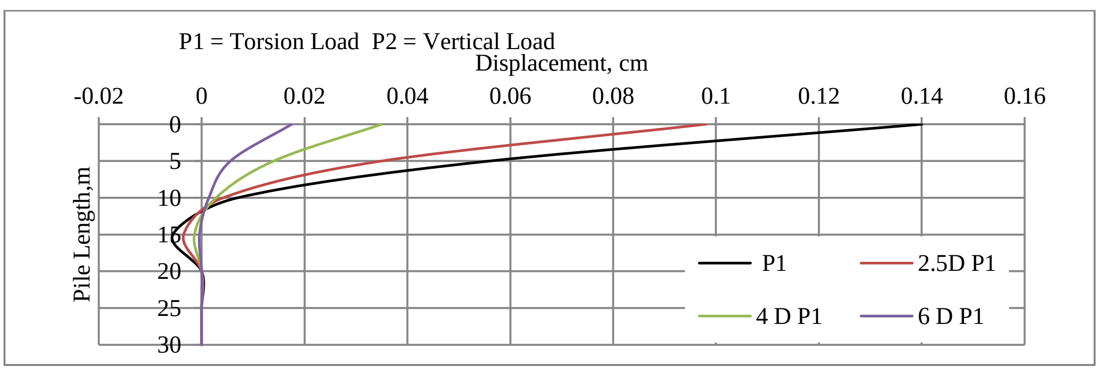
7(a) Displacement distribution for Pile 1 subjected to a horizontal load and Pile 2 with no applied load



7(b) Displacement distribution for Pile 1 subjected to a torsional load and Pile 2 with no applied load

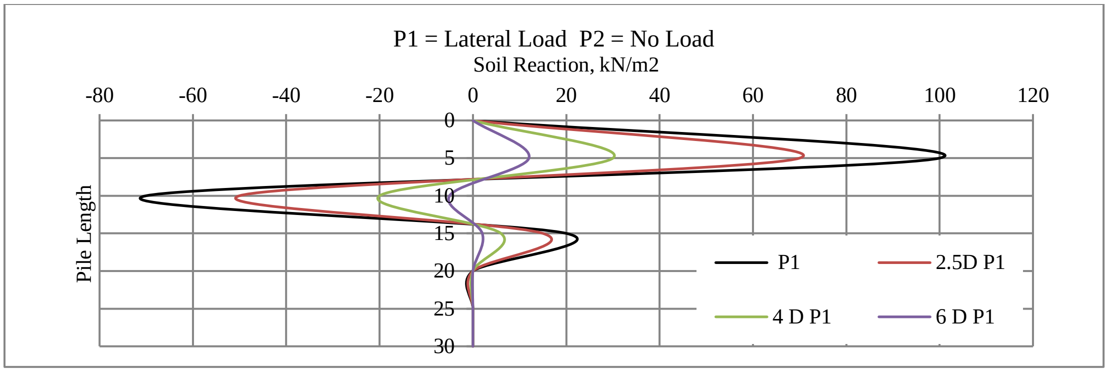


7(c) Displacement distribution for Pile 1 subjected to a horizontal load and Pile 2 subjected to a vertical load

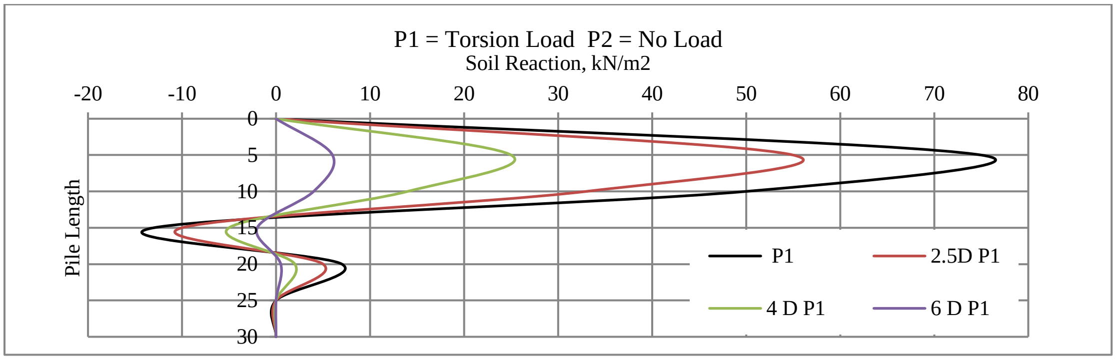


(d) Displacement distribution for Pile 1 subjected to a torsional load and Pile 2 subjected to a vertical load

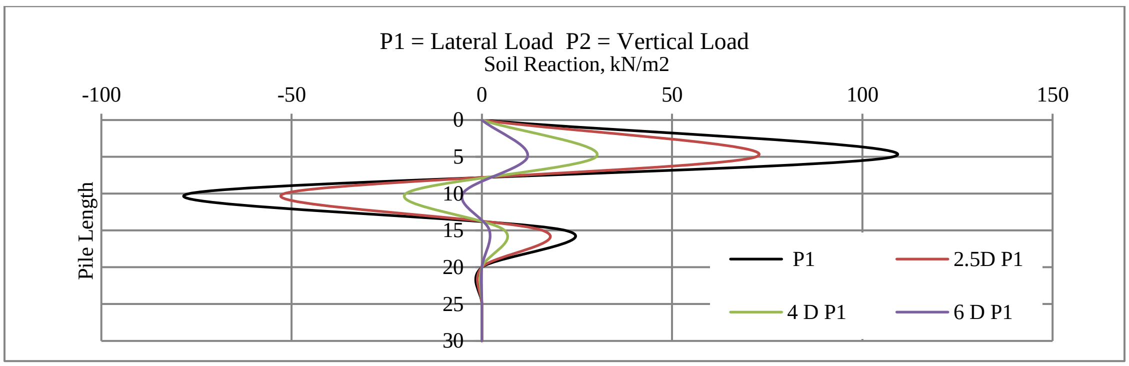
Figure 7 Displacement variation along piles depth for various loading



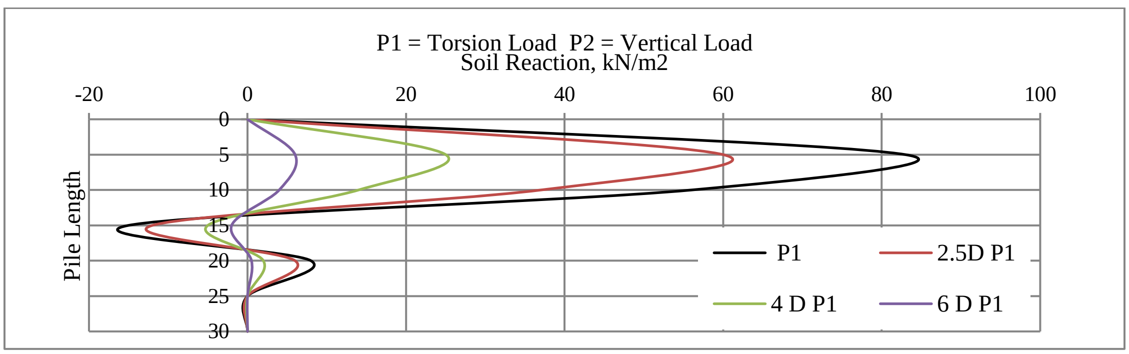
(a) Soil reaction distribution for Pile 1 subjected to a horizontal load and Pile 2 with no applied load



(b) Soil reaction distribution for Pile 1 subjected to a torsional load and Pile 2 with no applied load



(c) Soil reaction distribution for Pile 1 subjected to a horizontal load and Pile 2 subjected to a vertical load



(d) Soil reaction distribution for Pile 1 subjected to a torsional load and Pile 2 subjected to a vertical load

Figure 8 Soil reaction variation along piles depth for various loading

Limitations

The study calculated the magnitude of the load transferred between two adjacent piles under different dynamic loads (vertical, horizontal, and torsional). The two piles were embedded only in clay soil. The interaction between the soil and the piles was assumed to be fully bond. The piles used in the study were steel pipes filled with concrete, and the reinforcing steel in the piles was neglected to simplify the problem. The accuracy of the results depended on the verification accuracy obtained using the ABAQUS program. A complete list of abbreviations is listed in *Appendix I*.

5.Conclusion and future work

By analyzing the problem and the results obtained, several important conclusions can be drawn. The interaction between neighboring piles is a critical aspect in geotechnical engineering. Numerical simulations reveal that as the horizontal distance between two piles increases, the response significantly decreases due to a reduction in load transfer from the pile to the soil, regardless of the loading conditions.

The magnitude of load transferred from one pile to another is determined by assessing the shear forces and bending moments in the neighboring pile. Specifically, the shear forces transmitted from a loaded pile to an unloaded pile at a distance of 2.5D range from 11% to 20% of the torsional and lateral loads, respectively. Similarly, shear forces transmitted between two loaded piles at the same distance range from 16% to 28% of the applied loads. For bending moments, the transmission from a loaded pile to an unloaded pile at a distance of 2.5D falls within 19% to 23% of the applied torsional and lateral loads, whereas between two loaded piles, it ranges from 27% to 31%.

Moreover, a loaded pile subjected to lateral loads can induce shifts in the unloaded pile at rates of approximately 16% for lateral loading and 20% for torsional loading. Unloaded piles experience displacement due to soil-pile interaction when adjacent piles are loaded; the resulting displacements are around 23% and 25% under lateral and torsional loads, respectively.

The soil response is heavily dependent on the magnitude of load transferred from the piles to the soil, making the variations in the results highly sensitive to changes in load intensity. Inflection points for shear force, bending moment, displacement, and soil reaction are observed between 8 and 12 meters below the ground surface. Zero shear forces occur at depths between 18 and 23 meters, while zero displacement is recorded between 18 and 20 meters, depending on the loading conditions. Notably, the soil reaction persists to the deepest point of the pile. Finally, the fixity depth—where piles behave as fixed—occurs between 18 and 20 meters for all load cases.

Future investigations may be conducted to extend and deepen the findings of this study by considering the following aspects:

- Investigating piles submerged in sandy soils or multi-layered soil profiles.
- Modifying the soil plasticity model to compare different results.
- Analyzing piles made entirely of either steel or concrete.
- Increasing the number of piles or studying pile groups.
- Applying different types of loads to observe variations in behavior.
- Imposing alternative interaction models between the pile and soil, such as using an interface layer or surface-to-surface interaction.
- Calculating additional coefficients to enrich the analysis and broaden the understanding.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

None.

Authors contribution statement

Abdulameer Al-Mubarak: Study conception, experimental design, original draft writing and editing. **Rafi M. Qasim:** Prototype design and development, and experiment execution. **Ayad Al-Yousuf:** Supervision, development of assessment protocols and instrumentation, and analysis and interpretation of results.

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Appendix I

S. No.	Abbreviation	Description
1	D	Pile Diameter
2	FEM-BEM	Finite Element Method-Boundary Element Method
3	γ	Mass Density
4	σ	Young's Modulus
5	ν	Poisson's Ratio
6	C	Cohesion
7	σ	Yield Stress
8	ε	Strian
9	ø	Dilation Angle
10	e	Eccentricity
11	Fb0/fc0	The Ratio of Initial Equibiaxial Compressive Yield Stress to Initial Uniaxial Compressive Yield Stress.
12	k	The Ratio of the Second Stress Invariant on the Tensile Meridian
13	μ	Viscosity