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Comparative Finite Element Study of Single and Group Piles Adjacent to Slopes Under Lateral Cyclic Loading

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ABSTRACT

This study investigates the performance of a single pile and a (2×2) pile group located near saturated clayey slope under cyclic lateral loading using Finite Element Analysis (FEA). The simulations were conducted using Plaxis 3D with the Hardening Soil Model (HSM), which allows for a more accurate representation of soil behavior, especially in cyclic loading conditions. The model considered clayey soils with parameters derived from the official geotechnical report prepared by the Consulting Engineering Bureau (CEB) Laboratories of the University of Baghdad's College of Engineering. Both the single pile and pile group were placed at a distance of (4D) from an (8m) high slope with a (1:4) gradient. The loading conditions included static vertical loads and cyclic lateral loads. The most important results reached, pile groups reduced lateral displacement by 30-50% versus single piles, which suffered 20-40% greater displacement near slopes due to uneven soil support. One-way cyclic loading caused larger than two-way cyclic load permanent displacements, while two-way loading increased fatigue risks, with both degrading clay strength by up to 50%. Peak bending moments occurred at pile heads and slope crests, but group piles lowered these stresses by 30%.

Keywords: Finite element analysis, Cyclic load, Pile foundation, Clayey slope.

1. INTRODUCTION

The study of cyclic loading in geotechnical and structural engineering has witnessed substantial development over the decades, driven by the need to understand the effects of repeated dynamic forces such as earthquakes, wind, and traffic on soil–structure systems. Foundational contributions by early researchers paved the way for modern analysis. **(Darcy, 1856)** indirectly explored cyclic effects through his work on water infiltration in soils, while **(Terzaghi, 1943)** introduced the effective stress principle, a cornerstone in analyzing pore pressure behavior under cyclic conditions. Later, **(Seed and Idriss, 1971)** developed the Cyclic Stress Ratio (CSR) framework, which became the basis for practical liquefaction

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assessments. In pile foundation analysis, **(Matlock, 1970)** introduced a model for cyclic loading in soft clays, **(Gazetas and Dobry, 1984)** further contributed by modeling nonlinear soil–pile interaction during seismic events. Additional work by **(Andersen, 2015; Lehane and Jardine, 1994; Randolph and Gourvenec, 2017)** provided deeper insights into cyclic loading effects on marine and clayey soils. Cyclic loading also plays a critical role in slope stability, as it can increase excess pore water pressure and reduce shear strength, making slopes more susceptible to failure. **(Broms, 1964)** was among the first to investigate pile behavior in sloped ground, followed by theoretical developments from **(Poulos, 1971)** and design procedures from **(Reese, 1965)** .

One of the most important recent studies similar to the problem discussed in the research, tests conducted by **(Orense et al., 2012)** showed that unsaturated soils have higher cyclic strength and lower deformations under seismic stresses than fully saturated soils, with slope stability being negatively affected by increased saturation and initial shear stresses. **(Naeini and Hamidpoorzare, 2011)** studied the behavior of pile assemblies in slopes under earthquakes using ABAQUS software. He demonstrated that pile response is affected by their number, diameter, spacing, and location within the assemblage, in addition to the slope angle. The results indicated that the optimal design of pile assemblies in slopes must take these factors into account to reduce seismic collapses. **(Deendayal et al., 2016)** found in their study that the behavior of piles on slopes under seismic loading is affected by the pile length-to-diameter ratio and the slope angle to which they are anchored. Lateral displacements and bending moments increased as the slope angle became steeper and the L/D ratio decreased. **(Wang et al., 2021)** used finite element analysis to study the failure of layered clay slopes under seismic loading and soft clay behavior. The results showed that the slopes could fail in different ways, with failure zones becoming wider due to earthquake effects. **(Peng et al., 2023)** performed tests on piles under rotational lateral loads on slopes to examine the influence of rotation, load capacity, and slope angle. They observed an increase in bending moment and head displacement with more rotation, along with a change in the depth of the maximum moment. They also proposed a numerical model that matched the test results. Several experimental and numerical studies have investigated the behavior of piles under cyclic loading in various soil types and slope conditions. **(Islam and Gnanendran, 2013)** conducted experimental tests in sandy soils and found that cyclic loading can improve bearing capacity, especially at lower frequencies such as 0.2 Hz, which also enhance soil stiffness. However, higher frequencies led to increased permanent deformations and reduced benefits in capacity improvement. A numerical study by (**Deendayal, 2017)** in sandy conditions showed that increasing the L/D ratio lowers acceleration, displacement, and bending moments, although sloping ground was seen to increase these responses due to reduced passive soil resistance. In another combined experimental and numerical study, (**QU et al., 2020)** observed that piles on sloping ground experience more settlement than on level ground. While the number of cycles had a minor effect on vibration displacement, load amplitude significantly influenced it. Their numerical analysis confirmed experimental findings under elastic conditions. **(Yun and Han, 2023)** also reported that slope-induced kinematic forces amplify pile bending moments and displacements. Their pseudo-static analysis incorporating these forces reduced prediction errors to 3–35%. Moreover, pile group spacing (5.5D) and soil density were shown to strongly influence the dynamic behavior. **(Rathod et al., 2024)** reported over 60% reduction in lateral capacity due to cyclic loading in sandy soils. They also observed that shifting from horizontal to sloped ground reduced the bending moment by 25–40%. It was found that unidirectional cyclic loading caused more deflection than bidirectional loading, likely due to increased plastic stress **(Sundaramoorthy and Rathod, 2024)**. In their study, hybrid fiber-reinforced concrete (HFRC) piles were tested under lateral cyclic loads in dense sandy-clay soil. The HFRC piles showed better interaction with the surrounding soil, leading to less displacement and improved energy absorption. The hybrid reinforcement helped the piles perform better under lateral and axial cyclic loads. Recent large-scale tests on anchor piles for floating wind turbines showed that two-way cyclic loading led to greater displacement than one-way loading, even when the vertical force remained constant **(Chalhoub et al., 2025)**. Designing pile foundations near slopes under cyclic loads presents challenges, especially in clayey soils. Unlike sandy soils, which drain and settle faster, clay tends to lose strength over time under repeated loading due to the buildup of pore pressure and changes in structure. This increases displacement and the chance of slope failure. Therefore, clay slopes are more affected by dynamic loads and require extra design attention, such as drainage improvements and slope stabilization.

This study focuses on the behavior of single piles and pile groups under cyclic lateral loads, particularly near slopes. The analysis is carried out using (**PLAXIS 3D, 2022)** based on the finite element method to simulate the interaction between soil and piles during cyclic loading. The models include nonlinear soil behavior, the generation of excess pore water pressure, and different loading patterns. Parametric studies are conducted by changing the amplitudes of lateral displacement and the number of load cycles.

This study is divided into successive sections, beginning with the definition and classification of cyclic loads, followed by the finite element modeling methodology and soil properties used. Simulation results are then presented and validated, followed by a discussion of the results and design recommendations. This organization aims to provide a systematic and comprehensive analysis of the performance of single and group piles under cyclic loads near clayey slopes.

2. DEFINITION AND CLASSIFICATION OF CYCLIC LOAD

Cyclic loading refers to repeated or fluctuating forces that cause progressive changes in soil properties. Three key characteristics: Load reversibility (one-way/two-way), Frequency range (0.001-50 Hz) and Amplitude effects (strain accumulation). A slenderness ratio (L/D) of 20 was selected to ensure realistic lateral behavior under cyclic loading. The (2×2) pile group with 3D spacing was chosen to capture group interaction effects without excessive stress overlap. Referring to **Fig. 1**, where a typical (2×2) pile group is subjected to static vertical load (V) and a cyclic lateral load which is represented by the value the maximum and minimum values of the imposed lateral cyclic load (H_{max}) and (H_{min}) *and* (H_{mean}) is the mean lateral load, this can be mathematically expressed in Eq. (1), (2), and (3) by **(Long and Vanneste, 1994)**:

Symmetrical two-way loading :

$$\frac{H_{max}}{H_{min}} = -1 \;\; and \;\; H_{mean} = 0 \tag{1}$$

Asymmetrical two-way loading :

$$-1 < \frac{H_{max}}{H_{min}} < 0 \;\; and \;\; H_{mean} \neq 0 \tag{2}$$

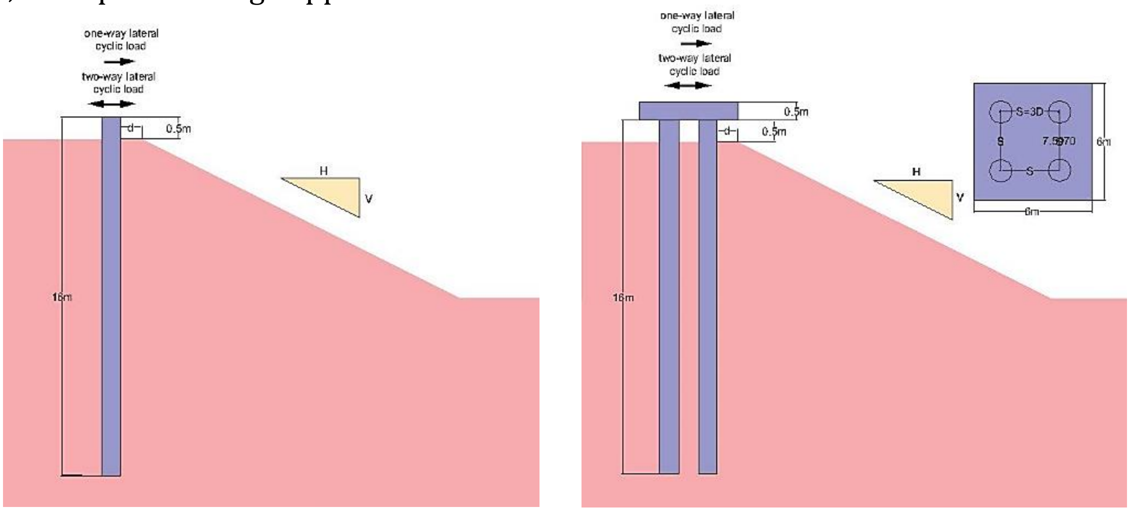
One-way loading: $$\frac{H_{max}}{H_{min}} > 1 \;\; and \;\; H_{mean} \neq 0 \tag{3}$$

Where, H_{max} and H_{min} are the maximum and minimum values of the imposed lateral cyclic load. The amplitude (A) of the cyclic lateral load is defined in Eq. (4) by **(Basack and Dey, 2012)** as:

$$A = \frac{H_{max} - H_{min}}{H_{us}} \quad (4)$$

H_{us} is the static ultimate lateral capacity of the pile group.

Table 1 systematically categorizes cyclic loading types based on their directionality, amplitude, and frequency characteristics. This classification provides a framework for analyzing pile foundation behavior under different dynamic loading scenarios. The effects of high-frequency (greater than 1 Hz) and low-frequency (less than 0.1 Hz) cyclic loads on deep foundations in clay soils differ significantly in terms of physical mechanisms, deterioration risks, and optimal design approaches.



(a) (b)

Figure 1. Two-dimensional geometry of the numerical model showing the configuration of: (a) single pile, (b) 2×2 pile group, placed near a clayey slope under cyclic lateral loading.

Table 1. Classification Table with Citations of Lateral Cyclic Loads, **(Wu et al., 2020; British Standard, 2006; Hopstad et al., 2018).**

Load Type	Main Cause	Amplitude (kN)	Cycle Duration (s)	Frequency (Hz)
One-way				
Wave Loading	Wave pressure on offshore structures	50–150	5–10	0.1–0.2
Wind Loading	Wind pressure on wind turbines	100–300	3–6	0.16–0.33
Traffic (Trucks)	Vibrations from nearby truck traffic	200–500	1–3	0.33–1.0
Two-way				
Earthquakes	Seismic shaking	±75–200	0.5–2	0.5–2.0
Industrial Vibrations	Heavy pumps or motors	±50–150	0.1–0.5	2–10
Train Traffic	Train-induced vibrations on bridges	±100–300	0.3–1	1–3.3

These differences are based on three main pillars: soil behavior under load, structural element response, and cumulative effects over time. For high frequencies, the main risk is rapid pore water pressure build-up. According to **(Andersen, 2015)**, frequencies above (1 Hz) inhibit water drainage from clay pores, leading to cyclic softening. Data show that pore water pressure can reach (90%) of effective stress after just 200 cycles at 3 Hz, causing a rapid loss of shear strength of up to (50%), according to **(Wu et al., 2020)**. This sharp impact increases the risk of sudden displacement of the pilings and material cracking, especially when amplitudes approach 20% of the ultimate load, as Eurocode 7 warns. In contrast, lower frequencies are characterized by slower but more persistent cumulative effects. Frequencies below (0.1 Hz) allow some pore water drainage but cause cumulative plastic strain. These deformations depend on the number of cycles, as the **(Poulos, 1989)** equation shows that deformation increases directly with the square root of the number of cycles. A study conducted by **(Zdravković et al., 2015)** on offshore wind turbines where lateral deformations of up to (3%) of the pile diameter were acceptable after (1000) cycles at a frequency of (0.05 Hz).

3. FINITE ELEMENT MODEL (FEM)

The finite element analysis was performed using Plaxis 3D software with the Hardening Soil Model (HSM) to examine the behavior of pile foundations on sloped ground. The (HSM) was selected because it reflects changes in soil stiffness under varying stress conditions. It is suitable for studying cyclic loading in clay soils, as it considers factors such as pore pressure buildup, stiffness loss, and permanent deformation. The model also includes shear and compression hardening, along with dilatancy, which provides a more realistic soil response. For modeling the piles, the volume representation method was used. Although this method requires more computational time compared to using pile elements, it offers a more accurate reflection of actual pile behavior. **Fig. 2** illustrates the fundamental concept of the core hardening mechanism within the model. It depicts how soil resistance to deformation gradually increases as loading progresses, represented by a series of expanding yield surfaces in stress space. Each curve marks the transition from elastic to plastic behavior at various loading stages. With the accumulation of plastic strain, these yield surfaces expand outward, reflecting an enhancement in the soil's strength **(Schanz et al., 2019).** However, this increase is bounded and asymptotically approaches the soil’s ultimate strength as defined by the Mohr-Coulomb failure criterion. This visual representation clearly demonstrates the model's ability to capture both stress-dependent stiffness and the memory effect inherent in soil response.

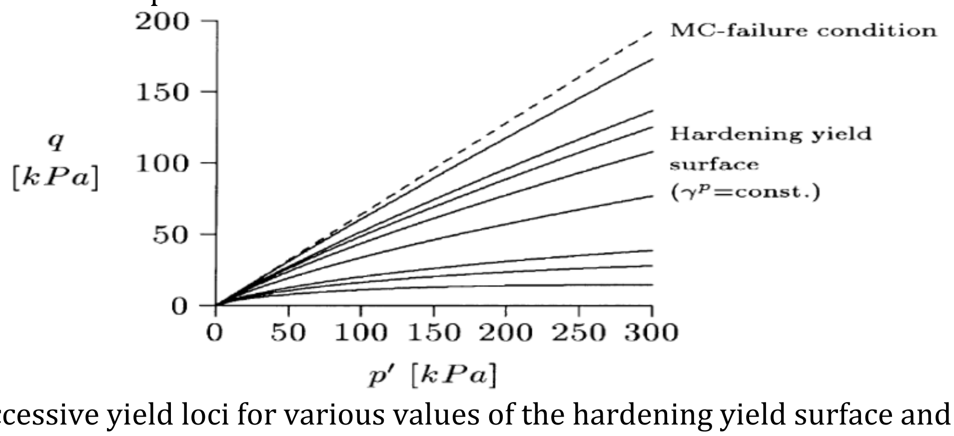


Figure 2. Successive yield loci for various values of the hardening yield surface and failure surface **(Schanz et al., 2019)**

In this study the viscous boundaries were applied to the right and left edges of the model. A medium mesh density was employed, resulting in (18,691) elements and (31,453) nodes. The piles are modelled as a volume element, while the cap modeled as a plate element.

4. SOIL PROPERTIES

The soil properties and geotechnical parameters presented by **(Hussein et al., 2024)** were acquired from the official geotechnical report prepared by the Consulting Engineering Bureau (CEB) Laboratories of the University of Baghdad's College of Engineering. Soil data for saturated clay were used. **Table 2** includes the most important mechanical properties of soil.

Table 2. Soil properties **(Hussein et al., 2024)**

Property	**Value**	**Unit**
Modulus of elasticity	20000	kPa
Cohesion	50	kPa
Saturated Unit Weight	20	kN/m^3
Poisson's Ratio	0.45	
Friction Angle	15°	

5. SIMULATION OF PILE AND SLOPE

The slope adjacent to the pile foundation has a height of (8 m) with a gradient of (1V:4H). The water table is located at the base level of the slope, which may influence the soil stability and bearing capacity of nearby pile foundations. Both single piles and (2×2) pile groups were analyzed at a close spacing of (2D), where the pile diameter is (0.8 m). The proximity to the slope and the groundwater level are key factors in evaluating slope stability and pile performance under these geotechnical conditions. **Table 3** presents the geometry of the pile and the slope.

Table 3. Pattern and characteristics of the employed concrete pile.

Pile Type	Single and 2×2 Group
Spacing	3d (2.4 m)
Pile Length	16 m
Pile Diameter	0.8 m
Pile Cap Size	(6×6) m

The dimensions and arrangement of the piles shown in **Table 3** were selected based on practical design standards and previous studies. A pile slenderness ratio of **(L/D = 20)** was adopted, which falls within the typical range for deep foundations in medium clay and provides adequate embedment to develop both lateral and vertical resistance **(Poulos and Davis, 1980).** A center-to-center spacing of (**3D)** was used to allow for interaction between the piles without causing significant stress overlap, in line with the guidelines of **(Randolph and Gourvenec, 2017)**. The pile cap, measuring **(6×6 m)**, fully covers the **2×2** pile group and facilitates effective load transfer. These design parameters are also aligned with the site conditions outlined in the geotechnical report by the Consulting Engineering Bureau **(Hussein et al., 2024)**, contributing to the accuracy of the model. A slope inclination of 1V:4H and a pile distance of (2D) from the slope crest were chosen to help maintain overall slope stability under vertical loading.The selected geometry ensures that the applied static load does not induce excessive displacement or failure in the slope before the onset of cyclic loading, thus providing a safe and stable baseline condition for further analysis.

6. LOADING AND BOUNDARY CONDITION

The failure loads are calculated using the load-settlement curves. Engineers generally agree that a failure load results in a settlement equal to (10%) of the pile's diameter or width, as proposed in **(Terzaghi, 1943)**. Applying static lateral load before cyclic testing is essential to establish baseline soil-pile interaction and detect initial nonlinear behavior. The numerical model was analyzed under combined static and cyclic loading conditions to simulate realistic in-service behavior. For static loading, (200 kPa) for group based on the study of **(Maheshwari and Viladkar, 2007)** and a vertical dead load of (1800 kN) was applied to represent the superstructure weight for single pile. The boundary conditions consisted of a fully fixed base (restrained in all directions) to represent bedrock, with roller-supported sides (restrained horizontally but free vertically) to simulate natural soil confinement. **Fig. 3** shows the time and amplitude diagram for a one and two wat lateral cyclic load. In this study, the frequency (f) of cyclic loading was selected as 0.165 Hz (10 cycles per minute), consistent with the range validated in **(Nimbalkar and Basack, 2024)** to simulate cyclic loads similar to those experienced by columns in offshore structures (such as offshore wind turbines). It represents a common wave or wind frequency in marine environments (where cyclic loads are often in the 0.1–0.2 Hz range). The cyclic load magnitude was explicitly by **(Long and Vanneste, 1994)** with a capacity of up to(50%) of ultimate lateral load.

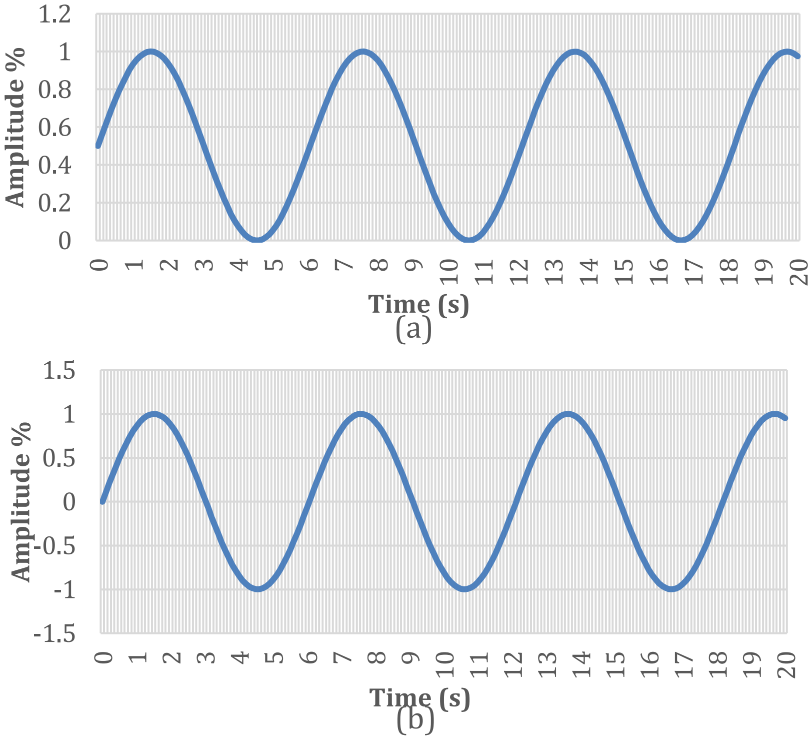


Figure 3. Time and amplitude diagram for (a) one-way lateral cyclic load, (b) two-way lateral cyclic load **(Nimbalkar and Basack, 2024)**

7. VALIDATION

The validation process for this study involved numerical simulations using Plaxis 3D to a **(3×3)** group-pile under cyclic horizontal loading. for numerical analysis which was conducted by **(JIN et al., 2010)**. As shown in **Fig. 4.**

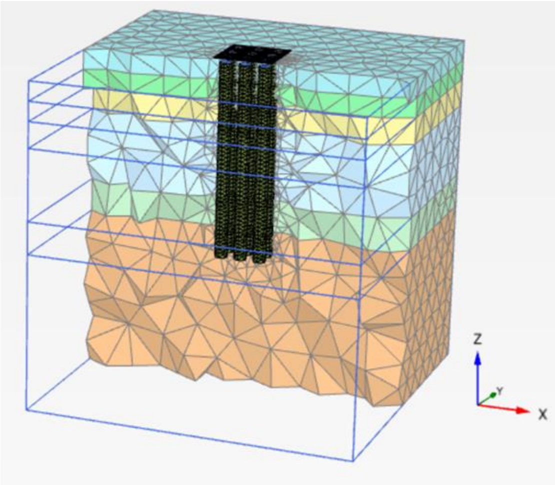


Figure 4. Numerical simulation by plaxis 3D program of case **(Jin et al., 2010)**.

The analysis employed the Mohr-Coulomb constitutive model to characterize the cohesive clay soil layers, by using DELEVER simulation peogram The pile foundation, consisting of reinforced concrete piles with (1.2 m) diameter and (30.4 m) length, was modeled Results demonstrated acceptable agreement with experimental data of bending moment distributions as shown in **Fig. 5** where the coefficient of determination (R^2) was found to be (0.75). This validation confirms the robustness of the 3D-FEM approach with Mohr-Coulomb and AFD models for analyzing cyclic loading effects on pile groups, while suggesting potential improvements through incorporation of more advanced constitutive models for soil behavior.

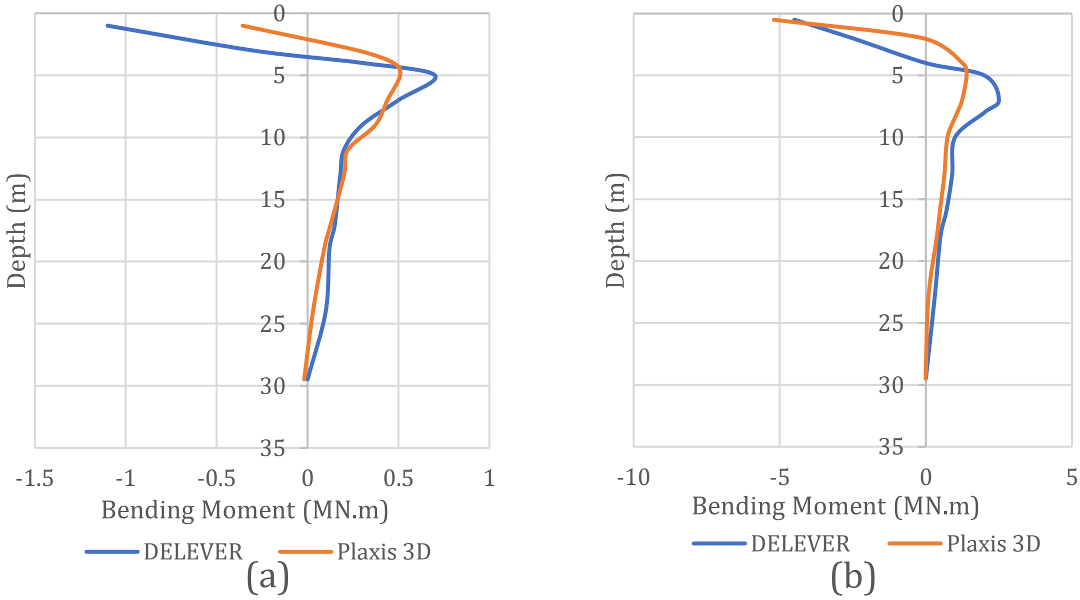


Figure 5. Comparisons of test and calculated results of bending moment in pile by DELEVER **(Jin et al., 2010)** and Plaxis 3D (a) load = 8 MN; (b) load = 20.5MN.

8. RESULTS AND DISCUSSION

8.1. Determination of the Settlement

According to **(Terzaghi, 1943)**, failure is known as a necessary load to displace (**10%**) of the pile's diameter, and due to lack of specific criterion for lateral displacement near slopes, the ultimate load can be considered as the load corresponding to the displacement of (**20%**) of the pile diameter as suggested by **(Rao et al. 1998).** A surface static load was applied on the piles cap in the static phase to simulate the pressure applied from the residential building; the value of the load was considered equal to **200 kPa** based on the study of Maheshunri and Viladkar **(Maheshwari and Viladkar, 2007)**, and (**1800 kN**) for lateral ultimate load. Shows the load-settlement curve in **Fig.6 (a)** for a single pile under vertical loading. The settlement increases with applied load until reaching the ultimate load capacity (defined at 10–20% of pile diameter displacement) after applied static load (after applying a safety factor of 2.5) 200 kPa. The single pile exhibits nonlinear behavior as the load approaches the ultimate capacity, indicating soil strength degradation. **Fig.6 (b)** Presents the load-settlement curve for a 2×2 pile group. The group shows higher stiffness (less settlement) compared to the single pile due to group interaction effects (load distribution among piles). However, the curve reveals progressive stiffness reduction under cyclic loading due to accumulated plastic strains in the clayey soil.

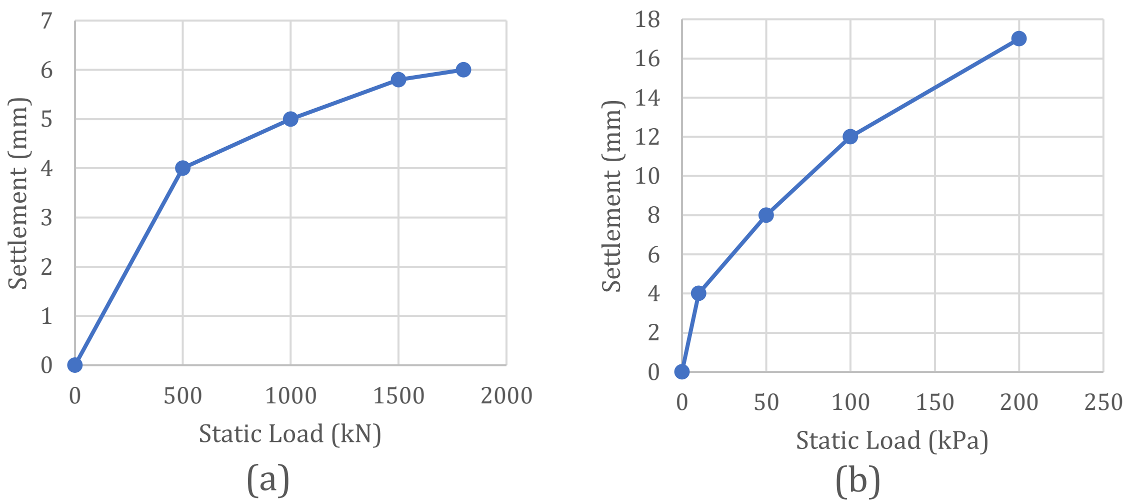
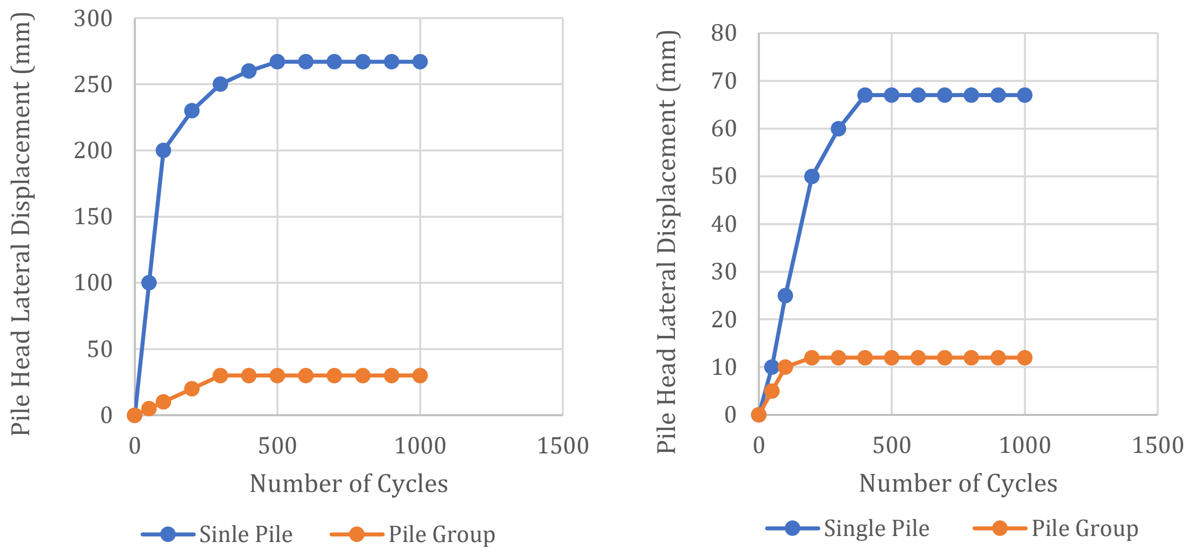


Figure 6. (a)The load-settlement curve of the single pile, (b) The load- settlement curve of the group of piles.

8.2 Pile Head Lateral Displacement with Lateral Cyclic Loading

Compare **Fig. 7 (a)** lateral displacement of a single pile vs. a pile in a group under one-way cyclic loading (unidirectional). the single pile exhibits larger displacements due to lack of lateral restraint from neighboring piles. After (1000) cycles at (50%) amplitude, the single pile shows significant permanent displacement caused by clay softening. **Fig. 7 (b)** Displays displacement under two-way cyclic loading. The pile group demonstrates lower cumulative displacement due to shared load distribution. Two-way loading causes oscillatory displacement around zero, but clayey soils remain prone to strength loss over cycles.

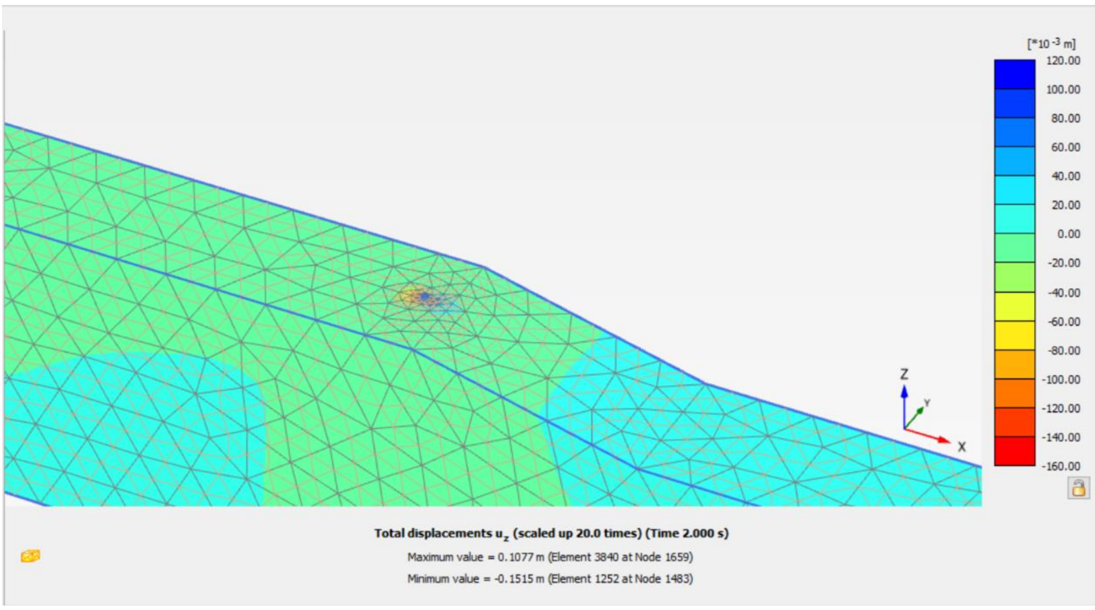


(a) (b)

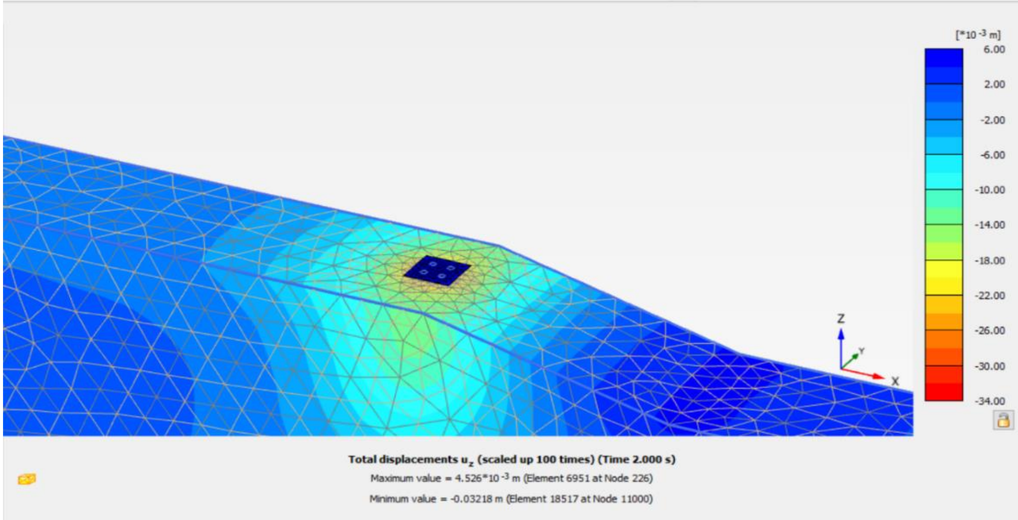
Figure 7. Pile head lateral displacement for a single pile and a pile within a group after 1000 cycles. (a) One-way Lateral cyclic load, (b) Two-way Lateral cyclic load.

8.3 Total Settlement

settlement contours after (1000) one-way cyclic load cycles shown in **Fig. 8.** The single pile develops localized settlement near the slope, highlighting soil weakness in this zone. The pile group exhibits more uniform settlement distribution due to load-sharing but still shows slope influence. **Fig. 9** depicts settlement under two-way cyclic loading. Permanent settlement is reduced compared to one-way loading, but soil displacement around the slope remains critical.

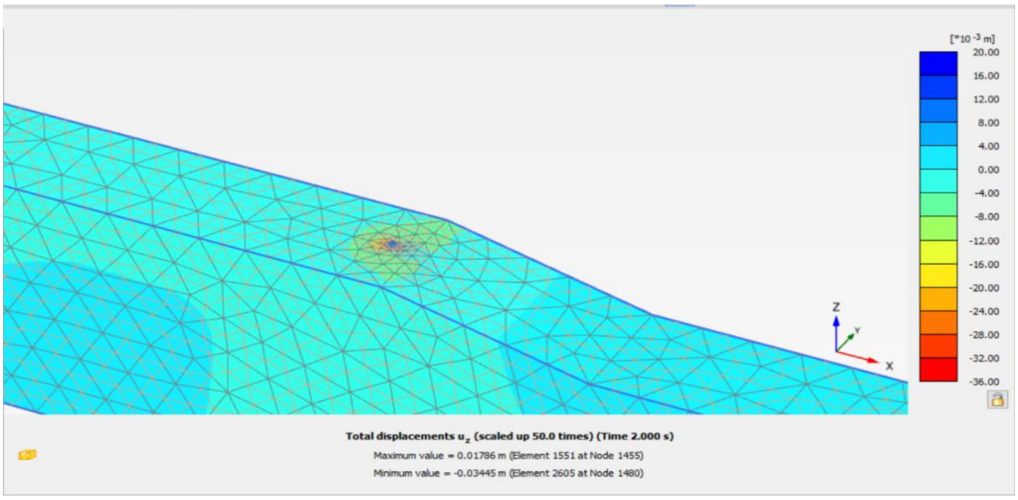


(a)

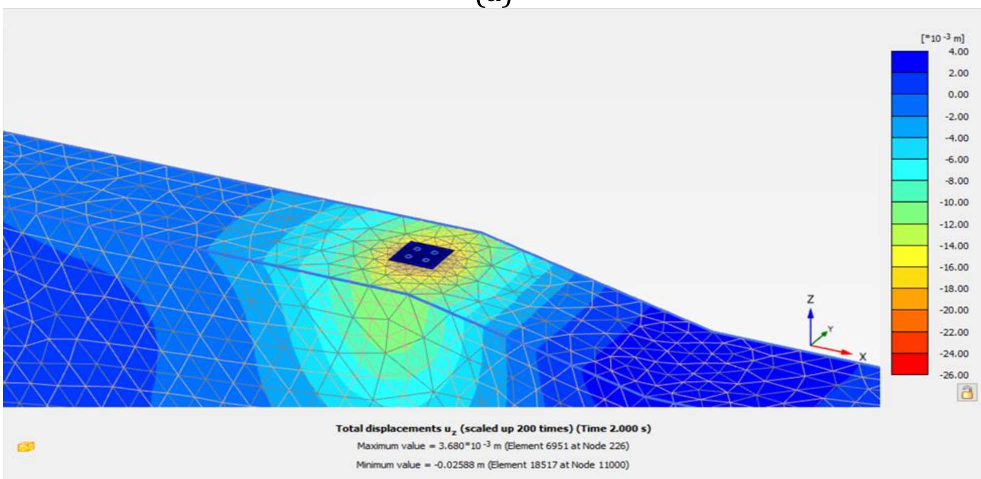


(b)

Figure 8. Numerical simulation using Plaxis 3D to analyze settlement of: (a) single pile, (b) pile group after 1000 one-way lateral cyclic load.



(a)



(b)

Figure 9. Numerical simulation using Plaxis 3D to analyze settlement of: (a) single pile, (b) pile group, after 1000 Two-way lateral cyclic load.

8.4 Pile Bending Moment

Fig. 10 (a) Illustrates bending moment depth profiles for the single pile. Maximum moments occur at Pile head (due to direct lateral load) Near the slope crest (due to reduced soil support). These critical zones are prone to cracking or structural failure under repeated cycling. **Fig. 10 (b)** Shows bending moments in the pile group. Moments are redistributed among piles, reducing peak values by (30%) compared to the single pile.

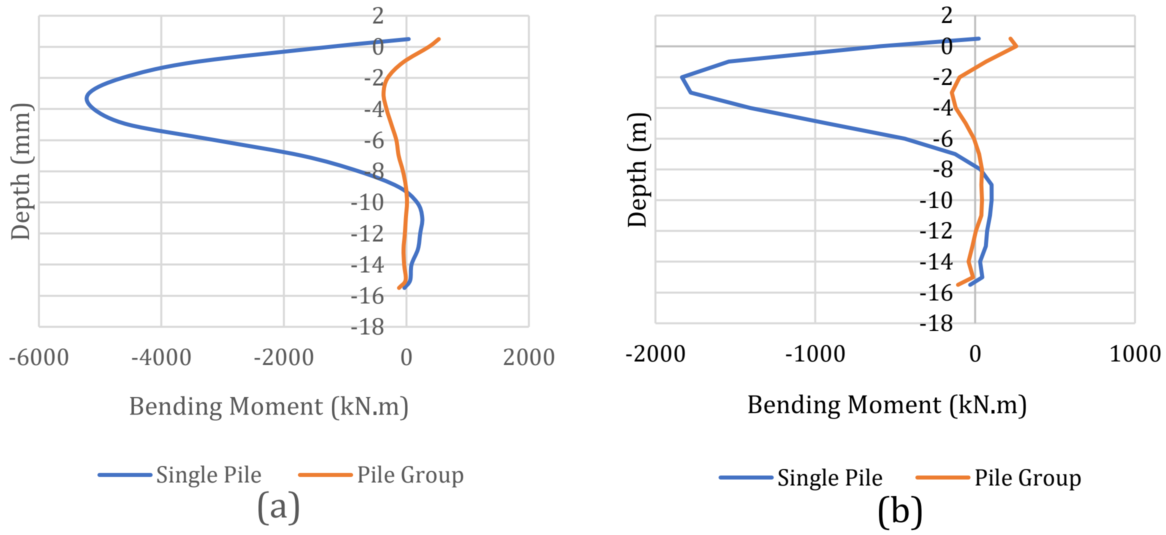


Figure 10. Pile Bending Moment Distribution, (a) One-way lateral cyclic load, (b) Two-way lateral cyclic load.

9. CONCLUSIONS

The behavior of piles near slopes under cyclic loading has attracted growing attention due to the complex soil-structure interaction. This study uses numerical analysis to evaluate single and group piles near a saturated clay slope, with the following section presenting the key results:

1. Pile groups (2×2) demonstrated 30–50% lower lateral displacements compared to single piles under cyclic loading due to load-sharing effects.
2. Single piles near slopes exhibited 20–40% higher displacements due to asymmetric soil support.
3. Two-way cyclic loading reduced permanent displacement but increased fatigue risks in piles from oscillatory stresses.
4. Piles adjacent to slope (1V:4H) showed localized settlement and higher bending moments near the slope crest.
5. Single piles had peak bending moments at pile head (direct lateral load) and slope crest (reduced soil support). Pile groups redistributed moments, reducing peak values by ~30% compared to single piles.
6. The model validation showed acceptable agreement between numerical and reference results, with a coefficient of determination (R^2) equal to 0.75, confirming the simulation's accuracy in predicting pile behavior.
7. To ensure stability and performance of piles in clayey soils, especially near slopes, it is recommended to use pile groups with a 3D spacing configuration to effectively reduce lateral displacement. Cyclic load amplitudes should be limited to less than 20% of the ultimate lateral capacity to prevent rapid degradation of the clay's structural integrity.

Continuous monitoring of pore water pressure is essential to detect and prevent sudden loss in shear strength. In high-risk zones, pile lengths should be extended beyond the potential slope failure plane to enhance overall system stability.

NOMENCLATURE

Symbol	Description
A	Amplitude of the cyclic lateral load
H_{max}	maximum lateral cyclic load
H_{mean}	mean lateral load
H_{min}	minimum lateral cyclic load

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Credit Authorship Contribution Statement

I, Maryam Hussein Ali, was solely responsible for the conceptualization, numerical modeling, data collection, analysis, validation, and preparation of the original manuscript. Asst. Prof. Ammar Abdul Hassan Sheikha contributed by supervising the research, reviewing the methodology, and providing essential academic guidance and support at all stages of the work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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دراسة مقارنة باستخدام طريقة العناصر المحدودة للركائز المفردة والمجموعة المجاورة للمنحدرات تحت تأثير الأحمال الدورية الجانبية

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الخلاصة

تبحث هذه الدراسة في أداء ركيزة واحدة ومجموعة ركائز (2×2) تقع بالقرب من منحدر طيني مشبع تحت الأحمال الجانبية الدورية باستخدام تحليل العناصر المحدودة (FEA). أجريت عمليات المحاكاة باستخدام Plaxis 3D مع نموذج التربة المتصلبة (HSM)، والذي يسمح بتمثيل أكثر دقة لسلوك التربة، وخاصة في ظروف التحميل الدوري. أخذ النموذج في الاعتبار التربة الطينية ذات المعلمات المستمدة من التقرير الجيوتقني الرسمي الذي أعدته مختبرات مكتب الاستشارات الهندسية (CEB) في كلية الهندسة بجامعة بغداد. تم وضع كل من الركيزة الواحدة ومجموعة الركائز على مسافة (4D) من منحدر مرتفع (8 أمتار) مع تدرج (1:4). تضمنت ظروف التحميل الأحمال الرأسية الثابتة والأحمال الجانبية الدورية. أهم النتائج التي تم التوصل إليها، قللت مجموعات الركائز من الإزاحة الجانبية بنسبة 30–50٪ مقارنة بالركائز الفردية، التي عانت من إزاحة أكبر بنسبة 20–40٪ بالقرب من المنحدرات بسبب دعم التربة غير المستوي. تسبب التحميل الدوري أحادي الاتجاه في إزاحات دائمة أكبر من التحميل الدوري ثنائي الاتجاه، بينما زاد التحميل ثنائي الاتجاه من مخاطر التعب، مما أدى إلى تدهور قوة الطين بنسبة تصل إلى 50%. وحدثت ذروة عزم الانحناء عند رؤوس الركائز وقمم المنحدرات، لكن الأكوام المجمعة خفّضت هذه الإجهادات بنسبة 30%.

الكلمات المفتاحية: تحليل العناصر المحدودة، الحمل الدوري، أساسات عميقة، منحدر طيني.