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Numerical Assessment of Pipe Pile Response under Seismic Excitation

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Abstract

The axial capacity and pile transference of loads under static loading have both been well reported, but further research is needed to understand the dynamic lateral responses. The pile load imposed during an earthquake may increase, but the soil's ability to support it may fall as a side effect of the vibration leading to more settlement. The key objective of this work is to identify what led to the substantial lateral destruction of the piles during the seismic event due to the kinematic effects. These failures were related to discontinuities in the subsoil as a result of sudden changes in soil strength due to shaking. The kinematic stresses exerted in a single pipe pile constructed in two sand layers under two different situations (dry and saturated states) are investigated in this study using numerical modeling. The bending moments were higher in the saturated sand soil than in the dry one which may be attributed to liquefaction. Generally, the acceleration increased through the loose layer (from bottom to top), and then significantly settled within the dense layer. It could be shown that using this modeling, one can estimate how a pile foundation will behave under "kinematic" loading driven by earthquakes. Therefore, the design and installation of drilled aluminum or steel piles in sand soil could make use of these present observations.

Keywords: Kinematic Response, Seismic Load, 3D Finite Element, Lateral Response, Maximum Acceleration.

التقييم العددي لاستجابة الركيزة الأنبوبية تحت الإثارة الزلزالية

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الخلاصة:

تمت دراسة قابلية تحمل الركيزة للاحمال المحورية ونقل الركيزة للأحمال تحت التحميل الثابت بشكل تفصيلي من قبل باحثين سابقين، ولكن هناك حاجة إلى مزيد من البحث لفهم الاستجابات الافقية للأحمال الديناميكية. قد يرتفع حمل الركيزة المفترض أثناء الزلزال، لكن قدرة التربة على دعمه قد تنخفض نتيجة للاهتزاز مما يؤدي إلى مزيد من الهبوط. ان الهدف الرئيسي لعمل الباحثين هو تحديد ما الذي أدى إلى تدمير كبير للركائز أثناء الحدث الزلزالي. بناء على نتائج التجارب المختبرية والحسابات العددية الأخرى، تمت الإشارة إلى هذه الأضرار على أنها التأثيرات الحركية للزلزال على الركائز. كانت هذه الإخفاقات مرتبطة بفوالق في باطن الأرض نتيجة للتغيرات المفاجئة في قوة التربة. تمت دراسة الضغوط الحركية التي تؤثر في ركيزة انبوبية مفردة في تربة مكونة من طبقتين من الرمل في حالتين مختلفتين (حالة جافة ومشبعة) في هذه الدراسة باستخدام النمذجة العددية. وفقًا لنتائج النمذجة والتحليل العددي، تم العثور على أقصى عزم للانحناء في الطبقة الرملية الرخوة على مسافة حوالي ٣,٥ متر تحت سطح التربة، ثم تناقصت بعد ذلك حتى أصبحت سالبة في الطبقة الرملية الكثيفة. وفقا لما تم الوصول اليه من نتائج بالامكان التنبؤ بكيفية تصرف الأساسات العميقة تحت الحمل "الحركي" الذي تسببه الزلازل. لذلك، يمكن أن تكون هذه الدراسة ذات اهميةفي تصميم وتركيب ركائز الألمنيوم أو الصلب في تربة رملية.

1. Introduction

Piles holding buildings are interacting with the soil in two different ways throughout a seismic event: kinematically and inertially. Inertial interaction happens as forces result from building activation by kinematics interaction. Kinematics interaction is the pile pressure generated by the motion of soil through seismic events [1]. According to Kim et al. [2], the high inertial impacts of the soil layers force a pile placed within these layers to follow the pattern of motion of the soil around it. Because of the supposed pile's great stiffness, the pile withstands this motion and attempts to reflect the shear waves. The distribution of soil particles adjacent to the pile differs dramatically from free-field action due to a phenomenon called wave scattering. As a result, the movement may lead the pile to become more curved, which would produce the kinematic response (bending moments and shear forces) in the pile. Some researchers claimed that the pile might act in an unpredictable manner because of the development of excess pore pressure, resulting in weak saturated soil and, as a consequence, a significant bending moment and shear stress on the pile [3]. Because of the formation of additional pore pressure in saturated soil, the pile shaft stiffness reduces throughout a seismic event and may evaporate after an assessment of ground shaking with the excess pore pressure [4, 5]. The axial load variation contributes to withstanding the bending moment generated by the soil's lateral loading, while the vertical pile displacement is caused by the fluctuation of its vertical loads [6]. Conducting shaking table tests, Tang et al. [7] examined the earthquake resistance of reinforced concrete pile groups built in moderate sand soil with a clay shell. The results showed that the peak bending moment was observed near the pile head during liquefaction aggravation. The computer modeling analysis showed that the building weight controls the inertial force while pile spacing has very little impact on kinematic forces. The term "inertial component" refers to the moment resulting from inertia forces, whilst the term "kinematic component" refers to the moment developed by soil movement [4].

Poulos and Davis [8] have proposed that the rigidity of the pile foundation in the horizontal direction is essential for constructing structures that are subjected to earthquakes, soil movement, and waves. In many investigations employing the 3D finite element approach [9, 10, 11,12], the response of piles during stress from the lateral direction was evaluated. Due to increased seismic activity in the Iraqi region in the past few years, Iraqi academics have been studying pile foundations in the sand during a range of earthquake movement patterns [13]. Additionally, pipe piles are often utilized because they can be created more affordably and easily, they can be analyzed and safety verified before being erected, and they may be customized to specific load requirements, which saves money by avoiding the necessity of further reinforcement. Therefore, the influence of static vertical and lateral loads with 3 different seismic excitations on the soil-pipe pile system with respect to kinematic interaction was examined in this research using MIDAS GTS NX finite element software. The laboratory observations of Hussein and Albusoda [14] were used to verify the software outputs.

2. Numerical Model

Based on the MIDAS GTS NX software, three-dimensional finite element models have been built while taking the shaking load nonlinearity into account. The laboratory tests, meshing, static and dynamic boundary conditions, and validation of the constitutive models utilized in the current work were all thoroughly described by Al-Jeznawi et al. [15]. A full-scale model was used in the current numerical analysis, and three different real earthquakes (Kobe, Halabja, and Ali Algharbi) were implemented as well. Hussein and Albusoda [14] employed 1g shaking table tests to analyze a closed-ended aluminum pipe pile (L/D=25) established in heterogeneous soil layers (brought from Al-Karbala city). Since these laboratory experiments were conducted for small-scale models, utilizing 1:35 as a model to prototype, the present numerical models were validated using this research observation, and the validation results were published by Al-Jeznawi et al. [15].

3. Soil Constitutive Modeling

Under dynamic loads, ground exhibits extremely nonlinear, flexible, and hysteretic behavior. The soil constitutive relations used in the approach to numerical simulation ought to handle all of these issues while striking a balance between accuracy and dependability to address the issue at hand. The soil parameters from the laboratory experiments [14] are shown in Table 1. Table 2 displays the pile's structural characteristics. A linear elastic constitutive relation was used for the pile element. Using the Modified Mohr-Coulomb failure criterion, connection elements with limiting shear resistance are used to describe the interaction between the pile and the all-around soil. The contact elements' normal and shear coefficients were identified after a thorough investigation.

A 0.56 m diameter pile is set up within a two-layer soil medium with an 11.2 m thickness of the upper layer of sand and a 16.8 m thickness of the bottom layer. It is believed that the central pile has reached the subsoil and has dropped into the thick sand below. In the saturated soil model, the water table is at the soil surface.

The applied static loads were considered as 50% of the total allowable pile load. As for the applied dynamic loads, three different ground accelerations (Halabja (PGA = 0.102 g), Ali Al-gharbi (PGA = 0.1g), and Kobe (PGA = 0.82 g)) were applied.

Table (1): Ground properties.

Properties	*Loose sand*	*Dense sand*
G (kPa)	*5000*	*10,500*
v	*0.25*	*0.3*
Ø (°)	*32*	*35*

D_r (%)	*30*	*70*
Gs (unitless)	*2.64*	*2.64*
k (cm/sec)	*0.0056*	*0.005*
ψ (°)	*2*	*5*

Table (2): Pile structural characteristics

Properties	***Value***
Material	*Aluminum*
Size (m)	*D_o = 0.56, D_i = 0.455, L = 17.5*
Slenderness ratio (L/D)	*25*
γ (kN/m³)	*30*
E (GPa)	*67*
I (m⁴)	*$4.36e^{-8}$*
A (m²)	*$2.7e^{-4}$*
ξ (%)	*5*

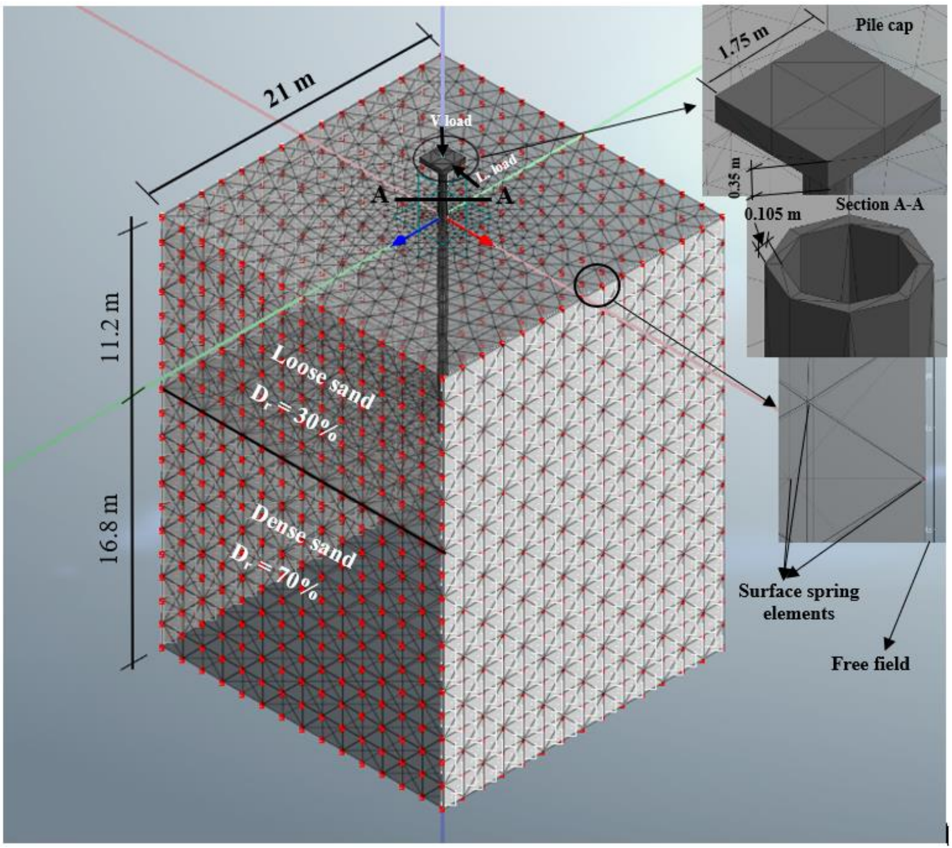


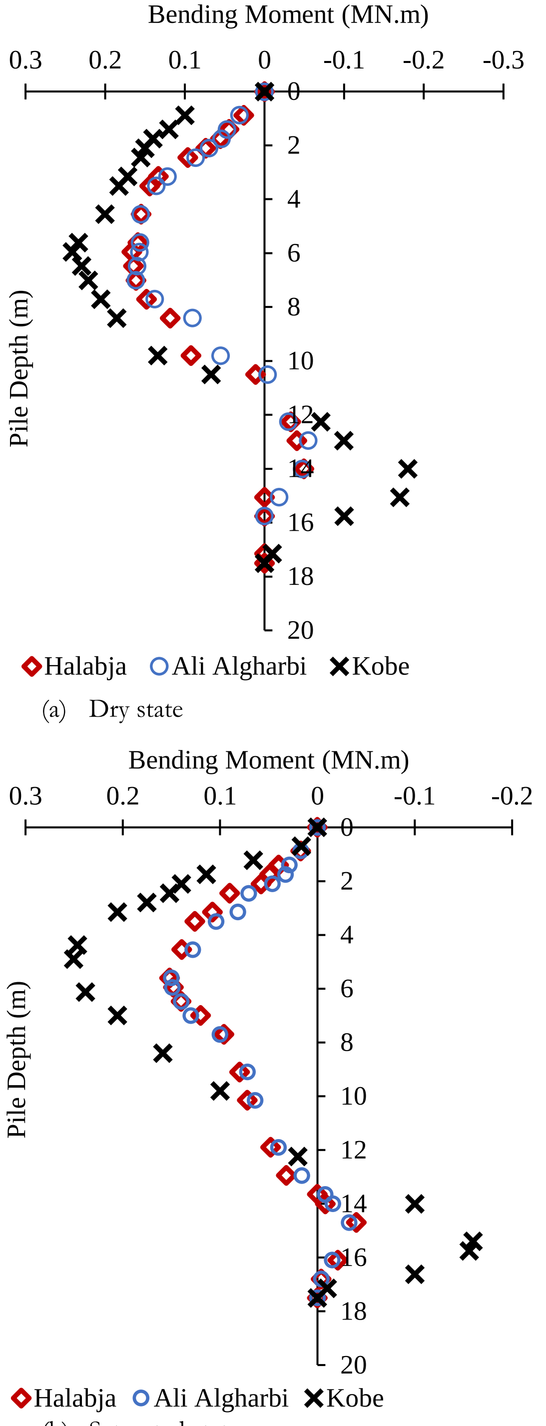
Figure (1): Configuration of soil-pile full-scale model [15].

4. Kinematic Response of Pile Shaft

Several methods are now offered to study the performance of piles subjected to lateral loads, ranging from sophisticated models like nonlinear dynamic modeling and 2D or 3D finite-element approaches to apply simplified approaches like the limit equilibrium and p-y curve assessment. The authors of the current work used MIDAS GTS NX software to build a full-scale finite element model depending on static load and 1g shaking table tests of a single pipe pile located in two sand soil layers. With sufficient soil constitutive models and the ability to use suitable dynamic boundary conditions, GTS NX is prepared to address problems with soil dynamics.

The state of a soil's profile affects how the soil behaves in an area during a seismic event. The soil movement of an area without any supporting structures is referred to as the "free field" motion of the spot. Any structural foundation that is embedded in the soil layer, such as a pile, is motivated by shaking of the ground to follow the movements of the soil that is surrounded. The piles, on the other hand, are extremely resistant and withstand such forced displacement while reflecting the next stress waves in the cycle. The ground behavior around the pile differs from what is happening in the free field as a result of this phenomenon, referred to as wave scattering. According to Ali V. et al. [16], near-field seismic events are distinct from far-field events since they have special qualities including enhanced acceleration transmitted to the pile. The pile will have curvature throughout the layer borders as a consequence of the compelled shaking because of the change in the stiffness of the adjacent layers. The pile is then subjected to shear forces and bending moments as a result, which referred to the pile's kinematic response. The variations between the layers below have the greatest impact close to the underlying layer boundary on the strength of these kinematic forces produced on piles [17]. It is important to note that the currently proposed recommendations specifically account for the inertial forces caused by earthquakes acting on the piles [15, 18].

The maximum bending moment under the influence of a couple of static and seismic loads is shown in Figure 2 for both saturated and dry circumstances. The saturated sandy soil's bending moment values were higher than the dry one (as presented in Table 3), which could be a result of the liquefaction event [4], the liquefaction propagation in the loose sand layer occurred shortly after the maximum value of the bending moment was attained. In the subsequent work, Hussein and El Naggar [19] found a similar pattern when testing a helical pile placed in saturated sand soil.

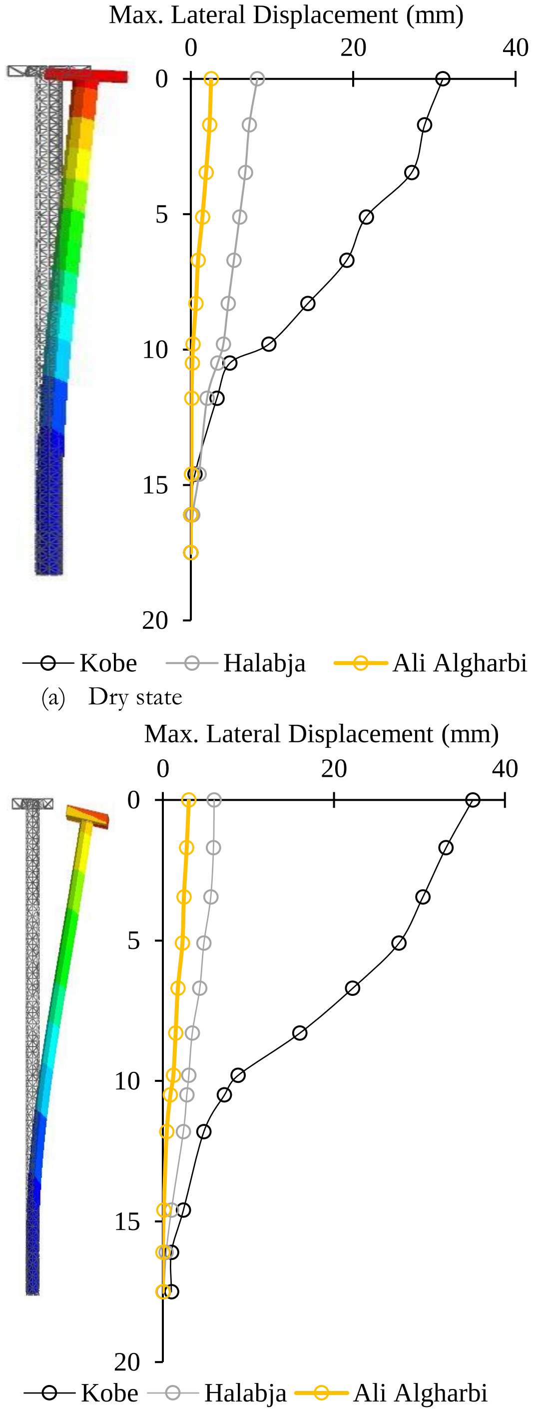


(a) Dry state

(b) Saturated state

Figure (2): Maximum bending moment along the pile shaft.

Identical research was conducted by Phanikanth et al. [20], who also used the embedded pile's lateral deformation for evaluating the kinematic effect. The largest lateral deformations under liquefied and non-liquefied soil layers are depicted in Figure 3 of the present work. At the head and the tip, the pile hadn't been strengthened versus lateral shaking. When a coupled static-dynamic force is applied to dry soil layers, it can be observed that the pile moves with the soil with a much smaller relative movement than saturated soil layers. Likewise, the pile cap had the greatest amount of lateral deformation (as presented in Table 3), which is consistent with other studies findings.

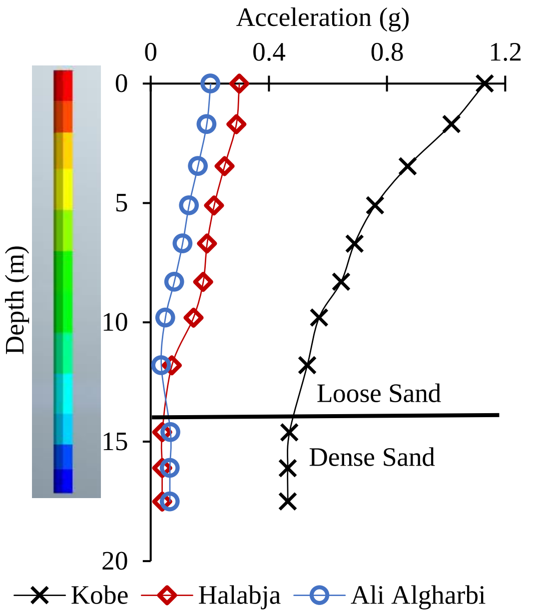


(a) Dry state

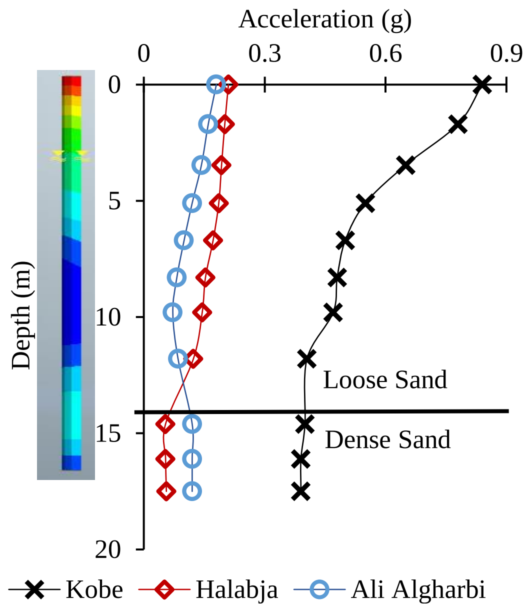
(b) Saturated state

Figure (3): Maximum lateral deformation along the pile shaft.

The highest pile acceleration in dry and saturated soils was shown in Figure 4 together with the effects of the three acceleration histories and soil state. Generally, the acceleration rose through the loose sand layer (from bottom to top), and then essentially settled within the dense sand layer. The soil weakening during seismic activation may be the cause of this amplification through the thin layer of loose sand. Overall, the acceleration from bottom to top that is amplified and has its greatest acceleration at the pile head agrees well with findings from earlier investigations [20]. The effects of the numerical modeling in the saturated and dry soil layers were thus reasonable.



(a) Dry state



(a) Saturated state

Figure (4): Maximum horizontal acceleration along the pile shaft.

Figure 3 shows the lateral deformation along the pile shaft under the influence of various acceleration histories in both dry and saturated circumstances. Because of soil densification, that in turn prevented pile movement with respect to relative displacement, the pile lateral displacements reach 0 in dry conditions (Figure 3). Nevertheless, pile lateral deformation dramatically increased within the loose sand layer (dry and saturated).

By observing that the static loads were maintained on the pile cap as illustrated in Figure 1, it can be deduced that the maximum pile lateral deformation was caused by the coupled effect of static and seismic loading on the pile head. Even though the soil state remained moist, the pile exhibited minimal deformation at the toe (in the deep sand layer). The latter can be explained by the soil plug's interaction, which is reinforcing the pipe pile's base and limits pile displacement.

Table (3): Summarizing the main results.

Dry condition			
PGA (g)	*0.82*	*0.102*	*0.1*
Lateral displacement (mm)	*30*	*9.4*	*4.3*
Maximum bending moment (MN.m)	*0.24*	*0.19*	*0.18*
Acceleration (g) @ pile head	*1.15*	*0.3*	*0.22*
Saturated condition			
PGA (g)	*0.82*	*0.102*	*0.1*
Lateral displacement (mm)	*38*	*8*	*2.5*
Maximum bending moment (MN.m)	*0.28*	*0.2*	*0.2*
Acceleration (g) @ pile head	*0.85*	*0.24*	*0.19*

5. Conclusion

In this study, the bending moment caused by the soil displacement (kinematic component) is investigated with the pile lateral deformation. In both the saturated and dry instances, the single pile was found to respond well with the laboratory findings. The distribution of maximal pile bending moments throughout the pile shaft has a significant impact on the pile design. The moment induced by soil displacement (the kinematic component) is examined in this work along with pile lateral movement. Based on numerical estimates, around the very first section of the pile from the soil surface, a substantial bending moment was noticed. Around the layer interface, where it briefly approached negative values, these bending moments then slightly declined.

The lateral deformation, moment, and shear force distribution of a single pile can be evaluated using the current numerical modeling applied in this work. An isolated pile or a single pile within a group can be subjected to a simultaneous lateral force and/or moment at the pile's head along with a free-field soil motion. This modeling allows for proper lateral movements and bending moment patterns on piles when assessed against lab experiment results. Subsequently the results of this analysis highlight the significance of the main pile shaft's structure in handling an expected bending force as accounting for a potential kinematic bending moment within a seismic event.

Notation

Symbol	***Meaning***
3D	Three dimensional
L/D	Slenderness ratio
PGA	Peak ground acceleration

V. load	Vertical load
L. load	Lateral load
G	Soil shear modulus
ν	Poisson's ratio
Ø	Angle of internal friction
Dr	Relative density
Gs	Specific gravity
k	Permeability
ψ	Dilatancy angle
γ	Unit weight
E	Young modulus
I	Moment of inertia
A	Cross section area
ξ	Damping ratio
2D	Two dimensional

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