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Civil and Environmental Engineering
Vol. 18, Issue 1, 96-103, DOI: 10.2478/cee-2022-0010

A SOIL-PILE RESPONSE UNDER COUPLED STATIC-DYNAMIC LOADINGS IN TERMS OF KINEMATIC INTERACTION

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Abstract

Although the axial aptitude and pile load transfer under static loading have been extensively documented, the dynamic axial reaction, on the other hand, requires further investigation. During a seismic event, the pile load applied may increase, while the soil load carrying capacity may decrease due to the shaking, resulting in additional settlement. The researchers concentrated their efforts on determining the cause of extensive damage to the piles after the seismic event. Such failures were linked to discontinuities in the subsoil due to abrupt differences in soil stiffness, and so actions were called kinematic impact of the earthquake on piles depending on the outcomes of laboratory tests and other numerical analyses. In this research, numerical modeling is used to explore the kinematic forces created in a single pile erected in two sand layers under two different conditions (dry and saturated states). Based on the obtained results from the physical model, the maximum bending moment was observed at a depth around 200 mm below the ground surface in the loose sand layer, then these values gradually reduced until it becomes negative in the dense sand layer. It has been demonstrated that this modeling may be used to predict how a pile foundation would respond to "kinematic" loading generated by ground movements during a seismic event. Consequently, the current findings could be used in the design and construction of bored aluminum or steel piles in Al-Karbala soil.

Keywords:

Earthquake;
Pile response;
Sandy soil;
Bending moment;
Lateral deflection.

1 Introduction

During an earthquake, piles supporting superstructures experience two interactions with the soil: kinematics and inertial interactions. Kinematics interaction is the pile loading caused by the soil movement from the development of seismic waves, and the inertial interaction is when forces owing to superstructure actuation via kinematics interaction [1]. Hussein and El Naggar [2] stated that the pile diameter may impact the kinematic pile-soil contact, which may affect pile stability. They investigated a pile with a diameter of 0.3 m and the results revealed that the softening of the dense sand layer caused the pile foundation to lose support, i.e. reduction in the frictional contact resistance between the pile and the soil, thus pile experienced deformation (i.e. kinematic response) with almost no relative movement. Kim et al. [3] stated that when a pile is embedded in the soil layers, the pile is compelled to track the surrounding soil movement because of the high inertial influences of these soil layers. However, the pile resists this movement and tries to reflect the shear waves due to the high rigidity of the intended pile. This situation is known as wave scattering, therefore, the movement of soil particles closed to the pile is significantly varied from free-field motion. In consequence, the pile may gain curvature due to this oscillation, resulting in the creation of bending moments and shear forces in

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the pile known as the kinematics response. Other authors stated that due to the rising development of excess pore pressure, the pile may behave in a complicated way, resulting in weak saturated soil and, as a result, a considerable bending moment and shear force on the pile [4, 5]. In saturated soil, the pile shaft resistance decreases during the seismic loading due to the development of extra pore pressure and this reduction may dissipate at the end of ground shaking along with the excess pore pressure [6]. The vertical pile movement creates a fluctuation in its vertical loads, and the axial load fluctuation helps to resist the bending moment caused by the soil's lateral loading [7]. Tang et al. [8] investigated the seismic behavior of a set of reinforced concrete piles constructed in a moderate sand layer with a clay shell using shaking table tests. According to the findings, the highest bending moment arrived at the liquefaction commencement, and the maximum BM appeared at the pile head. The experiment's computer modeling revealed that pile spacing has only a minor effect on kinematic forces, whereas the superstructure weight dominates the inertial force. A first derived finding that can more strongly affect pile design is the pattern of maximum pile bending moments along the pile shaft. The moment created by inertia forces is referred to as the 'inertial component,' whereas the moment caused by soil displacement is referred to as the “kinematic component”, [1].

In this study, MIDAS GTS NX was used to investigate the effect of couple static-dynamic loads on soil-pile interaction based on kinematic interaction. The static loads were vertical and lateral point loads applied to the pile cap. While the dynamic load was represented by the ground acceleration of Kope earthquake (peak ground acceleration = 0.82 g) recorded data. The observed results were validated with the experiment findings which were performed by Hussein and Albusoda in 2021 [9].

2 Numerical modeling approach

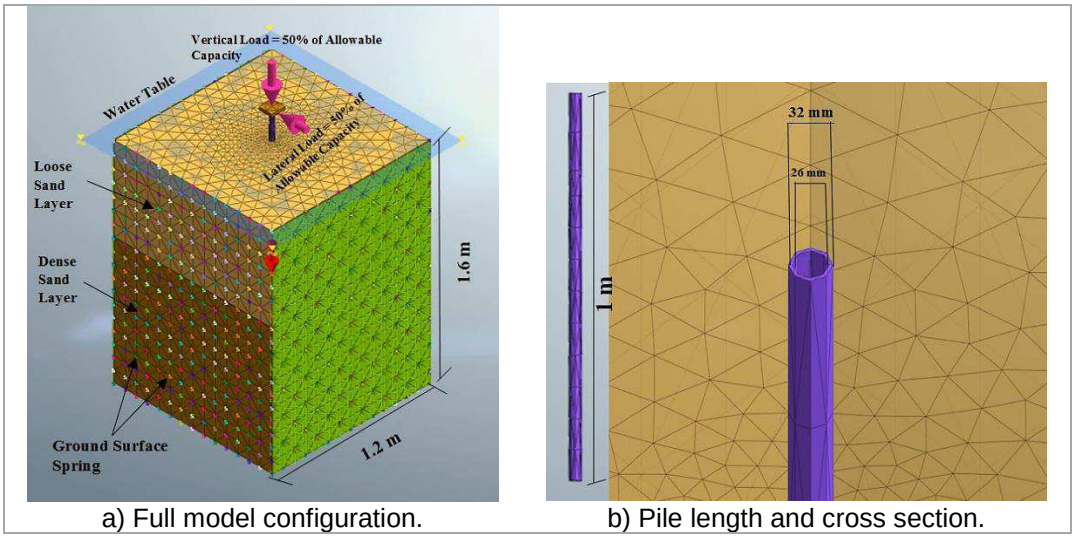
Numerical modeling is one of the most essential approaches for assessing infrastructure problems since it deals with non-linear stress-strain response [10]. The existing pile design approaches for earthquake loads concentrate on analyzing pile bending moments caused by lateral forces such as inertia loads and loads caused by ground movement, i.e. lateral loads. To investigate the performance of piles exposed to a lateral load, a variety of techniques are currently available, varying from advanced models such as nonlinear dynamic simulation and 2D or 3D finite-element techniques to the use of simplified methodologies such as the limit equilibrium approach and p-y analysis method.

The present study based on 1 g shaking table test of a single pile existed in two layers of granular soil, the authors adapted a scale-up finite element model using MIDAS GTS NX. With the presence of adequate soil constitutive models and the opportunity to implement appropriate dynamic boundary conditions, GTS NX is capable of solving issues associated to soil dynamics.

2.1 Soil constitutive model

Under dynamic loads, soil behaves in a hysteretic, highly nonlinear, and flexible manner. All of these difficulties should be addressed by the soil constitutive relationship employed in the numerical simulation process, while achieving a balance between precision and reliability to address the problem at hand. Table 1 presents the ground material properties from laboratory tests [9]. Table 2 shows the structure properties. Fig. 1 depicts the subsurface situation with the underlying soil parameters employed in the finite element simulation. For the pile component, a linear elastic constitutive relation was applied. To represent the interaction between the pile and the surrounding soil, connection elements with limiting shear resistance as per Modified Mohr-Coulomb failure criterion are employed. After an extensive studying, the normal and shear modulus of the contact elements were determined.

A 32 mm diameter pile installed through a two-layer soil medium with the upper sand layer is 640 mm thick, and the bottom is 1600 mm thick. The central pile is thought to have penetrated the subsoil and is socketed to the dense sand beneath. The water table is available at the ground surface elevation in the saturated soil model.



a) Full model configuration. b) Pile length and cross section.

Fig. 1: Two layers soil system with an aluminum pile.

Table 1: Soil layer properties.

Named	Loose sand	Dense sand
Shear modulus [kPa]	5e3	38e4
Poisson ratio	0.25	0.3
Friction angle [°]	32	35
Relative density [%]	30	70
Specific gravity [unitless]	2.64	2.64
Permeability, *k* [cm/sec]	5.6e-3	5.6e-3
Dilation angle [°]	2	5

Table 2: Pile properties

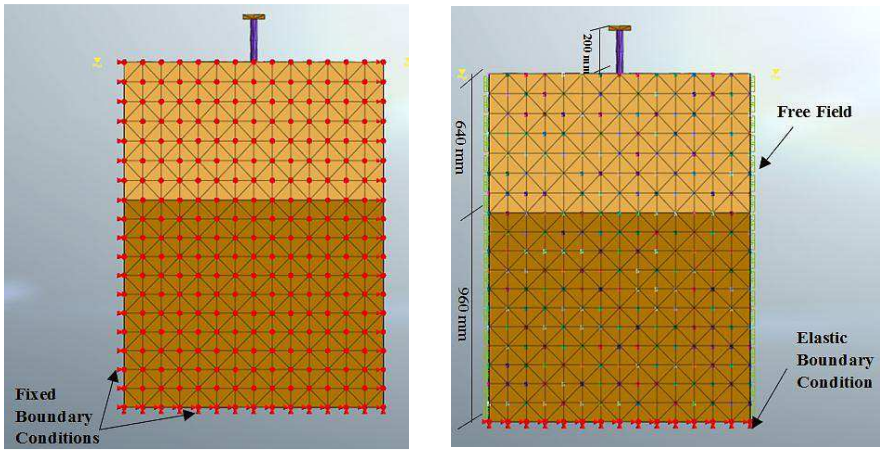
Properties	Pile	Pile cap
Material	Aluminum	Aluminum
Size [m]	Do = 0.032, Di = 0.026, L = 1.0	0.1 x 0.1 x 0.02
Slenderness ratio	25	-
γ [kN/m^3]	30	30
Young modulus [GPa]	67	67
I [m^4]	4.36e-8	-
Cross-sectional area [m^2]	2.7e-4	0.01
Damping ratio ξ	5 %	5 %

2.2 Boundary conditions

A fully linked system was used to model the interface and the soil medium. To minimize wave reflection, the lateral boundary conditions were treated as a free-field, while the bottom boundary was left undrained to allow excess pore pressure propagation. The horizontal acceleration was used to apply the seismic excitation to the soil bed (*x*-direction). The existence of the pile cap on the top of the pile was modelled with the pile extended 200 mm above the ground surface. The boundary condition suggested by Zienkiewicz et al. [11] ties the degrees of freedom at the lateral boundaries so that the border nodes at the same level move in the same way. This approach can accurately represent 1D soil reaction, but it reflects waves that are radiated far from the structural element, resulting in wave confinement within the mesh. According to Kontoe [12], when the wave propagating far from the structure is insignificant, the restricted degrees of freedom boundary requirements at the mesh edges are adequate.

The boundary reaction of the soil-pile model with limited degrees of freedom was assessed to the response of the comparable positions of the system without the pile exposed to the same simulated ground motion because there is no measure of the quantity of a wave propagating out from

the pile. By maximizing the margin between the pile and the lateral barrier, the disparity between the two systems was reduced to an acceptable level. In this situation, the cyclic soil constitutive behavior's material damping diminishes the wave, making the reflected wave inconsequential. Fig. 2 shows the static and dynamic boundary conditions which were implemented in this model.



a) b)

Fig. 2: Boundary conditions implemented in this study.

3 Kinematic responses of the pile body

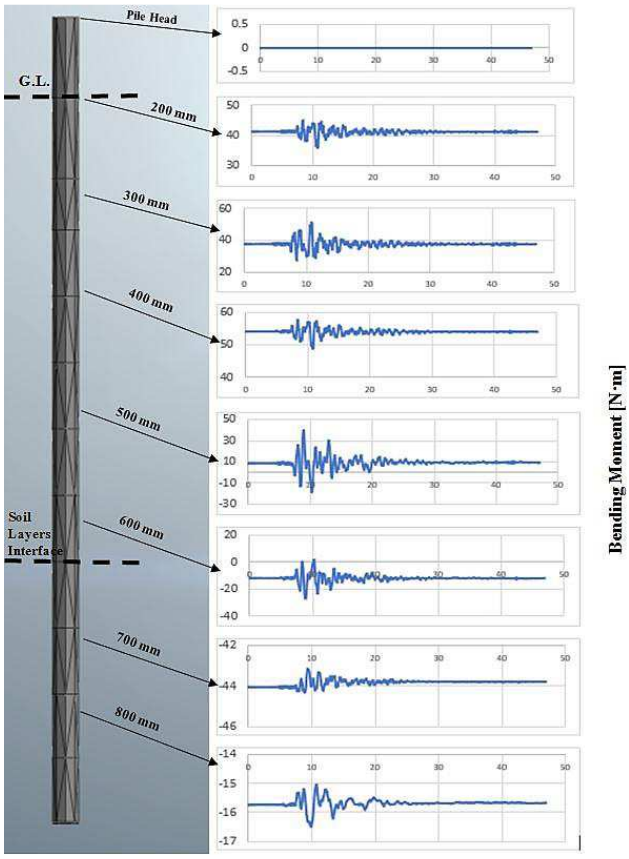
The soil behavior at a specific location in the event of an earthquake is determined by condition of the ground profile. The “free field” motion of a site refers to the soil response of a specific location without any structural elements. Ground motion drives any structural feature immersed in the soil layer, i.e. a pile, to pursue the movement of the surrounded soil. The piles, on the other hand, resist such forced displacement and reflect the incoming stress waves in the cycle due to their great rigidity. This is known as wave scattering, and as a consequence, the ground movement near the pile varies from the movement in the free field. Ali V. et al. [13] stated that Near-field earthquakes differ from far-field earthquakes in that they have unique characteristics, such as increased acceleration imparted to the pile. Owing to the variation in the stiffness of the neighboring layers, the pile will exhibit curvature along the layer boundaries as a result of the forced vibration. Subsequently, the pile is exposed to bending moments and shear stresses. This is known to as the pile's kinematic response. The amplitude of these kinematic forces created on piles is mostly determined by the differences between subsurface layers, with maximal influence near the underlying layer boundary [14]. It is worth noting that the current design guidelines only take into account the inertial forces acting on the piles as a result of earthquakes [15, 16].

The maximum and minimum (negative) bending moments created in the pile are presented in Figs. 3 and 4. The maximum value of each node in Figs. 3a and 4a were plotted with the pile length in Figs. 3b and 4b. The scaling law was used in Fig. 3 to validate the software outputs with the 1 g shaking table test findings. Susumu Iai [17] proposed the scaling factor for bending moment which was λ^3 as a prototype to model; where λ is the geometry scaling $\lambda = 2$. The results of the dry soil layers were compared with the findings of the 1 g shaking table test [9]. Generally, the scaled model 1:2 matched the piles' bending moment profile; however the pile bending moment values were a little exaggerated at some points due to scaling, nonlinear analysis control, and experimental set up.

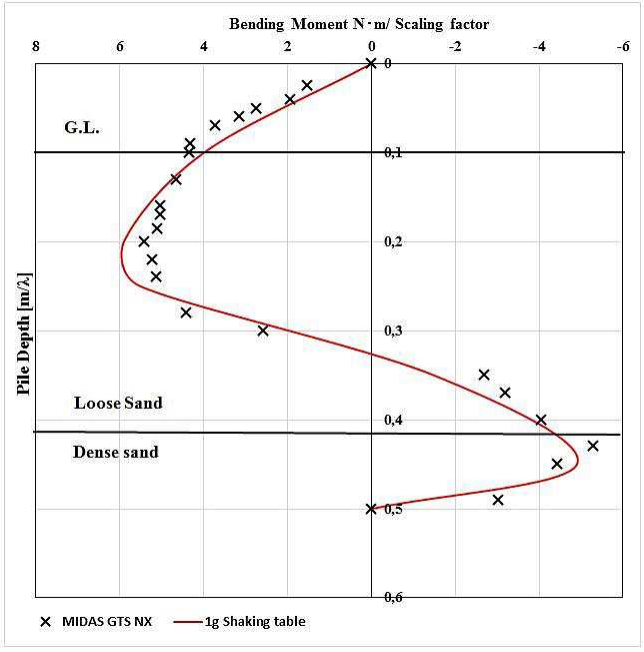
Figs. 3 and 4 present the maximum bending moment for both saturated and dry conditions under the effect of a couple static and dynamic loads. In both saturated and dry cases, the bending moment trends of the aluminum pipe pile obtained from MIDAS GTS NX is in good agreements to the 1 g shaking table results. However, the values of the bending moment of saturated sandy soil were larger than the previous one which may be attributed to the liquefaction phenomenon. It could be observed that the maximum value of the bending moment reached just after the liquefaction propagation in loose sand layer as shown on Fig. 5. The later study was performed by Hussein and El Naggar [6] showed similar trend was observed in testing the helix pile embedded in a liquefied soil.

The kinematic response was also evaluated by lateral deformation of the embedded pile, where similar assessment was performed by Phanikanth et al. [18]. In the current study, the maximum lateral deformations are shown in Fig. 6 under liquefied and non-liquefied soil layers. The pile was not

restrained against lateral movement at both the head and the tip. It is noticed that under the effect of a coupled static-dynamic load with dry soil layers, the pile follows the soil movement without a significant relative displacement as compared to the saturated soil layers. Additionally, the maximum lateral deflection was concentrated on the pile cap similar to the observations mentioned by several researchers.

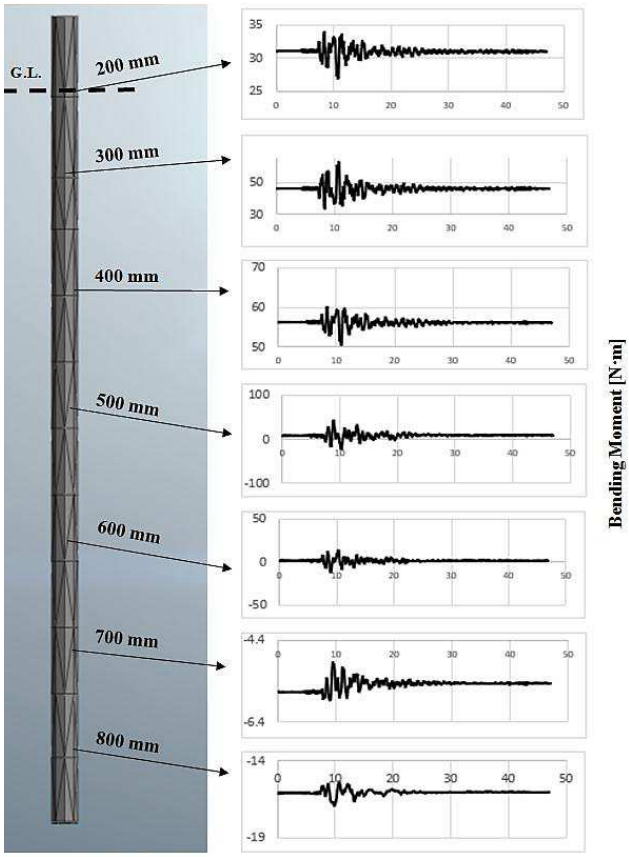


a) Bending moment of the assign nodes with time.

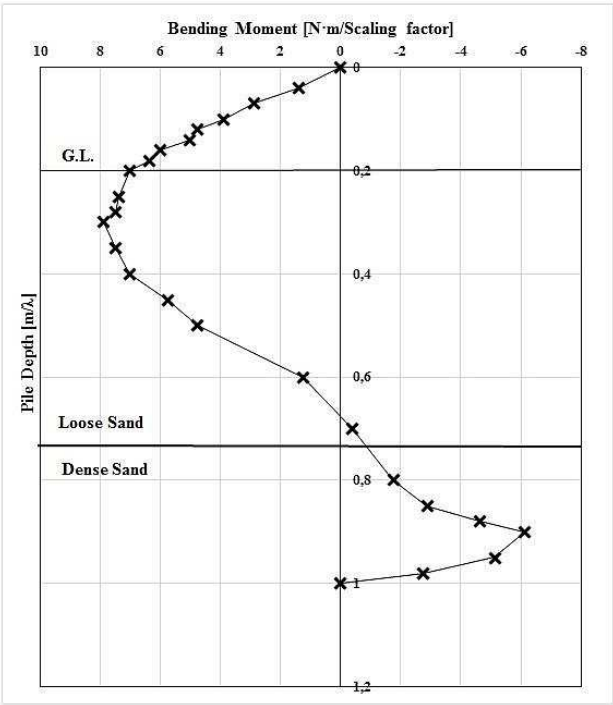


b) Maximum bending moment along the pile length.

Fig. 3: Maximum bending moment with time along the pile length of scaled down model to facilitate the comparison with 1 g shaking table results (non-liquefied soil).



a) Bending moment with time.



b) Maximum bending moment along the pile length.

Fig. 4: Maximum bending moment with time along the pile length of scaled-up model (λ = 2) (liquefied soil).

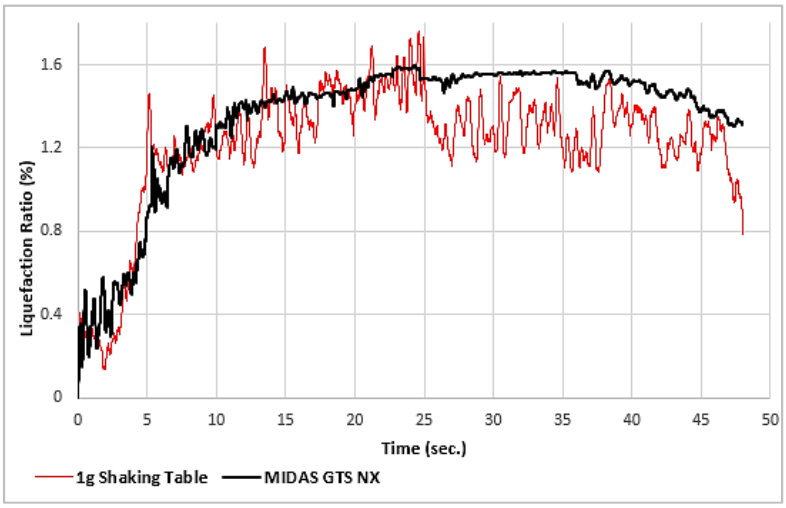
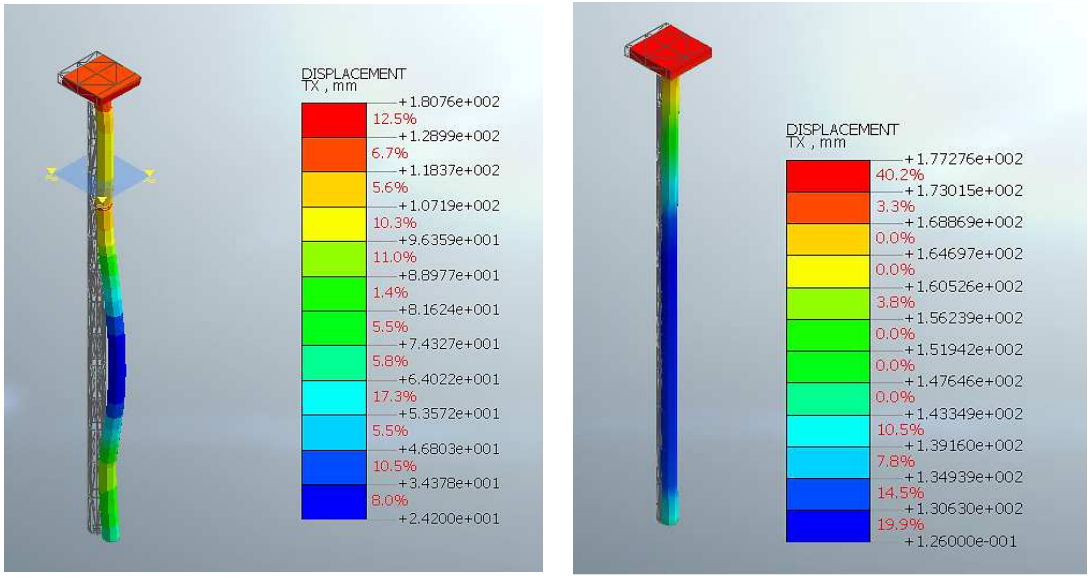


Fig. 5: Pore pressure ratio at 400 mm depth below the pile cap.



a) b)

Fig. 6: Maximum lateral pile deflection in case of a) liquefied soil, b) dry soil.

4 Conclusion

The findings of 1 g shaking table tests were used to construct and validate finite element models. The estimated responses of a single pile in the saturated and dry cases are in good agreements with the laboratory data very well. A first derived finding that strongly affects pile design is the pattern of maximum pile bending moments along the pile body. In this study, the moment caused by the soil displacement (kinematic component) are investigated with the pile lateral deformation. A considerable bending moment is created within the first quarter length of the pile from the ground surface, according to numerical calculations. Subsequently, these values of the bending moment slightly decreased near the layer interface where it reached negative values.

The present numerical modeling used in this study enables for the evaluation of a single pile's lateral deflection, moment, and shear force distribution. A lateral force and/or moment at the pile's head, as well as a free-field soil movement profile down its length, can be applied simultaneously to an isolated pile or an individual pile in a group. When compared to lab experiment observations, this modeling can produce lateral deflection, bending moment distributions on piles that are accurate. Finally, the findings of this study show the importance of the structure for the overall pile shaft to handle a nominal bending force while taking into account the kinematic bending moment that could occur during an earthquake.

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