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Nonlinear Soil Resistance of Pile Group Foundation Subjected to Harmonic Excitation Based on 3D FEM

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Abstract

Soil-structure interactions (SSIs) influence the seismic responses of the superstructure and foundation of buildings. Under a significant input motion that causes damage to structures, the SSI is influenced by the nonlinear behaviors of the free ground (i.e. site nonlinearity), soil close to the foundation (i.e. local nonlinearity), and structural members (i.e. structure nonlinearity). Examples of local nonlinearity are the yielding and gapping in the soil around pile shafts. These phenomena are influenced by the material nonlinearity of the soil, which differs for granular and cohesive soils. Additionally, the interaction among piles (i.e. the effect of pile groups) complicates local nonlinearity when two or more piles are installed in a narrow space. Therefore, the difference in soil type and the pile arrangement should be considered to accurately evaluate the seismic response of pile-group-supported buildings.

This study aims to investigate the dynamic response of piles, whose heads are subjected to harmonic excitations with different frequencies and amplitudes. The investigation was based on analyses employing the three-dimensional finite element method (3D FEM), which can be used to simulate experimental results. The target pile foundations are a single pile and a pile group in homogeneous granular or cohesive soils. The soil is modeled using perfect elasto-plastic media, governed by the Mohr-Coulomb yield criterion, and the piles are modeled using elastic shell elements for simplicity. The gapping at the pile-soil interface is also considered.

The results of this study are summarized as follows. In the single pile, the characteristics of the load-displacement relationship at the pile head differed for the granular and cohesive soil. The values of material damping and radiation damping for cohesive soil are lesser than those for granular soil due to pile-soil gapping. In the pile group, the characteristics of the hysteresis curves of the load-displacement relationship at the head of each pile were dependent on the location of the pile. The high-frequency loading caused pile-soil gapping, thereby influencing the lateral resistance of the pile groups in granular as well as cohesive soil. The equivalent stiffness and hysteresis dissipated energy of each pile in the group depended on location of the pile.

Keywords: Nonlinear soil-structure interaction, Pile group, Pile-soil gapping, 3D FEM

1. Introduction

Nonlinear soil-structure interaction (SSI) causes seismic damage to the superstructure and foundation of buildings. Examples of nonlinear phenomena that influence SSI are yielding and gapping in the soil around pile shafts, also known as local nonlinearity. The interaction among piles, referred to as the effect of pile groups, complicates the local nonlinearity when two or more piles are installed in a narrow space (e.g. Suzuki and Adachi (2003) [1], Hijikata et al. (2005) [2], Kashiwa et al. (2008) [3], Hirose et al. (2017) [4]).

The three-dimensional finite element method (3D FEM) can be used to effectively evaluate the nonlinear lateral resistance of pile groups, considering local nonlinearity. For example, Kashiwa et al. (2012) [5] analyzed the factors causing actual damage in a pile group foundation during the 1995 Hyogo-ken Nanbu (Kobe) Earthquake, using the soil-pile-superstructure coupled model. Ihara et al. (2016) [6] calculated the ultimate subgrade reaction for each pile in a 25-pile group and demonstrated that the distribution of the ultimate subgrade reaction is different for granular and cohesive soil. Nakano and Miyamoto (2018) [7] demonstrated that pile-soil gapping influences the hysteresis characteristics of the subgrade reaction of a pile group installed in cohesive soil. The abovementioned analyses have mainly dealt with static and seismic loads, and few studies have been conducted on the influence of local nonlinearity on the dynamic lateral resistance of pile groups subjected to simple dynamic loads, such as harmonic excitation.

This study aims to investigate the nonlinear lateral resistance of a pile group, whose head is subjected to harmonic excitation, using nonlinear 3D FEM. Here, a pile group in which nine piles are installed in a square arrangement is considered. Typically, piles are elastic, and soil is assumed to be homogeneous, overlie rigid bedrock, and be a perfect elasto-plastic body containing the Mohr-Coulomb yield criterion. Two types of soil with different angle of internal friction (ϕ) and cohesion (c), which govern shear strength, are considered, and the gapping between the piles and soil is taken into account. Through a series of analyses, the influence of soil type, pile location, and load frequency and amplitude on the lateral resistance of the pile group is discussed.

2. Model and analytical method

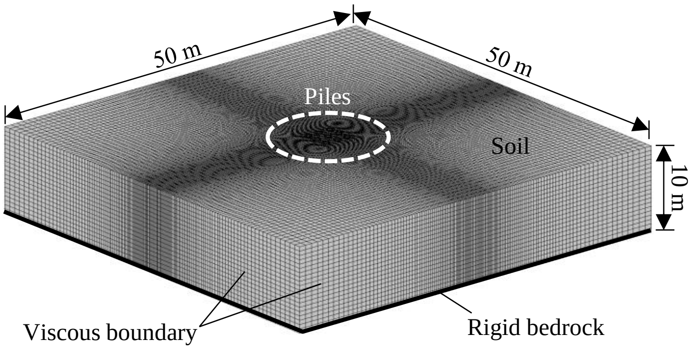
In the analyses, a single pile and a pile group in which nine piles are installed in 3 × 3 square arrangement are considered. Piles are steel pipe piles, which have a diameter of 600 mm, thickness of 9 mm, and length of 10 m. The pile heads are rigidly connected, simultaneously restricting their rotation, and the pile tips are clamped. The spacing between the pile centers is 2.5 times the pile diameter. Soil is assumed to be homogeneous, overlie rigid bedrock, and have a shear wave velocity of 100 m/s. The first natural frequency of elastic soil for the vertical incidence of the shear wave is 2.5 Hz. Two types of soil are considered as presented in Table 1, namely, granular soil with a large angle of internal friction ϕ, and cohesive soil with a large cohesion c.

The analyses are based on nonlinear 3D FEM. The present studies by authors have demonstrated the validity of 3D FEM by simulating a shaking-table test for a 25-pile group in granular soil based on Hirose et al. (2017) [4] and an in-situ loading test for a steel pipe pile in cohesive soil based on Nishida et al. (2019) [8]. Figure 1 illustrates the overview of the analysis model for a pile group. The piles are modeled using elastic shell elements, and the soil is modeled using perfect elasto-plastic solid elements containing the Mohr-Coulomb yield criterion. The initial shear stiffness of the soil is given by $G = \rho V_S^2$, where ρ is the density, and V_S is the shear wave velocity. At the side boundary of the soil model, the viscous boundary is used to consider the radiation damping, and a lateral force equivalent to the earth's pressure at rest is applied. At the pile-soil surface, a contact condition based on the penalty method is applied, accounting for gapping and slipping. The coefficient of friction when both contact surfaces are slipping is tan ϕ_s (= 0.7), where ϕ_s is the angle of internal friction for granular soil.

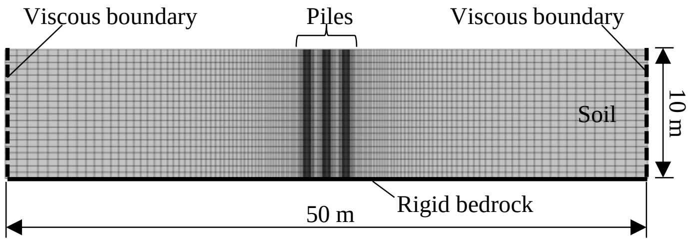
The pile heads are subjected to harmonic forced displacement. The load frequency is 0.5, 1.0, 2.5, 5.0, or 10 Hz, and load amplitude is 5, 10, or 20 mm.

Table 1 – Material constants for sandy and clay soil

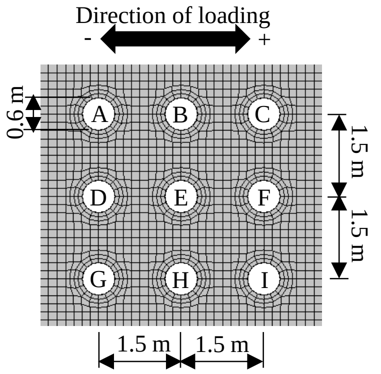
Soil type	ρ (g/cm^3)	V_S (m/s)	Poisson's ratio	ϕ (°)	c (MN/m^2)
Granular	1.8	100	0.35	35	1
Cohesive	1.5	100	0.45	0	50



(a) General view



(b) Vertical section



(c) Elements of soil around pile shafts and symbol of each pile

Figure 1 – Three-dimensional finite element model for a 3 × 3 pile group

3. Analytical results for single pile

This section presents the analytical results for a single pile. Figure 2 illustrates the hysteresis curves of the load-displacement relationship at the pile head for different load conditions. According to the results of the analyses for granular soil, depicted in Figure 2(a), the hysteresis curves for the load frequency of 0.5 Hz exhibit a spindle shape with a large area due to the yielding of the soil around the pile shaft. Pile-soil gapping occurs only in the areas close to the ground surface, and does not occur in areas deeper than 1.0 m. The hysteresis curves for the load frequency of 2.5 Hz are almost similar to those for the load frequency of 0.5 Hz. For load frequencies greater than 2.5 Hz, the hysteresis area gradually increases as the frequency increases. In terms of load amplitude, the hysteresis curves with larger amplitudes include those with smaller amplitudes.

According to the results of the analyses for cohesive soil, depicted in Figure 2(b), the hysteresis curves for the load frequency of 0.5 Hz exhibit a reverse S shape with a small area due to the pile-soil gapping. The gapping reaches a depth of approximately 3.0 m. Similar to the case of granular soil, for load frequencies greater than 2.5 Hz, the hysteresis area gradually increases as the frequency increases. However, the influence of the pile-soil gapping appears as a constriction of hysteresis curves. In terms of load amplitude, the hysteresis curves with larger amplitudes do not include those with small amplitudes, unlike in the case of granular soil.

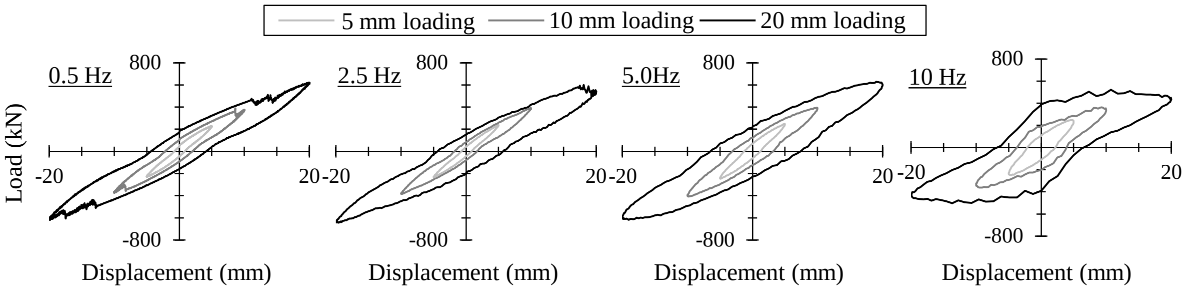
The equivalent stiffness K_{eq} and equivalent damping ratio h_{eq} are defined by the following equations to quantitatively discuss the hysteresis characteristics of the pile head lateral resistance.

$$K_{eq} = \frac{|F_1| + |F_2|}{2x_A} \tag{1}$$

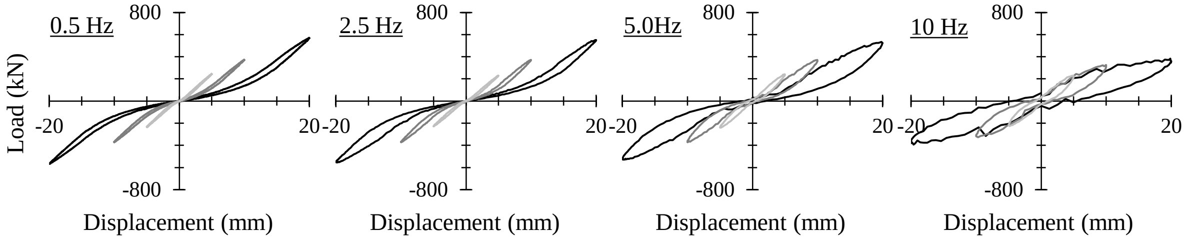
$$h_{eq} = \frac{1}{4\pi} \cdot \frac{\Delta W}{W}, \qquad W = \frac{1}{2}\left(\frac{1}{2}|F_1|x_A + \frac{1}{2}|F_2|x_A\right) \tag{2}$$

where x_A is the amplitude of the pile head displacement, F_1 and F_2 are the pile head loads when the pile head displacement reaches $+x_A$ and $-x_A$, respectively, W is the average of the elastic potential energy when the pile head displacement reaches $+x_A$ and $-x_A$, and ΔW is the hysteresis dissipated energy per cycle.

Figure 3 depicts the equivalent stiffness and equivalent damping ratio for different load conditions. In the graphs, the results of the linear analyses, where soil is assumed to be elastic and the pile-soil gapping and slipping are restricted, are plotted. The equivalent stiffness has a low frequency dependency and decreases as the load amplitude increases. The equivalent damping ratio remains constant as long as the load frequency is below 2.5 Hz, which is the first natural frequency of the surface ground. The damping at these frequencies is governed by material damping. Material damping increases as the load amplitude increases and is smaller for cohesive soil than for granular soil due to the pile-soil gapping. When the load frequency exceeds 2.5 Hz, the equivalent damping ratio gradually increases as the frequency increases. The damping in these frequencies is influenced by radiation damping. The gradient of the equivalent damping ratio is smaller for cohesive soil than for granular soil. This is because the pile-soil gapping reduces the area of the contact surface.

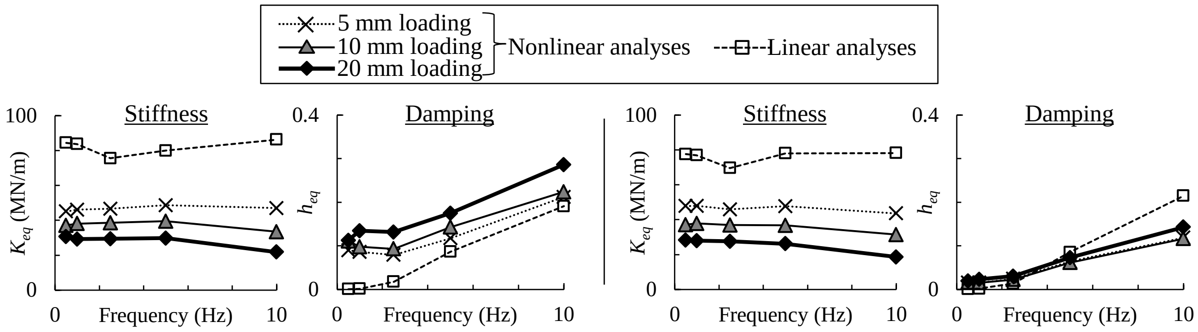


(a) Granular soil



(b) Cohesive soil

Figure 2 – Hysteresis curves of load-displacement relationship at head of single pile for different frequency and amplitude of excitation

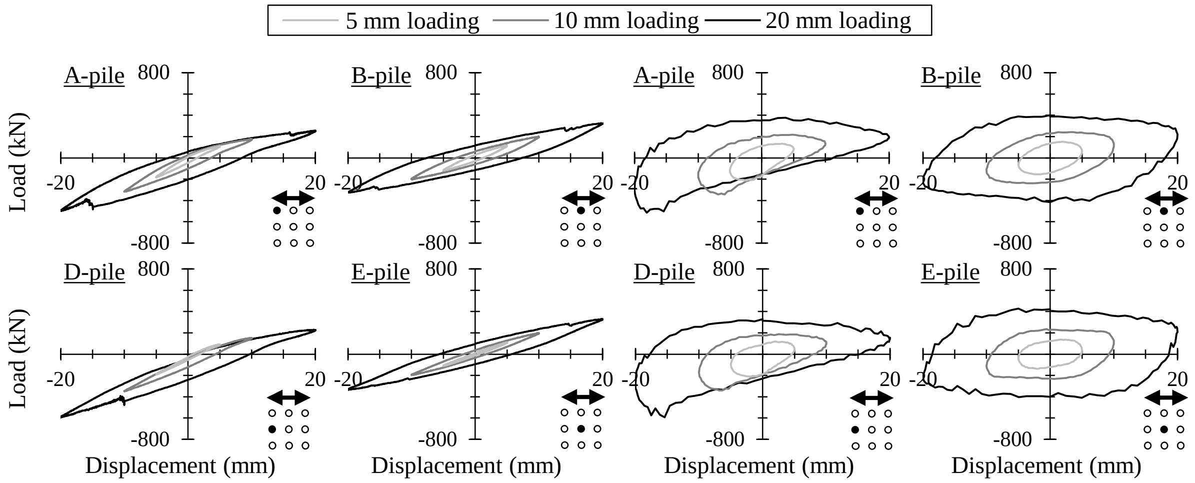


(a) Granular soil (b) Cohesive soil

Figure 3 – Equivalent stiffness and equivalent damping ratio at the head of a single pile for different frequencies and amplitudes of excitation

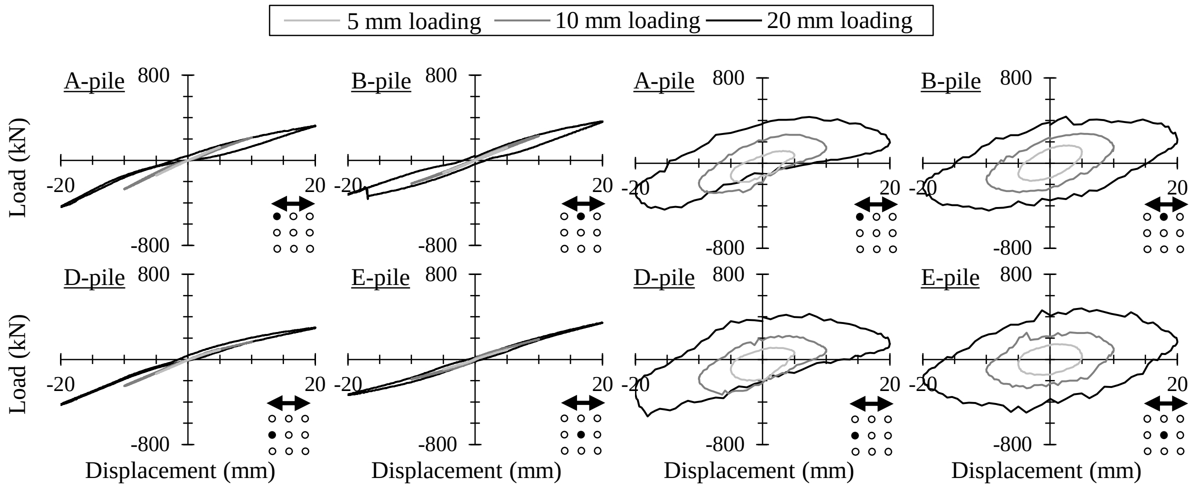
4. Analytical results for 3 × 3 pile groups

This section presents the analytical results for a pile group. Figure 4 depicts the hysteresis curves of the load-displacement relationship at the head of each pile in a pile group installed in granular soil. The symbol of each pile is indicated in Figure 1(c). According to the results of the analyses for the load frequency of 0.5 Hz, depicted in Figure 4(a), the hysteresis curves for piles B and E, which are located in the intermediate row, are symmetric. On the other hand, the hysteresis curves for piles A and D, which are located in the front/last row, are asymmetric. The maximum load obtained in the third quadrant, when piles A and D become leading piles, is larger than that obtained in the first quadrant. According to the analyses results for the loading frequency of 10 Hz, depicted in Figure 4(b), the hysteresis curves for piles B and E are symmetric and rounded due to their interaction with proximate piles. On the other hand, the hysteresis curves for piles A and D are asymmetric. While the curves in the second quadrant are rounded, the curves in the fourth quadrant are linearly shaped due to the pile-soil gapping. The pile-soil gapping reaches a depth of approximately 2.5 m for the load frequency of 10 Hz and does not occur in areas deeper than 1.0 m, for a load frequency of 0.5 Hz.



(a) 0.5 Hz loading (b) 10 Hz loading

Figure 4 – Hysteresis curves of load-displacement relationship at the head of each pile in a pile group installed in granular soil, for different frequencies and amplitudes of excitation

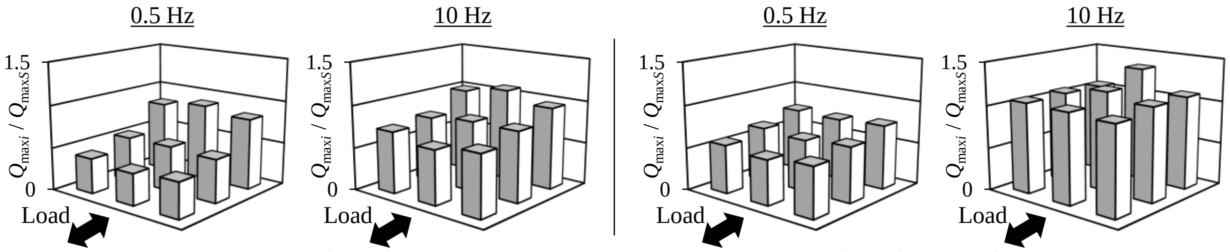


(a) 0.5 Hz loading (b) 10 Hz loading

Figure 5 – Hysteresis curves of load-displacement relationship at the head of each pile in a pile group installed in cohesive soil, for different frequencies and amplitudes of excitation

Figure 5 depicts hysteresis curves similar to those in Figure 4, except for cohesive soil. According to the results of the analyses for the load frequency of 0.5 Hz, depicted in Figure 5(a), the hysteresis curves for piles B and E are symmetric. On the other hand, the hysteresis curves for piles A and D are asymmetric. The hysteresis area is extremely small in the third quadrant due to the pile-soil gapping, which reaches a depth of approximately 2.5 m. The hysteresis curves for the load frequency of 10 Hz, depicted in Figure 5(b), exhibit similar characteristics to those of the granular soil.

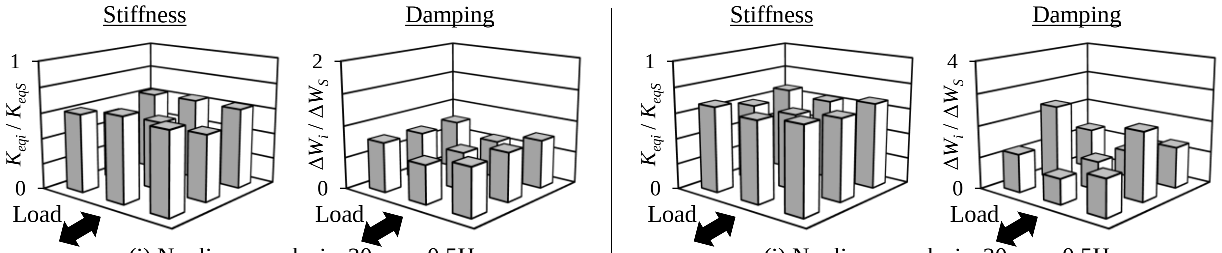
Figure 6 depicts the plus side maximum pile head load of each pile. In the graphs, the pile head load is normalized by that of a single pile. According to the graphs for granular soil, depicted in Figure 6(a), three piles located in the front row have a larger pile head load. The ratio of the pile head load against that of a single pile increases in all the piles when the load frequency changes from 0.5 Hz to 10 Hz. According to the graphs for cohesive soil, depicted in Figure 6(b), the pile head load is not very dependent on the pile location. Similar to the case of granular soil, the ratio of the pile head load increases in all the piles when the load frequency changes from 0.5 Hz to 10 Hz.



(a) Granular soil

(b) Cohesive soil

Figure 6 – Ratio of maximum pile head load of each pile in a pile group to that of a single pile, for 20 mm loading



(i) Nonlinear analysis, 20 mm, 0.5Hz

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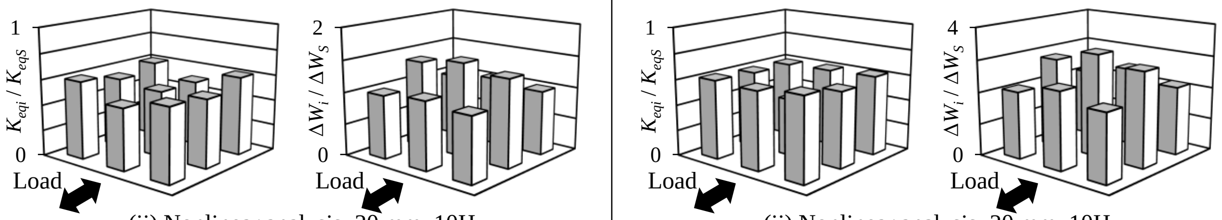
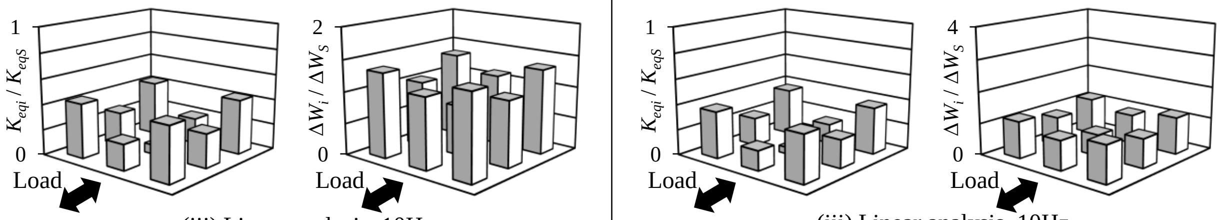


(ii) Nonlinear analysis, 20 mm, 10Hz

(ii) Nonlinear analysis, 20 mm, 10Hz



(iii) Linear analysis, 10Hz

(iii) Linear analysis, 10Hz

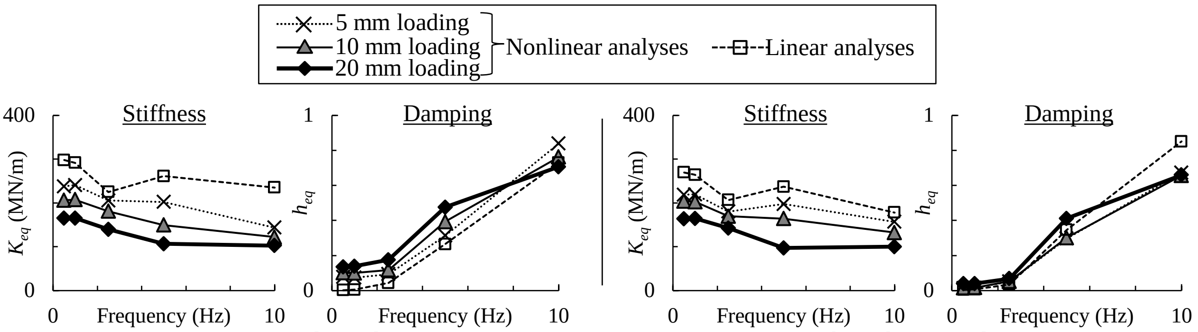
(a) Granular soil

(b) Cohesive soil

Figure 7 – Ratio of equivalent stiffness and equivalent damping ratio at the head of each pile in a pile group to those of a single pile, for 20 mm loading

Figure 7 depicts the equivalent stiffness and hysteresis dissipated energy of each pile. In the graphs, the equivalent stiffness and hysteresis dissipated energy are normalized by those of a single pile, respectively. Regardless of the soil type and load frequency, the piles located in front/last row exhibit a larger equivalent stiffness. In the nonlinear analyses for the load frequency of 10 Hz, the center pile exhibits larger hysteresis dissipated energy. This trend is different from the results of the 0.5 Hz load frequency and those of the linear analyses. Therefore, local nonlinearity and load frequency influence the distribution of hysteresis damping.

Finally, the equivalent stiffness and equivalent damping ratio are calculated from the relationship between the total amount of pile head load in all the piles and the pile head displacement to discuss the lateral resistance of the pile group as a whole. Figure 8 depicts the given equivalent stiffness and equivalent damping ratio. The equivalent stiffness decreases as the amplitude increases, and it decreases slightly as the frequency increases. The equivalent damping ratio remains constant at frequencies below 2.5 Hz, and gradually increases at frequencies above 2.5 Hz. Regardless of the soil type, the values of the equivalent damping ratio are larger than those of a single pile and attain their maximum value for the load amplitude of 20 mm and load frequency of 10 Hz, due to local nonlinearity.



(a) Granular soil (b) Cohesive soil

Figure 8 – Equivalent stiffness and equivalent damping ratio at the head of a pile group for different frequencies and amplitudes of excitation

5. Conclusion

In this study, 3D FEM analyses were performed to investigate the nonlinear lateral resistance of a single pile and a pile group subjected to harmonic excitation. Additionally, the influences of soil type (granular and cohesive soil), pile location, and load frequency and amplitude were discussed. The findings obtained from the analyses can be summarized as follows:

1) The characteristics of the hysteresis curves of the load-displacement relationship at the head of a single pile were different for the granular and cohesive soil; the hysteresis curves for the granular soil exhibited a spindle shape, whereas those for the cohesive soil exhibited a reverse S shape. Additionally, both the material damping and radiation damping values were smaller for the cohesive soil in comparison with those for the granular soil.

2) In the pile group, the characteristics of the hysteresis curves of the load-displacement relationship at the head of each pile were dependent on the pile location. The curves of the piles in the intermediate row were symmetric, whereas the curves of the piles in the front/last row were asymmetric. The high-frequency loading caused pile-soil gapping, thereby influencing the lateral resistance of pile groups in both the granular and cohesive soil.

3) The equivalent stiffness and hysteresis dissipated energy of each pile in the group was dependent on the pile location. The distribution of hysteresis dissipated energy varied with the local nonlinearity and load frequency.

These findings demonstrate that hysteresis damping, as well as stiffness and ultimate subgrade reaction, is dependent on the pile location, and pile-soil gapping influences the dynamic lateral resistance of a pile group. In this study, the patterns of the ground condition and pile arrangement were ideal and limited. The surrounding soil was steady; therefore, the reduction of soil stiffness due to site nonlinearity and the ground motion acting on pile shafts was not considered. Additionally, the nonlinearity of piles was also not considered. Therefore, further studies need to be conducted for the application of these findings to seismic response analysis models, considering nonlinear SSI.

6. Acknowledgements

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7. References

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