



A STUDY ON DYNAMIC BEHAVIOR OF MEDIUM-RISE BUILDING WITH PILE FOUNDATION SUPPORTED BY DIFFERENT DIAMETER PILES

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Abstract

When a building has high- and low-rise part or eccentrically-located core unit, it may need to use pile foundation supported by different length or diameter piles because of eccentricity for planar loading. However, there were only few studies about pile foundations having a mix of piles with different diameters, especially, in dynamic situations. Therefore, the elucidation of the impact on pile response due to irregularities in pile group foundations having a mix of piles with different diameters and that of the impact of the superstructure response will be effective as design findings in the future. In this study, the influences upon the dynamic behavior of building and pile by irregular pile position for the medium-rise building with pile foundation supported by different diameter piles are investigated using three dimensional finite element method (3D FEM). As a result, the irregularity of the pile group has relatively less impact on the response of the building. However, it is found that the irregularity makes significant impact on response of piles.

Keywords: 3 dimensional FEM, pile foundation, composite foundation, effect of pile group, dynamic interaction



1. Introduction

When supporting buildings with significant differences in the planar load distribution and having high- and low-rise parts, or when adopting a pile foundation in buildings where the core part is unevenly distributed, the support layer may be altered according to the support load or different types of piles with varying diameters and lengths may be used. However, pile foundations that combine such different types of piles are likely to have significant differences in the burden stress on each pile; hence, more detailed studies than those usually conducted for normal pile foundations are required [Architectural Institute of Japan (2001)].

Extensive research has been conducted on pile groups. The unique phenomena occurring in pile groups, known as the pile group effect; the problem of pile group efficiency, where the stiffness of the overall pile declines; and the problem of load-sharing ratio, where differences in borne stress arise according to the parameters of the pile arrangement, are all known [Architectural Institute of Japan (2000)]. [Hasegawa et al. (1990)] studied the impact of pile spacing, pile number, and soil characteristics on pile group efficiency through analyses using the thin-layer method. In addition, ways to evaluate the pile group efficiency include easy methods [Dobry et al. (1988); Hijikata et al. (1994)] that use the impact coefficient at the pile head position as well as research [Hijikata et al. (1995)] proposing a simple formula, in line with the practical design, to directly multiply the pile group efficiency (pile group coefficient) to the stiffness of the static single pile. In an attempt to solve the problem of the load-sharing ratio, [Wolf (1985)] have indicated that in a pile group foundation arranged in a circle, the pile load stress of piles arranged in an end position is larger than that of piles disposed near the center. Looking at a rectangular pile ground foundation, [Hasegawa et al. (1992)] divided the pile stress into stress caused by the building inertial force and ground vibrations and studied the sharing ratio for each. [Kitamura et al. (1997)] have conducted similar studies with the raft-part embedding depth of a pile foundation as the parameter.

On the other hand, when looking at the history of pile foundations that combine different pile types, [Fukuoka et al. (1998)] have conducted experiments and analyses on combined foundations of pile foundation and an underground continuous wall and have indicated that the piles inside the continuous wall and the continuous wall itself have almost the same vibration modes while the continuous wall, which is very rigid, bears almost all of the stress. [Yamada et al. (2000)] performed elasto-plastic analyses on piles having different lengths along the slope as well as pile foundations that have the underground continuous wall combined in some parts. They discovered that the response of the building increases with the rotations and twist input motions that occur from irregularities in the foundation, whereas the pile stress varies depending on the input direction of the seismic waves. In a study about the twist input motion of different types of foundations, [Iwaki et al. (2010)] investigated 303 buildings and reported that 54 of them mixed piles with diameters differing by more than 1.5 times and that 14 buildings mixed piles of different lengths.

However, most studies on pile foundations that adopt such different pile types focus on the pile length that combines different lengths and types of piles according to the support layer and slope [e. g. Yamada et al. (2000); Sahara et al. (2001)], and there were only few studies about pile foundations having a mix of piles with different diameters [Wolf (1985); Iwaki et al. (2010)]. Furthermore, as there are almost no examples examining the impact on the pile stress and superstructures in dynamic situations, the elucidation of the impact on pile response due to irregularities in pile group foundations having a mix of piles with different diameters and that of the impact of the superstructure response will be effective as design findings in the future.

For this reason, herein, we analyze the dynamic behavior of pile foundation buildings that have a mix of piles with different diameters according to an uneven distribution of the core portion in the superstructure for pile foundations arranged in a square form. This allows us to study the impact that mixed pile diameters have on the pile foundation and superstructure responses.

2. Study Overview

2.1 Overview of the targeted building

The target of examination was a six-story medium-rise RC structure having a pile foundation of a 7×7 main pile with pile spacing of 6 m. In addition to a basic model of the pile foundation building where all piles have the same diameter (hereinafter, referred to as “Same”), a central core structure model (“Ccore”) that has a large-diameter pile toward the middle presuming an uneven distribution of the core portion in the center (approximately 20% of the floor area being the core) and an eccentric core structure model (“Ecore”), presuming an uneven core part in the structural end portion (approximately 30% of the floor area being the core) were arranged to have three comparators. With piles of 1.5 m diameter being the standard (hereinafter, “standard pile”), we modelled the large-diameter piles having a pile diameter of 3.0 m (large-diameter pile = standard pile $\times 2.0$) in different positions. Fig. 1 shows the plan of the target pile foundation model.

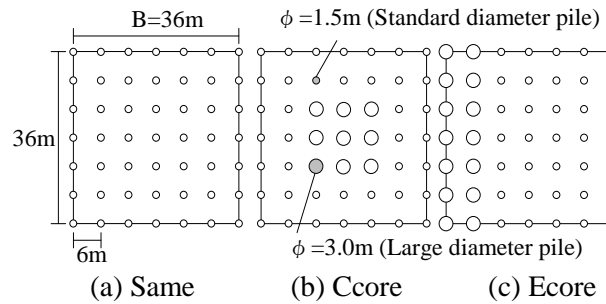


Fig. 1 – Plane view of pile foundation

2.2 Analysis model

Time-history response analysis was performed using the three-dimensional FEM model (hereinafter, “FEM”). Fig. 2(a) shows the details of the analysis model used in the study, using “Same” as an example, which has a two-layer soil comprising the surface layer with $V_s = 150$ m/s and an engineering bedrock at $V_s = 400$ m/s with a pile length of 22 m and a pile-tip embedment of 2 m. The soil was modelled as an eight-node solid element, whereas the pile was modelled with beam elements. We assumed a rigid foundation for the pile head and that all nodes are interconnected with rigid connections. Furthermore, the center of the pile had a cavity the size of its volume fraction and made a rigid connection with the soil (Fig. 2(b)). The building was set on beam elements and a multi degree of freedom system model (MDOF model) of the equivalent shear stiffness. To check the response of the building end, nodes were created at the building end of each mass point and a rigid connection was made to the central mass point. As boundary conditions, time-domain energy transmitting boundaries [Nakamura (2011)] were adopted for the sides of the soil and a viscous boundary was used as the bottom surface. There two analysis conditions: one is the “Linear Model” (Fig. 2(c)-(1)), which was linear for both the building and the soil. The other is the “Equiv. Li. Model” (Fig. 2(c)-2(2), hereinafter Equiv. Li. Model) that is considered for nonlinear characteristics of the soil and superstructure. In the latter model, the soil stiffness and damping ratio is calculated using SHAKE (equivalent linear analysis) with stress-strain ($G/G_0-\gamma$) and damping-strain ($h-\gamma$) relations shown in Fig. 3(a) as the equivalent physical properties (Fig. 3(b)). Also, the building has nonlinearity which consists of the tri-linear skeleton curves defined by assuming shear fracture of columns. Its hysteresis characteristic of Takeda model was used. The time-step was 0.01 and 0.002 sec. in the Linear Model and the Equiv. Li. Model respectively. The Newmark- β method ($\beta = 0.25$) was used for time integration. Furthermore, as this examination focuses on the impact of irregularities in the foundation on the superstructure, deviations from the rigidity and weight of the superstructure were not considered for the three basic models (Same, Ccore, and Ecore). Instead, we investigated a regular building built on the center of the foundation. Table 1 shows the various elements of the building. Table 2 shows various elements of the soil/pile, while Table 3 shows the natural frequency of each model (the superstructure is linear condition in Equiv. Li. Model). As eigenvalue analysis is difficult when using the FEM model, the natural frequency was calculated using the

transfer function (response acceleration at building top/response acceleration at free soil surface) obtained by inputting impulse waves from the soil bottom surface.

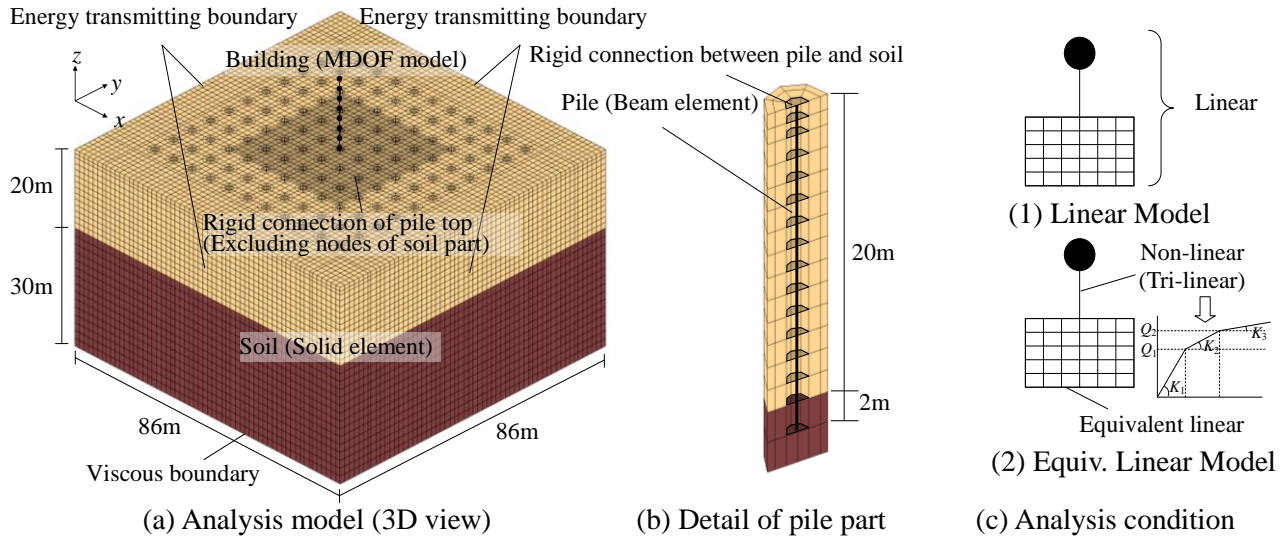


Fig. 2 – Analysis model

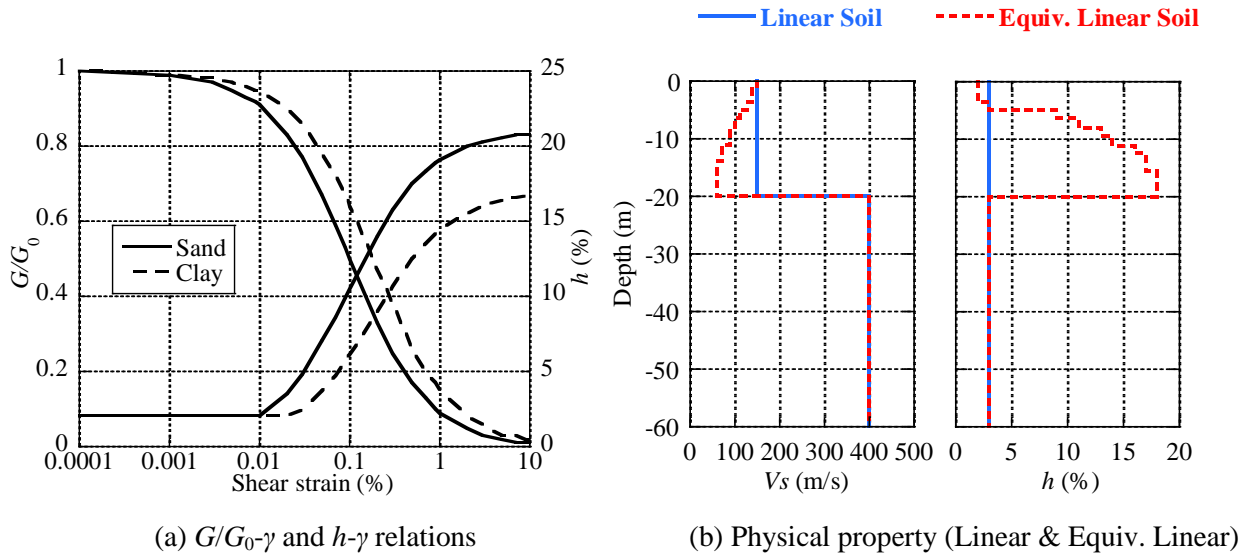


Fig. 3 – Nonlinear characteristics of the soil

Table 1 – Specification of building

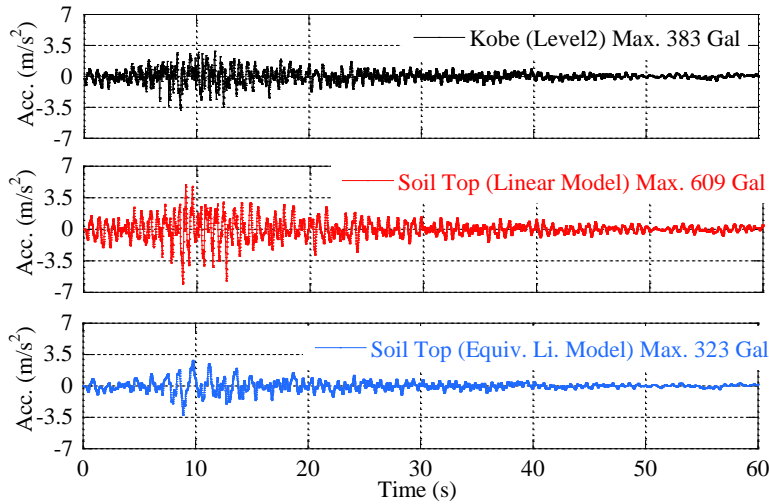
Floor No.	Story Height cm	Weight kN	Rot. Inertia Weight		Equivalent Shear Stiffness (K_1) ($\times 10^3$) kN/m	Non-linear characteristics			
			θ_x	θ_y		Decline rate of stiffness		Yield point	
			($\times 10^{-3}$) kNm ²			K_2/K_1	K_3/K_1	Q_1 (kN)	Q_2 (kN)
6	285	18,724	--	--	8,880	1.71E-01	1.00E-03	6,268	16,436
5	285	19,608	-	-	9,680	1.48E-01	1.00E-03	9,612	28,777
4	285	19,608	-	-	9,880	1.50E-01	1.00E-03	11,276	43,869
3	285	20,384	-	-	10,320	1.58E-01	1.00E-03	13,276	56,141
2	285	20,384	-	-	9,440	1.42E-01	1.00E-03	18,120	58,246
1	385	20,400	-	-	12,200	1.46E-01	1.00E-03	20,248	59,876
Base	-	31,168	3,256	3,496	-	-	-	-	-

Table 2 – Specification of soil and pile

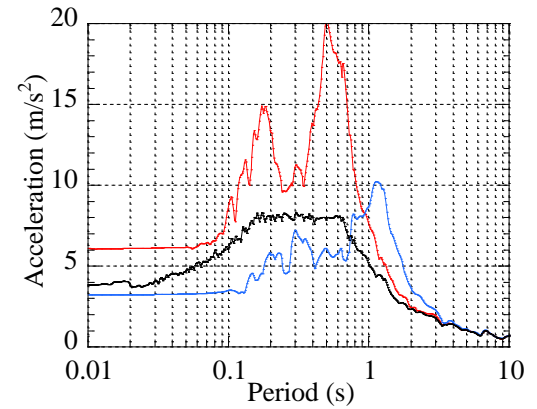
Part	Depth (m)	$V_s \cdot E$	ν	$\rho(\text{kN/m}^3)$	$h(\%)$
Surface layer	Sand 0 ~ -5	150(m/s)/Equiv.	0.45	14.7	3/Equiv.
	Clay -5 ~ -20				
Engineering bedrock	-20 ~ -30	400(m/s)	0.45	17.7	3
Pile	0 ~ -22	2.1E+7(kN/m ²)	0.2	23.5	3

Table 3 – Natural frequency of models

Model		Frequency (Hz)	
		1 st	2 nd
Foundation Fixed Model		2.78	7.99
(1) Linear Model	Same	1.95	7.91
	Ccore	2.05	7.91
	Ecore	2.15	7.91
(2) Equiv. Linear Model	Same	0.88	7.72
	Ccore	0.88	8.00
	Ecore	0.88	7.91



(a) Acc. Time History



(b) Acc. Resp. Spectrum (h=5%)

Fig. 4 – Applied seismic motion

2.3 Applied seismic motion

The applied seismic motion (maximum acceleration of 383 Gal) was set to the wave notified in the Kobe phase defined as Level 2 earthquake in seismic design of Japanese, which means its recurrence interval is approximately 500 years and was applied from the bottom surface of the model. Fig. 4 shows the applied seismic motion and the acceleration time history waveform.

3. Comparison of dynamic soil impedance and foundation input motion

To inspect the validity of the FEM model and to compare the transfer functions of dynamic soil impedance and foundation input motion for each pile foundation (Same, Ccore, Ecore), we created a massless rigid foundation, however, using piles having some mass excluding the building for the Linear Model. After determining the dynamic soil impedance and foundation input motion for each models, we compared it to the solution obtained through the three-dimensional thin-layer method [Waas et al. (1984)] (explanatory note: TLM; TLM is shown only “Ecore-Y” in Fig. 5, Fig. 6). Here, the dynamic soil impedance based on FEM was calculated by taking the transfer function of the displacement obtained after seismic wave excitation of the center of the foundation (excitation force/displacement of the foundation center). For the foundation input motion, an impulse wave was applied from the bottom surface and the transfer function was calculated using the acceleration in the free soil surface and the acceleration in the foundation center (horizontal or rotational acceleration of the foundation center/horizontal acceleration of the free soil). However, the building height ($H = 18.1$ m) was multiplied to the transfer function on the vertical axis for the direction of rotation and the foundation half-width ($B/2 = 18$ m) was multiplied onto the torsional direction. Furthermore, as Ecore is asymmetrical, seismic wave excitation is applied in both X and Y directions, but the legend denotes the X-excitation and Y-axis rotational excitation as Ecore-X, whereas the Y-excitation and X-axis rotational excitation is denoted by Ecore-Y.

Fig. 5 shows the horizontal, rotational, and torsional directional dynamic soil impedance in (a)–(c), respectively. FEM and the thin-layer method produced results suggesting a generally good response.

For the FEM model, near the 2 Hz region, which is the primary natural frequency of the building (Table 3 (1)), the rotational and torsional rigidity is large with Ccore and Ecore, which have large-diameter piles mixed in them, but in each direction, the value is similar to that of Same, and in the high frequency region, there is a large imaginary part and an increase in the dissipation damping effect. It is also possible to see that Ecore, which has eccentricity, does not show much difference depending on the direction of excitation.

Fig. 6 shows the horizontal, rotational, and torsional directional foundation input motion in (a)–(c), respectively. FEM tended to have a larger response in the waving phenomenon and response to rotational direction relative to the thin-layer method, but showed a generally responsive trend. Therefore, we decided that the study that used FEM was valid. However, we note that the response results of FEM suggest a somewhat excessive rotational input force.

For the FEM model, the Ccore and Ecore, which have large-diameter piles mixed in them, the horizontal input motion does not differ much compared with that with Same near the 2 Hz primary natural frequency, whereas the response was reduced by 20% to 30% in the high frequency region, showing an input decreasing effect according to an increase in pile rigidity. On the other hand, when compared with the horizontal direction, the rotational direction increased and excited to around 2–3 times that of Same. With Ecore-Y, the response of the input motion in the torsional direction was 10% and 30% to 40% of the horizontal input force of free soil near a frequency of 2 Hz and in the high frequency region, respectively.

Furthermore, the trend in the Equiv. Li. Model was generally the same as that mentioned above, and we did not provide further details for this reason.

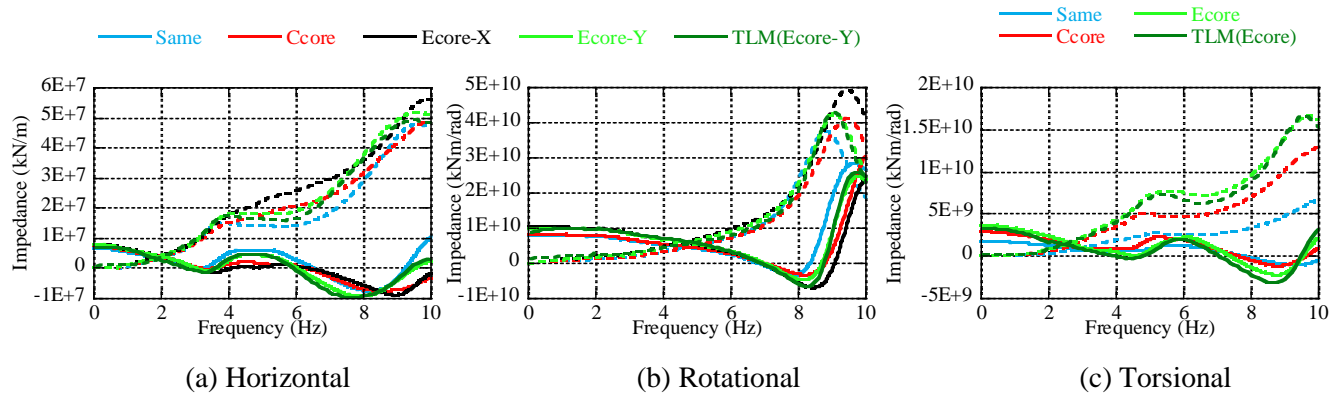


Fig. 5 –Soil impedance (Linear Model)

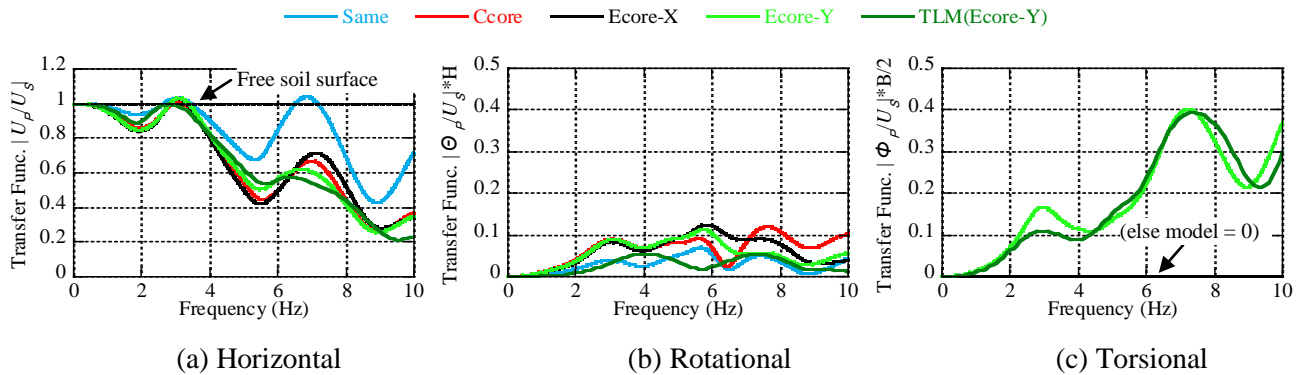


Fig. 6 –Foundation input motion (Linear Model)

4. Seismic response analysis using the soil-building coupled model

Next, a coupled FEM model that combines soil and building was used to perform seismic response analysis in order to compare the response of the superstructure and the pile foundation.

4.1 Comparison of superstructure response

Fig. 7(a) (Linear Model) and Fig. 7(b) (Equiv. Li. Model) each show the maximum response acceleration, maximum response shear force distribution in (1)-(2), respectively. Examining the Y-excitation of Ecore (Ecore-Y), we see that in maximum acceleration distribution, the responses of the building center and building end part differ due to twist; comparisons are made with them both combined.

Looking at (1) maximum response acceleration, the Linear Model show at most a 10% lower building bottom response in their Ccore and Ecore when compared with the Same model, but the differences between the three are relatively small. The differences in Equiv. Li. Model are even smaller than the Linear Model because of considering nonlinearity of the superstructure. The building edge of Ecore-Y (legend: Ecore-Y-Edge) is 5% and 20% greater than that of the Same Model in the Linear Model and the Equiv. Li. Model, respectively. With regards to (2) maximum shear force, both the Linear Model and the Equiv. Li. Model had a 5% differences in the building bottom portion, and similar to acceleration, the differences among the three were small. This is possibly due to the fact that there was no great difference between the dynamic soil impedance of each model, as indicated in Chapter 3. Moreover, with regards to the foundation input motion, the relatively small input reducing effect in the horizontal direction due to rotational input motion excitation had a noticeable impact in linear condition especially. However, the fact that inspection by FEM evaluates a slightly excessive rotational input requires attention. Furthermore, as the acceleration response of the building end part in Ecore-Y is limited to a maximum increase of around 10% relative to the center part, for the Linear Model, it is conceivable that the impact of the torsional input motion on the building response is limiting. However, as the building here is regular, more attention is necessary where twisting modes occur in irregular buildings.

Based on the above results, the impact of pile size mixing on the superstructure response is relatively small. However, since there are big differences to the stress applied on the piles, a detailed account on pile response will be given hereafter.

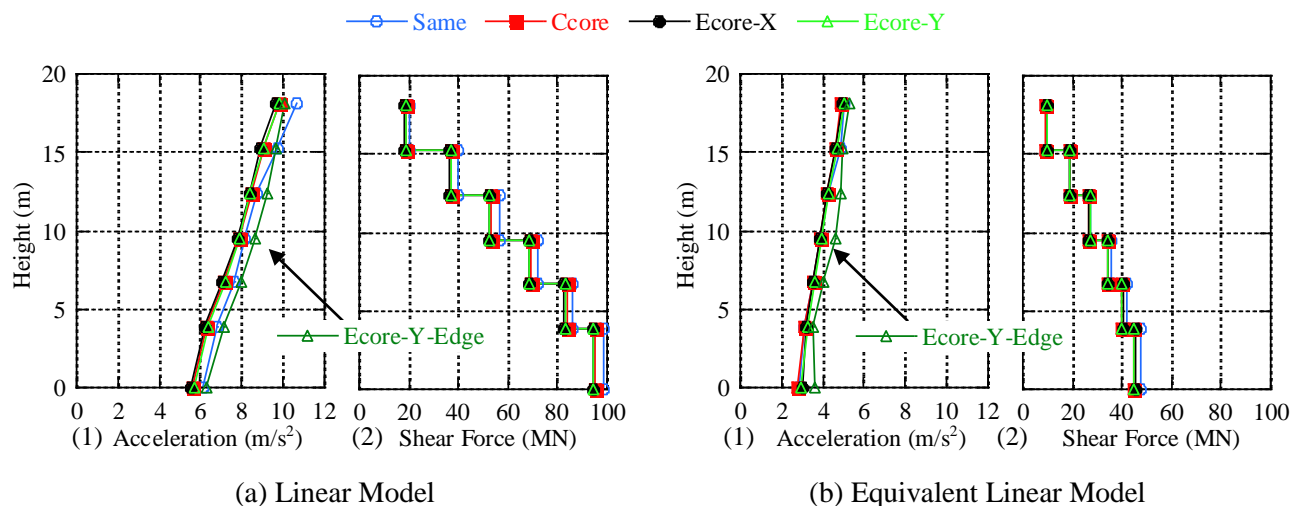


Fig. 7 –Distribution of maximum response value of superstructures

4.2 Comparison of pile response

First, in the Linear Model, we compare the maximum response at each of the pile heads of Ccore and Ecore with the maximum response in the Same Model. Simultaneously, analysis using the soil-pile FEM model is performed, excluding the building. By taking the difference of both the responses at the time of maximum

response in the soil-building coupled FEM model, we remove the Kinematic Interaction from the total stress on the piles and isolate the Inertia Interaction for study following in the steps of [Hasegawa et al. (1992)].

Table 4 shows the total stress (Total), which is the summation of the maximum stress of each 49 piles, and that of the stress only due to inertia (Inertia).

(a) Looking at the maximum response of the axial force considering only the fluctuation in axial force occurring as a result of seismic motion, as the values of Ccore and Ecore due to inertia are around the same as that for the Same Model, we can confirm that the increase of the total stress is largely due to the increase in foundation-locking due to kinematic motion of the soil.

(b) Looking at the maximum response of the shear force, the sums due to inertia tend to be on a decreasing trend, but those of the total stress increase because of kinematic motion of the soil.

(c) Looking at the maximum response of the bending moment, the sums of stress due to kinematic motion of the soil is significantly larger than those of stress due to inertia.

Table 4 – Summation of the maximum response value of the pile head (Linear Model)

Model	Maximum response section force					
	(a) Axial force (MN)		(b) Shear force (MN)		(c) Bending moment (MNm)	
	Total	Inertia	Total	Inertia	Total	Inertia
Same	89.0	85.6	96.6	94.3	252	194
Ccore	98.6	85.9	103	91.3	479	257
Ecore-X	118	87.5	104	91.7	600	300
Ecore-Y	106	87.0	101	92.5	561	282

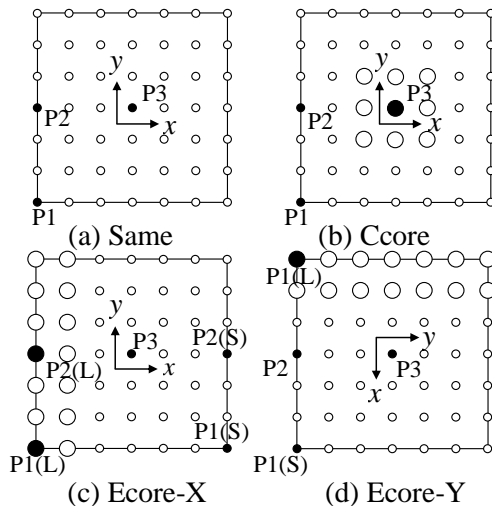
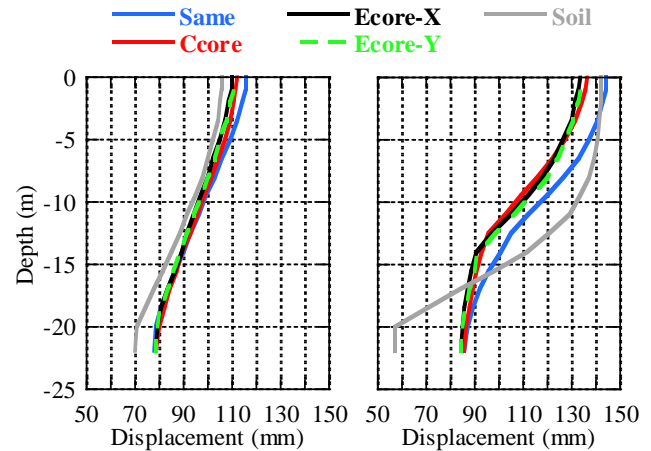


Fig. 8 – Resentative points of piles



(a) Linear Model (b) Equiv. Linear Model
Fig. 9 –Maximum response displacement distribution

Next, using the piles of the representative points (P1–P3) presented in Fig. 8, the depth direction maximum response of the Linear Model and the Equiv. Li. Model will be compared. The legend shows the large-diameter pile (L) and standard pile (S) according to differences in pile diameter. With Ecore, since the pile diameters are arranged front/back and left/right of the excitation direction of X-excitation (Ecore-X) and Y-excitation (Ecore-Y), comparisons shall be made by combining both results should multiple diameters correspond at a representative point, and for Ecore-Y, piles in the same position for a given excitation direction are compared (align the Y-axis to the right side of the face of the paper). Furthermore, with Ecore-Y, the response of orthogonal direction (X direction) against input direction (Y direction) is also shown in Fig. 10(d), (f) (explanatory note: Input orth. dir.).

Fig. 9 shows the maximum response horizontal displacement distribution of P3. The horizontal displacement distribution of the free soil at the time of maximum response displacement is also shown. In (a), the Linear Model showed the piles deforming according to the deformation of the free soil, while the Equiv. Li. Model showed some differences between piles and free soil. However, cases that mixed large-diameter piles afforded the same level of response for both models.

Fig. 10(a), (b) show the maximum response axial force distribution for P1 and P2, respectively, considering only the fluctuation in axial force occurring as a result of seismic motion.

(1) Focusing on P1 piles, we see a trend where the response becomes large for Ccore and Ecore relative to the Same Model, irrespective of the pile diameter in both the Linear Model and Equiv. Li. Model. With regards to Ecore-Y, which is asymmetrical, the load for the large-diameter piles ($\phi = 3.0$ m) was greater than that for the standard piles ($\phi = 1.5$ m), and it was understood that the difference in load-ratio occurs depending on the size of the pile cross-sectional area. However, under every soil condition, the difference in response due to pile diameter size is smaller for X-excitation (Ecore-X) than that for Y-excitation (Ecore-Y). This is because, in the case of X-excitation, the center of gravity shifts toward the large-diameter pile side ($-X$ side) due to deviation in pile arrangement, and the load for standard piles in the $+X$ end part increases according to their distance away from the center of rotation, which results in a smaller load on the large-diameter piles on the $-X$ side. In each of the three models (Same, Ccore, Ecore) for the Linear Model, the pile head responses were the greatest and tended to reduce according to the depth. However, the axial load is large up until near the boundary with the support layer in the Equiv. Li. Model, and it is understood that the influence of the kinematic motion of the soil is larger and that of inertia force by the superstructure is smaller than the Linear Model.

(b) Focusing on the P2 piles shown, for the Linear Model, with Ecore-X, the response of the standard piles in pile head was greater than that of the large-diameter piles, while that of the large-diameter piles was smaller than that of the Same Model. This is thought to be because while dense arrangement of large-diameter piles reduces the bearable stress due to pile group effect, the response in the standard piles ($+X$ side), as with the P1 piles, becomes greater because of deviations. Looking at the depth directional distribution of large-diameter piles, maximum response can be seen toward the middle of the piles because of the kinematic motion of the soil. On the other hand, for the Equiv. Li. Model, we see a trend where the response becomes large toward the middle of the piles irrespective of difference of the all models (Same, Ccore, Ecore) and also the pile diameter.

Fig. 10(c), (d) show the maximum response shear force distribution of the P1 and P3 piles, respectively.

(c) Focusing on the P1 piles, in the Linear Model, the response of the standard piles near the pile heads for Ccore and Ecore tended to be smaller than that in the Same Model. On the other hand, the response of the large-diameter piles in Ecore was larger than that in Same, and the mixing of highly rigid large-diameter piles seems to have reduced the load on the standard piles. However, for the large-diameter piles in Ecore, the load for Ecore-Y is smaller than that for Ecore-X. This is thought to be due to the pile group effect being greater for the piles arranged in series relative to the direction of excitation, compared with those arranged in parallel; in other words, the impact of decreasing bearable stress is apparent more significantly in the large-diameter piles. On the other hand, for the Equiv. Li. Model, the response of the piles near the pile heads is totally smaller than that of Linear Model because the superstructures reach a non-linear state and inertia force of it is smaller. However, with Ecore-Y, the response of the pile near the pile head gets greater due to being attributed to the excitation of the torsional input motion. Furthermore, when looking at the depth directional distribution, in the Linear Model, the stress on the large-diameter piles of Ecore-X and Ecore-Y occurring in the depths did not have much of a difference, confirming the large effect of the pile group effect at the pile head, while, in the Equiv. Li. Model, the shear force is large up until near the boundary with the support layer, and it is understood that the influence of the kinematic motion of the soil is larger than the Linear Model.

(d) Focusing on the P3 piles, in the Linear Model, the load on the standard piles of Ecore tends to be small. The response was large for large-diameter piles of Ccore, where even the piles toward the center, where in general the pile group effect is thought to be large when mixing large-diameter piles, was bearing a large amount of stress in both the Linear Model and Equiv. Li. Model.

Fig. 10(e), (f) show the maximum response of the bending moment distribution for the P1 and P3 piles, respectively.

In both (1) P1 and (2) P3 piles, irrespective of the Linear Model or the Equiv. Li. Model, the stress borne at the pile heads of large-diameter piles in Ccore and Ecore was large compared with that of the standard piles, and the standard piles tended to be around the same level or less. Furthermore, it can be seen that the large-diameter piles toward the center of Ccore bear a large amount of stress, as with the large-diameter piles toward the end part of Ecore-X. It has been pointed out that the stress borne by the piles toward the center of the foundation tends to increase because of the pile group effect [Fukuoka et al. (1998)] occurring due to kinematic motion of the soil. The fact that the load on the large-diameter piles toward the center of Ccore is around the same as that on the large-diameter piles toward the end part of Ecore is thought to be due to the stress from kinematic motion of the soil becoming dominant. Furthermore, the responses of the large diameter pile near the pile head for Ecore-Y smaller than that of Ecore-X. This is because, in the Ecore-Y, the response of orthogonal direction gets greater due to being attributed to the excitation of the torsional input motion and that of input direction gets smaller to a certain degree.

Based on the above, where large-diameter piles are mixed, although highly stress-resistant large-diameter piles largely bear the stress of shear force and bending moment, it is necessary to be careful during the design process since the load on standard piles increases due to axial forces.

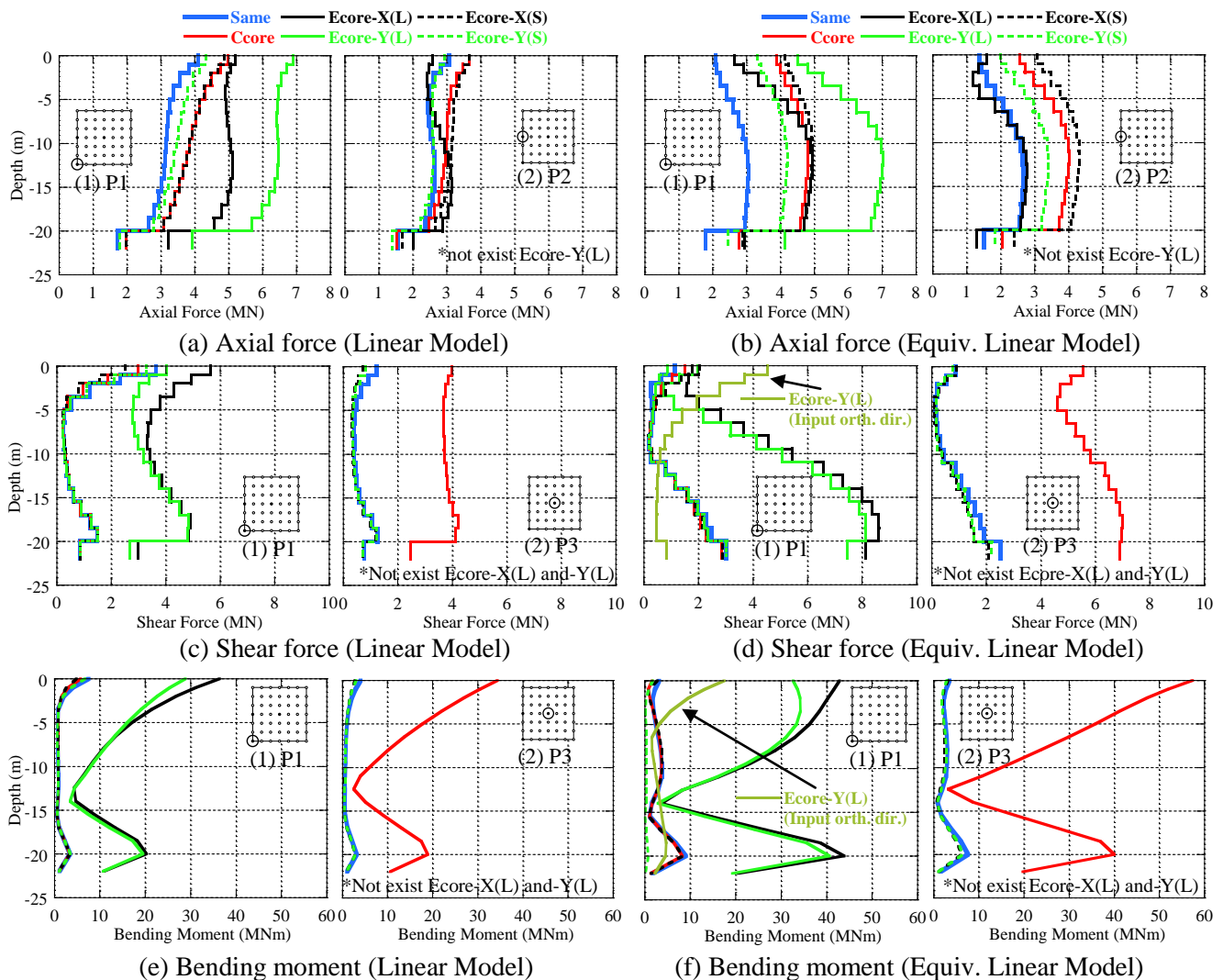


Fig. 10 – Distribution of maximum response section force of the representative piles



5. Conclusion

In this report, we used three-dimensional FEM models to study the effect that the irregularity in a pile foundation building having a core section, where 20%–30% of the total piles are a mix of piles of different diameters, can have on the superstructure and the pile response. Based on the aforementioned results, we present our findings below.

- Compared with normal pile foundations comprising same-diameter piles, there was little change in the dynamic soil impedance in the pile foundations that have different diameters of piles (large-diameter piles) mixed in it.
- With regards to the foundation input motion, even if the effect of horizontal input motion decreases in high frequency range, it is difficult to cause a difference to the building response.
- As a result of deviations in large-diameter pile placement, for large-diameter piles, torsional input motion becomes excited and the response of the building end part becomes larger compared with those for normal pile foundations. However, only in buildings without the twisting mode, the difference in response to regular pile foundations was only 20% when considering non-linear conditions; hence, the impact of torsional input motion is comparatively small.
- Mixing large-diameter piles causes fluctuations in the axial force to become larger due to the increase the impact of kinematic motion of the soil, which consecutively increases the axial force load on the standard piles near the end part of the foundation, when compared with regular foundations. On the other hand, with regard to shear force and bending moment, the load on the standard piles have the potential of decreasing as much of the stress is borne by the large-diameter piles.
- Even where large-diameter piles are placed toward the center (where the pile group effect is large), these piles bear a large part of the shear force and bending moment, compared with the standard piles. Particularly with the bending moment, as the kinematic motion of the soil is dominating, a level of load similar to that arising when placing the large-diameter piles in the end part arises.

Furthermore, all analyses in this study were performed under linear conditions (including equivalent linear conditions) for the soil and pile, and analyses that consider each non-linear property will be an area of further research.

6. References

- [1] Architectural Institute of Japan (2001): Building foundation structure design guidelines, pp.189
- [2] Architectural Institute of Japan (2000): Problems on the seismic resistance of pile foundation, pp.71-80
- [3] Hasegawa M., Nakai S. (1990): A study of the pile group efficiency based on the impedance function of pile foundation, *Architectural Institute of Japan Structural System Papers*, Issue No. 417, pp.133-145
- [4] Dobry R., Gazetas G. (1988): Simple method for dynamic stiffness and damping of floating pile groups, *Geotechnique* 38, No.4, pp.557-574
- [5] Hijikata K., Yagishita F. et al. (1994): Facile dynamic impedance evaluation method of pile groups, *Architectural Institute of Japan Structural System Papers*, Issue No. 455, pp.73-82
- [6] Hijikata K., Imamura A. et al. (1995): Study on the evaluation method of pile group coefficient, *Architectural Institute of Japan Structural System Papers*, Issue No. 476, pp.57-66
- [7] Wolf J. (1985): Dynamic soil-structure interaction, pp.428-433
- [8] Hasegawa M., Nakai S. (1992): A study of seismic stress on piles and its evaluation method, *Architectural Institute of Japan Structural System Papers*, Issue No. 432, pp.105-118



- [9] Kitamura E., Miyamoto Y. et al. (1997): Study on seismic response characteristics of pile group foundations having embedment, *Architectural Institute of Japan Structural System Papers*, Issue No. 492, pp.53-60
- [10] Fukuoka A., Miyamoto Y. et al. (1998): Empirical study on the seismic response analysis method of composite foundations, *Architectural Institute of Japan Structural System Papers*, Issue No. 506, pp.109-116
- [11] Yamada A., Miura K. (2000): Elasto-plastic seismic response characteristics of a structure that combines different types of structural foundations, *Architectural Institute of Japan Structural System Papers*, Issue No. 529, pp.113-119
- [12] Iwaki R., Fukuwa N. et al. (2010): Effects of irregularity in foundation form and mix of foundation forms on the twist foundation input motion, *Architectural Institute of Japan Structural System Papers*, Issue No. 649, pp.531-538
- [13] Sahara M., Akino N. et al. (2001): On the subsiding nature of buildings supported by friction pile foundation of different pile lengths, *Architectural Institute of Japan Structural System Papers*, Issue No. 544, pp.77-84
- [14] Nakamura N. (2011): Three-dimensional seismic response analysis applying the time-domain energy transmitting boundary of the two-dimensional plane, out-of-plane problem, *Architectural Institute of Japan Structural System Papers*, Issue No. 664, pp.1077-1084
- [15] Waas G., Hartmann H. G. (1984): Seismic analysis of pile foundations including pile-soil-pile interaction, *Proceedings of 8th World Conference of Earthquake Engineering*, Vol. 5, pp.161-175