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EVALUATION OF A LARGE SCALE PILE GROUP FOR A NONLINEAR EARTHQUAKE RESPONSE ANALYSIS OF PILE-SUPPORTED BUILDINGS BY USING FRAME MODELS

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SUMMARY

In Japan, it is necessary to confirm earthquake-proof safety of existing buildings immediately for a coming big earthquake in the near future. Most of important buildings and facilities, for example thermal power plants and high-rise buildings, which are located on claimed ground such as water front, have pile supported foundations. To evaluate the earthquake resistance performance of these pile-supported buildings, a dynamic earthquake response analysis or a static increment analysis is often conducted by using a frame model. The frame model is usually composed with the beam elements as piles and soil spring elements as soil surrounding piles. In this paper, we propose the evaluation method of these soil springs for nonlinear earthquake response analysis of the structures supported by a large number of piles. And the applicability and the problems of proposed method are examined by applying it to an assumed pile foundation. Concretely, the impedance matrix of pile group is translated to the tridiagonal matrix which consists of axis springs and shear springs calculated by assuming uniform displacement distribution and movement displacement distribution of soil surrounding piles. As a result, we can estimate soil springs considering the difference of pile position. But, there is also a possibility of becoming overestimate or underestimate depending on pile position. Further examination is necessary in the future.

INTRODUCTION

It is supposed that some very large earthquakes around the NANKAI trench, for example, TONANKAI EARTQUAKE, NANKAI EARTHKUAKE, and SOUTEI TOKAI EARTHQUAKE, will occur in the near future. To reduce damage caused by these earthquakes, it is very necessary to scrutinize earthquake-proof safety of existing buildings as soon as possible. Especially, because the damage of lifeline facilities like the electric power plants or the gas pipelines influence on the restoration activity after a large earthquake, it is important to assess earthquake-proof safety of these facilities. In Japan, most of thermal power plants are constructed on inshore claimed ground. Many high-rise buildings are also constructed on soft soil. Most of these buildings are supported by pile-foundations. To evaluate the

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earthquake resistance performance of these pile-supported buildings, a dynamic earthquake response analysis or a static increment analysis is often conducted.

The subjects of this study are supposed to be large structures supported by a large number of piles like electric power plants. The finite element method and a method by use of a mass-spring model are applied to a nonlinear earthquake response analysis in time domain. For mass-spring models, the sway-rocking model and the Penzien model (Penzien *et al.*, 1964) are representative. The static increment analysis uses the frame model consisting of beams and springs as shown in Fig.1. From the point of the present general computer environment, the finite element method is not so applicable for the nonlinear earthquake response analysis of these structures because of a large number of degrees of freedom caused by a wide analysis area and many piles. In the case of the SR model, it is necessary for the soil-pile system to be translated to soil springs. Hijikata *et al.*(1995) propose the conventional evaluation method of soil springs. This method is applicable from a small pile group to a large pile group. Though this is able to consider the site nonlinearity by use of the equivalent linear model, it is difficult to install both of the local nonlinearity of soil around pile and the material nonlinearity of piles. In the case of the Penzien model, the soil system is translated to soil springs around piles. The degrees of freedom need to be decreased because of a large number of piles. Fukuoka *et al.*(1996) or Hasegawa and Mori(1998) indicate a single stick model of the soil-pile-structure system, and propose the condensation method of impedance of group pile to soil springs. Moreover, soils springs are translated into horizontal axis springs and shear springs as shown in Fig.1. The demerit of this method is that it is impossible to evaluate the response of each pile accurately. Sako and Miyamoto(1999) perform the nonlinear response analysis by use of the three-dimensional frame model installed axis springs and shear springs at each pile. The stiffness of these springs is given as the average of the condensed pile’s springs. Kimura *et al.*(2005) propose the method that the soil springs (horizontal axis spring and shear springs) of the condensed pile, which Miyamoto et al.(1995) or Hasegawa and Mori(1998) propose, are allotted to each pile. In this method, these soil springs are distributed to each pile in proportion to the ratio of coefficient of subgrade reaction, which is calculated to be equivalent to the shear force contribution ratio at pile head. Sako(2000) proposes the method of substituting equivalent horizontal axis springs and the shear springs for the impedance of group pile. In this method, the axis springs and the shear springs are calculated from the subgrade reaction caused by the displacement mode of the pile when the compulsion displacement is given to the pile head and by the shear transformation of each depth of each pile one by one. Hasegawa *et al.*(2001) try the static increment analysis of a pile-supported building that consists of the independent footing supported with two or more piles by the frame model using the axis springs calculated in consideration of the pile group effect in an independent footing.

Wen and Fukuwa(2006) propose a simple method that the problem of a large number of piles is converted to that of a small number of piles. In this method, a group pile is divided into some blocks including some piles and these piles are condensed into a single pile. It is more practical than the above mentioned three-dimensional frame model. In this study, by using this method, we propose a conventional analysis model for the nonlinear earthquake response analysis and the static increment analysis of structures supported by a large number of piles. Especially the evaluation process of axis springs and shear springs is indicated in this paper. In addition, nonlinearity of axis springs and shear springs and an evaluation of input motions are also important problems on carrying out these analyses. These are supposed to be future problems.

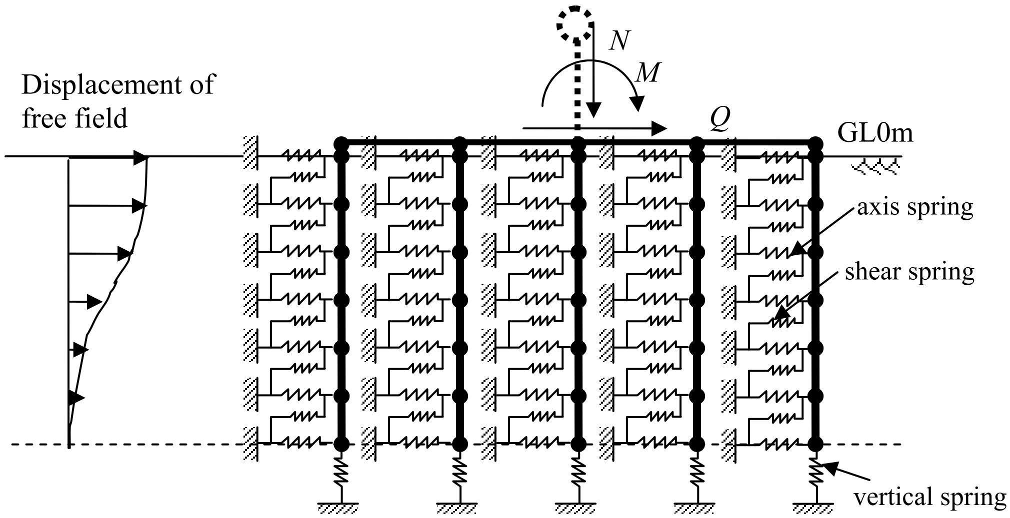


Figure 1 An example of a fame model for a dynamic or static response analysis of a pile

FORMULATION

The proposed method has three steps as follows.

Step 1: A pile group is divided into some blocks including some piles. These piles are condensed into a single pile. (see Fig.2(a)).
Step 2: An impedance matrix of a small number of condensed piles is calculated by the thin layer method (see Fig.2(b)). This matrix is full.
Step 3: This impedance matrix is translated into the tridiagonal matrix which consists of both horizontal axis springs and shear springs (see Fig.2(c)).

At Step 2, an impedance matrix of a small number of condensed piles is calculated by the multipoint excitation method as shown in Fig.3 proposed by Wen and Fukuwa(2006). If the sum of the exciting force F^l acting on the multiple points of the nodal surface l is one, the exciting force F_i^l on the nodal surface S of the i-th pile is written as the following equation:

$$F_i^l = \frac{w_i^l}{\sum_{m=1}^{N^l} w_m^l} \tag{1}$$

where w^l and N^l are a weight and the number of piles in each block at the nodal surface l, respectively. The displacement u_j^{kl} of the j-th pile on the nodal surface k is written as follows:

$$u_j^{kl} = \sum_{i=1}^{N^l} F_i^l u_{ij}^{kl} = \frac{\sum_{i=1}^{N_l} w_i^l u_{ij}^{kl}}{\sum_{m=1}^{N^l} w_m^l} \tag{2}$$

where u_{ij}^{kl} is the thin layer solution. Consequently the displacement U^{kl} of the condensed pile at nodal surface R is presented as the following equation:

$$U^{kl} = \frac{\sum_{j=1}^{N^k} w_j^k u_j^{kl}}{\sum_{j=1}^{N^k} w_j^k} = \frac{\sum_{j=1}^{N^k} \sum_{i=1}^{N^l} w_j^k w_i^l u_{ij}^{kl}}{\sum_{j=1}^{N^l} w_j^l \sum_{m=1}^{N^k} w_m^k} \tag{3}$$

where N^k is the number of piles in each block at the nodal surface k. If the weight is even, Eq.(3) is rewritten as following equation:

$$U^{kl} = \frac{\sum_{j=1}^{N^k} \sum_{i=1}^{N^l} u_{ij}^{kl}}{N^k N^l} \tag{4}$$

This procedure can be used for multipoint excitation between different blocks. Finally the compliance matrix of a small number of condensed piles is made by compilation of U^{kl} of each pile. The impedance matrix [K] is given as the inverse of the compliance matrix.

At Step3, the impedance matrix [K] of the condensed pile at Step 2 is replaced to the tridiagonal matrix composed of axis springs k_a and shear springs k_b in Eqs.(5), (6) and (7) as shown in Fig.4 (refer to Miyamoto *et al.* ,1995, Hasegawa *et al.* ,2001).

$$\{F\} = [K]\{u\} = ([k_a] + [k_b])\{u\} \tag{5}$$

$$[k_a] = diag\langle k_a^l \rangle = \begin{bmatrix} k_a^1 & & & & & & \\ & k_a^2 & & & & & \\ & & \ddots & & & & \\ & & & k_a^l & & & \\ & & & & \ddots & & \\ & & & & & \ddots & \\ & & & & & & k_a^n \end{bmatrix} \tag{6}$$

$$[k_b] = k_b^l \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} = \begin{bmatrix} k_b^1 & -k_b^1 & & & & & \\ -k_b^1 & k_b^1 + k_b^2 & -k_b^2 & & & & \\ & & \ddots & & & & \\ & & -k_b^{l-1} & k_b^{l-1} + k_b^l & -k_b^l & & \\ & & & & \ddots & & \\ & & & & & k_b^{n-2} + k_b^{n-1} & -k_b^{n-1} \\ & & & & & -k_b^{n-1} & k_b^{n-1} \end{bmatrix} \tag{7}$$

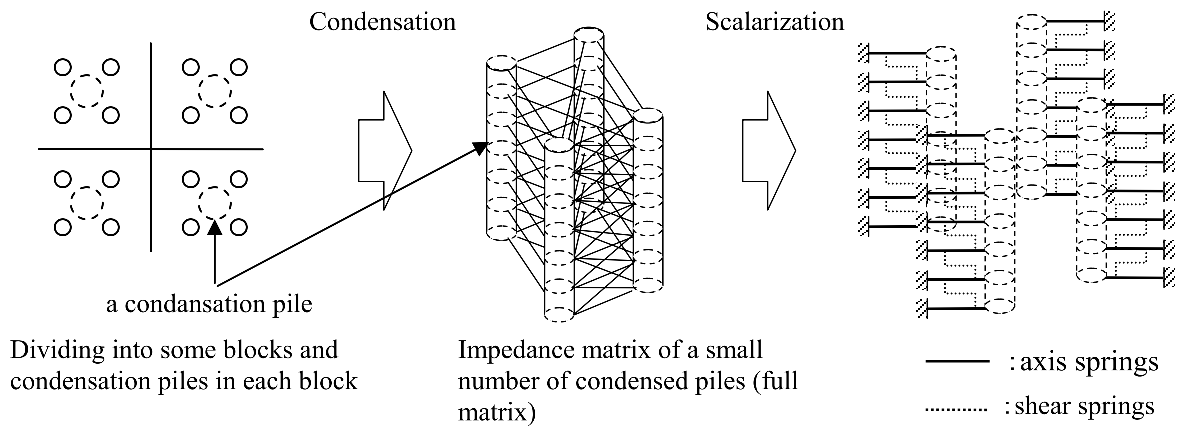
Axis springs of each condensed pile are calculated as shown in Eq.(8) by supposing the uniform displacement distribution (see Fig.5(a)) as {u} in Eq.(5).

$$k_{ai}^{\ k} = \sum_{j=1}^{N_P} \sum_{l=1}^{N_L} K_{ij}^{kl} \tag{8}$$

where N_L and K_{ij}^{kl} are the number of soil layer and the impedance matrix of a small number of condensed piles, respectively. As shown in Eq.(9), shear springs of each condensed pile are given by supposing the moving displacement distribution (see Fig.5(b)) as {u} in Eq. (5).

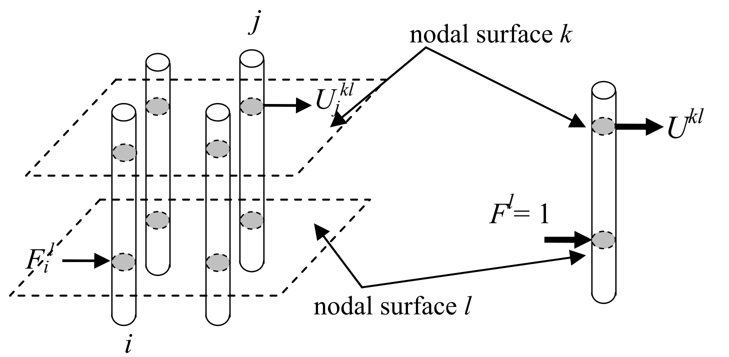
$$k_{bi}^{\ k} = \sum_{j=1}^{N_P} \sum_{l=1}^{k} K_{ij}^{kl} - k_{ai}^{\ k} \tag{9}$$

When the dynamic response analysis or the static increment analysis of a pile-supported building is performed, stiffness of each spring at low frequency, for example 0.lHz, is applied.



(a) Step 1 (b) Step 2 (c) Step 3

Figure 2 Schematic flow of the proposed method



(a) Pile group (b) Condensed pile (average)

Figure 3 Schematic diagram of multipoint excitation solution (Wen and Fukuwa, 2006)

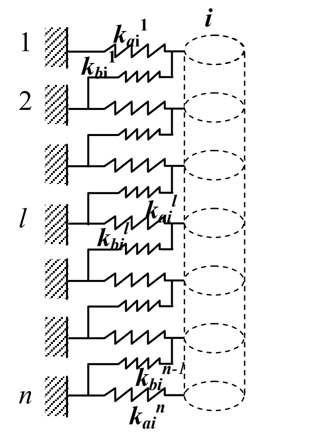
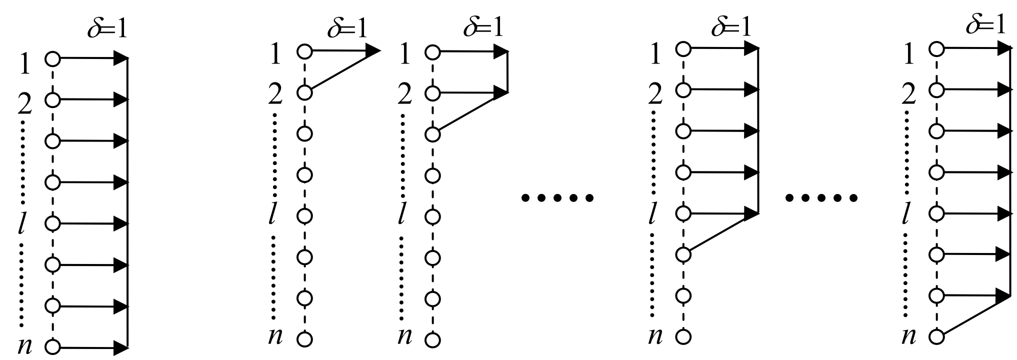


Figure 4 Analytical model composed of axis springs and shear springs



(a) Uniform Displacement Distribution (for axis springs)

(b) Moving Displacement Distribution (for shear springs)

Figure 5 Displacement distributions to make axis springs and shear springs

NUMERICAL EXAMPLES

To examine the characteristics of the proposed method, a simple numerical analysis is performed by use of an assumed model as shown in Fig.6. In this figure, B, E, I_p, ρ_p and h_p are the diameter, the Young's modulus, the geometrical moment of inertia, mass density and damping factor of piles, respectively. And ρ, h, ν, Vs are mass density, damping factor, Poisson's ratio and shear wave velocity of soil, respectively. The semi-infinite uniform foundation soil is applied. The shear wave velocity Vs of soil is 100m/s or 200m/s. Piles are assumed to be cast-in-place reinforced concrete. The length of each pile is 15.3m. The tip of each pile is installed at GL-15m. The base of foundation is separated at 0.3m away from the ground surface. The numbers of piles N_p are 4(2×2), 16(4×4) and 36(6×6). The ratio S/B of the pile interval to the diameter of the pile is 3, 5 and 10. The excitation direction is x-direction. The next chapter compares the results given by the proposed method with both those given by the previous method and precise solutions about horizontal pile head impedances and stiffness distributions of soil springs.

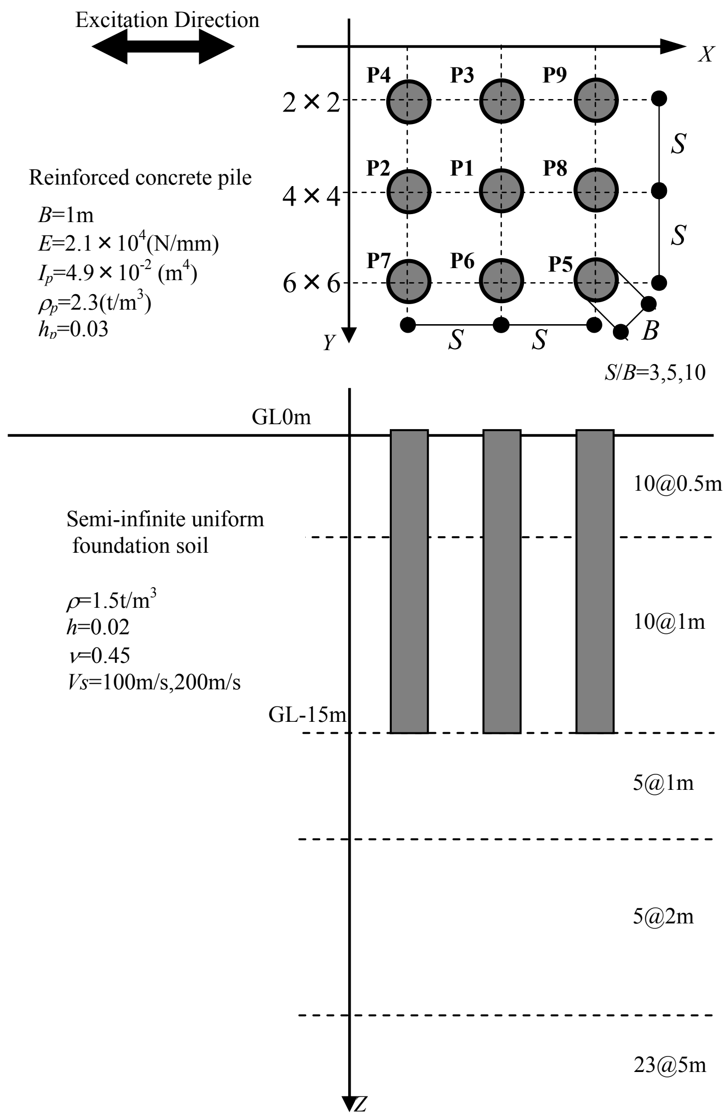


Figure 6 Analysis Model

RESULTS AND DISCUSSIONS

Comparison of the horizontal pile head impedance K_H

The comparison results of horizontal pile head impedance K_H are shown in Figs.7-9. The calculated frequencies of vibrations are 0.1, 1, 2, 3, 4, and 5Hz. These Figures indicate the results of three cases as follows.

Case1: The horizontal pile head impedance by use of the impedance of group pile (Hasegawa, 1993). The results are indicated by black solid lines or broken ones.

Case2: The horizontal pile head impedance by the proposed method in this study. The results are indicated by blue solid lines or broken ones.

Case3: The horizontal pile head impedance by using the impedance matrix of the condensed pile (Miyamoto *et al.*, 1995 or Hasegawa and Mori, 1998). The results are indicated by red solid lines or broken ones.

Fig.7 shows the effect of the number of piles on the horizontal pile head impedance at *Vs*=100m/s and *S*/*B*=5. The stiffness (real part of the impedance) at 0.1Hz of Case2 is about 0.5 to 0.7 times smaller than Case1, and is almost same as Case3. The reason is considered that the uniform displacement distribution, which is used for evaluation of axis springs, does not so correspond to the real pile displacement. Fig.8 shows the effect of the shear wave velocity of soil *Vs* on the horizontal pile head impedance at N_p=16 and *S*/*B*=5. Fig.9 shows the effect of the pile interval *S*/*B* on the horizontal pile head impedance at *Vs*=100m/s and N_p=16. The same tendency as Fig.7 is recognized in Fig.8 and 9. It is shown that, as for the pile head impedance, the proposed method can perform the evaluation equivalent to the method using the condensed pile's impedance (Case3). On the other hand, the results of the imaginary part of the impedance correspond well in 2 Hz or less except the case of N_p=4.

Comparison of the pile head shear force contribution ratio

Figs.10 and 11 show comparison of the pile head shear force contribution ratio at 0.1 Hz, *Vs*=100m/s, 200m/s , N_p=16 and *S*/*B*=5 between Case1 and Case2. It is shown that the proposed method (Case2) overestimates the shear force at the corner pile (P1) and underestimates that at the center pile (P4). However, it is necessary to examine separately about the shear force contribution rate of piles when the ground motion is worked on them because this is a result in case of the pile head excitation.

Frequency characteristic of soil springs

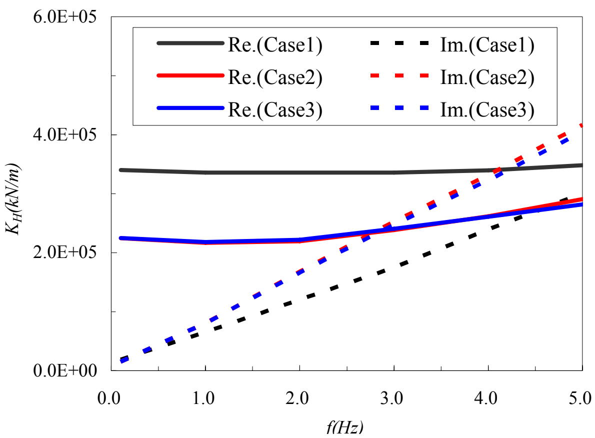
Fig.12 presents the frequency characteristic of axis springs k_a both of P1 and P4 (as shown in Fig.6) in the case of *Vs*=100m/s, N_p=16 and *S*/*B*=5. It is found that axis springs depend on the frequency strongly and that the effect of the additional mass is growing as the position of the axis spring becomes deep (see Fig.12(a), (b)). Especially this tendency is strongly recognized in P4. The imaginary part of axis springs grows as the frequency rises (see Fig.12(c), (d)). Fig,13 shows the frequency characteristic of shear springs k_b both of P1 and P4 (as shown in Fig.6) in the case of *Vs*=100m/s, N_p=16 and *S*/*B*=5. The shear springs of P1 don't depend on the frequency strongly. On the other hand, those of P4 increase as the frequency rises in the frequency domain treated in this study. The imaginary parts of shear springs are much smaller than those of real parts. These facts mean that shear springs have little damping effects.

Comparison of axis spring $\boldsymbol{k_a}$ **and shear spring** $\boldsymbol{k_b}$

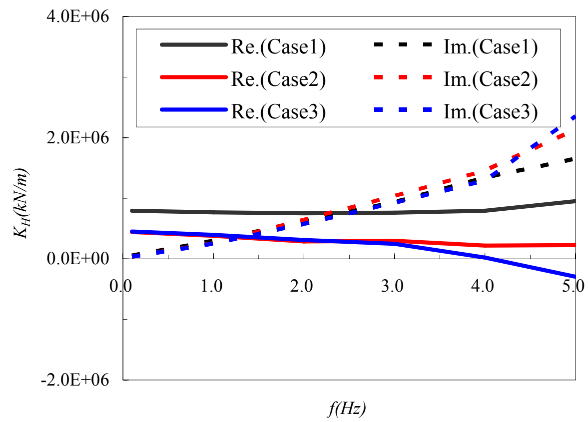
Figs.13-19 show the stiffness distribution of the axis springs k_a and the shear springs k_b at 0.1 Hz. In these figures, the results of Case3 above mentioned are indicated by red solid lines. Sign P* in these figures correspond to the pile number shown in Fig.6. Fig.14 shows the distribution of axis springs k_a with difference of the number of the piles in the case of *Vs*=100m/s and *S*/*B*=5. It is found that the proposed method can evaluate axis springs according to each pile position. Moreover, the tendency similar to the shear force contribution rate of each pile is recognized. As for this result of N_p=16, the axis spring of P1 is the largest among the all piles. P4 is the smallest stiffness. In the case of N_p =36, P5 is the largest and P4 is the smallest. On the other hand, the result of Case3 gives these average values. Fig.15 shows the distribution of axis springs k_a with difference of the pile interval in the case of Vs=100m/s and N_p=16. It is understood that the larger the pile interval is, the smaller the differences of the axis spring stiffness of each pile. This tendency harmonizes with a relationship between the pile interval and the pile group effect. Fig.16 shows the effect of the shear wave velocity Vs on the distribution of axis springs k_a at S/B=5 and N_p=16. It is found that a relative relation of axis spring stiffness is almost the same in both cases though absolute values change depending on the shear wave velocity Vs.

The stiffness distribution of the shear spring k_b is shown in Figs.17-19. It is understood that the stiffness of the shear spring of each pile almost becomes the same value regardless of the pile position, the number of the piles, and the pile interval. This means that the shear springs are not influenced by the pile group effect.

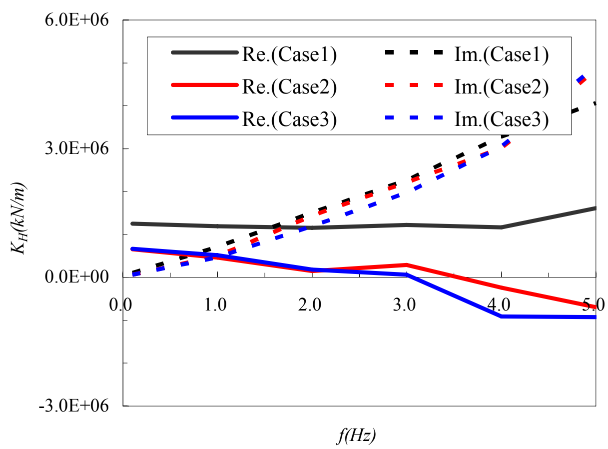
Fig.20 shows the damping coefficient distribution of axis springs in the case of Vs =100m/s, N_p =16, and f=1.0Hz. It is found that the larger the pile interval is, the smaller the differences of damping coefficient of each pile as well as the stiffness distribution of axis springs.



(a) N_p=4

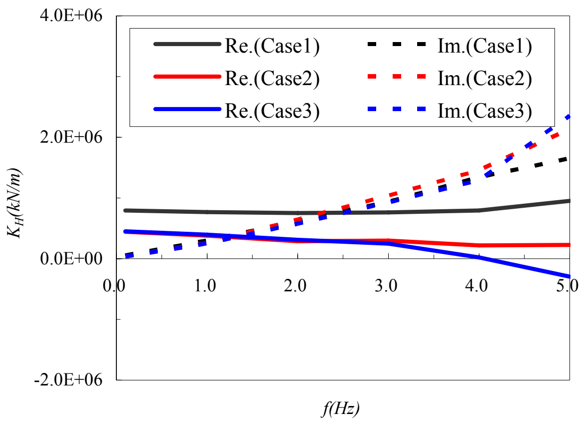


(b) N_p =16

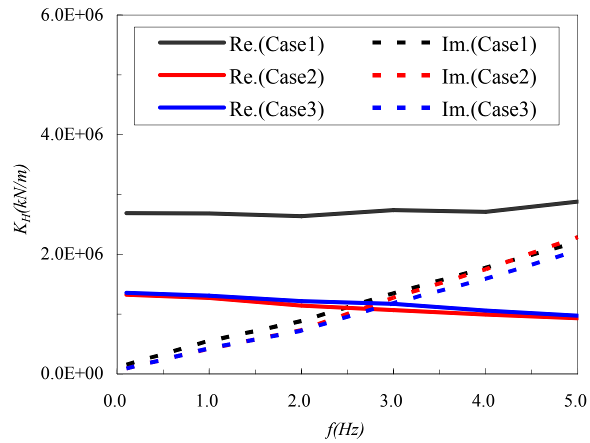


(c) N_p =36

Figure 7 Comparison of Horizontal Impedance Functions K_H (Vs=100m/s, S/B=5)

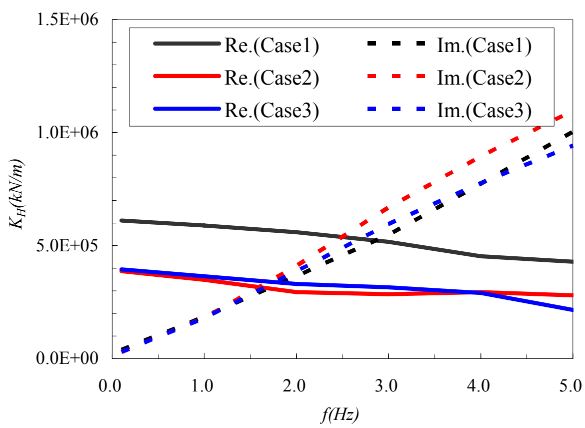


(a) *Vs*=100m/s

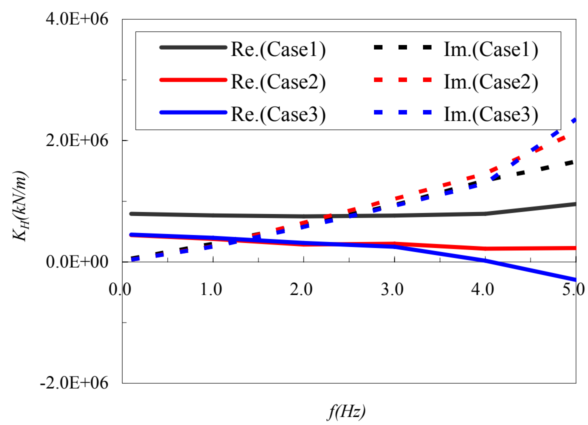


(b) *Vs*=200m/s

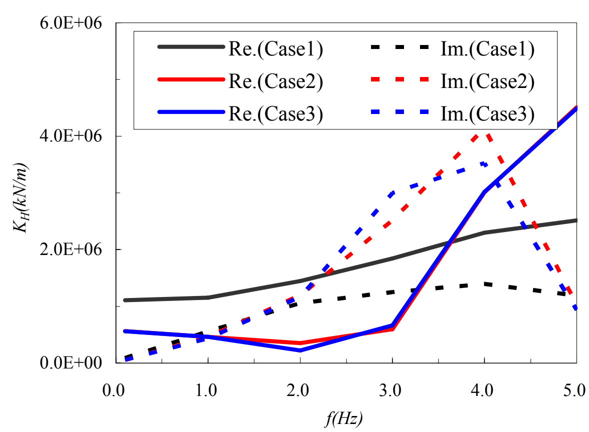
Figure 8 Comparison of Horizontal Impedance Functions K_H (N_p =16, S/B=5)



(a) S/B =3

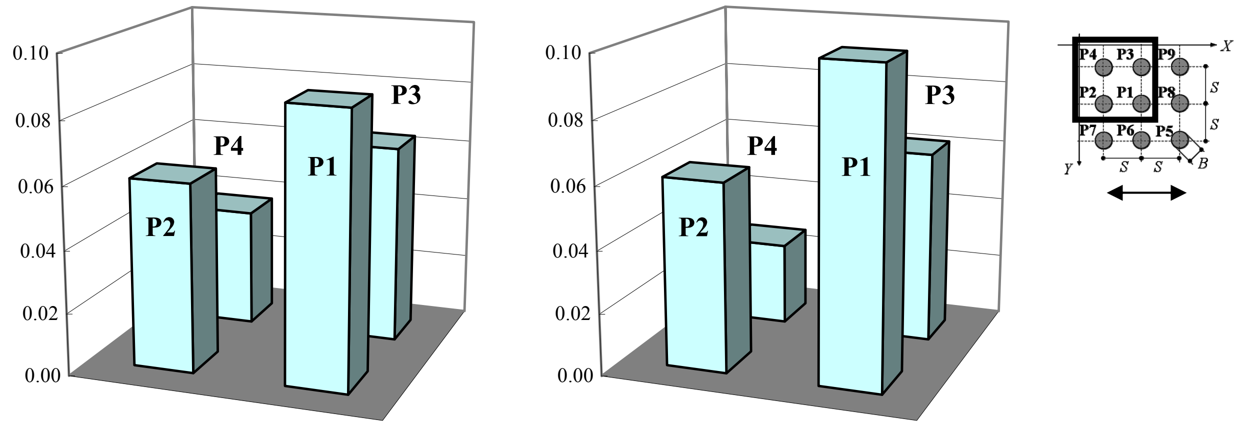


(b) S/B =5



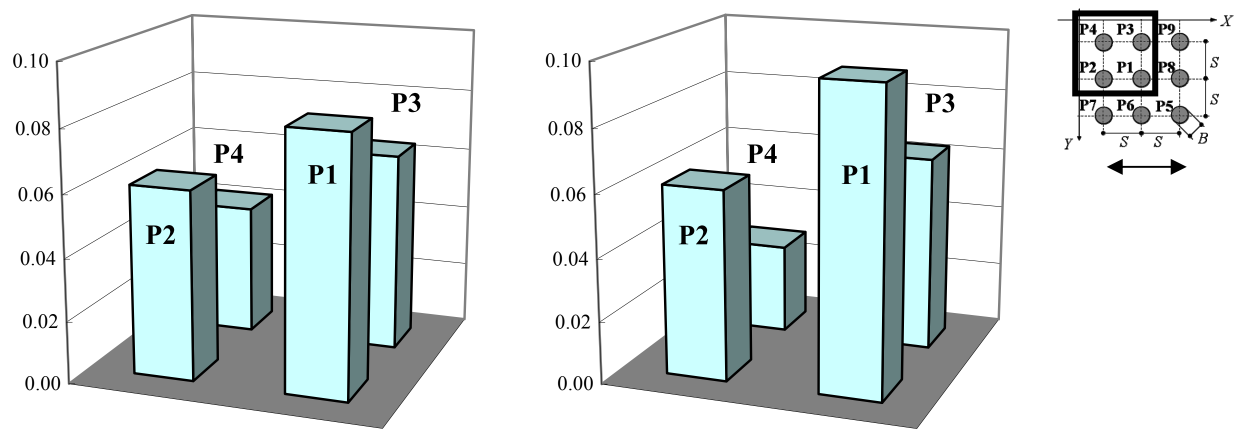
(c) S/B =10

Figure 9 Comparison of Horizontal Impedance Functions K_H (*Vs*=100m/s, N_p =16)



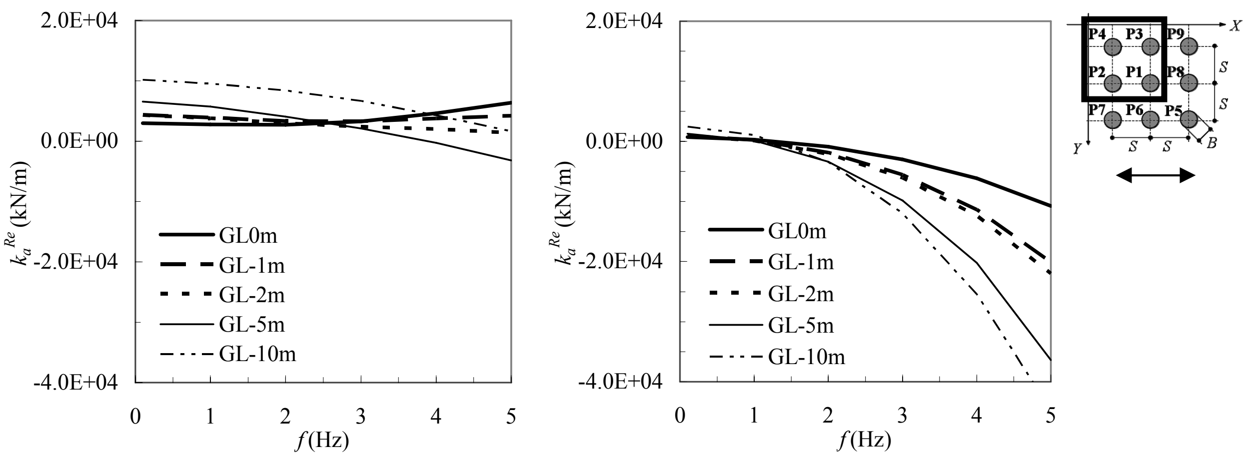
(a) Case1　　(b) Case2

Figure 10　Comparison of the pile head shear force contribution ratio (Vs=100m/s, N_p =16, S/B =3)



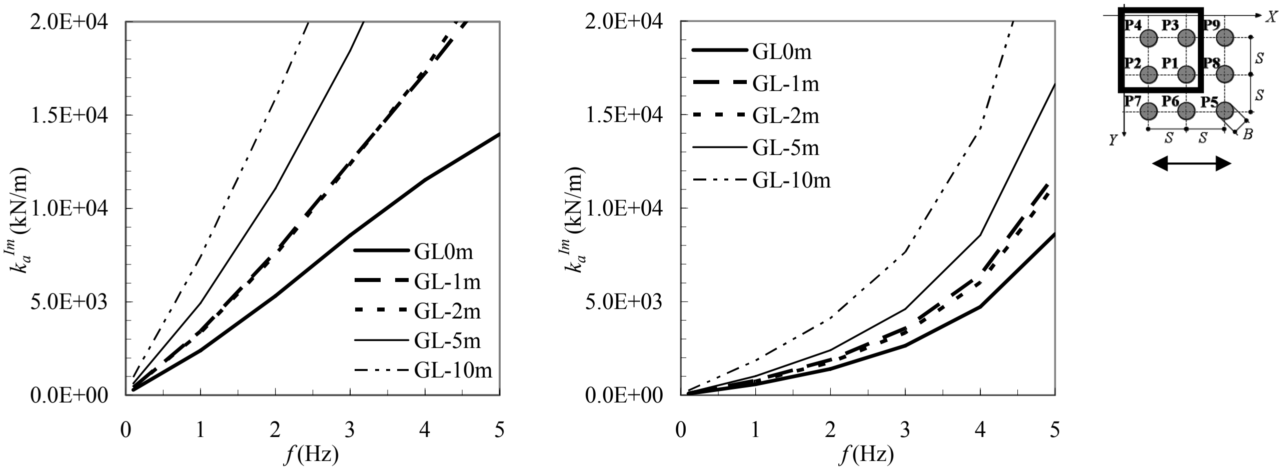
(a) Case1　　(b) Case2

Figure 11　Comparison of the pile head shear force contribution ratio (Vs=200m/s, N_p =16, S/B =3)



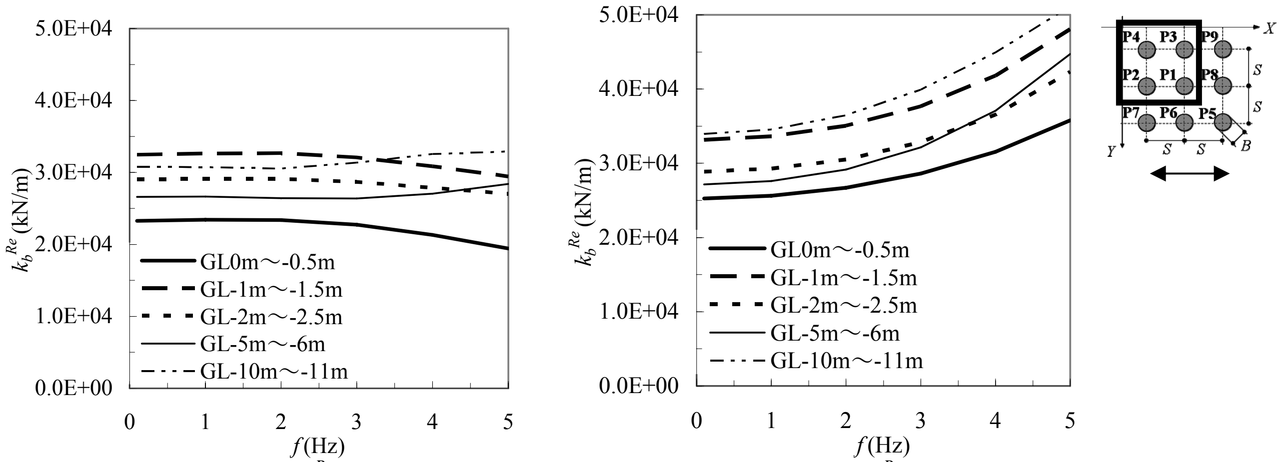
(a) k_a^R (P1)　　(b) k_a^R (P4)

Figure 12　The frequency characteristic of axis springs k_a (Vs=100m/s, N_p =16, S/B =5)

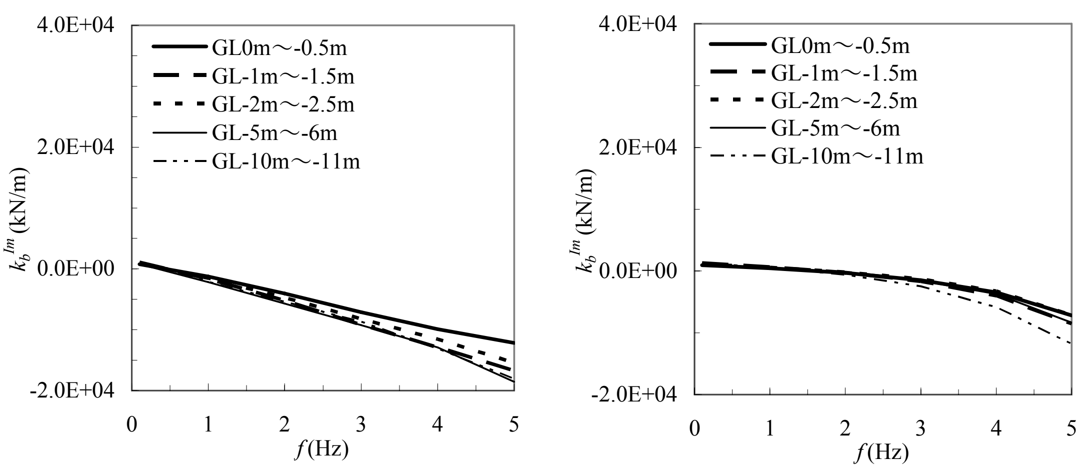


(c) k_a^{Im} (P1) (d) k_a^{Im} (P4)

Figure 12 The frequency characteristic of axis springs k_a (*Vs*=100m/s, N_p =16, *S/B* =5, continued)

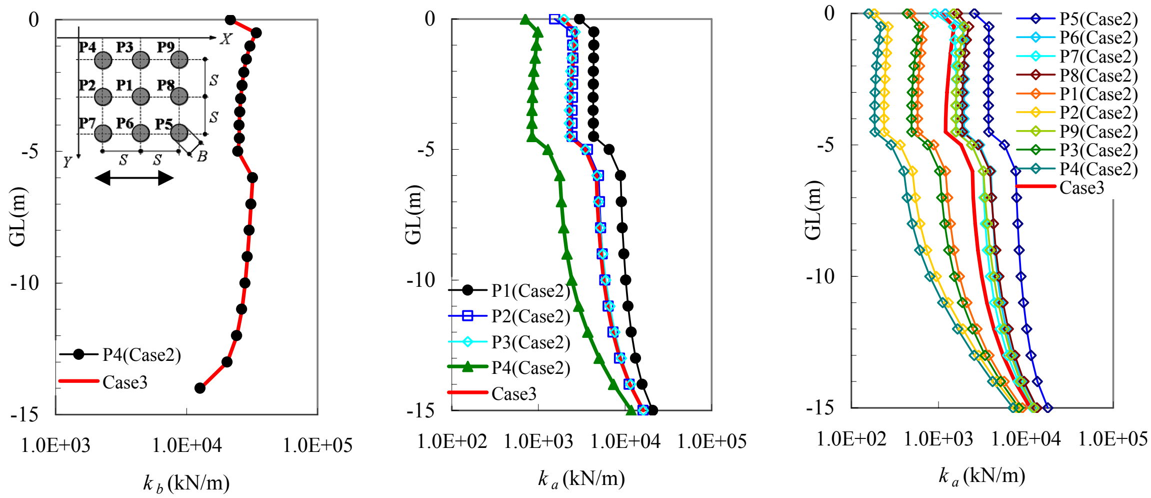


(a) k_a^{Re} (P1) (b) k_a^{Re} (P4)



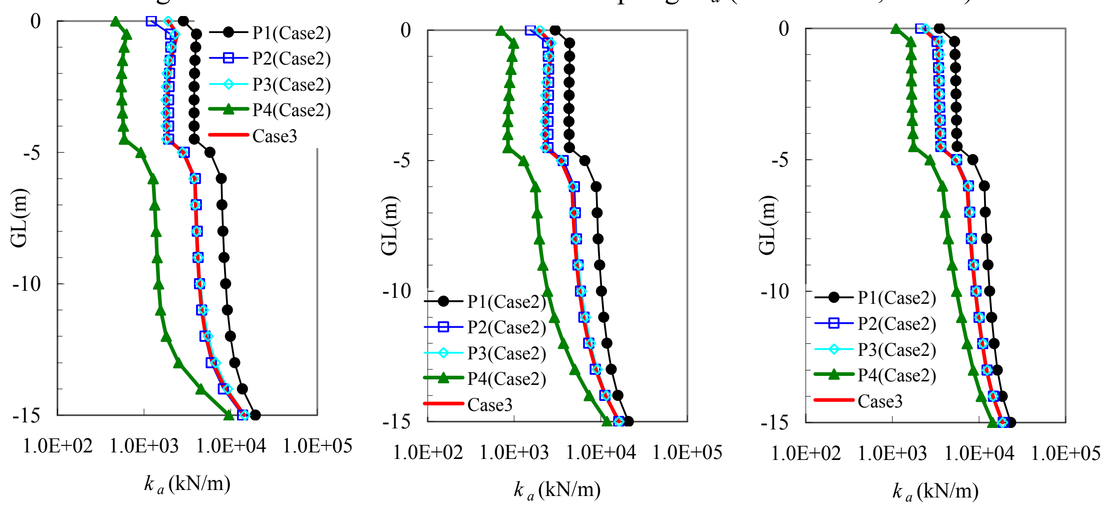
(c) k_a^{Im} (P1) (d) k_a^{Im} (P4)

Figure 13 The frequency characteristic of shear springs k_b (*Vs*=100m/s, N_p =16, *S/B* =5)



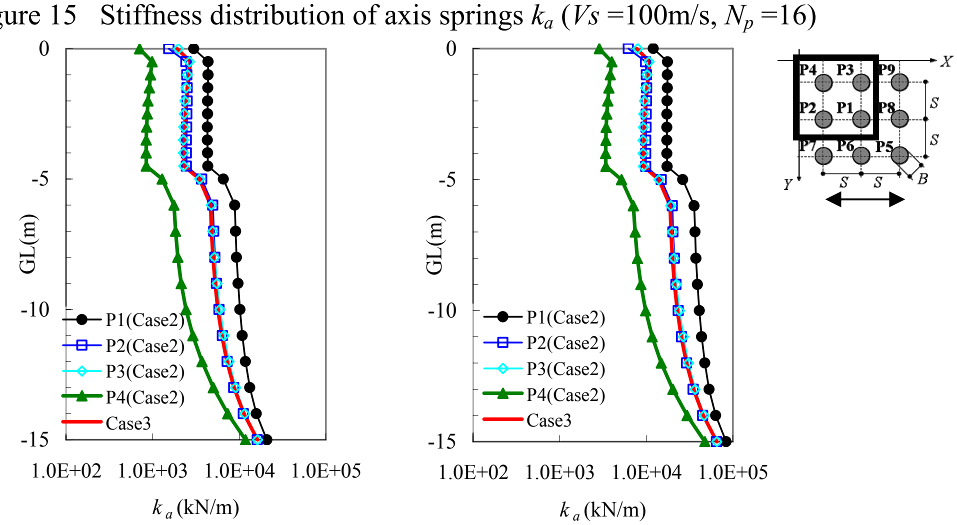
(a) N_p =4 (b) N_p =16 (c) N_p =36

Figure 14 Stiffness distribution of axis springs k_a (Vs =100m/s, S/B=5)



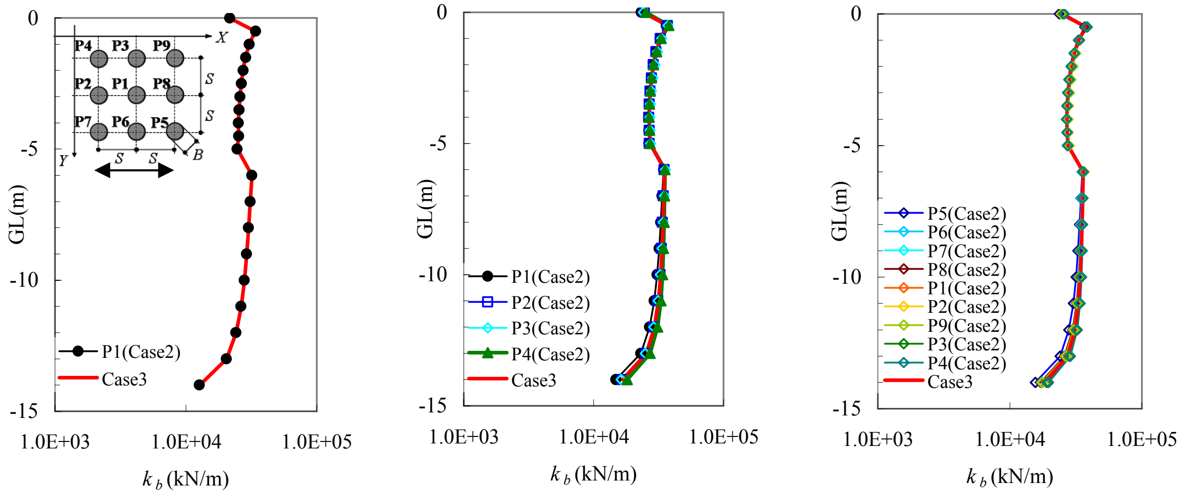
(a) S/B =3 (b) S/B =5 (c) S/B =10

Figure 15 Stiffness distribution of axis springs k_a (Vs =100m/s, N_p =16)



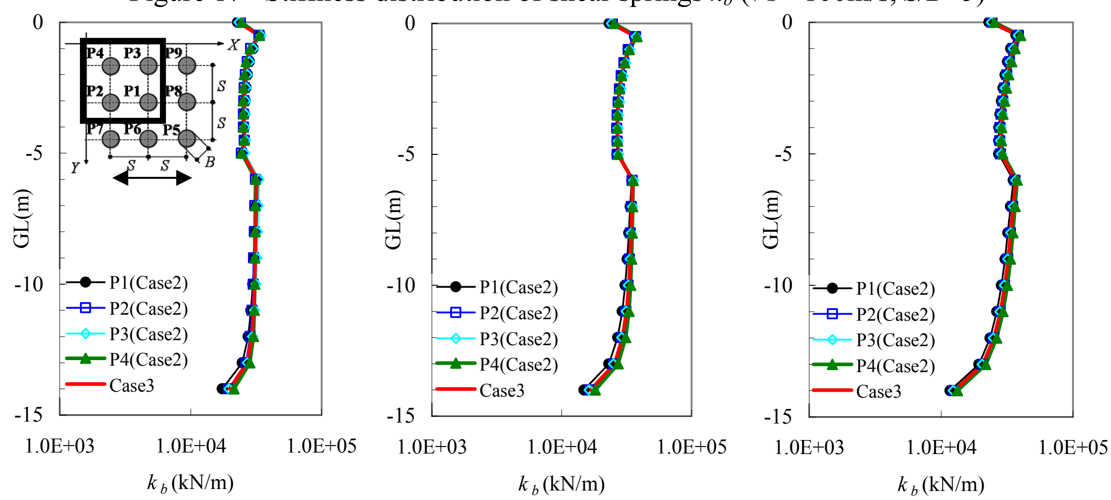
(a) Vs =100m/s (b) Vs =200m/s

Figure 16 Stiffness distribution of axis springs k_a (S/B =5, N_p =16)



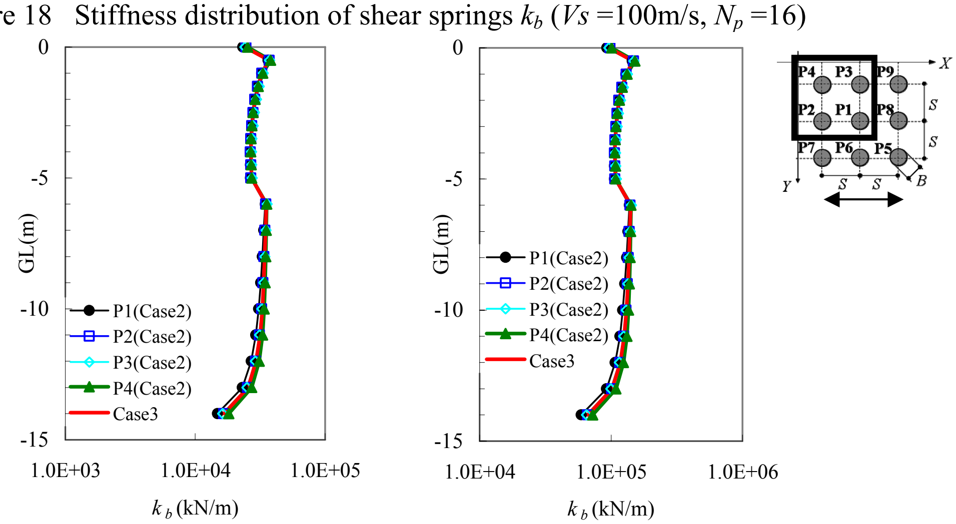
(a) N_p =4 (b) N_p =16 (c) N_p =36

Figure 17 Stiffness distribution of shear springs k_b (Vs =100m/s, S/B=5)



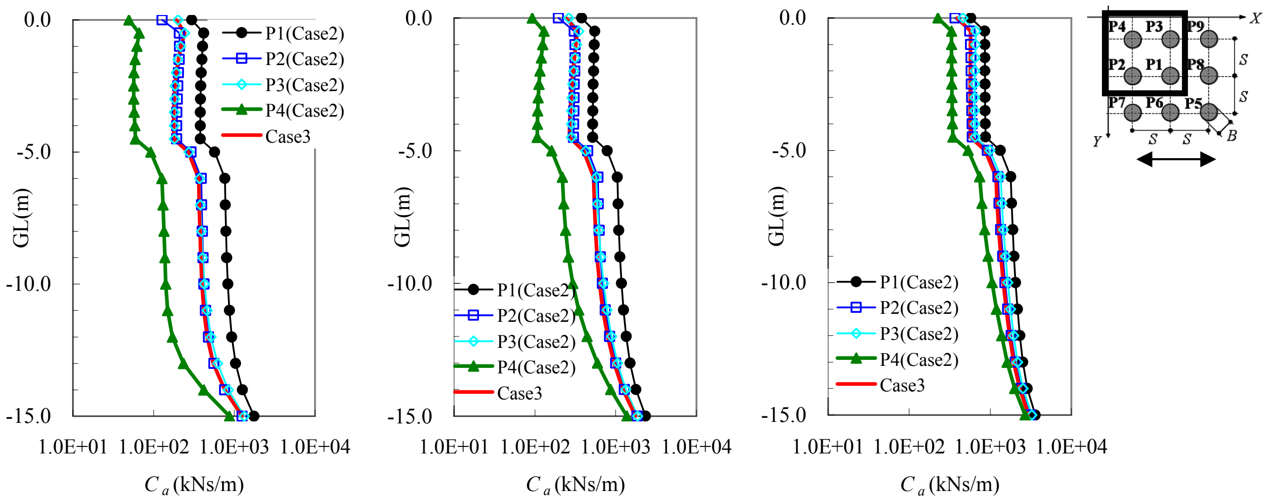
(a) S/B =3 (b) S/B =5 (c) S/B =10

Figure 18 Stiffness distribution of shear springs k_b (Vs =100m/s, N_p =16)



(a) Vs=100m/s (b) Vs =200m/s

Figure 19 Stiffness distribution of shear springs k_b (S/B =5, N_p =16)



(a) *S/B* =3 (b) *S/B* =5 (c) *S/B* =10

Figure 20 Damping coefficient distribution of axis springs C_a (Vs =100m/s, N_p =16, f=1.0Hz)

CONCLUSIONS AND FUTURES

We have proposed the evaluation method of the soil springs around piles of the frame model for the nonlinear earthquake response analysis and the static increment analysis of the structures supported by a large number of piles. A simple numerical analysis has been performed by use of an assumed model to examine the characteristics of the proposed method. Conclusions are as follows.

1. The proposed method can evaluate stiffness of axis spring according to the pile position.
2. The proposed method can perform the evaluation equivalent to the method using the condensed pile impedance (Miyamoto *et al.*, 1995 or Hasegawa and Mori, 1998).
3. The proposed method overestimates the shear force at the corner pile and underestimates that at the center pile from the point of the pile head shear force contribution ratio.

We will study on the nonlinearity both of axis springs and shear springs and input motions working on each pile in the future.

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