AN INNOVATIVE METHOD FOR EVALUATING THE DYNAMIC RESPONSE OF INELASTIC STRUCTURES WITH FREQUENCY-DEPENDENT SSI

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ABSTRACT :

This paper presents application examples of the Gyromass Element Method (GEM), a newly proposed method (Saitoh 2007) that can calculate the time-history response of inelastic structures supported by soil-foundation systems showing frequency-dependent oscillations in impedance functions. A "gyromass" is an element defined as a unit system that generates a reaction force due to the relative acceleration of the nodes between which the gyromass is placed. In this study, the precision of simulations by using GEM is assessed. This study also confirms the feasibility of a model formed by combining the previously proposed models.

KEYWORDS: Soil-structure interaction, impedance functions, inelastic response, parameter model

1. Introduction

In general, soil-foundation systems show various frequency-dependent impedance characteristics, such as rapid oscillations or cut-off frequencies, depending on the types of foundations, soil profiles, and the direction of excitations, etc. In contrast, many recent studies of structural dynamics have focused on the inelastic behavior of structural systems because the methodology of performance-based seismic design, which has been applied to seismic codes and guidelines in many countries, allows modeling of the inelastic behavior of structural systems. The frequency dependency of soil-foundation impedance characteristics is usually considered in a numerical method performed in the frequency domain, whereas the nonlinearity of superstructures is in the time domain because the inelastic behavior of materials and structural members strongly depends on the stress path being integrated stepwise. Although a variety of methods and techniques by which the frequency-dependent impedance functions can be considered in a time-history analysis have been proposed, the most powerful and acceptable tool in practice is a simple model approximating the impedance functions by frequency-independent spring, dashpot, and mass elements [e.g., Meek and Veletsos (1974), Wolf and Somaini (1986), Nogami and Konagai (1986, 1988), Wolf (1994), Wolf and Song (2002)]. The reason for this is that the frequency-independent elements can be applied directly to conventional structural analysis. In recent years, various types of simple models consisting of these elements (generally called spring-dashpot-mass models) have been proposed for soil reaction, shallow foundations, embedded foundations, etc. Although increasing the number of elements and degrees of freedom results in more accurate fitting to the ideal impedance functions, in practical applications, simple models having a small number of elements and degrees of freedom are used. In general, however, such simple models show a moderate variation with frequency, and thus do not express the frequency-dependent impedance functions with sufficient accuracy.

Saitoh (2007) proposed a simple model by which various types of frequency-dependent impedance functions can be simulated using a mechanical element called a "gyromass". The gyromass is frequency-independent and is defined as a unit system that generates a reaction force due to the relative acceleration of the nodes between which the gyromass is placed. In this study, this gyromass-based numerical method is called the Gyromass Element Method (GEM). In Saitoh (2007), a numerical example was presented where the nonlinear response of a single-degree-of-freedom system (SDoF system) supported by a 2x2 pile group was calculated. However, although this example demonstrates the advantage of GEM, more detailed application examples for simulating various impedance functions are necessary to enhance the feasibility of this method. In this study, therefore, several examples of the application are presented to accomplish this.

2. Application Examples for Simulating Impedance Functions

One of the most impressive examples is the application to impedance functions of pile groups. The reason for this is that impedance functions of pile groups in general show complicated oscillations with frequency. These oscillations usually occur due to "in-phase" and "out-of-phase" pile-to-pile interactions, as explained in Dobry and Gazetas (1988). It is known that simulating impedance functions of pile groups by using spring-dashpot-mass models is quite difficult since some of these parameters often take negative values, which is considered to be unrealistic, and in general, unstable in numerical calculations. Here, a 3x3 pile group is taken as an application example using the published results of a rigorous solution (Kaynia and Kausel (1982)).

2.1 Introduction of Type II model

In the following simulation, one of the proposed models, called the "Type II Model", is used. Details of this model are described in Saitoh (2007); therefore, an explanation of the fundamentals of this model is omitted here. Fig.1 shows that the Type II model consists of two types of unit systems: one is the base system, and the other is the core system composed of a spring k and a unit having a gyro-mass $\overline{m}$ and a dashpot c arranged in parallel. The base system and the core system are arranged in parallel. As described in Saitoh (2007), an additional core system having different coefficients can be arranged in parallel with the Type II model in order to enhance the precision of the simulation, if needed. The impedance functions of the Type II model having multiple core systems shown in Fig.1 can be expressed by the following formula:

$$F(a_0) = K\left\{1 + \sum_{i=1}^{N} \frac{\beta_i\left[\mu_i a_0^2\left(\mu_i a_0^2 - 1\right) + \gamma_i^2 a_0^2\right]}{\left(1 - \mu_i a_0^2\right)^2 + \gamma_i^2 a_0^2} - \mu_0 a_0^2 + i\,a_0\left[\sum_{i=1}^{N} \frac{\beta_i \gamma_i}{\left(1 - \mu_i a_0^2\right)^2 + \gamma_i^2 a_0^2} + \gamma_0\right]\right\} u(a_0), \quad (1)$$

where the coefficient K is equivalent to the static stiffness ($a_0 = 0$); γ_i, μ_i, and β_i are, respectively, the dimensionless coefficients of the damper and the gyro-mass, and the stiffness ratio of the i-th core system shown in Fig. 1; and N is the total number of core systems.

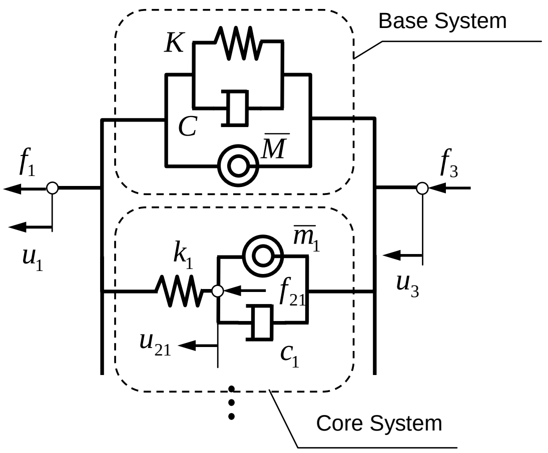

Fig. 1 Type II Model.

TABLE 1 Dimensionless coefficients of simple models simulating impedance functions of a 3x3 pile group.

coefficient	Base	Core-1	Core-2	Core-3
Re.($K_d^{(9)}/9K_s$)	0.56	0.56	0.56	0.56
γ_0	7.80	0.16	0.16	0.00
μ_0	0.00	1.60	1.60	1.60
β_1		2.00	1.67	1.65
γ_1		3.90	4.20	4.20
μ_1		7.00	8.50	9.50
β_2			1.20	0.25
γ_2			0.50	0.45
μ_2			0.90	1.80
β_3				1.25
γ_3				0.40
μ_3				0.80

2.2 Effect of the number of core systems on simulation

Fig. 2 shows a comparison of a horizontal impedance function of a 3 × 3 pile group (stiffness ratio of pile to soil $E_p/E_s = 1000$, slenderness ratio $H/d = 15$, Poisson's ratio $\nu = 0.4$, material damping of soil $\beta_s = 0.05$, and distance ratio $S/d = 10$, where S is the axis-to-axis distance of the piles and d is the diameter of the piles) simulated by the Type II model with the published results. In this comparison, the effect of the number of core systems upon the precision of the simulation is assessed. The properties used here are summarized in Table 1. Fig. 2 indicates that the precision of the simulation gradually increases as the number of core systems increases: in particular, the oscillations

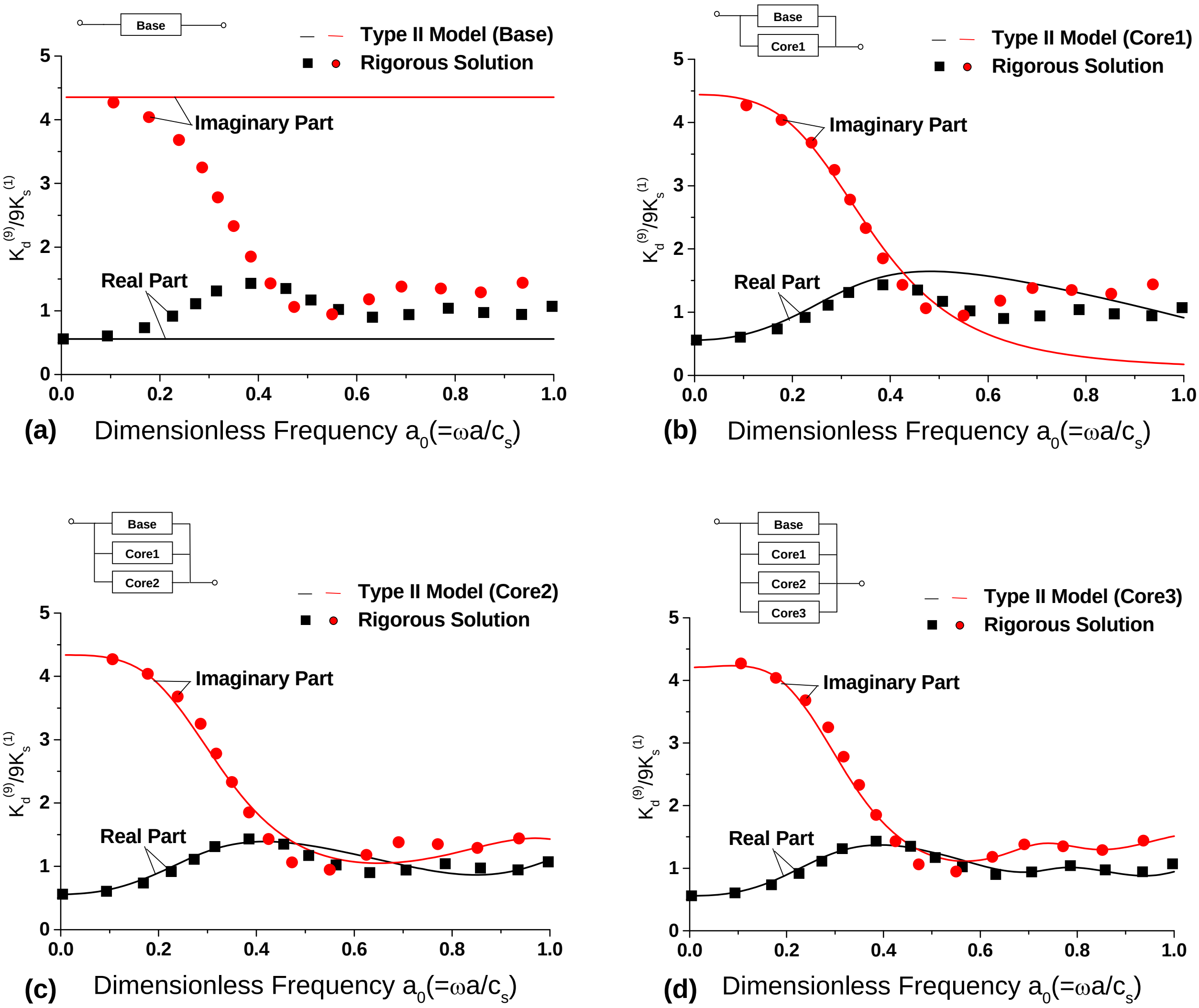

Fig. 2 Normalized horizontal impedance functions of a 3×3 pile group simulated by using Type II model, showing (a) base system with no core system, (b) single core system, (c) double core systems, and (d) triple core systems. Comparison with the rigorous solution of Kaynia and Kausel (1982). (Imaginary part of the impedance is divided by the dimensionless frequency a_0; $K_d^{(9)}$ is the dynamic impedance of a 9-pile group; $K_s^{(1)}$ is the static stiffness of a single pile.)

in the high frequency region appearing in the rigorous impedance functions shows good agreement with the simulated results by using the Type II model that consists of three core systems.

2.3 Combination of Type I and II models

In the previous study [Saitoh (2007)], Type I and Type II were independently used for expressing the impedance functions showing cut-off frequencies and oscillations, respectively. The Type I model consists of two types of unit systems: one is the base system, and the other is the core system composed of a gyro-mass $\overline{m}$ and a unit having a spring k and a dashpot c arranged in parallel. The base system and the core systems are arranged in parallel. As described in Saitoh (2007), an additional core system having different coefficients can be arranged in parallel with the Type I model in order to enhance the precision of the simulation, if needed. Here, as described in Saitoh (2007), the impedance functions of the Type I model having multiple core systems can be expressed by the following formula:

$$F(a_0) = K\left\{1 + \sum_{i=1}^{N} \frac{\beta_i \mu_i a_0^2 \left(\mu_i a_0^2 - \gamma_i^2 a_0^2 - 1\right)}{\left(1 - \mu_i a_0^2\right)^2 + \gamma_i^2 a_0^2} - \mu_0 a_0^2 + i\, a_0 \left[\sum_{i=1}^{N} \frac{\beta_i \gamma_i \mu_i^2 a_0^4}{\left(1 - \mu_i a_0^2\right)^2 + \gamma_i^2 a_0^2} + \gamma_0\right]\right\} u(a_0). \tag{2}$$

The Type I model is shown in Fig. 3. It is expected that a combination of the Type I and Type II models would be applicable for simulating more complicated impedance functions. Fig. 4 shows an impedance function of a soil-pile foundation designed for supporting a six-story building. This impedance function was evaluated by using the *Thin Layer Method*. Details of this analysis are described in the book published by AIJ (2006).

Fig. 4 (a) shows the simulated impedance functions obtained using the Type I model consisting of three core systems. The properties of the models shown here are summarized in Table 2. The Type I model is considered to be suitable for simulating impedance functions that have cut-off frequencies; as a whole, good agreement can be seen in the figure. One drawback of the Type I model in this simulation may be the imaginary part below 1.5 Hz: a small difference appears due to the fact that the Type I model shows a sudden increase in the imaginary part, which is compatible with the increase in the imaginary part at cut-off frequencies. Fig. 4 (b) shows a comparison with the impedance functions simulated by using the Type II model. The agreement is good in the imaginary part within the entire frequency region, whereas a slight difference appears in the real part below 2 Hz. At present, the influence of these differences upon the response of structural systems is not clear. Improvement of the proposed models is probably necessary to enhance the precision of the structural response.

Fig. 4 (c) shows a comparison with a revised model consisting of two core systems of Type I and one core system of Type II, and Fig. 4 (d) shows a comparison with another revised model that consists of one core system of Type I and two core systems of Type II. In Fig.4 (c), better agreement can be seen below 1.5 Hz because, in the core system of Type II, the imaginary part tends to increase. Fig. 4 (d) also shows better agreement in the real part, to some extent, between the simulated results and the numerical solution below 2 Hz. It is concluded, therefore, that the combination of the Type I and Type II models may be effective for improving the agreement between the impedance functions.

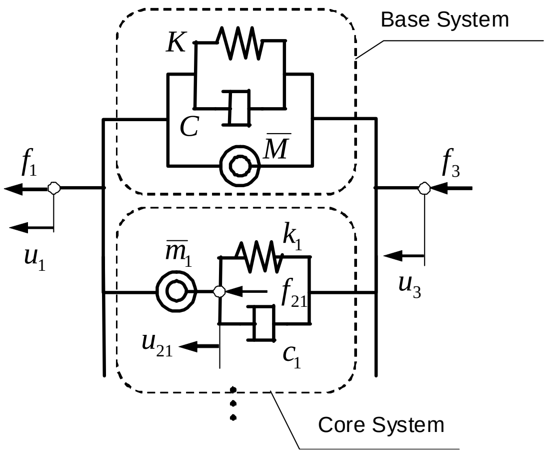

Fig. 3 Type I Model.

TABLE 2 Dimensionless coefficients of simple models simulating impedance functions of a pile group, published by AIJ (2006).

coefficient	(a)	(b)	(c)	(d)
K	607000	607000	607000	607000
γ_0	0.30	0.00	0.00	0.50
μ_0	0.50	2.40	0.75	1.30
β_1	0.39	0.70	0.40	0.30
γ_1	2.90	0.95	4.00	2.00
μ_1	16.0	4.80	16.0	9.00
β_2	0.52	0.65	0.56	0.81
γ_2	1.00	0.41	0.86	1.20
μ_2	6.00	0.90	4.80	6.00
β_3	0.08	0.95	0.33	0.22
γ_3	0.50	0.85	0.80	0.50
μ_3	2.00	1.80	2.50	1.50

: Using core system of Type I

: Using core system of Type II

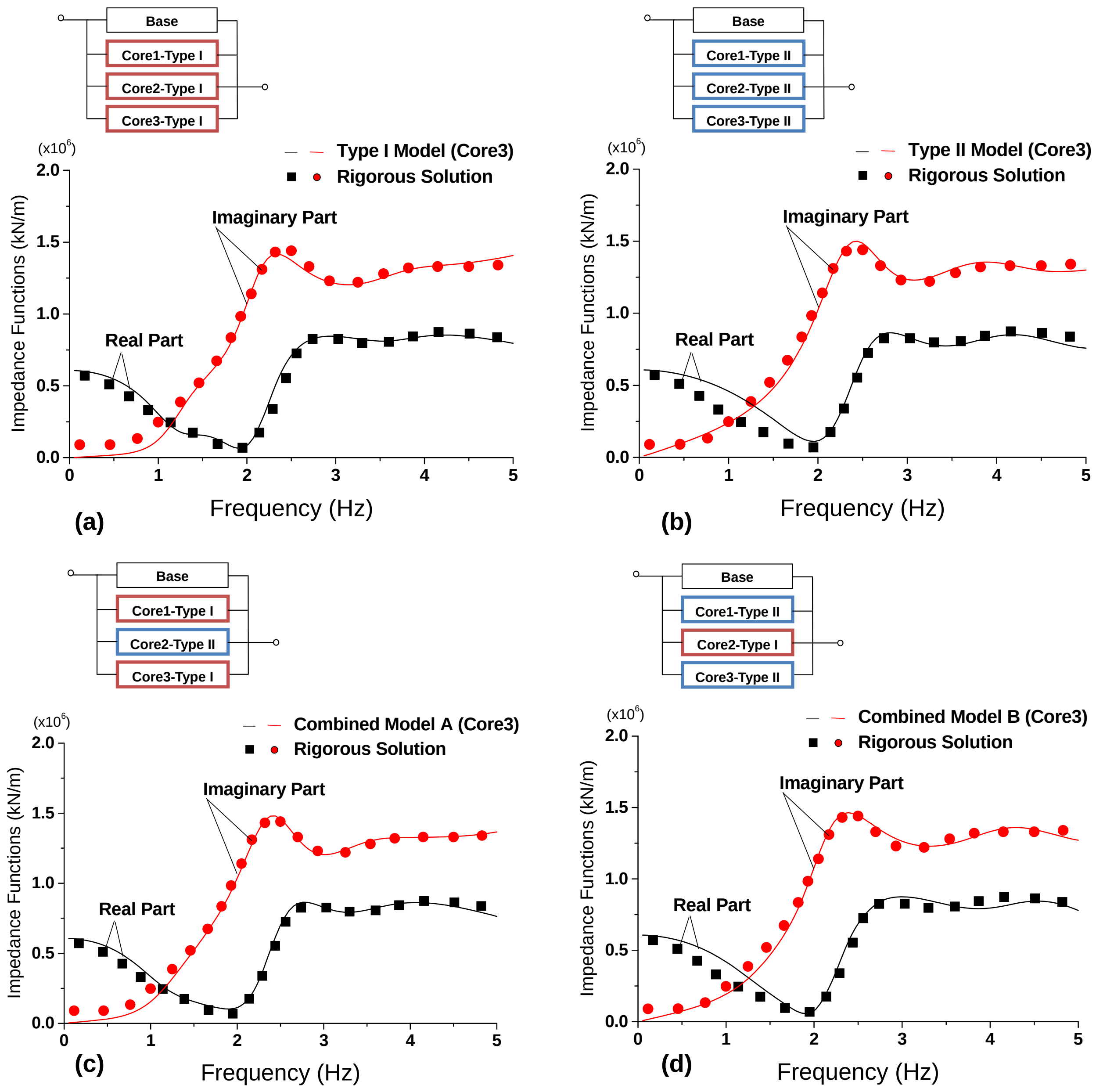

Fig. 4 Horizontal impedance functions of a designed pile group simulated by using Type I, Type II, and combined models, using (a) triple Type-I core systems, (b) triple Type-II core systems, (c) combined double Type-I core systems and single Type-II core system, and (d) combined single Type-I core system and double Type-II core systems. Comparison with the numerical results published by AIJ (2006).

3. NONLINEAR RESPONSE OF STRUCTURAL SYSTEMS INFLUENCED BY PRECISION OF SIMULATION OF IMPEDANCE FUNCTIONS

In this section, the influence of the different impedance functions simulated by using the Type II models studied in Fig. 2 upon the nonlinear response of structural systems is assessed. In this study, a structural system consisting of a

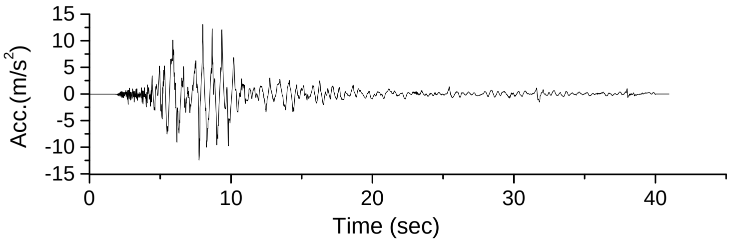

Fig. 5 Time-history of 2004 Ojiya EW (K-NET).

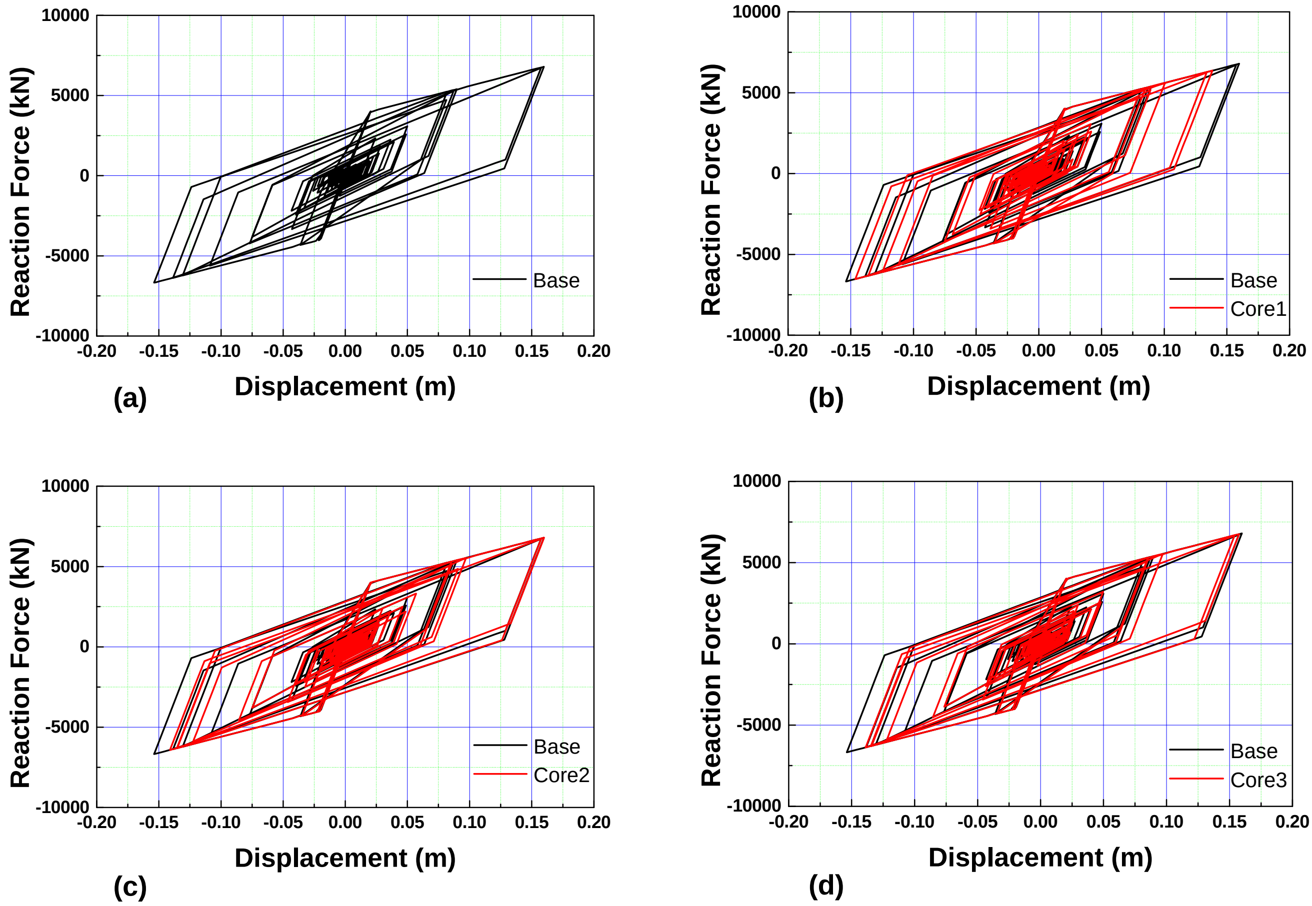

Fig. 6 Hysteresis loop of inelastic superstructure ($k_y = 0.8$) supported by a 3×3 pile group simulated by using Type II models shown in Fig. 2. (a) Base system with no core system, (b) Single core system, (c) Double core systems, and (d) Triple core systems.

superstructure, which is represented by an inelastic one-degree-of-freedom system, and an elastic soil-pile system represented by a footing mass and the Type II models shown in Fig. 2. This structural system is identical to the one studied in Saitoh (2007), where the equation of motion of the system is described. The footing is assumed to be free only in the lateral direction, whereas the movements of the footing are completely restrained in the rotational and vertical directions. Moreover, the inelastic one-degree-of-freedom system supported by the soil-pile system consists of a mass and a spring that transfers only the shear force between the footing and the superstructure. The inelasticity of the superstructure is assumed to be comparable to the Clough model. The spring of the superstructure has a bi-linear

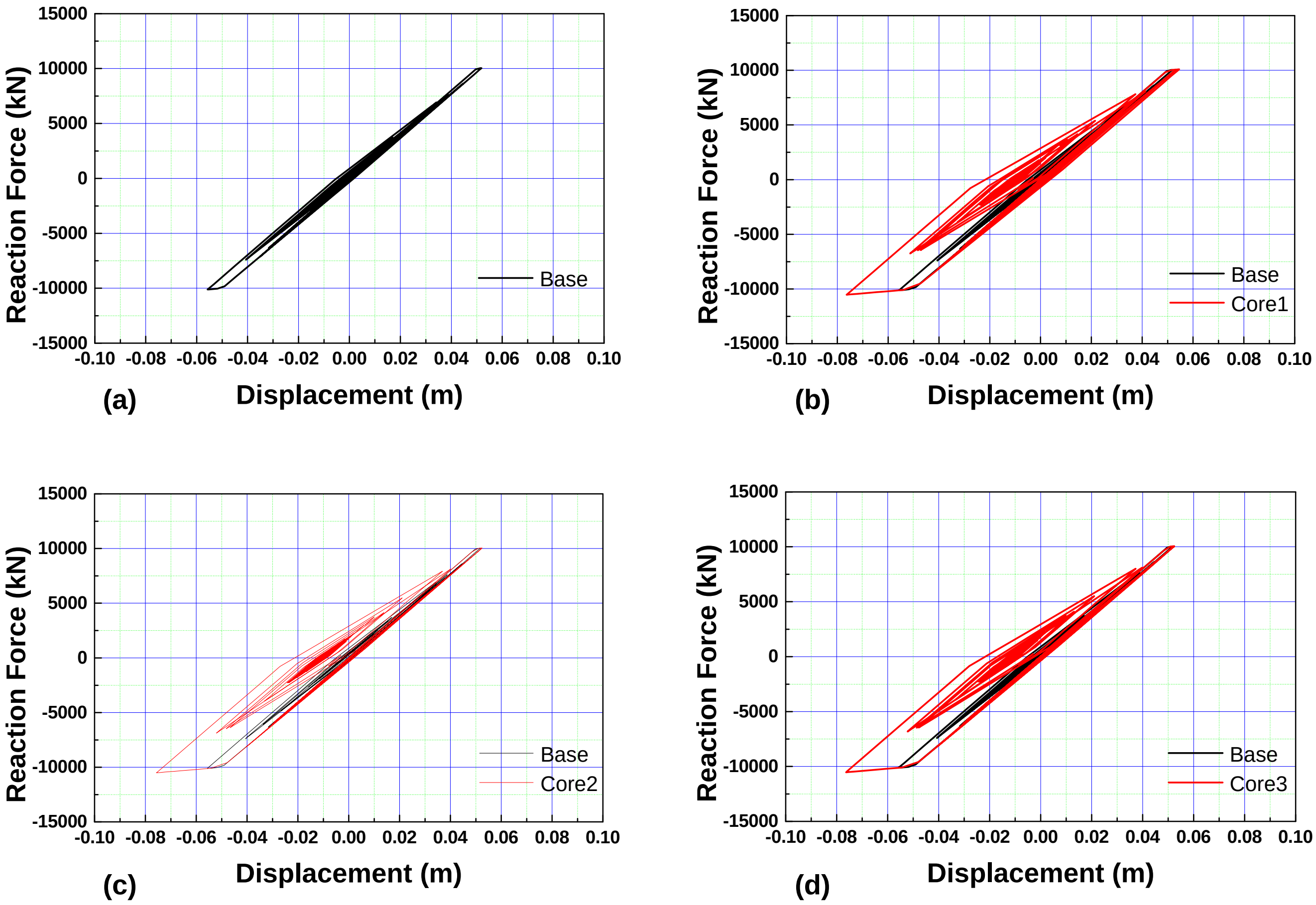

Fig. 7 Hysteresis loops of inelastic superstructure ($k_y = 2.0$) supported by a 3×3 pile group simulated by using the Type II models shown in Fig. 2. (a) Base system with no core system, (b) Single core system, (c) Double core systems, and (d) Triple core systems.

skeleton curve where the ratio of the tangent stiffness to the initial stiffness is assumed to be $\alpha = 0.1$. The properties of the model are as follows: The masses of the superstructure and footing are $m_s = 500$ t and $m_f = 200$ t, respectively. The effective foundation input motion in the horizontal direction is assumed to be an observed earthquake record called 2004 Ojiya EW (K-NET) shown in Fig. 5. This earthquake wave contains a wide range of frequency components with extremely large amplitude. Time-history analysis is performed by using Newmark's method ($\beta = 1/6$) as a numerical integration scheme, where the time interval is 0.002 s. Moreover, the modified Newton-Raphson method is applied as a numerical iterative procedure for calculating the nonlinear response of the system. In this analysis, the parameter a/c_s and the static stiffness $K_s^{(1)}$ are assumed to be 0.02 s and 153400 kN/m, respectively.

Fig. 6 shows a comparison of the hysteresis loops of the superstructure when the yielding strength coefficient k_y equals 0.8. The hysteresis loop where the impedance function is simulated without any core system, shown in Fig. 6 (a), differs from the other hysteresis loops where core systems are used for simulating the impedance functions. The results also show that the response of the superstructure tends to decrease when the impedance functions are more precisely simulated. In addition, it is noted that an appreciable difference in the responses appears in cases with and without considering the second core system that may affect the impedance functions beyond the frequency a_0 =0.4, as shown in Figs. 2 (b) and (c).

Fig. 7 shows a comparison of the hysteresis loops of the superstructure when the yielding strength coefficient k_y equals 2.0. The figure indicates that a marked difference appears in the responses with and without considering core systems. In addition, the results show that additional second and third core systems have little effect upon the response of the structure. Moreover, it is interesting to note that the response of the superstructure tends to increase when the impedance functions are more precisely simulated: this tendency is opposite to the one exhibited in the case where the yielding strength coefficient k_y equals 0.8.

It is concluded, therefore, that the accuracy of simulating frequency-dependent impedance functions may have different influences on the response of the structure, depending on, for example, the yielding strength of the structure. The natural frequency of the structural system and the types of input motions could be responsible for differences in the response.

4. CONCLUSIONS

In the present study, application examples of the Gyromass Element Method (GEM) are presented. More advanced techniques combining Type I and II models are also shown. The results of nonlinear analyses show the importance of accurate simulation of the frequency-dependent impedance functions by using GEM.

REFERENCES

Meek, J. W. and Veletsos, A. S. (1974). Simple models for foundations in lateral and rocking motion. *Proc., 5th World Conf. on Earthquake Engrg.*, Vol. 2, Rome, Italy, 2610-2613.

Wolf, J. P. and Somaini, D. R. (1986). Approximate dynamic model of embedded foundation in time domain. *Earthquake Engrg. & Struct. Dyn.*, 14, 683-703.

Nogami, T. and Konagai, K. (1986). Time domain axial response of dynamically loaded single piles. *J. Engrg. Mech.*, ASCE, 112(11), 1241-1252.

Nogami, T. and Konagai, K. (1988). 'Time domain flexural response of dynamically loaded single piles. *J. Engrg. Mech.*, ASCE, 114(9), 1512-1525.

Wolf, J. P. (1994). Foundation vibration analysis using simple physical models. Eaglewood Cliffs, NJ: Prentice-Hall.

Wolf, J. P. and Song, C. (2002). Some cornerstones of dynamic soil-structure interaction. Engrg. Struct., 24, 13-28.

Saitoh, M. (2007). Simple model of frequency-dependent impedance functions in soil-structure interaction using frequency-independent elements, *Journal of Engineering Mechanics*, ASCE, Vol.133, No.10, 1101-1114.

Kaynia, A., and Kausel, E. (1982). Dynamic stiffness and seismic response of pile groups. *Research Report, R82-03, Dept. of Civil Engrg.*, MIT, Cambridge, Mass.

AIJ. (2006), Seismic Response of Analysis and Design of Buildings Considering Dynamic Soil-Structure Interaction, Architectural Institute of Japan.

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