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A Simplified Method for Expression of the Dynamic Stiffnesses of Large-Scaled Grouped Piles in Sway and Rocking Motions

巨大群杭基礎の水平および回転剛性の簡便な評価手法

Yuanbiao YIN* and Kazuo KONAGAI**
尹 元彪・小長井 一男

* Member, M. Eng., Engineering Department, New Structural Engineering Ltd., 1-42-20, Kameido, Koto-Ku, Tokyo 136-0071
(PhD Candidate, Institute of Industrial Science, University of Tokyo, 4-6-1, Komaba, Meguro-Ku, Tokyo 153-8505)
** Member, Dr. Eng., Professor, Institute of Industrial Science, University of Tokyo, 4-6-1, Komaba, Meguro-Ku, Tokyo 153-8505

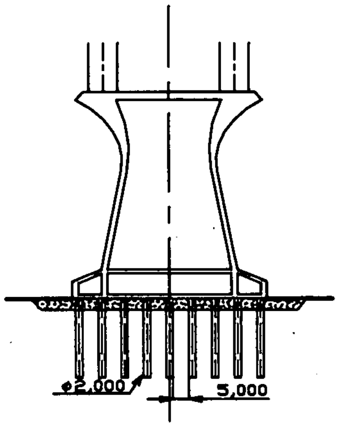
In this paper a simplified method, in which a group of piles is viewed as a single equivalent upright beam, is presented for expression of the dynamic stiffnesses of grouped piles subjected to lateral force and bending moment. An effective computer program with very little memory, based on the Thin Layered Element Method, is used for this purpose. The results of the program are compared with those calculated by the 3-dimensional Finite Element Method for several cases of large-scaled grouped piles. The results obtained lead to the conclusion that the simplified method that is presented is sufficiently accurate for the purpose of preliminary evaluation of the pile cap stiffnesses for sway and rocking motions of large-scaled grouped piles.

Key Words: soil-pile interaction, large-scaled grouped piles, equivalent single upright beam

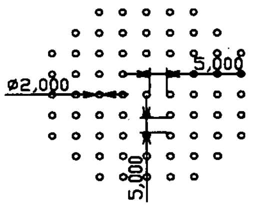
1. Introduction

The foundations for trans-straits long-span bridges, such as the Akashi Kaikyo Bridge, etc. in Japan are usually constructed with massive caissons settled on soft rocks. However, for future projects, which may be planned at a deeper sea level of more than 60 meters and with a high depth of soft soil strata, the type of caisson foundation used up to now will not only take a longer time for construction but will also have a large impact on the environment due to the huge amount of excavation of sea bed soils necessary to reach a deep soft rock layer. Hence the concept of improvement of the soil layers encountered under the bridge piers with driven hollow steel pipes$^{1)}$ may be considered challenging, reasonable and with a lesser impact on the environment. To realize this, a light foundation such as a hollow raft pier with the shape of a stamp$^{2)}$ (Fig. 1) is required. In addition, advanced design tools including accounts for the pronounced soil-structure interaction under seismic conditions, which is discussed in this paper, are needed.

Piles, grouped beneath a superstructure, interact with the surrounding soil during an earthquake, and the dynamic pile-soil-pile interaction often affects the motion of the superstructure to a considerable extent. Straightforward



(a) elevation



(b) plan

Fig.1 A new structural type for trans-straits bridge foundation evaluation of the pile-soil-pile interaction, however, is cumbersome especially in dealing with tens or hundreds of piles grouped together. Hence a simplified approach for the evaluation of such dynamic pile-soil-pile interaction is highly desirable for the purpose of treating the dynamic behavior of an entire soil-foundation-structure system. Some simplified approaches, such as the Ring-Pile method[3] and Closely-Spaced-Plates model[4] have been proposed. In these methods, respectively, piles with the soil caught among them are re-grouped into several concentric cylinders (piles arranged in concentric circles) and into soil-pile-striped upright plates, allowing close evaluation of interaction effects to be made with less time and trouble. This paper presents a further simplified approach in which a group of piles is viewed as a single equivalent upright beam, which is based on the observations of soil remaining caught among piles after lateral push-over field experiments[5] (Fig. 2). The stiffnesses calculated by the presented simplified method are to be compared with those obtained by 3-D FEM to verify its effectiveness for the cases of large-scaled pile group foundations.

2. Equivalent Single Upright Beam

In discussing the equivalent upright beam, straightforward evaluation of pile-soil-pile interaction is first necessary to provide rigorous solutions. Based on Tajimi and Shimomura's Thin-Layered Method[6] ,which allows soil-embedded foundation interaction effects to be rigorously evaluated, a numerical program "*TLEM*"(Ver.1.1)[7] has been developed for soil-pile group interaction analyses. The Thin-Layered Element Method is a method for describing soil strata rather than foundations. In this method, a soil deposit is treated as an infinite stratified medium with the inclusion of a cylindrical hollow in which the foundation is fitted. The piles are assumed to be upright Timoshenko or Beronoulli-Euler beams. The evaluation of pile-soil-pile interaction effects in this program is based on the superposition method that was originally proposed by Poulos[8) 9)]. In this approximation, only two piles, an active pile and a passive pile as shown in Figure 3, are considered in the formulation of a global flexibility matrix, and other piles' effects on these two piles are totally ignored. Kanya and Kausel[10] have shown that the superposition scheme gives reasonable results not only for static loads but for dynamic loads as well.

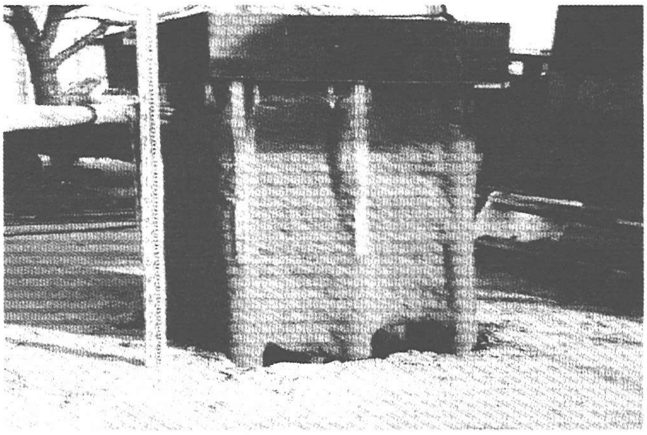


Fig. 2 Soil observed remaining caught among piles after lateral push-over field experiments

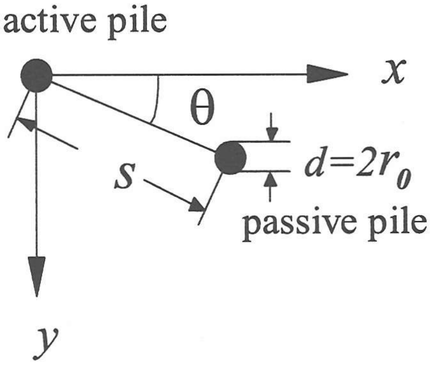
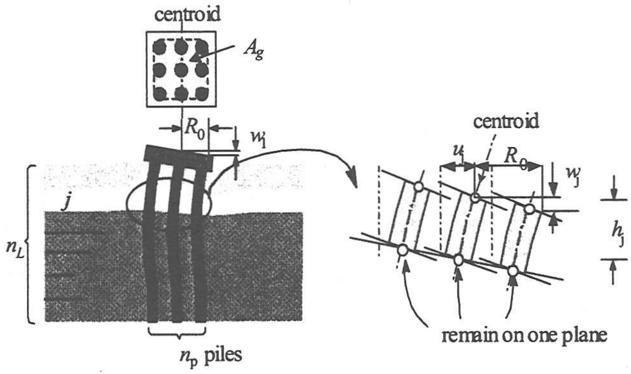


Fig. 3 Active and passive piles



(a) soil-grouped piles system **(b)** sliced elements

Fig. 4 Assumptions for evaluation of equivalent single beam

In contrast to the above approach, the present single upright beam is a composite of n_p piles and the soil caught among them embedded in a horizontally stratified infinite soil deposit with material damping of the frequency-independent hysteretic type (Fig. 4). Following the *TLEM* assumption, the soil deposit overlying its rigid bedrock should include a cylindrical hollow of radius R_0. The cross-section, πR_0^2, of this hollow is assumed to be identical to the beam's cross-section A_G enclosed with the broken line circumscribing the outermost piles in the group [Fig. 4(a)]. The motion of the hollow is assumed to be compatible with that of the beam. The soil-pile composite together with its exterior soil is divided into n_L horizontal slices as shown in Fig. 4. The following assumptions are adopted to derive the stiffness matrix of the equivalent single beam:

(i) Pile elements within a horizontal soil slice are all deformed at once keeping their intervals constant, and the soil caught among the piles moves in a body with the piles.

(ii) Frictional effects due to bending of piles (external moments on each individual pile from soil) are ignored.

(iii) The top ends of piles are fixed to a rigid cap.

(iv) All upper or lower ends of the sliced pile elements arranged on the cut-end of a soil slice remain on one plane [Note this assumption does not necessarily mean that each pile's cross-section remains parallel with this plane. See Fig. 4(b)].

With assumptions (i), (ii) and (iii), lateral external forces $\{P_x\}$ are described in terms of lateral displacements $\{u_x\}$ and anti-symmetric vertical motion of the cap w_1 as:

$$\{\mathbf{P}_x\}=[\mathbf{L}][\mathbf{D}]^{-1}\left\{[\mathbf{L}]\{\mathbf{u}_x\}+\left\{\frac{w_1}{R_0}\ \vdots\ 0\ \cdots\ 0\right\}^T\right\} \quad \text{......(1)}$$

where

$$[\mathbf{L}]=\begin{bmatrix} -\frac{1}{h_1} & \frac{1}{h_1} & 0 & 0 & \cdots & 0 \\ \frac{1}{h_1} & -\frac{1}{h_1}-\frac{1}{h_2} & \frac{1}{h_2} & 0 & & \vdots \\ 0 & \frac{1}{h_2} & -\frac{1}{h_2}-\frac{1}{h_3} & \frac{1}{h_3} & & \vdots \\ 0 & 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & & \ddots & \ddots & \ddots & \frac{1}{h_{n_L-1}} \\ 0 & \cdots & \cdots & 0 & \frac{1}{h_{n_L-1}} & -\frac{1}{h_{n_L-1}}-\frac{1}{h_{n_L}} \end{bmatrix}$$

......(2a)

$$[\mathbf{D}]=\frac{1}{6}\begin{bmatrix} 2\frac{h_1}{EI_p} & \frac{h_1}{EI_p} & 0 & 0 & \cdots & 0 \\ \frac{h_1}{EI_p} & 2\left(\frac{h_1}{EI_p}+\frac{h_2}{EI_p}\right) & \frac{h_2}{EI_p} & 0 & & \vdots \\ 0 & \frac{h_2}{EI_p} & 2\left(\frac{h_2}{EI_p}+\frac{h_3}{EI_p}\right) & \frac{h_3}{EI_p} & & \vdots \\ 0 & 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & & \ddots & \ddots & \ddots & \frac{h_{n_L-1}}{EI_p} \\ 0 & \cdots & \cdots & 0 & \frac{h_{n_L-1}}{EI_p} & 2\left(\frac{h_{n_L-1}}{EI_p}+\frac{h_{n_L}}{EI_p}\right) \end{bmatrix}$$

......(2b)

with $EI_p=n_p \times E_pI_p$ (E_pI_p =bending stiffness of a single pile), which represents the bending stiffness of the equivalent single beam in sway motion according to assumption (i).

Moment M_1 at the top ends of rigidly capped piles due to the lateral displacements $\{\mathbf{u}_x\}$ is expressed as:

$$M_1=\left\{\text{1st row of matrix}\,[\mathbf{D}]^{-1}[\mathbf{L}]\right\}\{\mathbf{u}_x\}^T+D_{1,1}^{-1}\cdot\frac{w_1}{R_0}$$

......(2c)

where, $D_{1,1}^{-1}$ = upper-left corner component of the matrix, $[\mathbf{D}]^{-1}$.

Assumption (iv) implies that the overall anti-symmetric rocking motion of a pile group is controlled by axial motions of the piles. In other word, the external moments on the overall soil-pile system from its surrounding soil are eventually sustained by the piles that experience alternate push and pull in their axes. External moments due to the anti-symmetric vertical motions $\{w\}$ are described as:

$$\left\{\frac{\mathbf{M}}{R_0}\right\}=[\mathbf{Q}]\{\mathbf{w}\} \quad \text{......(3)}$$

where,

$$[\mathbf{Q}]=\begin{bmatrix} \frac{EI^G}{R_0^2h_1} & -\frac{EI^G}{R_0^2h_1} & 0 & 0 & \cdots & 0 \\ -\frac{EI^G}{R_0^2h_1} & \frac{EI^G}{R_0^2h_1}+\frac{EI^G}{R_0^2h_2} & -\frac{EI^G}{R_0^2h_2} & 0 & & \vdots \\ 0 & -\frac{EI^G}{R_0^2h_2} & \frac{EI^G}{R_0^2h_2}+\frac{EI^G}{R_0^2h_3} & -\frac{EI^G}{R_0^2h_3} & & \vdots \\ 0 & 0 & & & & 0 \\ \vdots & & & & \ddots & -\frac{EI^G}{R_0^2h_{n_L-1}} \\ 0 & \cdots & \cdots & 0 & -\frac{EI^G}{R_0^2h_{n_L-1}} & \frac{EI^G}{R_0^2h_{n_L-1}}+\frac{EI^G}{R_0^2h_{n_L}} \end{bmatrix}$$

......(4)

Herein, EI^G is another bending stiffness parameter describing the rocking motion of the equivalent single upright beam. This EI^G is evaluated following the same procedure as that used for the evaluation of bending stiffness of a reinforced concrete beam. Namely, EI^G can be expressed as:

$$EI^G=\sum_{i=1}^{n_p}\left\{E_pI_p+E_pA_p\cdot(x_{p,i}-x_0)^2\right\}\cdots(4a)$$

where, $x_{p,i}$ is the x coordinate of each pile and x_0 is the x coordinate of the centroid of the cross-section A_G [Fig. 4(a)].

Given Equations (1)-(4), the global stiffness matrix of the equivalent single beam is finally expressed as:

$$\begin{Bmatrix} \mathbf{P}_x \\ \cdots \\ \frac{\mathbf{M}}{R_0} \end{Bmatrix}=\left[\begin{array}{ccc} [\mathbf{L}][\mathbf{D}]^{-1}[\mathbf{L}] & \vdots & \text{1st column of } [\mathbf{L}][\mathbf{D}]^{-1}/R_0 \text{ and zeros for other columns} \\ \cdots\cdots\cdots\cdots & & \cdots\cdots\cdots\cdots \\ \text{1st row of } [\mathbf{D}]^{-1}[\mathbf{L}]/R_0 \text{ and zeros for other rows} & \vdots & D_{1,1}^{-1} \text{ and } [\mathbf{Q}] \end{array}\right]\times\begin{Bmatrix} \mathbf{u}_x \\ \cdots \\ \mathbf{w} \end{Bmatrix}$$

......(5)

With Equation (5) and layer boundary force-displacement relation, the equations of motion for the entire soil-foundation system can be obtained. By solving the equations of motion in frequency domain, the pile cap stiffnesses can be evaluated[15].

"*TLEM*" has been upgraded for evaluation of the behaviors of an equivalent single beam (Ver. 1.2). The results obtained by the equivalent single beam with "*TLEM*" (Ver. 1.2) have been shown to agree well with rigorous solutions from "*TLEM*" (Ver. 1.1) for cases of ordinary group pile foundations[11]. Further, the presented approach has also been proved to be very useful for the project of developing a new experimental method for real-time simulation of soil-structure interaction effects on shaking tables[12][13][14], and particularly effective for an equivalent linear simulation of the dynamic interaction between nonlinear soil and grouped piles in real time[15]. In this study, the simplified approach by the equivalent single beam has been extended to large-scaled pile group foundations comprised by some tens of steel piles with large diameter and relatively high stiffness, as mentioned in detail in the following section.

3. Dynamic Stiffnesses of Large-Scaled Grouped Piles

Four different arrangements of grouped steel piles (Table 1 and Fig. 5) and 2 cases of soil deposit (Table 2) are discussed herein. Each pile head is assumed to be fixed at a rigid massless footing.

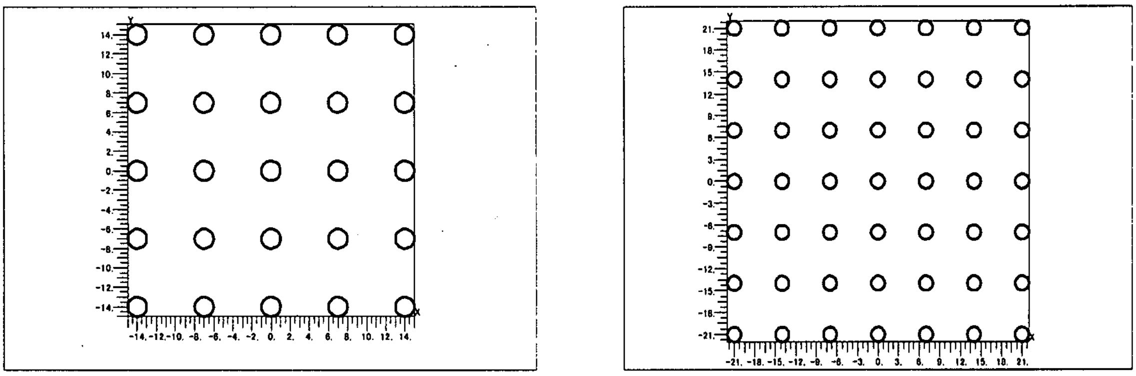
For comparison, a 3-dimensional static Finite Element Analysis is carried out by using *MSC NASTRAN* programming[16]. As for the finite element modeling, steel piles are modeled as beam elements and others as solid elements (Fig. 6). As shown in Figure 6, half of the domain was eliminated by taking advantage

Table 1 Parameters for steel piles

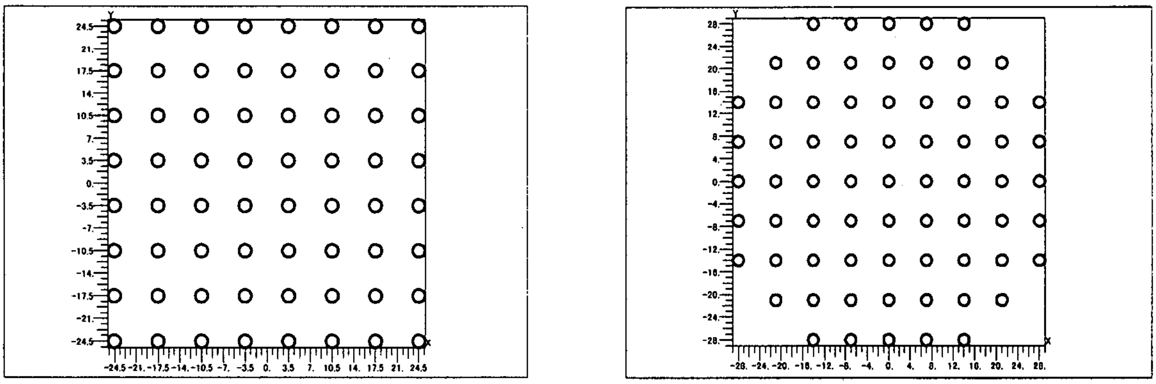
Length (m)	*Outer diameter d (m)*	*Thickness (cm)*	*E_p (kN/m^2)*	*γ_p (kN/m^3)*	*Piles's interval s (m)*
20	2	2	2.06E+08	76.93	7

Table 2 Parameters for soil deposit

No. of soil deposit	*Thickness (m)*	*Vertical slices*	*Poisson's ratio ν*	*γ (kN/m^3)*	*V_s (m/s)*		*E (kN/m^2)*	
					case1	*case2*	*case 1*	*case 2*
1	2.5	1@2.5m	0.49	20.678	190	60	2.27E+05	2.27E+04
2	15.5	1@3.5m+4@3m	0.49	20.482	270	85	4.54E+05	4.54E+04
3	12.0	6@2m	0.47	19.502	441	441	1.14E+06	1.14E+06
4	30.0	1@2m+2@14m	0.39	25.382	1400	1400	1.41E+07	1.41E+07



(a) n_p=25 piles (5×5)　　(b) n_p=49 piles (7×7)



(c) n_p=64 piles (8×8)　　(d) n_p=69 piles

Fig. 5 Plane arrangement of pile groups (x , y coordinate expressed in meter)

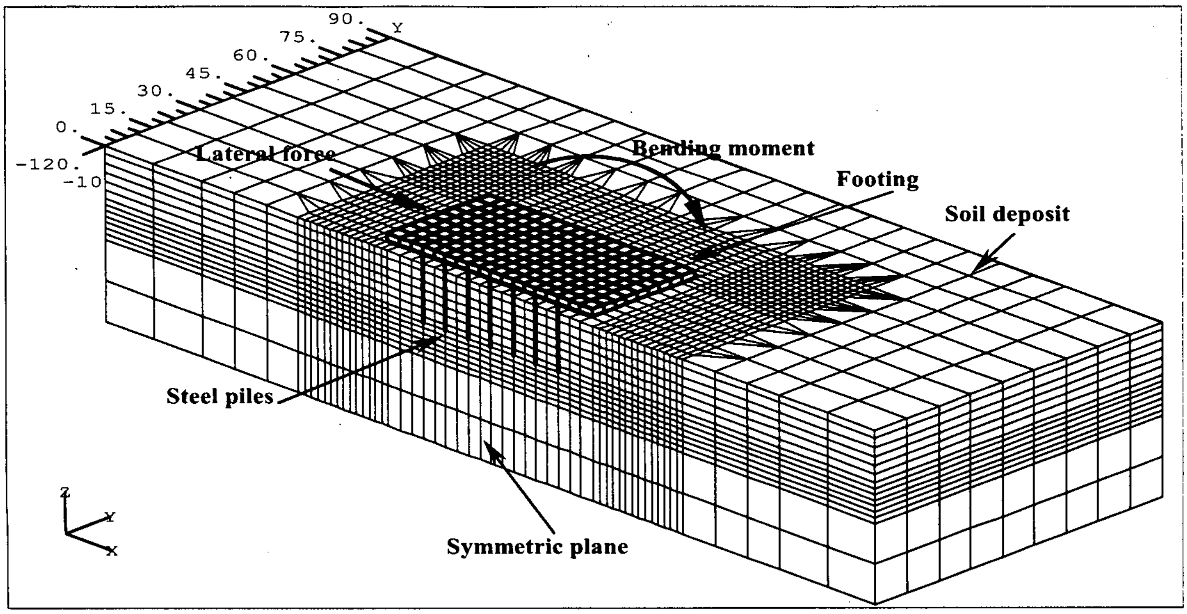


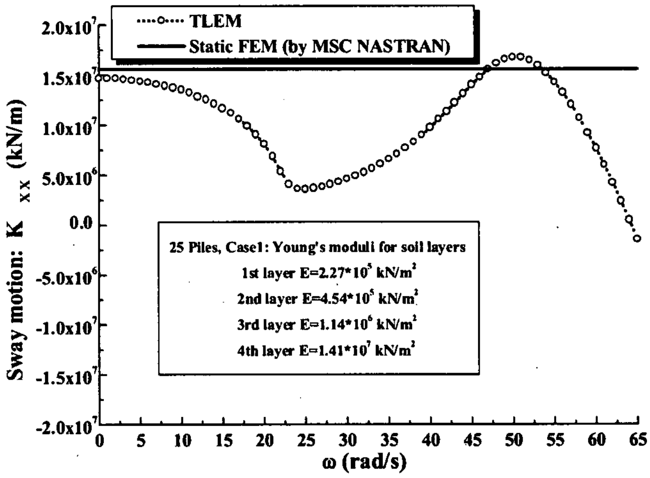
Fig. 6 3-D meshes for FEM

of the symmetry with respect to the center plane parallel to the loading direction. The static stiffnesses for sway and rocking motions are calculated with proper constrains on the footing respectively.

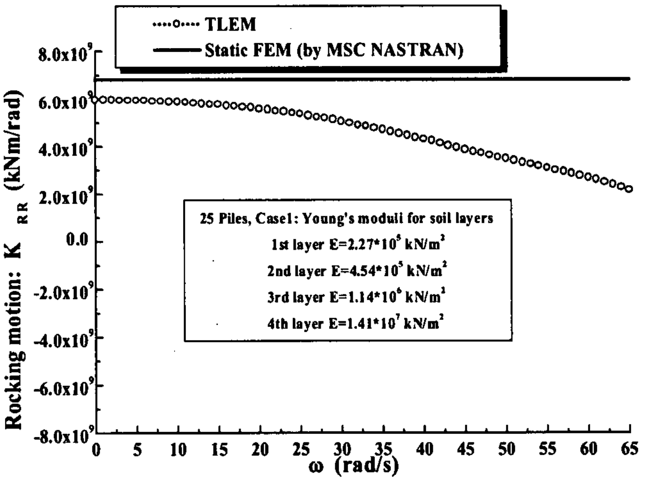
Figure 7 shows pile cap stiffnesses K_{xx} and K_{RR} for sway and rocking motions respectively for the soil deposit case 1 with n_p=25 piles. The results for the equivalent single beam calculated by *"TLEM"*(Ver. 1.2) are plotted as functions of circular frequency ω in open circles. Downward dips in the plot of K_{xx} occur at essentially the resonance circular frequency of the soil stratum for vertical shear wave propagation. It is noted that the dips in K_{xx} are clear and significant. When this characteristic is to be considered, the conventional simplified method using a parabolic curve to approximate the original curve of K_{xx} may be necessary to be replaced with another scheme[11]. This will be discussed in another publication. On the other hand, the pile cap stiffness for rocking motion decreases slowly as the circular frequency increases in the range of frequency f=0-10*Hz*.

For comparison, the static results for FEM by *MSC NASTRAN* programming are shown as straight lines in corresponding figures. In the above case, the initial values of the pile cap stiffnesses K_{xx} and K_{RR} for the equivalent single beam agree well with the static solutions from FEM.

Figures 8, 9 and 10 show the results for the soil deposit case 1 with n_p=49 piles, n_p=64 piles and n_p=69 piles respectively, and the curves of K_{xx} and K_{RR} have shown the same tendencies as the case of n_p=25 piles. From these results, it seems that the initial values of the pile cap stiffnesses K_{RR} calculated by *"TLEM"*(Ver. 1.2) deviate less while the values of K_{xx} deviate more from those by FEM when the total number of piles increases. This may be

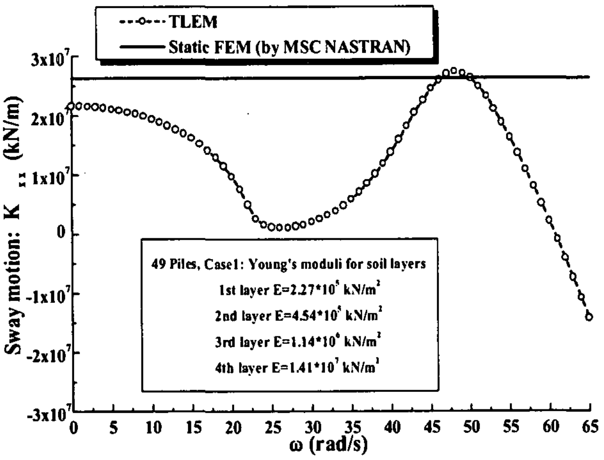


(a) stiffness for sway motion

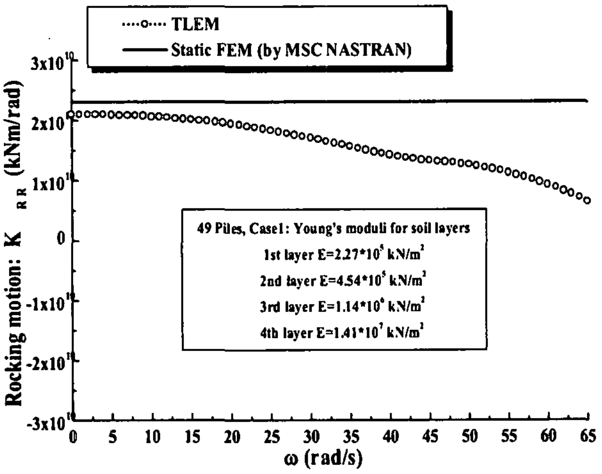


(b) stiffness for rocking motion

Fig. 7 Stiffnesses for sway and rocking motions considered to be because of the simplification by *"TLEM"*(Ver 1.2), which may underestimate the stiffness of grouped piles in sway motion when the number of piles increases.

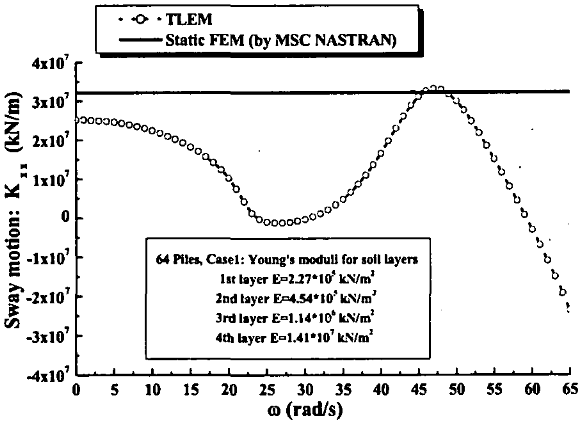


(a) stiffness for sway motion

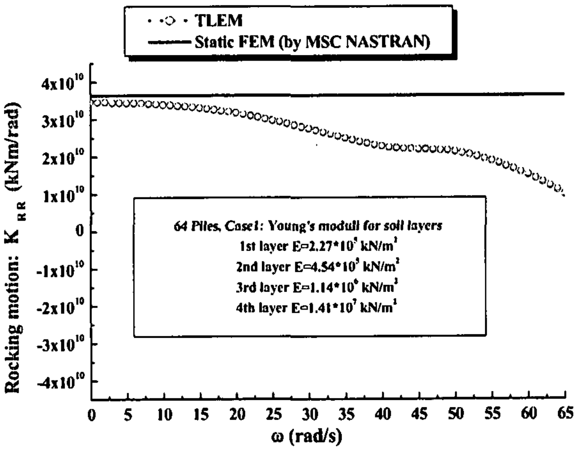


(b) stiffness for rocking motion

Fig. 8 Stiffnesses for sway and rocking motions [n_p=49 piles; soil deposit=Case 1]

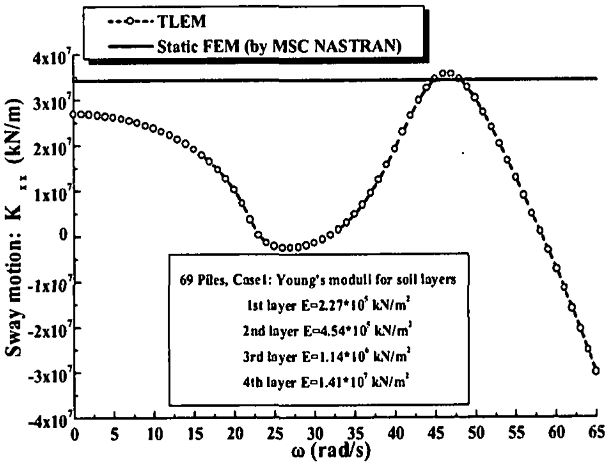


(a) stiffness for sway motion

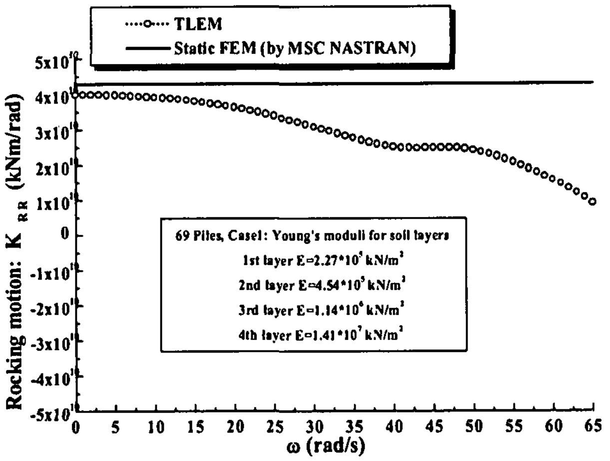


(b) stiffness for rocking motion

Fig. 9 Stiffnesses for sway and rocking motions [n_p=64 piles; soil deposit=Case 1]



(a) stiffness for sway motion



(b) stiffness for rocking motion

Fig. 10 Stiffnesses for sway and rocking motions [n_p=69 piles; soil deposit=Case 1]

Table 3 Results from *"TLEM"(Ver. 1.2)* and *FEM* for all cases discussed

Soil deposit: Case 1	***n_p=69 Piles***		***n_p=64 Piles***		***n_p=49 Piles***		***n_p=25 Piles***	
	TLEM	FEM	TLEM	FEM	TLEM	FEM	TLEM	FEM
Kxx (kN/m)	2.69E+07	3.42E+07	2.52E+07	3.22E+07	2.16E+07	2.63E+07	1.47E+07	1.56E+07
K_{RR} (kNm/rad)	3.99E+10	4.29E+10	3.47E+10	3.64E+10	2.11E+10	2.31E+10	5.97E+09	6.82E+09
Ratio: TLEM/FEM	*Ratio of Kxx=*	***0.786***	*Ratio of Kxx=*	***0.784***	*Ratio of Kxx=*	***0.822***	*Ratio of Kxx=*	***0.943***
	Ratio of K_{RR}=	***0.931***	*Ratio of K_{RR}=*	***0.952***	*Ratio of K_{RR}=*	***0.912***	*Ratio of K_{RR}=*	***0.875***

Soil deposit: Case 2	***n_p=69 Piles***		***n_p=64 Piles***		***n_p=49 Piles***		***n_p=25 Piles***	
	TLEM	FEM	TLEM	FEM	TLEM	FEM	TLEM	FEM
Kxx (kN/m)	4.35E+06	5.64E+06	4.08E+06	5.26E+06	3.451E+06	4.324E+06	2.284E+06	2.559E+06
K_{RR} (kNm/rad)	2.60E+10	2.56E+10	2.31E+10	2.10E+10	1.368E+10	1.358E+10	3.610E+09	3.979E+09
Ratio: TLEM/FEM	*Ratio of Kxx=*	***0.771***	*Ratio of Kxx=*	***0.775***	*Ratio of Kxx=*	***0.798***	*Ratio of Kxx=*	***0.893***
	Ratio of K_{RR}=	***1.017***	*Ratio of K_{RR}=*	***1.101***	*Ratio of K_{RR}=*	***1.007***	*Ratio of K_{RR}=*	***0.907***

Finally, results of initial values of K_{xx} and K_{RR} from *"TLEM"*(Ver. 1.2) compared with the static ones from FEM for all cases discussed in this paper are summarized in Table 3. Also the corresponding ratios are shown in Figure 11. It seems that for case 2 of the soil deposit, the ratios of K_{xx} (values of *TLEM / FEM*) are slightly smaller than the corresponding ones for case 1 of the soil deposit. This may be due to the larger difference of the shear wave velocity between the 2nd layer (*Vs*=85m/s) and the 3rd layer (*Vs*=441m/s) of the soil deposit for case 2 than that for case 1. However, as a whole, the results from *"TLEM"*(Ver. 1.2) are sufficiently accurate for the purpose of preliminary evaluation of the pile cap stiffnesses for sway and rocking motions of large-scaled pile group foundations. It is also worth noting that both the results for the case of n_p=69 piles of octagonal arrangement and the case of n_p=64 piles of rectangular arrangement discussed herein have almost the same precisions, implying that *"TLEM"*(Ver. 1.2) is not so sensitive to the plan shape of the arrangement of piles.

4. Conclusions

In this paper, the simplification of grouped piles as a single equivalent upright beam has been applied to large-scaled pile group foundations with several tens of steel piles for evaluation of the pile cap stiffnesses for sway and rocking motions. For comparison, a 3-dimensional static Finite Element Analysis has been carried out with 4 different arrangements of grouped steel piles and 2 cases of soil deposit. The principal conclusions of this study are as follows.

1.) The computer program *"TLEM"*(Ver. 1.2) based on the concept of simplification of grouped piles as a single equivalent upright beam has been proved to be very effective for evaluation of the dynamic stiffnesses of large-scaled grouped piles in sway and rocking motions.

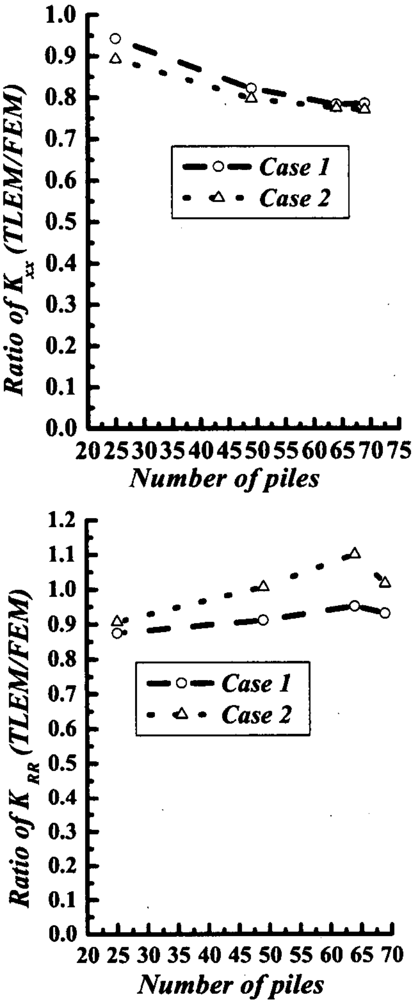


Fig. 11 Ratios of *TLEM/FEM*

2.) The results from *"TLEM"*(Ver. 1.2) have been proved sufficiently accurate for the purpose of preliminary evaluation of the pile cap stiffnesses for sway and rocking motions of large-scaled pile group foundations, despite the inhomogeneous soil-profiles and arrangements of piles as discussed in this paper.

3.) Compared to the large memory and long computation time of several hours necessary for obtaining K_{xx} or K_{RR} separately by FEM, depending on the total number of nodes for the model and the power of computer used, *"TLEM"*(Ver. 1.2), which occupies very little memory, takes only several seconds to calculate all the relevant results concurrently and thus will be very useful in design practice.

4.) It is found that the dips shown in the plot of K_{xx} for large-scaled pile groups are clear and significant, implying that a simplified method of K_{xx} different from the conventional one, where the dips were ignored, should be considered. Moreover, a further study to use the simplified method presented in this paper to develop a new experimental method for real-time simulation of soil-structure interaction effects in the cases of large-scaled grouped piles on shaking table is in preparation. All of this will be discussed in future publications.

5.) In engineering practice, the Chang's formula is widely used[17]. In this method, the stiffness of one pile in sway motion is estimated and the stiffness for grouped piles is multiplied by the number of piles. However, the Chang's formula generally leads to an overestimation of the stiffness in sway motion. The detailed discussion can be found in the reference 18).

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