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Dynamic behaviors of a composite foundation

K. Urao, K. Masuda & E. Kitamura
Information Processing Center, Kajima Corporation, Japan

Y. Miyamoto
Kobori Research Complex, Kajima Corporation, Japan

A. Fukuoka
Kajima Technical Research Institute, Kajima Corporation, Japan

ABSTRACT: A composite foundation has been employed in a high-rise building constructed on a soft soil. A composite foundation consists of a group of piles enclosed by diaphragm wall. Because the piles are enclosed, their dynamic behavior is expected to be quite different from that of unenclosed piles. As a few studies have been executed on composite foundations, their dynamic behavior has not been clearly established.

The study described in this paper was conducted to investigate the static and dynamic behavior of composite foundations and to propose a practical earthquake response analysis model for such a structure. The applicability of the proposed model was confirmed by correlation analyses with the forced vibration test results on the actual composite foundation.

1 INTRODUCTION

Many high-rise buildings are under construction or being planned on reclaimed coastal areas, especially around the Bay of Tokyo in Japan. As this area is covered with soft soil on an underlying firm soil layer, special attentions must be paid to foundation works in design of buildings. A composite foundation, consisting of diaphragm walls and piles, is currently considered to be the most suitable and has been employed in buildings in this area.

Severe earthquakes have occurred in this area in the past several decades. Thus, aseismic design is important for structural safety. A aseismic design requires accurate earthquake response analysis taking account of dynamic interaction between the composite foundation and the surrounding soil. Due to the complex conformation of the composite foundation, 3-dimensional analysis is necessary. However, a 3-dimensional model is not favorable for earthquake response analysis in practical design works because it requires a large amount of computational effort.

This paper examines static fundamental mechanics of the composite foundation using the 3-dimensional Finite Element Method (3D-FEM). Based on the 3D-FEM analysis results, a simplified practical model is derived for the earthquake response analysis of the building on the composite foundation. The adequacy of the proposed model's dynamic characteristics is discussed through comparison with the dynamic Axi-symmetric Finite Element Method (Axi-FEM) analyses, which gives a more rigorous solution(Tyson 1983). Furthermore the applicability of this model is confirmed by correlation analyses with forced vibration test results on the actual composite foundation.

2 STATIC BEHAVIORS OF THE COMPOSITE FOUNDATION

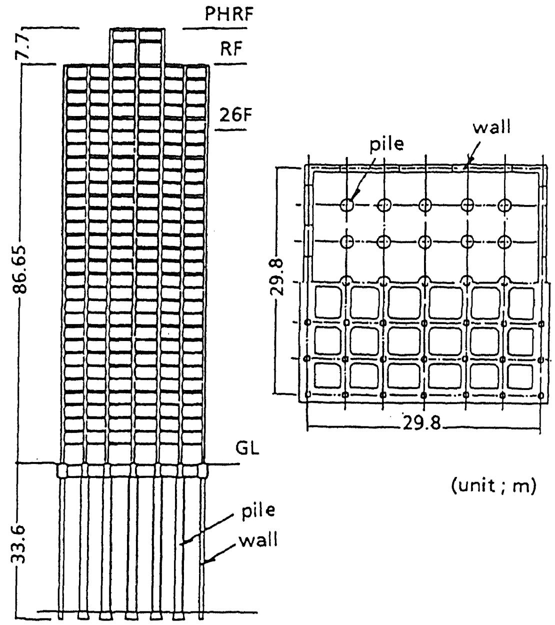
2.1 *Outline of static 3D-FEM analysis*

A typical composite foundation is illustrated in Figure 1. The diaphragm wall is 30m square, 1m thick and 33m deep. Twenty-five piles, 33m long and 1.8m in diameter, are driven inside the wall. Both the diaphragm wall and the piles are constructed of reinforced concrete. Table.1 shows the soil profile.

To examine the static fundamental mechanics of the composite foundation, 3D-FEM analyses were conducted. Figure 2 shows the mesh layout of the 3D-FEM model. The wall is modeled by shell elements and the piles by solid elements of the equivalent sectional area. As boundary conditions, fixity is assumed in the z-direction at the side interfaces, and rigidity at the bottom. A static unit lateral force and a unit moment are applied separately at the top of the foundation.

2.2 *Results of static 3D-FEM analysis*

Figure 3 shows the displacement distribution of the composite foundation in the vertical direction. The horizontal displacements at each position of the web part are almost the same and slightly larger than that of the flange part. There is no difference between the rotational displacements of each part. The Kirchhoff's hypotheses were found to be applicable to the wall. Figure 4 shows the stress participation and distribution in the vertical direction. The greater part of the applied force is resisted by wall. The web part of the wall plays a very important



(a) framing plan (b) foundation plan

Fig.1 Composite Foundation

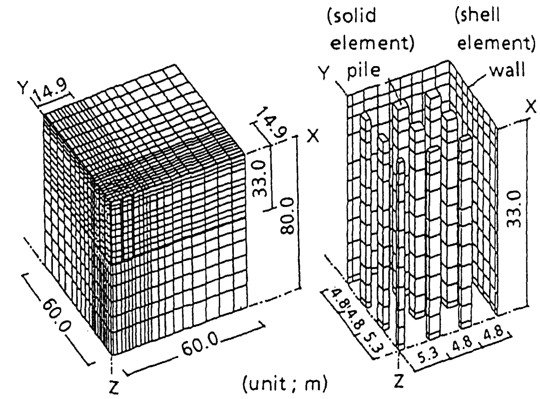
Table 1. Soil profiles

Depth (m)	Unit weight (ton/m^3)	Shear Wave Velocity (m/sec)	Poisson's ratio	Damping factor
0.0 ~ 2.0	1.90	90	0.48	0.05
2.0 ~ 4.0	1.80	90	0.49	0.05
4.0 ~ 7.0	1.95	150	0.49	0.05
7.0 ~ 12.0	1.95	180	0.49	0.05
12.0 ~ 15.0	1.80	210	0.49	0.02
15.0 ~ 22.0	1.90	210	0.49	0.02
22.0 ~ 26.0	2.00	240	0.49	0.02
26.0 ~ 32.0	1.95	220	0.49	0.02
32.0 ~	2.20	460	0.44	0.02

role in resisting this force. The stress in the piles is negligible.

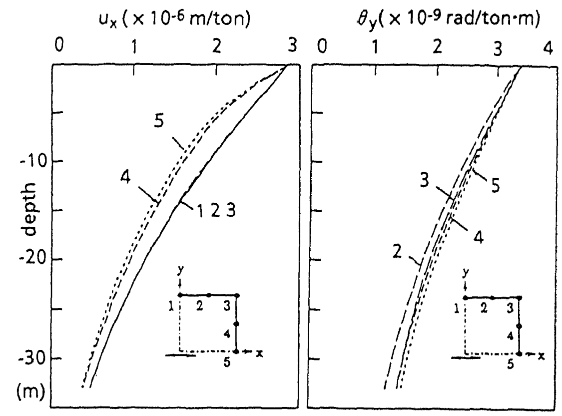
3 A PRACTICAL LUMPED MASS MODEL

Based on the results of 3D-FEM analysis, a practical model of the composite foundation was set for the earthquake response analysis. The model, shown in Figure 5, consists of lumped masses and soil springs. The lumped masses have the mass and the rotational



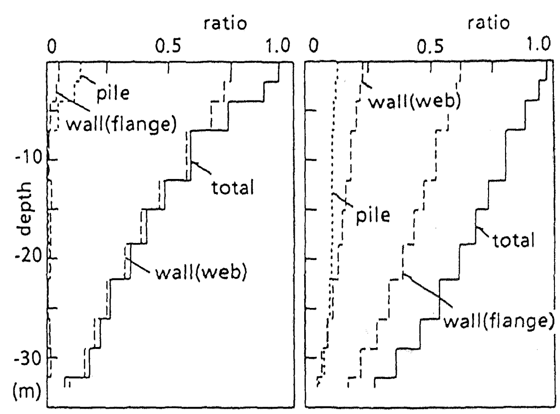
(a) whole model (b) wall and pile model

Fig.2 Mesh layout of 3D-FEM model



(a) horizontal (lateral load) (b) rotational (moment load)

Fig.3 Displacement distribution



(a) shear force (lateral load) (b) moment (moment load)

Fig.4 Stress participation and distribution inertia of both the wall and piles. The springs between the adjoining lumped masses have the shearing rigidity of the web part only and the total flexural rigidity of the wall. The stiffness of the piles is neglected.

The soil springs are evaluated by the Thin Layered Element Method(TLM; Kausel 1982, Tajimi 1984). The soil corresponding to the wall is discretized in both plane and depth as shown in Figure 6(a). Applying Green's functions to all the nodes in the soil volume, the soil flexibility matrix is obtained. Then the soil stiffness matrix is also obtained as an inverse matrix of the flexibility matrix. This stiffness matrix is reduced to the matrix which has dimensions associated with the number of lumped masses, applying the rigid body mode assumption at each depth as shown in Figure 6(b). The side rotational springs are eliminated for simplicity.

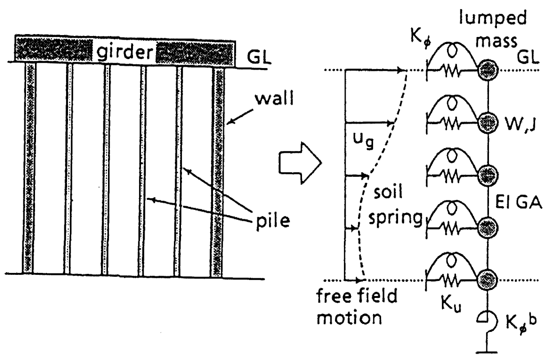


Fig.5 Proposed model of the composite foundation

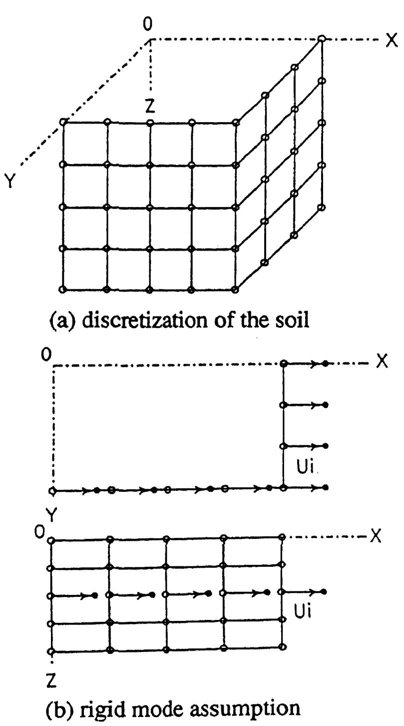


Fig.6 Estimation of the soil spring

Table 2. Parameters of the practical model

Model Parameter	Estimation
Mass (W)	Diaphragm wall +piles
Rotational inertia (J)	Diaphragm wall
Shear rigidity (GA)	Web part of Diaphragm wall
Flexural rigidity (EI)	Diaphragm wall
Horizontal soil spring at side(K_u)	Calculated by TLM
Rotational soil spring at side(K_ϕ)	Neglected
Rotational soil spring at bottom($K_\phi b$)	Calculated by TLM

Earthquake inputs are applied at each end of the soil springs, which are calculated by one-dimensional shear wave propagation theory.

The estimation method for modeling is summarized in Table 2.

4 COMPARISON STUDY WITH AXI-FEM ANALYSIS

To verify the adequacy of this practical model for the dynamic analysis, comparative studies with Axi-FEM analysis was carried out for both the impedance functions and the foundation input motion.

4.1 *Outline of Axi-FEM analysis*

Figure 7 shows the mesh layout of the Axi-FEM model. Piles are modeled by ring pile elements, and the wall by shell elements in Axi-FEM modeling. Piles are rearranged in concentric arrangements, whose geometrical moment of inertia is equal to that of the original arrangements. The energy transmitting boundary is adopted at the side interface, and the viscous boundary at the bottom.

4.2 *Results of comparison study*

Figure 8 shows a comparison of the impedance functions. The dots on the vertical axes(0 Hz) show the impedance functions obtained by static 3D-FEM analysis. The horizontal impedance functions coincide with those obtained by both Axi-FEM and 3D-FEM. The real part of the rotational impedance functions is somewhat underestimated due to the elimination of side rotational springs. As the foundation input motion, the transfer functions at the massless foundation to the horizontal free field motion at GL-32m are shown in Figure 9. Both horizontal and rotational amplitudes are

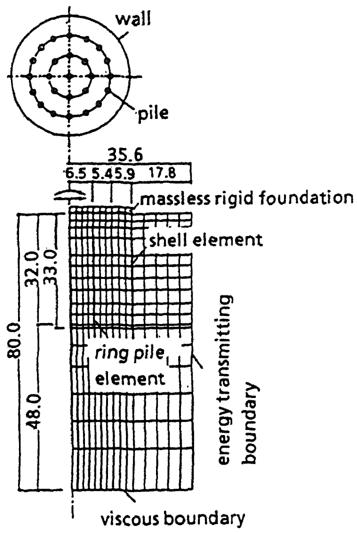


Fig.7 Mesh layout of Axi-FEM model

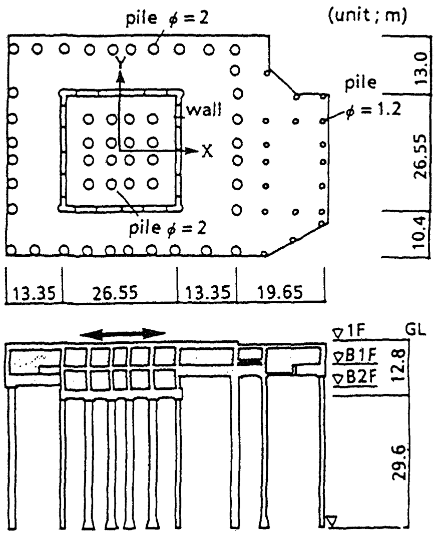
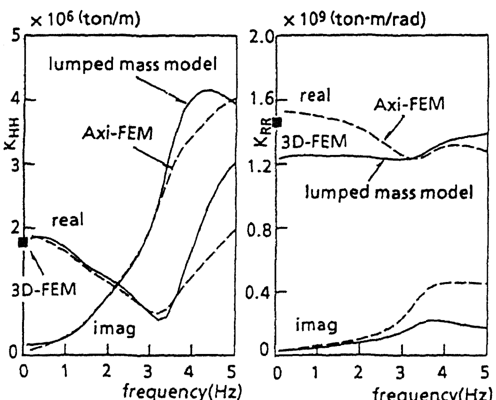
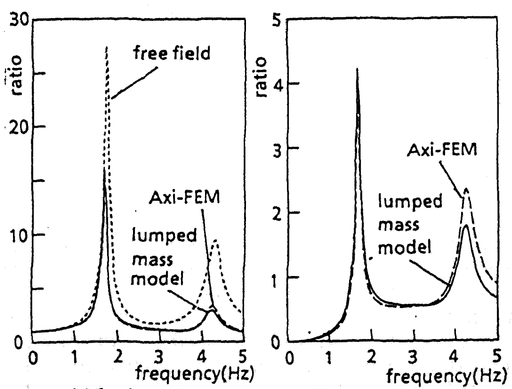


Fig.10 Tested composite foundation



(a) horizontal (b) rotational

Fig.8 Impedance function



(a) horizontal (b) rotational (vertical at r=17.8m)

Fig.9 Foundation input motion

in good agreement. It is well known that the response characteristics at the lower three resonance frequencies up to 5Hz predominate for the earthquake response of high-rise buildings.[1] It is clear from Figure 8-9 that both the impedance functions and the foundation input motion of the composite foundation are accurately evaluated in that frequency range using the proposed model.

5 CORRELATION ANALYSIS

Further correlation analyses were conducted using the forced vibration test results on the actual composite foundation to confirm the applicability of this model.

5.1 *Outline of the forced vibration test*

As shown in Figure 10, the tested structure is a composite foundation comprising the 26.55m-square diaphragm wall and several piles on both sides of the wall. The wall is 1.2m thick and 29.6m long. The piles inside the wall are 29.6m long and 2m in diameter, while those outside the wall are 33.5m long and 2m and 1.2m in diameter. Both wall and piles are constructed of cast-in-place reinforced concrete. The soil profile at the test site, shown in Table.3, can be idealized as layered strata. The forced vibration test was conducted using one unit of vibration generator(maximum excitation load of 3ton) installed at the center of the diaphragm wall on the first floor.

The horizontal and rotational resonance curves and phase lag curves at each floor were obtained from the test results. The horizontal and rotational impedances were also derived from test results based on a rigid body assumption at each floor. Figure 11 shows the resonance mode at 2Hz, at which the horizontal phase lag is about 90 degrees. The horizontal displacements at each floor are almost the same and the vertical ones are fairly small.

5.2 *Analytical lumped mass model*

Figure 12 shows the analytical lumped mass model for correlation studies. Taking account of the soil layering, the basement was subdivided into four lumped masses and the wall into nine. Model parameters were set according to the proposed estimation method. The soil spring was evaluated assuming that the wall exists up to the ground surface, disregarding the outer basement. An extra rotational spring was attached to the lumped mass corresponding to the B1F floor level. This spring constant was evaluated from the vertical stiffness of piles situated outside the wall.

5.3 *Examination of correlation analysis*

In Figure 13-14, the horizontal and rotational resonance-phase lag curves at the 1F floor are compared with test results, respectively. They are basically in good agreement, although there are some differences regarding the rotational phase lag in the frequency range over 4Hz. Figure 15-16 show the comparison of the horizontal and rotational impedance functions. The horizontal impedance functions are in good agreement. The analytical results for the rotational impedance functions are about the same as the average value of the test results, which are scattered.

6 CONCLUSIONS

The composite foundation is very effective in maintaining the stability of a structure subject to static and dynamic loads. However, its dynamic behavior has not been ascertained, and an earthquake response analysis model has not been established.

This paper describes the derivation of the practical earthquake response analysis model based on the static 3D-FEM and the dynamic Axi-FEM analyses. This practical method was examined using the forced vibration test results and its applicability was confirmed.

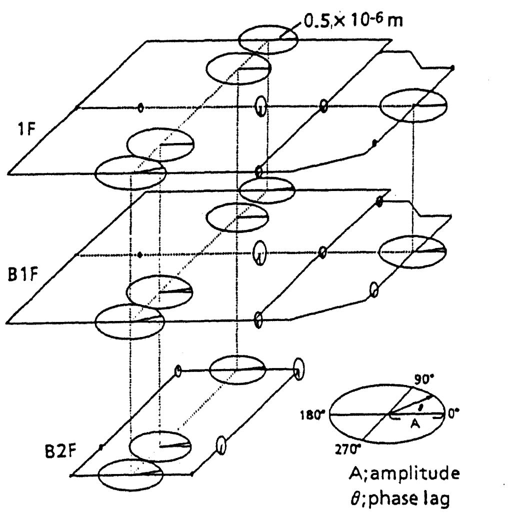


Fig.11 Resonance mode at 2Hz

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Table 3. Soil profiles

Depth (m)	Unit weight (ton/m^3)	Shear Wave Velocity (m/sec)	Poisson's ratio	Damping factor
0.0 ~ 2.0	1.73	80	0.495	0.02
2.0 ~ 4.0	1.60	110	0.491	0.02
4.0 ~ 7.0	1.66	160	0.494	0.02
7.0 ~ 8.0	1.62	90	0.498	0.02
8.0 ~ 10.5	1.70	160	0.494	0.02
10.5 ~ 17.5	1.58	100	0.494	0.02
17.5 ~ 25.5	1.62	120	0.497	0.02
25.5 ~ 28.5	1.69	190	0.491	0.02
28.5 ~ 31.5	1.63	360	0.467	0.02
31.5 ~	1.84	440	0.449	0.02

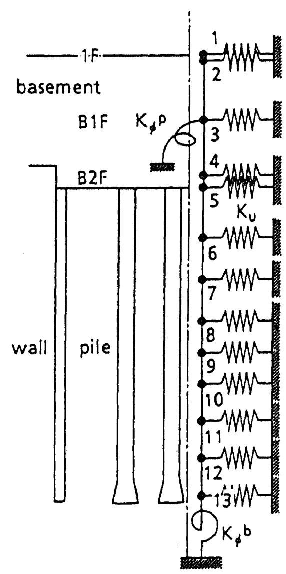

Fig.12 Analytical lumped mass mode

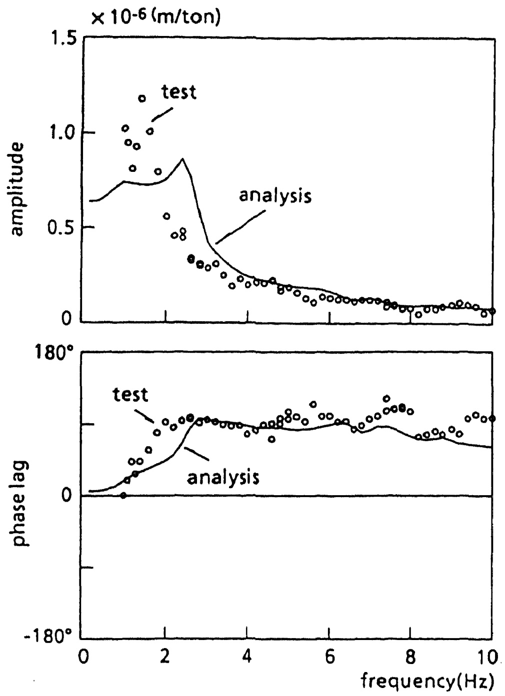

Fig.13 Comparison of horizontal resonance curve and phase lag curve

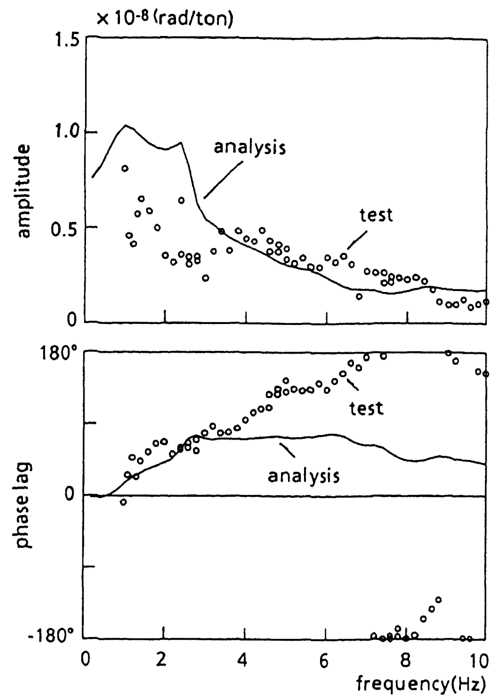

Fig. 14 Comparison of rotational resonance curve and phase lag curve

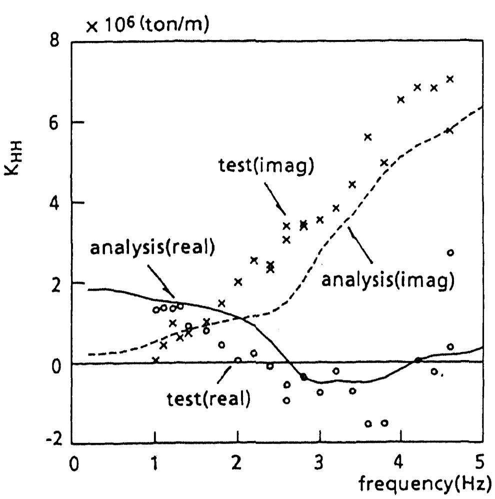

Fig.15 Comparison of horizontal impedance function

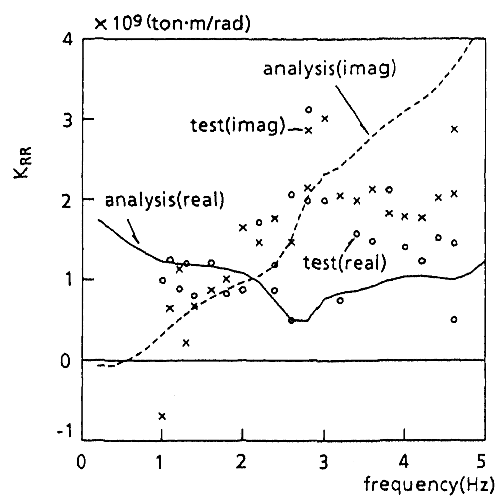

Fig.16 Comparison of rotational impedance function

REFERENCES

Kausel, E. & Peek, R. (1982). Dynamic Loads in the interior of a layered stratum. *B.S.S.A.* 72; 1459-1481

Tajimi, H.(1984). A contribution to theoretical prediction of dynamic stiffness of surface foundation. *Proc. of 8th W.C.E.E.*;873-880

Tyson, T.R. & Kausel, E.(1983). Dynamic analysis of axisymmetric pile groups. *M.I.T. Research Report* R83-07.