【カテゴリーⅠ】

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COMPARATIVE ANALYSIS OF PILE FOUNDATIONS IN AN ELASTIC GROUND SUBJECTED TO SINUSOIDAL INPUT ACCELERATIONS

正弦波を受ける杭基礎の弾性応答比較解析

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Analyses of a single pile, a pile group and a piled raft in a homogenous elastic ground subjected to earthquake are carried out using FEM and a simplified analysis method. In the FEM analyses, the raft and the piles are modelled by solid elements, or the raft is modelled by the thin plate elements and the piles are modelled by beam elements. As a simplified analysis method, a three-dimensional dynamic analysis of piled raft foundations subjected to earthquake using a hybrid model is proposed in this paper. In the analysis, the flexible raft and the pile are modelled as thin plates and beam elements, respectively. The soil is treated as springs and dashpots. The results from different modelling are compared, in order to investigate adequate modelling of raft, pile and ground and to investigate dynamic responses of the pile foundations. It is shown from the analyses that horizontal displacements and horizontal accelerations are not influenced by methods of modelling. In contrast, vertical responses such as vertical displacements hence the rocking motion of the pile, axial forces of the pile are influenced by methods of modelling, although the vertical responses are much smaller than the horizontal responses. Details of the results of the analyses are presented, and suggestions for the improvement of the simplified analysis method are discussed.

***Keywords**: Piled raft, Hybrid model, Dynamic analysis, Earthquake, Deformation, Load distribution*
パイルド・ラフト，ハイブリッドモデル，動的解析，地震，変形，荷重分布

1 INTRODUCTION

Generally, piles are widely used for foundations in order to support mainly the static vertical load from the superstructure. However, in seismic areas, a pile foundation may be also subjected to dynamic horizontal load due to an earthquake. In recent years, there has been an increasing recognition that the inclusion of the resistance of the raft in pile foundation design can lead to a considerable economy without compromising the safety or the performance of the foundation. Responses of piled rafts subjected to earthquakes were experimentally investigated using centrifuge devices[1)2)3)] and a shaking table device at 1-g field[4)5)]. However, analytical approaches on this aspect are still limited, except an analytical study by Nakai et al[6)].

When we employ FEM for analysis of a pile foundation subjected to an earthquake, modelling of soil (constitutive law) and modelling of raft and pile will be key factors in order to obtain a reliable result from the analysis. It would be desirable to model the raft and the piles by solid elements. However, as procedure of this modelling requires cumbersome task, the raft is often modelled by thin plate elements and the piles are modelled by beam elements. One of objectives of this paper is investigation on the influence of different FEM modelling of the raft and the pile on the analysis results. So, superstructure is not modelled explicitly and the soil is modelled as an isotropic linear elastic material in this particular paper.

As a simple routine design tool for piled raft foundation subjected to static combination load (vertical load, horizontal load, moment load), a computer program PRAB (Piled Raft Analysis with Batter piles) has been developed[7)8)]. Later, the program was extended to accommodate three-dimensional simplified analysis of piled raft foundation subjected to ground movements such as tunnelling induced ground movements[9)10)].

In this study, PRAB was extended so that it can be used to analyse the behaviour of piled raft foundation subjected to an earthquake. The extended program is called D-PRAB hereafter. In this method, the raft is modelled as thin plate elements, the pile is modelled as beam elements, and the soil is treated as springs and dashpots. The dynamic responses of the foundations are calculated also using the simplified method and compared with the FEM analysis results, in order to examine a validity of the proposed simplified analysis method.

Analysis results of a single pile, a pile group and a piled raft using FEM and the simplified analysis method are presented, and advantages of the piled raft over the pile group are demonstrated. And suggestions for the improvement of the simplified analysis method are discussed.

2 METHOD OF ANALYSIS

2.1 Analytical model and governing equations used in D-PRAB

Figure 1 illustrates the analytical model for piled raft foundation subjected to earthquake used in D-PRAB. This model was extended from the model used in the analysis of piled raft subjected to static load[7)8)9)10)]. The flexible raft is modelled as thin plate elements with masses, the pile is modelled as beam elements with masses, and the soil is treated as springs and dashpots connected to the raft and pile nodes.

The load-displacement relationship of the group piles and the raft can be written in matrix form as

$$\left[K_{\mathrm{p}}\right]\{w\}+\left[M_{\mathrm{p}}\right]\{\ddot{w}\}=\left\{F_{\mathrm{p}}\right\}+\{P\} \tag{1}$$

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$$[K_r]\{w\}+[M_r]\{\ddot{w}\}=\{F_r\}-\{P\} \quad (2)$$

where $[K_p]$ is the pile stiffness matrix, $[K_r]$ the raft stiffness matrix, $[M_p]$ the pile mass matrix, $[M_r]$ the raft mass matrix, $\{w\}$ the displacement vector, $\{F_p\}$ the external force vector acting on the pile, $\{F_r\}$ the external force vector acting on the raft, and $\{P\}$ is the internal force vector.

The hybrid modelling of the pile and the soil as shown in Figure 2 is adopted. The values of the vertical spring, k, the horizontal springs, k^x and k^y, the vertical radiation damping, c, and the horizontal radiation damping, c^x and c^y, per unit shaft area are approximated by means of Equations (3) and (4), based on the work of Novak *et al.*[11].

$$k=\frac{2.75G_s}{\pi d},\ k^x=k^y=\frac{4G_s}{d} \quad (3)$$

$$c=\frac{G_s}{V_s},\ c^x=c^y=\frac{4.5G_s}{V_s} \quad (4)$$

where G_s and V_s are the shear modulus and the shear wave velocity of the surrounding soil respectively, and d is the outer diameter of the pile.

The values of the soil spring at the pile base, k_b, the damping, c_b, and the lumped soil mass, m_b, per unit pile base area can be estimated as follows[12]:

$$k_b=\frac{8G_s}{\pi d(1-\nu_s)} \quad (5)$$

$$c_b=\frac{3.4}{\pi(1-\nu_s)}\frac{G_s}{V_s} \quad (6)$$

$$m_b=16r_o\rho_s\frac{0.1-\nu_s^4}{\pi(1-\nu_s)} \quad (7)$$

in which ν_s and ρ_s are the Poisson's ratio and the density of the soil, respectively, and r_o is the pile radius.

The values of the vertical spring, k_r, the horizontal springs, k_r^x and k_r^y, the vertical radiation damping, c_r, and the horizontal radiation damping, c_r^x and c_r^y, per unit raft base area can be estimated as follows[13]:

$$k_r=\frac{4G_s}{\pi a(1-\nu_s)},\ k_r^x=k_r^y=\frac{32(1-\nu_s)G_s}{\pi a(7-8\nu_s)} \quad (8)$$

$$c_r=\frac{3.4}{\pi(1-\nu_s)}\frac{G_s}{V_s},\ c_r^x=c_r^y=\frac{18.4(1-\nu_s)}{\pi(7-8\nu_s)}\frac{G_s}{V_s} \quad (9)$$

where a is the equivalent radius of the raft element.

Using Equations (3) to (9), the soil resistance can be written in matrix form as follows:

$$[K_s]\{w\}+[C_s]\{\dot{w}\}+[M_s]\{\ddot{w}\}=\{P\} \quad (10)$$

where $[K_s]$, $[C_s]$, and $[M_s]$ are the stiffness matrix, the damping matrix and the mass matrix of the soil.

Finally, from Equations (1), (2) and (10), we get

$$[K]\{w\}+[C]\{\dot{w}\}+[M]\{\ddot{w}\}=\{F\} \quad (11)$$

where $[K]=[K_p]+[K_r]+[K_s]$, $[C]=[C_s]$, $[M]=[M_p]+[M_r]+[M_s]$, and $\{F\}=\{F_p\}+\{F_r\}$.

Newmark's β method[14] is used for solving Equation (11).

The external force vector $\{F\}$ is active loads applied to the structure directly or passive loads such as earthquake-induced loads.

In the case of the pile foundation subjected to earthquake load, the induced external force vector $\{F\}$ can be calculated by means of Equation (12).

$$\{F\}=[K_s]\{w_0\}+[C_s]\{\dot{w}_0\} \quad (12)$$

where $\{w_0\}$ is the free field ground movement vector and $\{\dot{w}_0\}$ the velocity induced by an earthquake.

Pile-soil-pile, pile-soil-raft and raft-soil-raft interactions are taken into account based on Mindlin's solutions in PRAB for static analysis.

However, in the dynamic analysis proposed in this paper, the above interactions are not considered, although these interactions exist also in the dynamic response of the piled raft. The influence of the neglect of the interactions in D-PRAB will be discussed through the comparisons of the calculated results using FEM and D-PRAB.

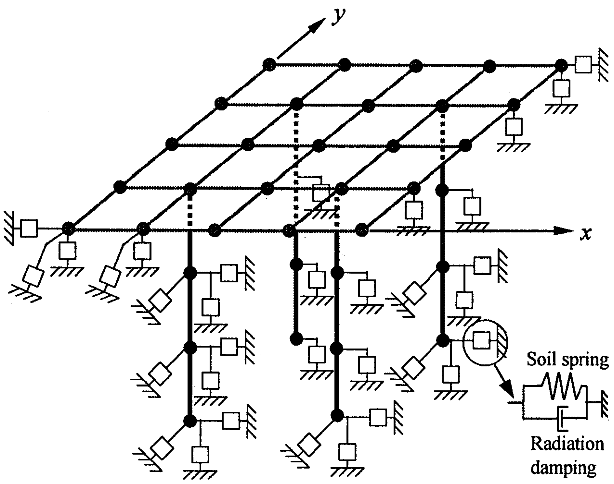


Fig. 1. Plate-beam-spring-dashpot model of a piled raft.

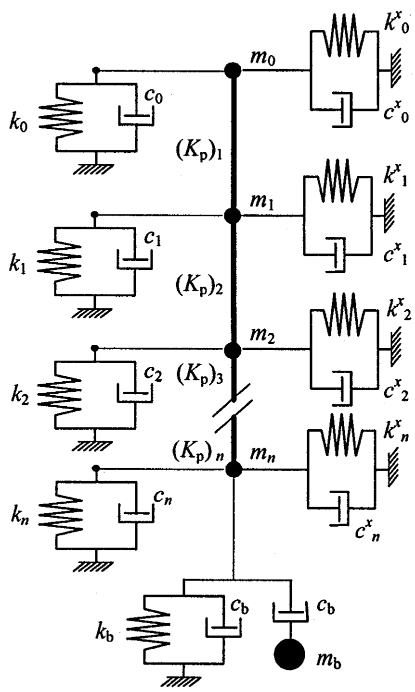


Fig. 2. Hybrid modelling of the pile and the soil.

2.2 Analytical procedure used in D-PRAB

Figure3 show the analysis procedure used in D-PRAB. In the dynamic analysis of a foundation subjected to earthquake load, first, the response of free field ground movements is calculated. Second, the calculated free field ground movement profiles at each position of pile and raft nodes are used to estimate the forces at each node. These forces are then used as the external forces in Equation (11). Equation (11) can be solved for the pile settlements, deflections and rotations from which the axial forces, the shear forces and the bending moments can be obtained.

2.3 Method of ground motion analysis used in D-PRAB

The free field ground movement during an earthquake may be attributed primarily to the upward and downward propagating shear waves. If the boundaries between different soil layers are essentially horizontal and each soil layer deforms in simple shear mode without volumetric strain, the soil deposit may be modelled as a series of lumped masses interconnected by springs and dashpots[15] as shown in Figure 4.

When the soil deposit is subjected to a horizontal seismic motion through its base, the equation of motion of the system may be represented in matrix form as:

$$[K_\mathrm{m}]\{u\}+[C_\mathrm{m}]\{\dot{u}\}+[M_\mathrm{m}]\{\ddot{u}\}=-[M_\mathrm{m}]\{\ddot{u}_\mathrm{g}\} \qquad (13)$$

where $[M_\mathrm{m}]$ is the soil mass matrix, $[C_\mathrm{m}]$ the soil damping matrix, $[K_\mathrm{m}]$ the soil stiffness matrix, and $\{u\}$is the vector of the relative displacements between each layer. Each element of $[M_\mathrm{m}]$, $[C_\mathrm{m}]$ and $[K_\mathrm{m}]$ can be defined as

$$M_{\mathrm{m}i}=\frac{(\rho_{i-1}+\rho_i)}{2}\times\Delta z\ ,\ K_{\mathrm{m}i}=\frac{G_i}{\Delta z},\ C_{\mathrm{m}i}=\frac{c_i}{\Delta z} \qquad (14)$$

where G_i is the shear modulus, ρ_i is the density and c_i is the damping factor of the soil, and Δz is the thickness of each soil layer. The damping factor, c_i, takes account of strain rate dependency of the soil. The horizontal free field ground movement vector $\{u_0\}$ can be calculated by Equation (15).

$$\{u_0\}=\{u\}+\{u_\mathrm{g}\} \qquad (15)$$

where $\{u_\mathrm{g}\}$ is the input seismic displacement.

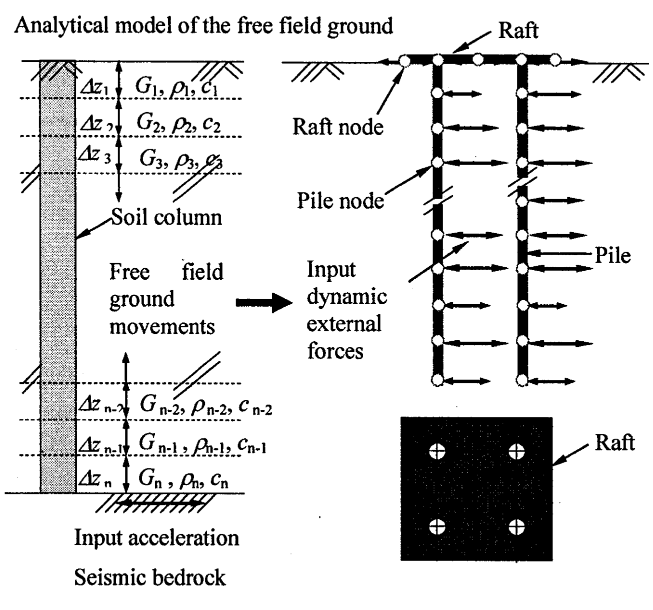


Fig. 3. Analysis procedure used in D-PRAB.

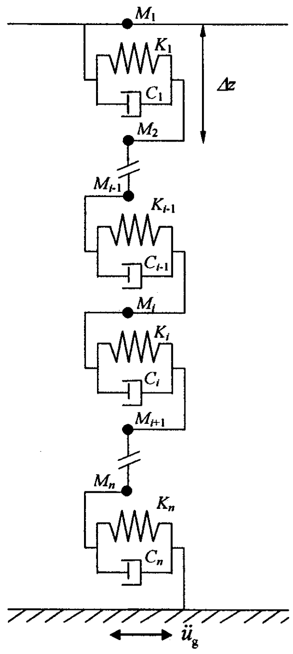


Fig. 4. Lumped mass-spring-dashpot model.

It should be noted that the existence of the pile foundation structure is neglected in calculation of the movements of the free field. Validity of this assumption will be demonstrated below through comparison of analysis results calculated by FEM and the proposed simplified method.

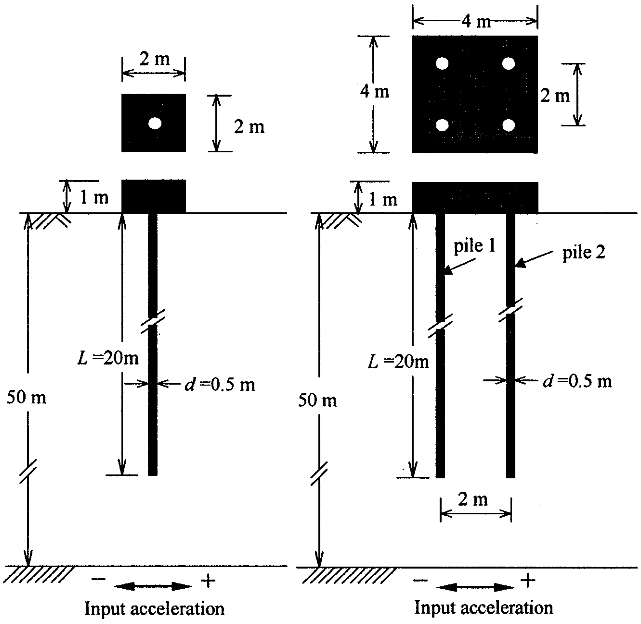
3 COMPARATIVE ANALYSES

3.1 Analytical conditions

In this paper, the problems as shown in Figure 5 are analysed. Only elastic responses of soil and pile foundations are analysed for the first step of this work. The soil, the pile and the raft were treated as elastic homogeneous materials in the analyses. The soil, the pile and the raft properties are summarised in Table 1. All analyses were carried out using these properties.

Figure 6 shows the analysis model used in FEM. A commercial FEM program Soil Plus[16] was used for FEM analyses. Considering the plane symmetric condition of the problem, only a half of the ground and the foundation were modelled. Vertical displacements at the bottom were fixed and time history of horizontal input acceleration was applied to the bottom. Free-field boundary conditions were set at the side walls of the model ground, vertical displacements at the side walls were fixed so as to the soil elements far from the foundation deform in simple shear mode to simulate semi-infinite ground. With this boundary condition, the response of the ground without the foundation corresponds to that of the free field.

In the FEM analyses, two types of modelling of the raft and the pile were used: the raft and the piles are modelled by solid elements with an octagonal cross-section (designated as FEMS); the raft is modelled by thin plate elements and the piles by beam elements (FEMB). Bending moments of the piles are directly calculated when the piles are modelled by beam elements, whereas pile bending moments are not directly obtained from FEM analysis when the piles are modelled by solid elements. Hence, bending moment of a pile segment was estimated as shown in Figure 7. Axial strains at both sides the pile segment, ε_A and ε_B, are calculated from the vertical displacements of the nodes to obtain bending strain ε_bm.



(a) Capped single pile (b) Pile group & piled raft

Fig. 5. Problems analysed.

Table 1. Material properties used in analyses.

Property	Value
Soil:	
Young's modulus	5.96×10^4 kPa
Poisson's ratio	0.49
Density	2 ton/m^3
Shear wave velocity	100 m/s
Pile:	
Young's modulus	3.84×10^7 kPa
Poisson's ratio	0.16
Density	2.4 ton/m^3
Longitudinal wave velocity	4000 m/s
Shear wave velocity	2626 m/s
Length	20 m
Diameter	0.5 m
Unit squared raft (pile cap):	
Young's modulus	3.84×10^7 kPa
Poisson's ratio	0.16
Density	2.4 ton/m^3
Width	2 m
Thickness	1 m

Bending moment, M, is then calculated from ε_{bm} with Young's modulus, E, second moment of area, I, and radius, r_o, of the pile.

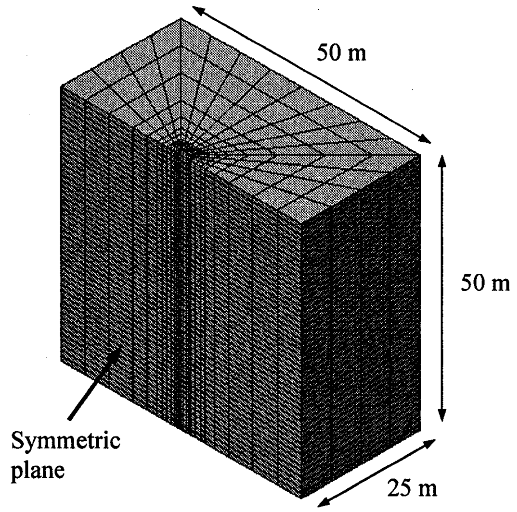
In the case of FEM analyses of single pile and pile group, a gap of 0.1 m between the raft base (pile cap) and the ground surface was incorporated in the model. On the other hand, in the analysis of single pile and pile group using D-PRAB, the values of the vertical and horizontal soil springs and soil dashpots at the raft base were set at 0.

The input acceleration was applied at the base of the ground model (at z = 50 m).

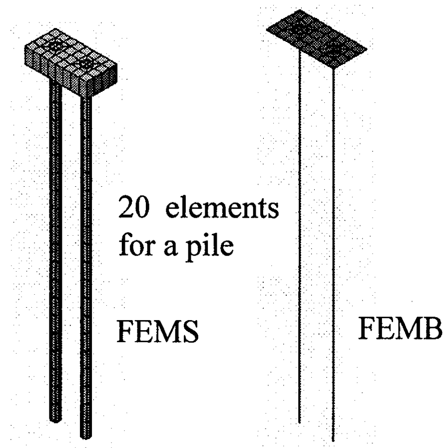
Figure 8 shows the input accelerations at the depth z = 50 m that are calculated using the following equation:

$$\ddot{u}(t)=\sqrt{\beta e^{-\alpha t}t^{\gamma}}\,\sin(2\pi f t) \qquad (16)$$

where $\alpha = 2.2$; $\beta = 0.375$; $\gamma = 8.0$; $f = 0.5$ and f=1.0 Hz.

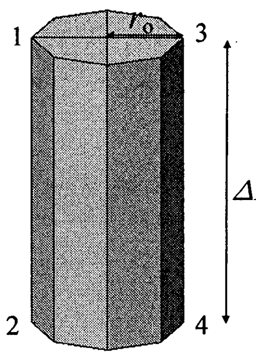


(a) Whole model (Plane symmetric)



(b) Two types of modelling of raft and piles

Fig. 6. Analysis model used in FEM.



$$\varepsilon_A = (w_2 - w_1)/\Delta L$$
$$\varepsilon_B = (w_4 - w_3)/\Delta L$$
$$\varepsilon_{bm} = (\varepsilon_A - \varepsilon_B)/2$$
$$M = \frac{EI\varepsilon_{bm}}{r_o}$$

Fig. 7. Calculation of bending moment of a pile segment.

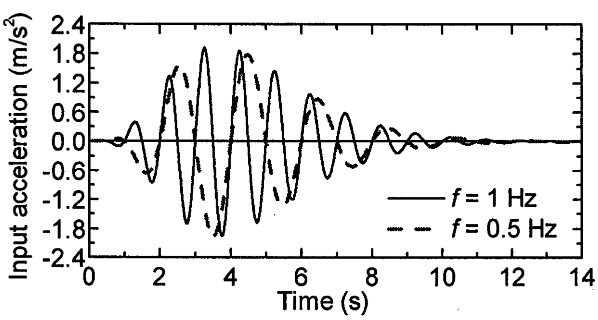


Fig. 8. Input accelerations.

3.2 ANALYSIS RESULTS

3.2.1 Results of free field ground motion analysis

Figures 9 and 10 show the free field ground movements at the ground surface (z = 0 m) and z = 20 m, calculated using D-PRAB and FEM without foundation, for the case of input frequencies of f = 0.5 Hz and f =1.0 Hz, respectively. The absolute displacements are plotted in the figures.

It is seen that the solutions calculated using D-PRAB match very well with those calculated using FEM. Very large horizontal soil movement responses were obtained in the case of f = 0.5 Hz. This frequency is equal to the natural frequency, f_n, of the ground, which is calculated based on Equation (17).

$$f_n = V_s / 4H \tag{17}$$

where H is the depth of the homogeneous ground.

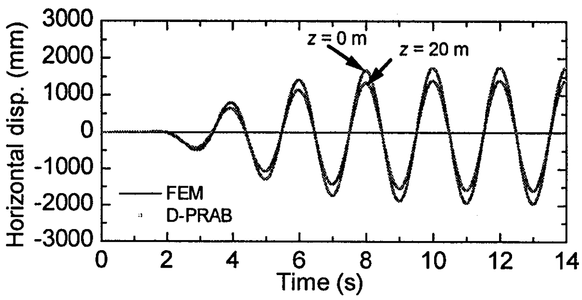


Fig. 9. Free field ground movements (f = 0.5 Hz).

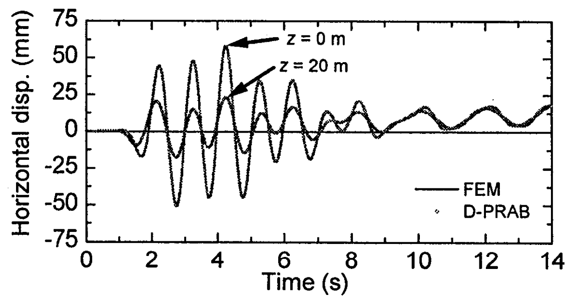


Fig. 10. Free field ground movements (f = 1.0 Hz).

3.2.2 Analysis results of single pile

Figures 11 and 12 show the horizontal accelerations and displacements at the pile head of the capped single pile calculated using FEM (FEMS and FEMB) and the proposed method D-PRAB for the case of input frequency of f = 0.5 Hz. The calculated results from the various solutions are undistinguishable. The maximum absolute horizontal displacement of about 2 m occurs at a time t = 13 s. The distributions of lateral displacements and bending moments of the pile at t = 13 s are shown in Figures 13 (a) and (b). The distributions of lateral displacements from the various solutions are identical and almost equal to the free field ground movements. In contrast, differences of bending moments are found between the solutions.

When comparing the solutions from FEMS (piles are modelled by solid elements) and FEMB (piles are modelled by beam elements), bending moments of the pile from about 10d (d = pile diameter) from the top and tip calculated from FEMB overestimate those calculated from FEMS. This trend is pronounced near the pile tip. This is due to that rotational resistance at the bottom of the pile cannot be taken into account in FEMB where the cross-sectional area of the pile is inherently zero.

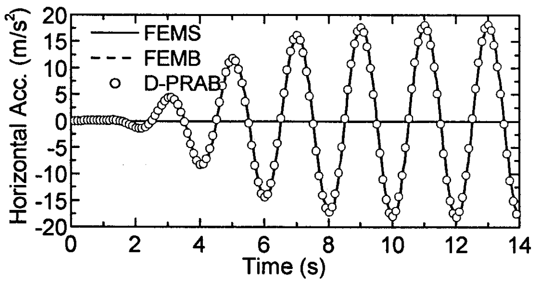


Fig. 11. Horizontal acceleration at pile head (f = 0.5 Hz).

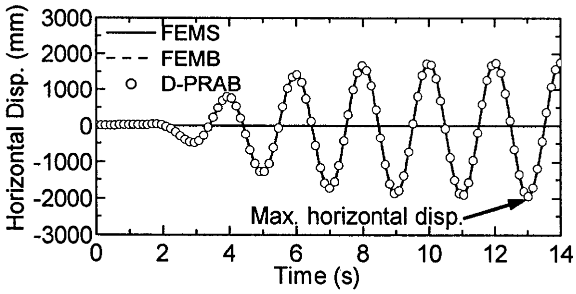
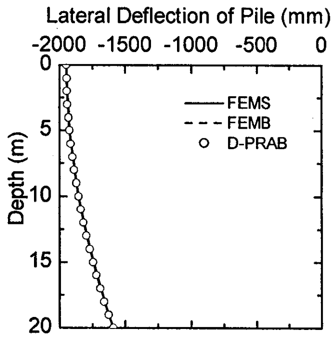
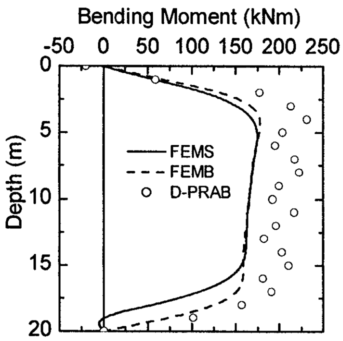


Fig. 12. Horizontal disp. at pile head (f = 0.5 Hz).



(a) Lateral deflection



(b) Bending moment

Fig. 13. Single pile responses (f = 0.5 Hz).

The bending moments calculated from the proposed simplified method D-PRAB are larger than those calculated from FEM. This may be attributed to that the interactions between soil springs through the soil are not considered in the current D-PRAB.

Figures 14, 15 and 16 show the dynamic responses of the pile for the case of input frequency of f = 1.0 Hz. The dynamic responses of the pile from the various solutions are again comparable especially for the lateral deflections. The distributions of the bending moments from the various solutions have a trend similar to those for the input frequency of 0.5 Hz (Fig. 13(b)).

It can be seen from the above results that the solutions of the proposed method match well with those calculated using FEM for a wide rage of input acceleration frequencies.

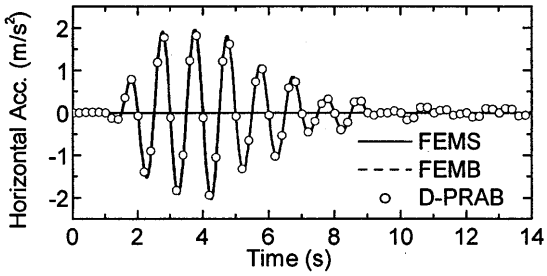


Fig. 14. Horizontal acceleration at pile head (f = 1.0 Hz).

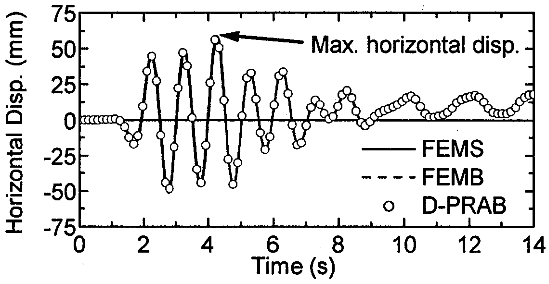
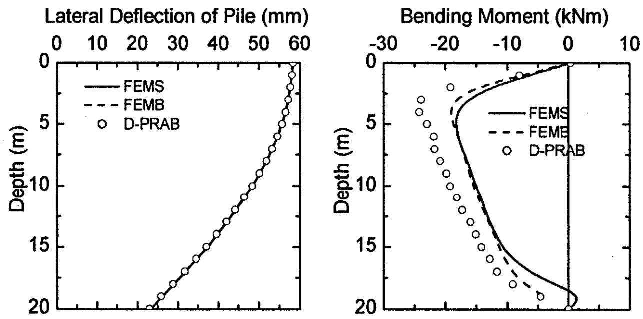


Fig. 15. Horizontal disp. at pile head (f = 1.0 Hz).



(a) Lateral deflection (b) Bending moment

Fig. 16. Single pile responses (f = 1.0 Hz).

3.2.3 Analysis results of pile group and piled raft

Figures 17 and 18 show the horizontal accelerations and displacements at the pile head in the pile group for the case of input frequency of f = 1.0 Hz calculated using the various analyses. The horizontal accelerations and displacements at the pile head in the piled raft were almost the same as those shown in Figures 17 and 18, although figures are not indicated. It can be seen from the figures that the dynamic responses from the various solutions match very well in both pile group and piled raft.

The lateral deflections, bending moments, vertical movements and axial forces along the pile in the pile group and those along the pile in the piled raft at a time when the horizontal displacement at the pile head shows the maximum absolute value are plotted in Figures 19 and 20.

The distributions of the lateral deflections of the pile from the various solutions are almost equal in both cases of the pile group and the piled raft. The trends of the differences in the bending moment distributions from the various solutions are similar to those for the case of the single pile. That is, bending moments of the pile near the top and tip calculated from FEMB overestimate those from FEMS, and the bending moments calculated from the simplified method D-PRAB are larger than those from FEM.

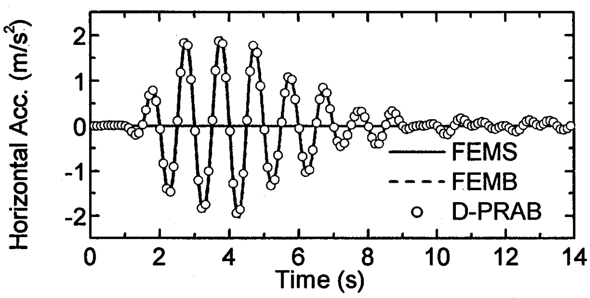


Fig. 17. Horizontal acc. at pile head in pile group (f = 1.0 Hz).

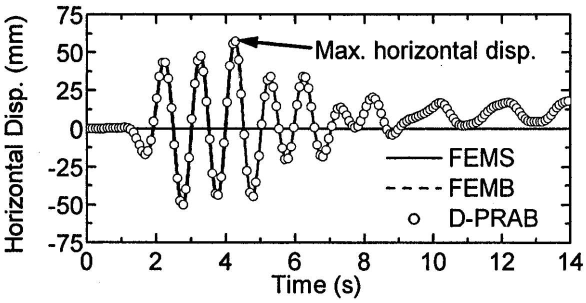
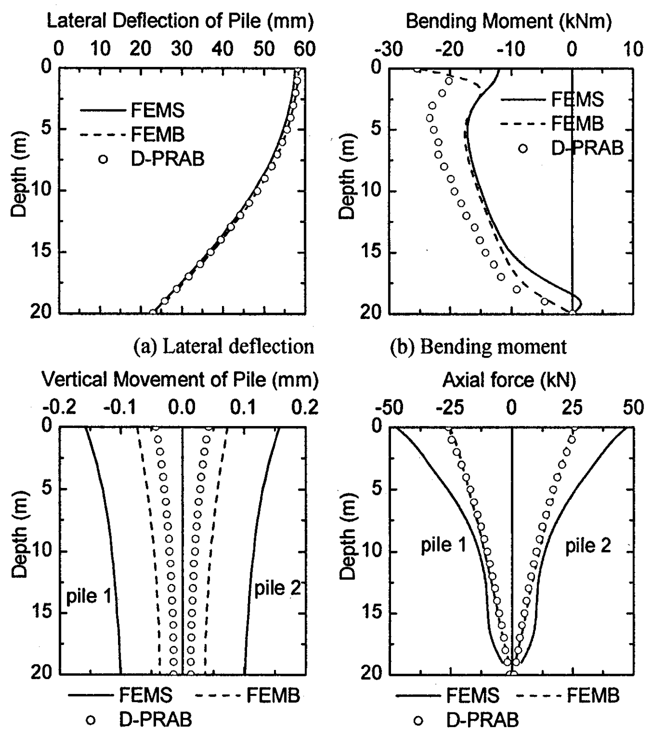


Fig. 18. Horizontal disp. at pile head in pile group (f = 1.0 Hz).

Vertical displacements of the pile from the various solutions are very small or negligible compared to the lateral deflections (Fig. 19(c) and Fig. 20(c)).

However, it is useful to discuss the vertical responses of the pile for improvement of the simplified method D-PRAB, because vertical displacements are expected to become larger when the influence of the superstructure is considered. The vertical displacements of the pile calculated using D-PRAB are a little bit of smaller than those calculated from FEMB, but much smaller than those calculated from FEMS.



(a) Lateral deflection (b) Bending moment

(c) Vertical movement (d) Axial force

Fig. 19. Responses of pile group (f = 1.0 Hz).

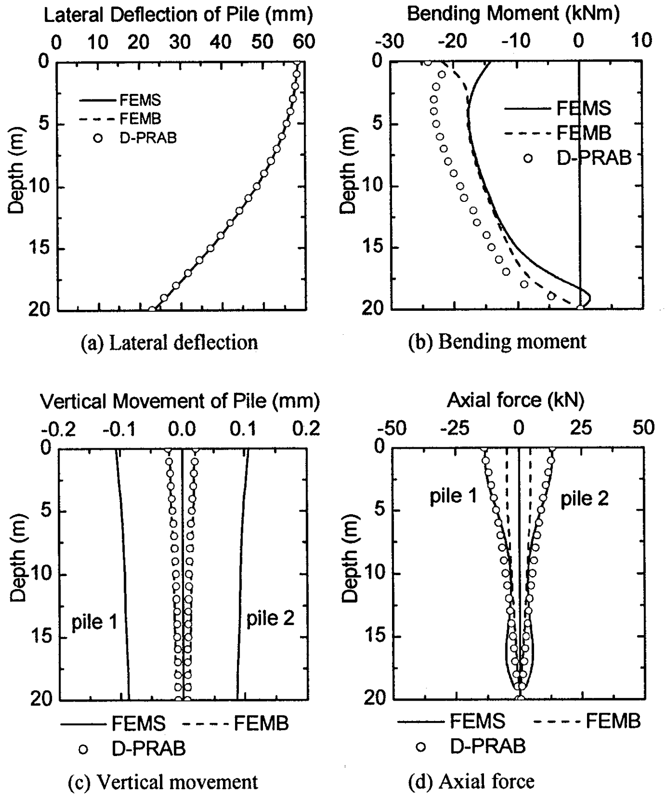


Fig. 20. Responses of piled raft (f = 1.0 Hz).

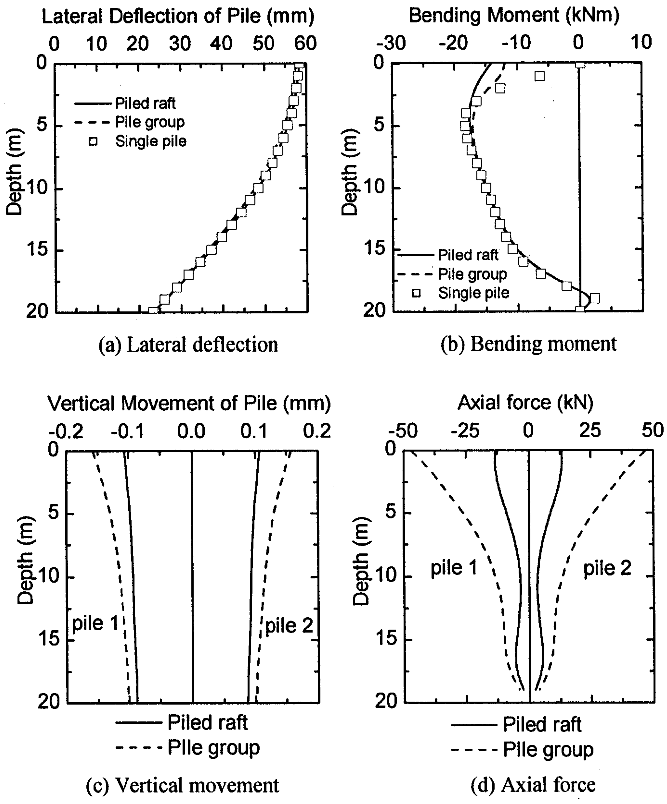


Fig. 21. Comparisons of the pile responses from FEMS (f = 1.0 Hz).

The difference of the vertical pile responses between FEMS and FEMB may be attributed to the beam modelling of the piles adopted in FEMB where pile-to-pile distance is 2.0 m that is smaller than pile surface-to-pile surface distance of 1.5 m in FEMS. Hence, interaction between the piles becomes smaller in FEMB than in FEMS, resulting in smaller vertical displacements in FEMB. Although the pile is modelled as beam elements in D-PRAB, the effect of the pile diameter is incorporated in the estimation of the soil spring in D-PRAB. However, as mentioned, interactions between the soil springs through the soil are not taken into in the current D-PRAB. This leads to smaller vertical displacements in D-PRAB.

3.2.4 Comparison of single pile, pile group and piled raft

Hereafter, the pile responses of the single pile, the piles in the pile group and the piled raft at time instants when the horizontal displacement at the pile head shows the maximum absolute value are compared based on the analysis results from FEMS which is thought to be most reliable in the various solutions.

Figure 21(a) shows a comparison of the lateral deflections of the piles. It can be seen that the lateral deflections of the piles in all types of foundations are almost identical.

Figure 21(b) shows a comparison of the bending moments of the piles. As might be expected, the bending moment at the pile head of the single pile is zero. Below a level of 10d from the pile head, the bending moment profiles of the piles in all types of foundations are almost the same.

Figures 21(c) and 21(d) show comparisons of the vertical movements and the axial forces of the piles in the piled raft and those of the piles in the pile group. It can be seen from the figures that the vertical movements and the axial forces of the piles in the piled raft are smaller than those of the piles in the pile group, *i.e.*, the rocking motions of the piled raft are smaller than those of the pile group.

4 CONCLUSIONS

Dynamic behaviours of a single pile, a pile group and a piled raft in a homogenous elastic ground subjected to earthquakes were analysed using FEM and a simplified analysis method D-PRAB. In FEM analyses, raft and piles were modelled by solid elements (called FEMS), or raft was modelled by thin plate element and piles by beam elements (called FEMB). Comparisons of the analysis results were made, in order to examine validity of the various analysis methods and to investigate difference of dynamic responses of the foundations.

From the comparative analyses using the various solutions, following findings were derived:

1) Horizontal accelerations and displacements of the single pile, the pile group and the piled raft calculated using the various methods are almost the same.
2) FEMB and D-PRAB tend to underestimate the vertical displacements of the pile compared to FEMS that is regarded as the most rigorous approach, although the vertical displacements are very small compared to the horizontal displacements.

From the comparison of the foundations calculated using FEMS, following findings were indicated:

3) Lateral displacements of the single pile, the pile group and the piled raft are almost the same for an earthquake.
4) Rocking motion of the piled raft is smaller than that of the pile group. The axial forces of the pile in the piled raft are much smaller than those in the pile group.

It should be noted here that the above findings are valid for the cases that strains induced in the soil are small enough where the soil exhibits only elastic response and that effect of a superstructure does not exist. Comparison of the analysis results with observation would be also desirable to confirm these conclusions.

Following improvements are recommended for D-PRAB:

1) Incorporation of dynamic interactions between the soil springs though the soil, in order to obtain more reliable vertical responses of the foundation.
2) Modelling of the superstructure for the analysis of a total structure composed of a superstructure and a substructure including piles.

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和文要約

1. はじめに

近年，地震荷重を受ける杭基礎設計においてラフト底面と地盤の摩擦抵抗を考慮することにより基礎の安全率や性能を損なうことなく経済的に設計することが望まれるようになってきている。地震力を受けるパイルドラフト基礎の挙動を明らかにするため，遠心装置[1)2)3)]や1g場における振動台[4)5)]を用いた実験的研究が行われているが，解析的研究は中井ら[6)]の研究を除いて，数少ないのが現状である。

地震荷重を受ける杭基礎に対して有限要素法を用いて解析を行う際，地盤・杭およびラフトのモデル化は信頼できる解析結果を得るための重要な事柄である。本来，杭やラフトはソリッド要素にモデル化されるべきだが，煩雑な作業が必要とされるため，通常，杭は梁要素に，ラフトは薄板要素にモデルされる。そこで，本論文の目的は，杭およびラフトの異なるモデル化が有限要素法解析結果に与える影響を究明することである。なお，地盤は均一線形弾性体として取り扱う。

また，筆者らは三次元静的簡易変形解析プログラムPRAB[7)8)]を地震力を受けるパイルドラフト基礎の挙動を動的に解析することができるよう拡張したD-PRAB (Dynamic - Piled Raft Analysis with Batter piles)を開発した。本提案手法では，杭は梁要素に，ラフトは薄板要素に，地盤はばね要素としてモデルされる。論文では，正弦波を受ける杭基礎を解析対象として，有限要素法解析（使用解析プログラム：三次元有限要素法解析プログラムSoil Plus[16)]）結果と本提案手法による解析結果を比較検討することにより，その妥当性を検証する。

2. 簡易解析手法

2.1 解析モデルと支配方程式

D-PRABにおいてパイルドラフト基礎は，図1に示すようにラフトは質点と薄板要素，杭は質点と梁要素，地盤はラフト質点と杭質点それぞれに連結された独立したばねとダッシュポットでモデル化されている。杭周辺地盤の杭単位面積あたりの鉛直および水平（X，Y）方向のばねとダッシュポットはそれぞれ式(3)，(4)[11)]で表現される。杭先端地盤の杭単位面積あたりの鉛直方向のばね，ダッシュポットおよび付加質量はそれぞれ式(5)，(6)，(7)[12)]で表現される。また，ラフト下部地盤のラフト単位面積あたりの鉛直および水平（X，Y）方向のばねとダッシュポットはそれぞれ式(8)，(9)[13)]で表現される。

パイルドラフト基礎の支配方程式は式(11)で表現される。地震荷重が作用する杭基礎の場合，外力ベクトル$\{F\}$は式(12)で表現される。式(11)の解法には，Newmarkのβ法を用いている。

現時点におけるD-PRABは，杭—地盤—杭，杭—地盤—ラフト，ラフト—地盤—ラフトの動的相互作用を考慮していない。

2.2 解析手順

地震荷重を受ける基礎の動的解析におけるD-PRABの解析手順は，第一に自由地盤における時刻歴応答変位および応答速度を計算する。第二に第一で得られた各杭，ラフト節点位置における強制地盤変位および強制地盤速度を用いて式(12)より各杭，ラフト節点位置における強制外力を計算する。第三に式(11)より基礎の各応答値を計算する。

2.3 自由地盤における応答解析手法

地盤は水平成層地盤とし，純せん断変形のみを考える。自由地盤は図4に示すように質点と水平ばねおよびダッシュポットでモデル化[15)]している。解析モデルの運動方程式は式(13)で表現される。

3. 比較解析

3.1 解析条件

解析対象は図5に示すように，深さ50mの均一弾性地盤にコンクリート杭で支持されたパイルキャップ（2m×2m×1m）付の単杭，4本杭で構築された群杭およびパイルドラフト（ラフトは4m×4m×1m）とした。Soil Plusで用いた解析モデルを図6に示す。Soil Plusでは，杭とラフトはソリッド要素でモデル化（FEMS）した場合と，杭は梁要素，ラフトは薄板要素でモデル化（FEMB）した場合の2タイプとした。単杭および群杭の場合，ラフトと地盤間隔は0.1mとした。解析諸元を表1に示す。解析においては，材料は線形弾性体としている。

地震基盤における入力地震波は式(16)に示す正弦波とし，周波数fは，0.5Hz, 1.0Hzを採用した。f＝0.5Hzは地盤の卓越周波数である。

3.2 解析結果

3.2.1 自由地盤の応答解析結果

Soil PlusとD-PRABで計算された杭先端（GL-20m），杭頭位置における時刻歴応答変位結果は良い一致を示す。

3.2.2 単杭の解析結果

FEMSとFEMBの解析結果より，杭頭位置における時刻歴応答加速度，変位および杭頭変位が最大値を示した時刻の杭の水平変位分布における違いはない。曲げモーメント分布もほぼ一致する。D-PRABで計算された杭頭位置における時刻歴応答加速度，変位および杭頭変位が最大値を示した時刻の杭の水平変位分布はFEMSおよびFEMBと良い一致を示す。曲げモーメント分布は，FEMSおよびFEMBと比較して大きな値を示す。これはD-PRABにおいて地盤間の相互作用を考慮していないためである。

3.2.3 群杭とパイルドラフトの解析結果

FEMS, FEMBおよびD-PRABで計算された杭頭位置における群杭とパイルドラフトの時刻歴応答変位結果は良い一致を示す。また，杭頭変位が最大値を示した時刻の杭長さ方向における水平変位はいずれの解析方法および群杭とパイルドラフトに関わらず等しい。曲げモーメント分布は，単杭の場合と同じ解析結果傾向を示す。杭先端および杭頭においてはFEMBとD-PRABの解析結果はFEMSより大きな値を示す。杭の鉛直変位は，D-PRABの解析結果がもっとも小さい値を示す。また，FEMSとFEMBの解析結果の違いは，杭表面間隔の相違とそれに伴う地盤間相互作用の影響度合いの相違である。

3.2.4 単杭，群杭とパイルドラフトの比較

FEMS, FEMBおよびD-PRABで計算された水平変位はどれもほぼ等しい値を示す。曲げモーメントも単杭の杭頭モーメントがゼロを除けばほぼ等しい。鉛直変位と軸力は，パイルドラフトが群杭より小さな値を示す。

4. 結論

正弦波を受ける均一弾性地盤における単杭，群杭，パイルドラフト基礎を対象としてSoil PlusとD-PRABを用いて動的解析を行った。

各解析手法より計算された単杭，群杭とパイルドラフトの杭の応答水平加速度と変位は，ほぼ同じ値を示す。FEMBとD-PRABの鉛直変位解析結果はFEMSより小さな値を示す。

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