Dynamic Stiffness of Pile Groups in a Multilayered Soil Part 2: Dynamic Analysis Method for Pile Groups and Comparison with the Test Results

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ABSTRACT

A rational analysis method is presented for calculation of the dynamic stiffness of pile groups in multilayered soil. In this paper, thin layered method is applied, and the dynamic stiffness matrix is evaluated at the pile heads. The pile is modelled as compressible Timoshenko-beam elements and the soil as visco-elastic thin layered elements.

After the correlation studies between the analysis and the test results of the pile foundation with a gap between the foundation bottom and the ground surface, the analysis method herein is amended for the dynamic stiffness of the pile foundation without a gap or with embedment. From these correlation analyses, the presented methods are verified to be applicable for the evaluation of pile group foundation stiffness.

1 INTRODUCTION

The dynamic analysis methods for pile foundations are roughly classified into (1) spring - lumped mass system, (2) FEM, and (3) method based on the wave propagation theory. Among these, the last one is the method which can calculate the dynamic stiffness of pile groups with good accuracy. Three dimensional thin layered method (TLM) [1] is applied to the dynamic stiffness analysis for pile group foundations in this paper. This method is the semi-analytical finite element method based on the wave propagation theory, and dynamic interaction between the pile and soil can be evaluated accurately with low computation cost.

In this paper, the analysis methods are described for calculation of the dynamic stiffness of pile group foundations under three conditions; with a gap between the foundation bottom and the ground surface; without a gap; and with embedment. The correlation analyses are executed for the dynamic stiffness of the four-pile foundation model as reported in the previous paper Part 1 [2], and the applicability of the analysis methods are verified by comparison studies with the test results.

2 ANALYSIS METHODS

In previous Part 1, the forced vibration tests were presented for the four-pile foundation model with a gap (test step 2), without a gap (step 3) and with embedment (step 4). The analysis methods for each test condition are summarized in Fig. 1 and explained below.

Phase 1 : Dynamic stiffness of pile group foundation with a gap is calculated by TLM. The piles are modelled as compressible Timoshenko-beam elements and assumed to be fixed to the rigid foundation, and the soil is assumed to be bonded completely to the pile. The semi-infinity of soil is expressed with analytical half-space boundary. Dynamic stiffness of the single pile and the soil displacement are obtained accurately. As for the pile groups, after composing the flexibility matrix at the pile heads of the entire group piles, the dynamic stiffness is obtained by reducing the inverse of the flexibility matrix. For the rigorous evaluation of the flexibility matrix for the entire group piles system, the calculations of pile head displacements caused by the unit load applied on the other pile heads are required. However, the approximate flexibility matrix is used in this paper. Assuming the soil-single pile system and applying the unit load on the pile head, the soil surface displacements due to these loading are approximately used for the flexibility matrix of entire group piles system as shown in Fig. 2.

Phase 2 : Dynamic stiffness in case of the contact between the foundation bottom and the ground surface is calculated approximately from the decomposing technique [3] as ;

$$K_p^* = K_p + K_s - K_{sp} \tag{1}$$

where, K_p^* , K_p , K_s , K_{sp} are the dynamic stiffness of pile foundation without a gap, pile foundation with a gap (obtained in Phase 1), surface foundation, and foundation supported by soil columns, respectively.

Phase 3 : The stiffness of the embedded foundation on the pile groups is evaluated by adding the backfilling soil springs to the pile groups stiffness. Both stiffnesses are assumed to be calculated independently. The stiffness obtained in Phase 2 is applied to that of pile groups, while the backfilling soil springs are calculated from Novak's theory [4].

From these methods, the dynamic stiffnesses of pile group foundations under each condition are evaluated.

3 COMPARISONS OF THE ANALYSIS WITH TEST RESULTS

For verification of above mentioned analysis methods, correlation analyses are conducted with the test results of the four-pile model reported in previous Part 1.

3.1 Phase 1 (with a gap)

Fig. 3 illustrates the soil profile, and Table 1 indicates the analysis conditions. The analysis for case(1) uses the soil constants obtained from the soil investigation results, while the shear wave velocity of the soil around the piles is decreased to 90% and 80% respectively for the cases (2) and (3).

Fig. 4 shows a comparison of the dynamic stiffness of the soil-piles system. For the comparison with the test results, the horizontal (K_H) and rotational (K_R) dynamic stiffness for each analytical condition are calculated by using the test results of the horizontal displacement u_0 and the rotation angle ϕ at the block bottom center.

$$\begin{aligned} K_H &= K_{HH} + K_{HR}\cdot(\phi/u_0) \\ K_R &= K_{RR} + K_{HR}\cdot(u_0/\phi) \end{aligned} \tag{2}$$

Where, K_{HH} , K_{HR} , and K_{RR} are the stiffnesses calculated by TLM. The results of case(2) with the shear wave velocity of the soil reduced to 90% show good agreement with the test results. When the accuracy of the usual soil investigation results are considered, the decreasing shear velocity of 90% is acceptable. Accordingly, this analysis method is verified to be applicable from the practical point of view.

3.2 Phase 2 (without a gap)

For the calculation of the dynamic stiffness of surface foundation (K_S), the effective contact length of the block bottom is chosen as shown in Fig. 5. The soil properties of case(2) in Phase 1 are used for this analysis.

Fig. 6 shows the analysis results in Phase 2. The results of case(4), using the original length of the block bottom, shows the increasing tendency of dynamic stiffness in comparison with the test results. This result shows that the contact earth pressure of the corner of the block bottom is reduced by piles, and the contact earth pressure distribution is different from that of the surface foundation. Case(5) with the effective length ℓs =0.8 shows good agreement with the test results, except for the vertical dynamic stiffness.

3.3 Phase 3 (with embedment)

Table 2 indicates the analysis conditions for backfilling soil, and Fig. 7 illustrates the analysis models. For the cases (7) and (8), soft zone of soil around the block side is taken into consideration. As for the base of the block, the dynamic stiffness obtained from case(5) in Phase 2 is used.

Fig. 8 shows the analysis results. The results of case(6) without soft zone shows a large deviation from the test results, especially in the imaginary part. The results of case(7), with soft zone at half part of the backfilling soil layer, shows good correspondence with the test results, while the case(8), with soft zone over the backfill soil layer, reduces the dynamic stiffness considerably. The deviation between analysis and tests in vertical dynamic stiffness is due to the deviation explained in Phase 2.

3.4 Displacement Distribution of the Pile

Fig. 9 shows the comparison as for the horizontal displacement along a pile of the four-pile model. The broken line is the static displacement obtained from Chang's method (the theory of beams on elastic springs). The test results and the analysis results by TLM are drawn as the absolute values of the dynamic displacement with complex values. As the analysis conditions, the horizontal displacement at the pile head (0.1m below the pile head) and rotation angle of the block are adjusted to the test values. The soil properties of case(2) is used for this analyses.

The test results is reproduced very well by TLM. The displacements by Chang's method exhibits a rapidly decreasing distribution in comparison with the tests. In detail, the deviation between the analyses and tests increase slightly in the order of test step 2 to 4. The reason for this is the fact that the methods using a single pile model for analysis does not take into account the vibration force which flows into the soil through the block bottom and the sides.

4 CONCLUDING REMARKS

An analysis method for the dynamic stiffness of pile groups in multilayered soil using thin layered method has been presented. From the correlation of analysis results with test results, the following concluding remarks are derived.

(1) For the dynamic stiffness of the pile foundation with a gap between the foundation bottom and the soil surface, the applied method is efficient and rational.

(2) For the case of contact, the dynamic stiffness can be evaluated by the method of decomposing the stiffness of the system to be solved, and by consideration of the effective contact length of the foundation.

(3) For the case of embedment, the embedding effect is evaluated by adding the backfill soil springs to the dynamic stiffness of the pile groups. The soft backfill soil zone must be taken into account.

(4) By this method, the displacement distribution of the pile is also analyzed with good accuracy. From the analysis results, the static displacement obtained from Chang's method show a rapidly decreasing tendency in comparison to the dynamic displacement obtained from this method and the tests.

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[3] Masuda,K.,Urao.K.,et al.(1988),"Forced Vibration Test and Its Analytical Study for Embedded Foundation Supported by Pile Groups", Proc. of 9th WCEE, Tokyo, Japan.

[4] Novak,M.,Nogami,T.,Aboul-Ella,F.(1978),"Dynamic Soil Reactions for Plain Strain Case", J. of Eng. Mech. Div., ASCE, Vol.104, No. EM4.

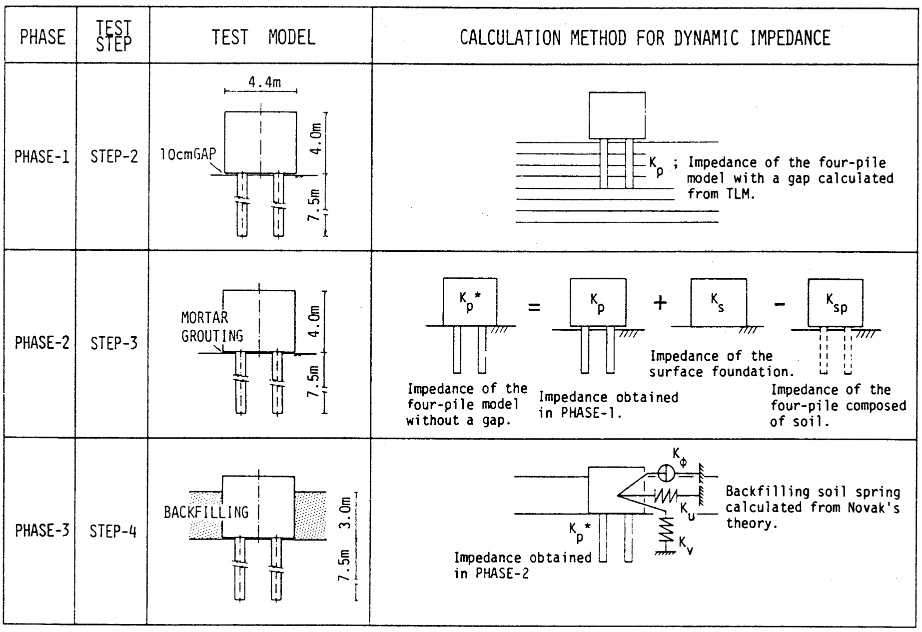


Fig. 1 Analysis Process.

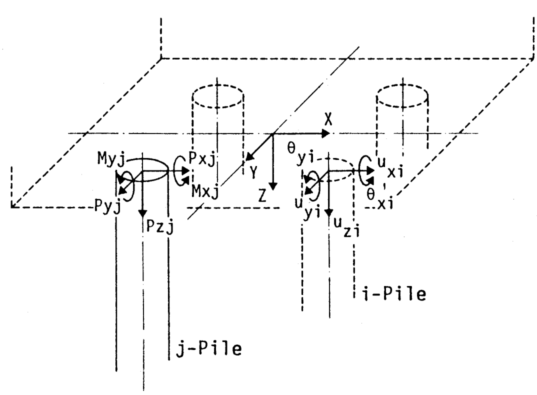


Fig. 2 Description of the Calculation Method for Pile Head Flexibilities.

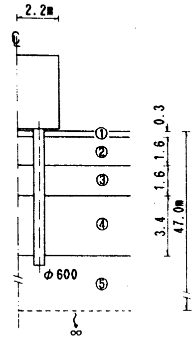
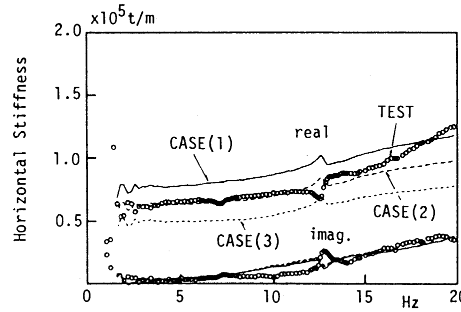


Fig. 3 Analysis Model
for Phase-1.

Table 1 Analysis Conditions for Phase-1.

	S-Wave Velocity Vs(m/s)			Mass Density γ(t/m³)	Poisson's Ratio ν	Damping Factor h(%)
	CASE(1)	CASE(2)	CASE(3)			
①	180	162	144	1.80	0.219	2.0
②	250	225	200	1.80	0.179	2.0
③	320	288	256	1.80	0.292	2.0
④	320	288	256	1.80	0.429	2.0
⑤	510	510	510	1.75	0.459	1.0

	Mass Density γ(t/m³)	Young's Modulus E(t/m²)	Poisson's Ratio ν	Damping Factor h(%)
Pile	2.4	2.4×10^6	0.167	0



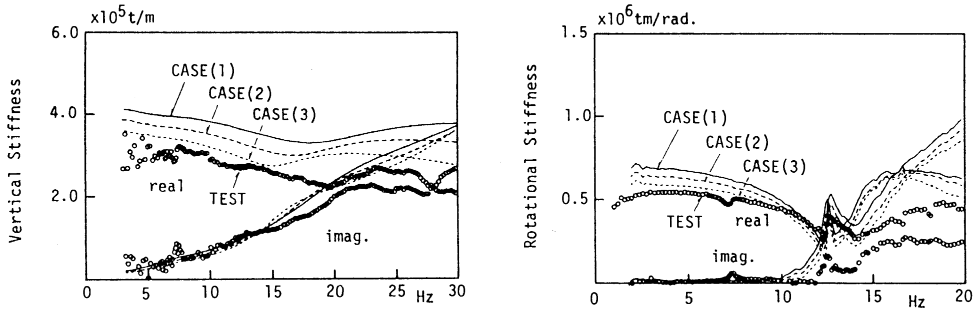


Fig. 4 Comparison of Analysis with Test Results in Phase-1; Dynamic Stiffness of the Four-Pile Model with a Gap.

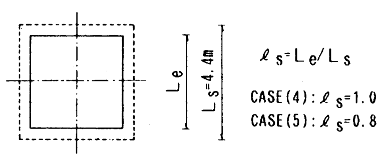
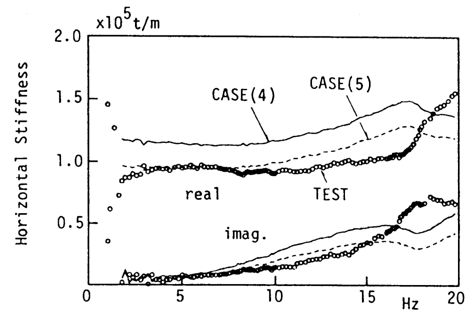


Fig. 5 Analysis Condition for Phase-2; Effective Contact Length of the Block Bottom.



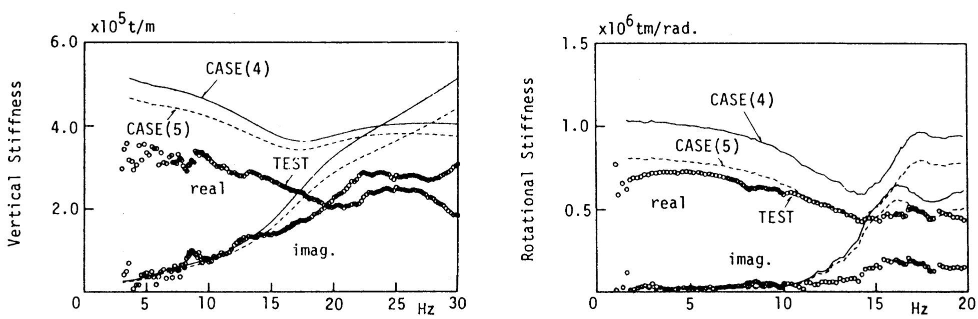


Fig. 6 Comparison of Analysis with Test Results in Phase-2; Dynamic Stiffness of the Four-Pile Model without a Gap.

Table 2 Analysis Conditions for Backfilling Soil in Phase-3.

	S-Wave Velocity Vs(m/s)	Mass Density γ(t/m³)	Poisson's Ratio ν	Damping Factor h(%)
①	95	1.85	0.199	3.0
②	145	1.85	0.341	3.0
③	50	1.85	0.199	3.0

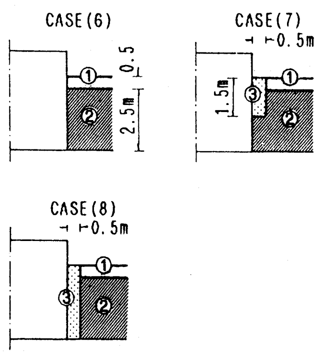


Fig. 7 Analysis Model for Backfilling Soil in Phase-3.

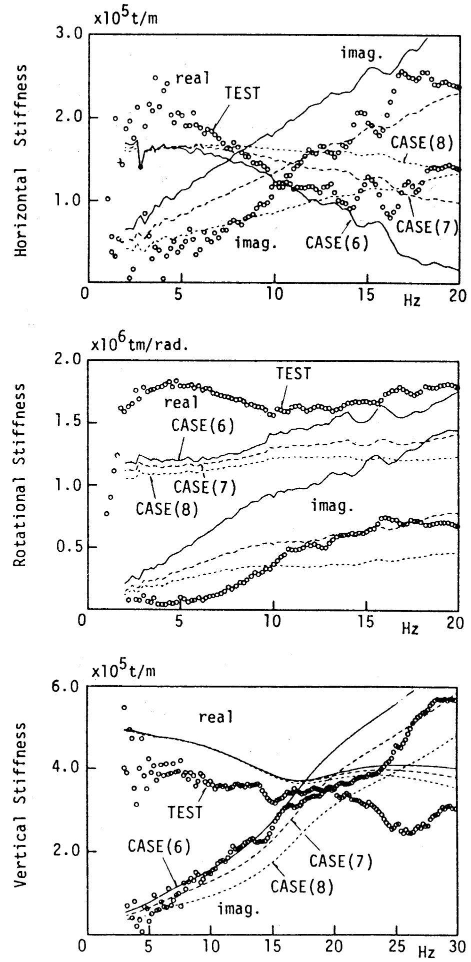


Fig. 8 Comparison of Analysis with Test Results in Phase-3; Dynamic Stiffness of the Four -Pile Model with Embedment.

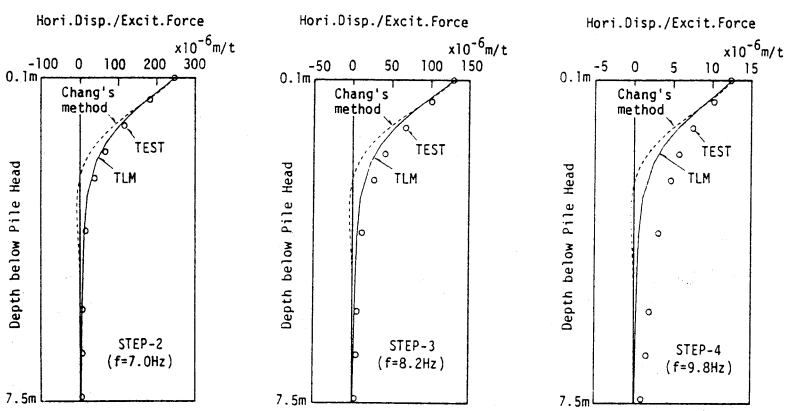


Fig. 9 Comparison of Analysis with Test Results; Horizontal Displacement Distributions of Pile.