COEFFICIENT OF DYNAMIC HORIZONTAL SUBGRADE REACTION OF PILE FOUNDATIONS ON PROBLEMATIC GROUND IN HOKKAIDO

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Abstract

In this study, static loading tests and dynamic shaking tests of pile foundations were conducted by using centrifuge models on problematic peaty ground, which is distributed widely in Hokkaido area of Japan. The test results were analyzed focusing on the coefficients of both static and dynamic horizontal subgrade reaction of the pile foundation, and the following findings were obtained.

1) The dynamic interaction characteristics between piles and grounds for the problematic peat are quite different from that for usual clay and sandy soils on the basis of the results of dynamic centrifuge model tests.
2) The ratio (α) of the coefficient of dynamic horizontal subgrade reaction (K_{he}) and that of static horizontal subgrade reaction (K_h) for peat does not be coincident with the values specified in the Specifications for Highway Bridges in Japan.

Introduction

Regarding methods for estimating seismic performance of pile foundation as prescribed in the Specifications for Highway Bridges (Japan Road association, 2002), it is known that the influence of deformations of pile foundations during earthquakes may be obtained from linearly modeled springs, which normally represent subgrade resistance to the pile foundation. In this method, the coefficient of dynamic horizontal subgrade reaction (K_{he}) is ex-pressed as the product ($K_{he} = \alpha K_h$) of the coefficient of static horizontal subgrade reaction (K_h) and a correction factor (α), when the seismic intensity method or the ultimate lateral strength method during earth-quake is adopted. The correction factor is thus set in a relatively simplified manner at 2.0 for the seismic intensity method and 3.0 for the ultimate lat-eral strength method. Since that the pile system is performed as a typical soil-structure interaction problem during earthquake as shown in FIGURE 1, and its horizontal behavior is supposed to be more complicated comparing with that of the superstructure, however, it is hard to say that the current seismic design method, in which the dynamic subgrade reaction is considered to be uniformly distributed, could correctively reflect the practical dynamic behavior of the pile foundation.

In this study, a series of static loading tests and dynamic shaking tests for pile foundations by using centrifuge models on problematic peaty ground was comprehensively programmed, and the dynamic performance of the pile foundation for different ground conditions was discussed. This paper introduces the detail of the test program, and consideration on the coefficient of dynamic horizontal subgrade reaction

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(K_{he}) for the problematic peaty ground, which is distributed widely in Hokkaido area of Japan, on the basis of the test results.

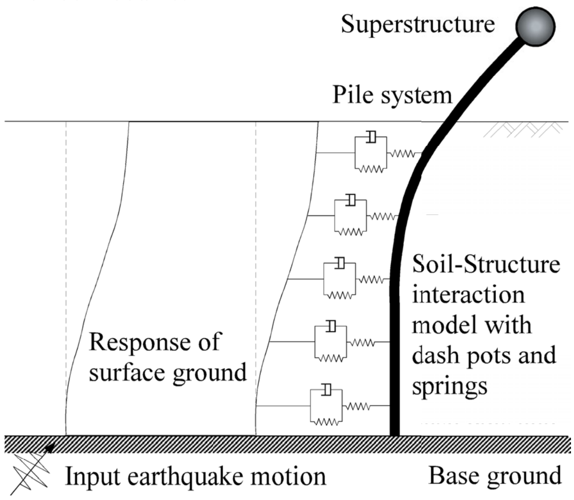

FIGURE 1. DYNAMIC INTERACTION MODEL OF PILE FOUNDATION.

Overview of the centrifuge model test

In the centrifuge model test, a laminar container with inner dimensions of 700 mm x 200 mm x 350 mm was used, and 1/50 scaled models of the pile foundation were prepared for the test. Both the static and dynamic tests have been carried out at a 50G (G: gravitational acceleration, 9.81 m/s^2) centrifugal acceleration level on the 5 m diameter beam centrifuge at Civil Engineering Research Institute of Hokkaido.

As shown in FIGURE 2, a single pilesuperstructure system was used in the model test. The model pile was prepared by specially finishing steel pipe, with 10 mm in outer diameter, 0.2 mm in wall thickness and 400 mm in length. 12 Strain gauges were installed inside the model pile for measuring the longitudinal bending during test. A prototype steel pipe pile with 500 mm in outer diameter, 10 mm in thickness and 20 m in length was simulated in the test.

In the model, the lower end of model pile was fixed to the bottom of the model container, and then filled with a gypsum layer with 4 cm in thickness to form a fixed condition of the pile end. To simulate the weight of superstructure, a mass block of 0.4 kg was fixed to the upper side of the model pile. The equivalent mass in prototype scale was 50 tons. The fact that nature frequency of the shaking table and model container system is far higher than that of the model ground and pilesuperstructure system was confirmed through a preliminary shaking test by input white noise with a frequency spectrum of 1 to 10 Hz in prototype scale. The similarity rates of the model are shown in TABLE 1.

Kaolin clay and peat were used as model ground materials to verify the characteristics of subgrade reaction for different ground type. For the peaty ground, moisture content and preconsolidation surcharge loads were changed as the test conditions. TABLE 2 shows the test cases and ground conditions. The model grounds were prepared by compacting the model material layer by layer in a thickness of 2 cm and a constant unit weight. Accelerometers for picking up input motion, response of the model ground and superstructure, were respectively installed in the positions as shown in FIGURE 2.

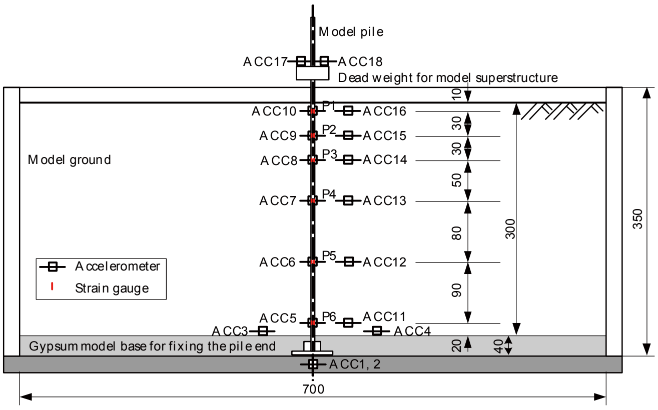

FIGURE 2. MODEL SETUP (unit: mm).

TABLE 1. SIMILARITY RATES.

Item		Notation	Unit	Scale	Model	Prototype
Ground Thichness	Surface ground	H_{g1}	m	$1/\lambda$	0.3000	15.000
	Base ground	H_{g2}	m	$1/\lambda$	0.0400	2.000
Pile	Embedding depth	L	m	$1/\lambda$	0.3300	16.500
	Outer diameter	D	m	$1/\lambda$	0.0100	0.500
	Wall thickness	t	m	$1/\lambda$	0.0002	0.010
	Modulus of elasticity	E	MPa	1	$2.1\text{x}10^5$	$2.1\text{x}10^5$
	Moment of inertia	I	m^4	$1/\lambda^4$	$7.3952\text{x}10^{-11}$	$4.6220\text{x}10^{-4}$
	Cross-sectional area	A	m^2	$1/\lambda^2$	$6.1575\text{x}10^{-6}$	$1.5394\text{x}10^{-2}$
Mass of superstructure		M	ton	$1/\lambda^3$	$4.000\text{x}10^{-4}$	50.000
Input acceleration level		a	G	λ	1	0.020

Note: $1/\lambda$=model/prototype=1/50

TABLE 2. TEST CASE AND GROUND CONDITIONS.

Test case	CASE1	CASE2	CASE3	CASE4	CASE5
Ground material	Kaolin	Peat			
Unit weight γ_t (kN/m^3)	10.24	9.582	7.551	7.551	7.551
Moisture content W_0 (%)	-	200	150	150	150
Pre-consolidation surcharge p_0 (kN/m^2)	-	0	0	25	50
Cone index p_c (MN/m^2)	0.35	0.20	0.13	0.25	0.15

<u>STATIC HORIZONTAL SUBGRADE REACTION</u>

Outline of the static horizontal loading test

The static horizontal loading tests of piles for the respective ground conditions were carried out using displacement controlled method, in which horizontal load is applied to the head of model pile at a rate of 0.1 mm/min via a motor driven loading device. Pile displacement was measured using a pair of laser type displacement transducers and the bending strains of the pile were measured from the strain gauges. The maximum displacement of model pile at ground surface was set to be approximately = 2.5 mm (125 mm in prototype scale) according to the permissible displacement for the prototype pile, and the keeping time for the maximum load was set to be 15 minutes in accordance with the criteria of loading test for piles specified by the Japanese Geotechnical Society (1983).

Calculation of the coefficient of static subgrade reaction using Winkler's spring model

From the results of the static horizontal loading test, the relationships between horizontal load, distribution of the horizontal pile displacement and the longitudinal bending moment distribution of the pile were obtained. The coefficient of static horizontal subgrade reaction (K_{h1}) was back calculated using Winkler's spring model based on the elasticity theory. The reference horizontal displacement of the pile at the ground surface for the back analysis was set to be equivalent to 1% of the pile diameter according to the Specifications for Highway Bridges. The calculated are shown in TABLE 3. As an example, the relationships between horizontal load, distribution of the horizontal pile displacement and the longitudinal bending moment distribution of the pile for CASE1 (Kaolin clay ground) is shown in FIGURE 3.

TABLE 3. STATIC COEFFICIENT OF SUBGRADE REACTION K_{h1}.

Test case	CASE1	CASE2	CASE3	CASE4	CASE5
Ground material	Kaolin	Peat			
Moisture content W_0 (%)	-	200	150	150	150
Pre-consolidation surcharge p_0 (kN/m^2)	-	0	0	25	50
K_{h1} (kN/m^2)	5367	2200	2625	3010	3750

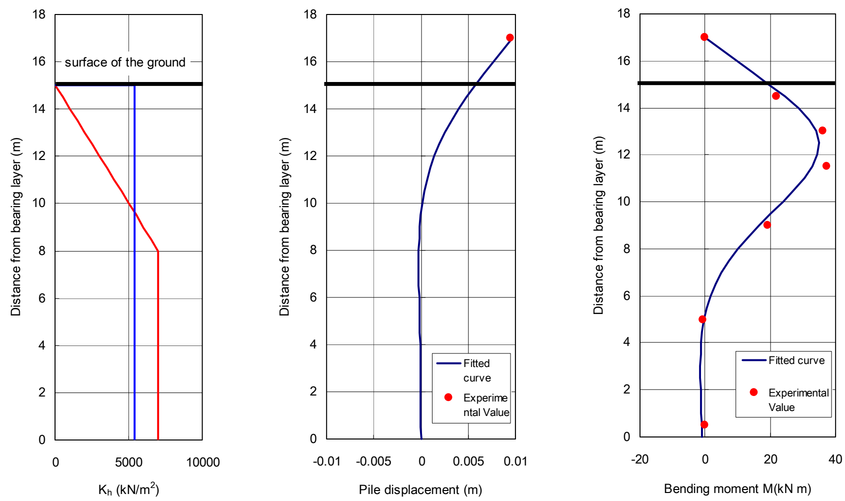

FIGURE 3. RELATIONSHIP BETWEEN K_{h1}, DISTRIBUTION OF HORIZONTAL PILE DISPLACEMENT AND BENDING MOMENT OF THE PILE (CASE1).

Calculation of the coefficient of static subgrade reaction using p-δ curve method

FIGURE 4 and 5 illustrate the relationship between the subgrade reaction p and relative displacement of the pile and ground for all the test cases. Based on these relationships, the coefficients of static subgrade reaction (K_{h2}) for different type of ground and different depth of the pile were calculated as shown in TABLE 4 and FIGURE 6.

Chang's method (Chang, 1937) is usually adopted for estimating the horizontal resistance of pile foundation, in which the coefficients of subgrade reaction are supposed to be uniformly distributed. It was revealed that the distribution of K_{h2} along the pile length was not uniform for different ground condition.

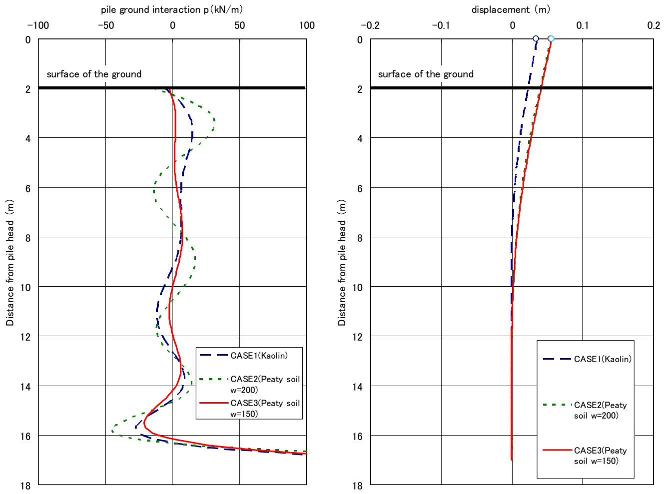

FIGURE 4. DISTRIBUTIONS OF p AND δ FOR CASE1, 2 AND 3.

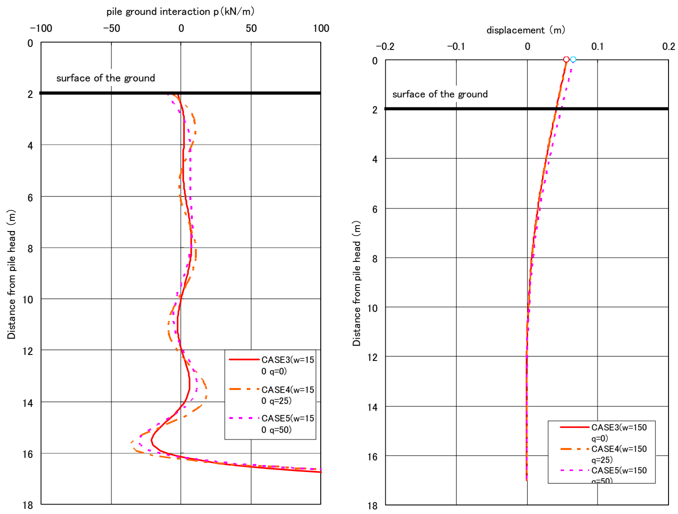

FIGURE 5. DISTRIBUTIONS OF p AND δ FOR CASE3, 4 AND 5.

TABLE 4. STATIC COEFFICIENTS OF SUBGRADE REACTION K_{h2}.

Test case		CASE1	CASE2	CASE3	CASE4	CASE5
Ground material		Kaolin	Peat			
Moisture content W_0 (%)		-	200	150	150	150
Pre-consolidation surcharge p_0 (kN/m^2)		-	0	0	25	50
K_{h2} (kN/m^2)	GL-2.0m	2879	1379	134	297	72
	GL-3.5m	7182	615	371	715	1638

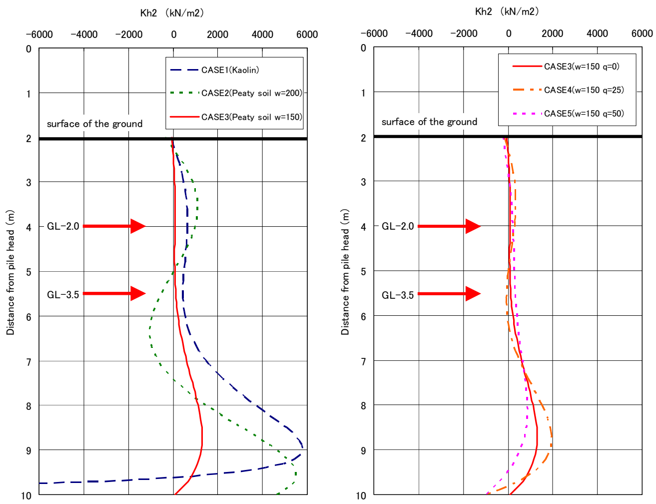

FIGURE 6. DISTRIBUTION OF K_{h2} ALONG THE PILE LENGTH.

DYNAMIC HORIZONTAL SUBGRADE REACTION

Method used for calculation of the coefficient of dynamic subgrade reaction

In the current Specifications for Highway Bridges, the determination of the coefficient of dynamic subgrade reaction is by means of determining a correction factor for predicting the ground stiffness relative to the coefficient of static subgrade reaction. In this study, the following methods: (a) p-δ curve method; and (b) eigenvalue analysis, were adopted for calculating the coefficients of dynamic subgrade reaction. The correction factors which were determined on the basis of the above mentioned methods are discussed by comparing with the coefficient of static subgrade reaction.

The relative displacement of pile and ground and the dynamic subgrade reaction p for calculation of the coefficient of dynamic subgrade reaction were supposed to change with the nature frequency of the pile foundation. Thus, as a method for calculating the coefficient of dynamic subgrade reaction, analysis was conducted at the natural frequency of the pile foundation, for which the relative displacement of pile and ground appears to be the most remarkable state. Then the coefficients of both dynamic and static subgrade reaction were compared with each other. FIGURE 7 illustrates the transfer functions of the pile foundation, which were obtained by the curve fitting of the peak Fourier spectrum for shaking tests using sine waves with different frequency. The natural frequencies of the pile foundation for different test case are shown in TABLE 5.

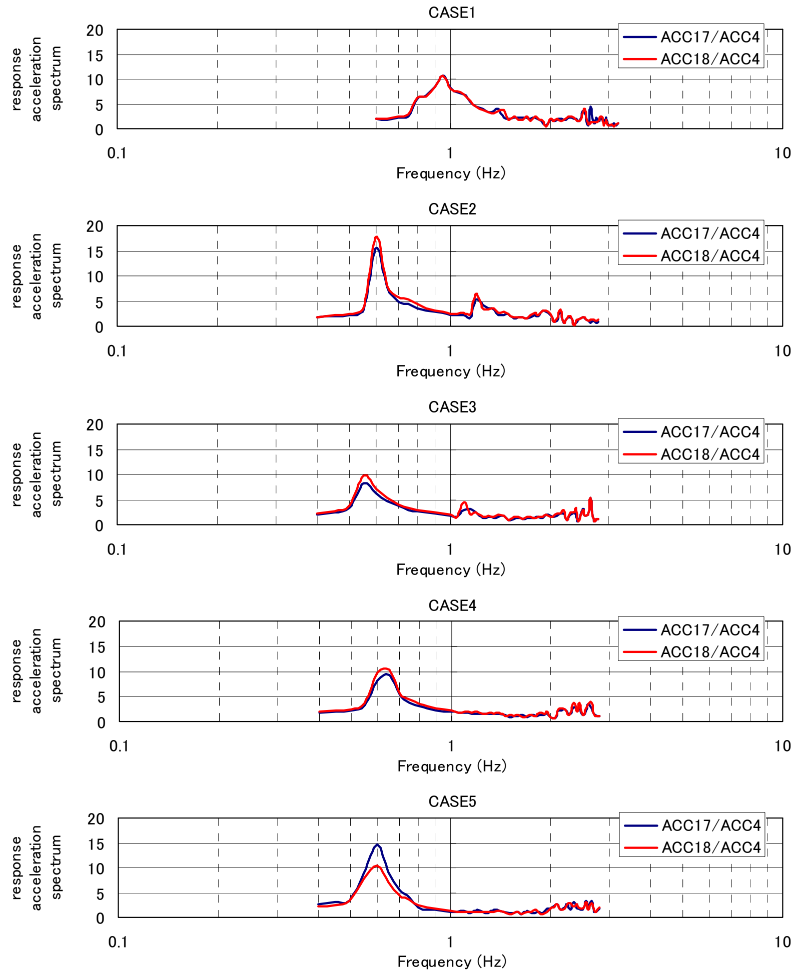

FIGURE 7. TRANSFER FUNCTIONS OF THE PILE FOUNDATIONS.

TABLE 5. NATURAL FREQUENCIES OF THE PILE FOUNDATIONS.

Test case	CASE1	CASE2	CASE3	CASE4	CASE5
Ground material	Kaolin	Peat			
Moisture content W_0 (%)	-	200	150	150	150
Pre-consolidation surcharge p_0 (kN/m^2)	-	0	0	25	50
Natural frequency f_p (Hz)	0.95	0.60	0.55	0.65	0.60

Eigenvalue analysis method

Numerous experimental and theoretical studies have been conducted focusing on dynamic interaction behavior between pile and ground, verification for such studies has also been carried out using two- and three-dimensional FEM numerical analyses (e.g. Ogawa & Ogata, 1997). In this study, therefore, the coefficient of dynamic subgrade reaction was firstly evaluated using eigenvalue analysis (mode analysis with free vibration) by supposing that the shape of longitudinal distribution of the dynamic subgrade reaction is as same as that of static subgrade reaction. Through the model analysis, the natural frequency of the pile foundation can be obtained for a given subgrade reaction (FIGURE 8). The coefficients of dynamic subgrade reaction (K_{he1}) at the natural frequency of the pile foundation for the test cases were respectively determined from the relationships between the natural frequency of the pile foundation and the coefficient of dynamic subgrade reaction. The coefficients of dynamic subgrade reaction (K_{he1}) obtained from the eigenvalue analyses for the test cases are shown in TABLE 6, together with the coefficients of static subgrade reaction (K_{h1}) and the ratio of K_{he1} to K_{h1} (=correction factor).

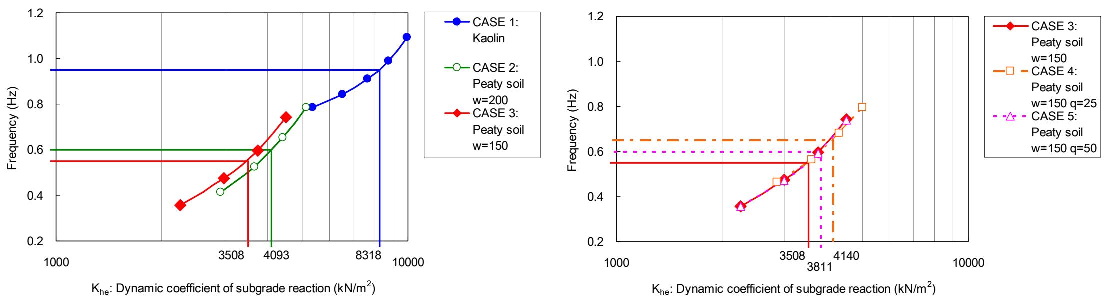

FIGURE 8. RELATIONSHIPS BETWEEN NATURAL FREQUENCY AND K_{he1}.

TABLE 6. COEFFICIENT OF DYNAMIC SUBGRADE REACTION K_{he1}.

Test case	CASE1	CASE2	CASE3	CASE4	CASE5
Ground material	Kaolin	Peat			
Moisture content W_0 (%)	-	200	150	150	150
Pre-consolidation surcharge p_0 (kN/m^2)	-	0	0	25	50
K_{he1} (kN/m^2)	8318	4093	3508	4140	3811
K_{h1} (kN/m^2)	5367	2200	2625	3010	3750
$\alpha = K_{he1}/K_{h1}$	1.550	1.860	1.336	1.375	1.016

p-δ analysis method

As another method for calculating the coefficient of subgrade reaction through interaction between the pile and ground, a socalled p-δ method for determining the coefficient of dynamic subgrade reaction (K_{he2}) was adopted. In this method, the coefficient of dynamic subgrade reaction K_{he2} is expressed as p/ , where p is the dynamic subgrade reaction force to the pile, and is the relative displacement between pile and ground. The analysis was carried out under the condition that the interaction between pile and ground behaves elastically, since the shaking tests were performed at a low input acceleration level of around 0.02G in prototype scale. The plasticizing of the pile and ground was not taken into account in the calculation.

Pile displacement p and subgrade reaction force p was calculated from the distribution of bending moment along the pile length by supposing that the pile is an elastic beam supported with Winkler's elastic springs. The distribution of bending moment was determined by a curve fitting for the measured bending strains of the pile. The functions used for curve fitting were approximated with the polynomials of an 11thfunction. The displacement of the pile p was calculated by integrating twice the fitted curve and considering the boundary conditions of the pile, while the subgrade reaction p was predicted by differentiating twice the fitted curve. The boundary conditions of the pile for determining the indefinite constants generated from the integration, were taken as that the deflection angle and displacement at the fixed lower end were supposed to be zero. Displacement in the ground g during shaking was calculated by the secondorder Fourier integration of ground acceleration measured. To ignore the noise mixed in the measured data, band filter processing was carried out for the measured acceleration prior to integration. Relative displacement between pile and ground was finally calculated from p and g. FIGURE 9 illustrates the flowchart of calculations mentioned above.

FIGURE 10 to 14 show the relationship of subgrade reaction force p and relative displacement between pile and ground at different depth for all the test cases. Unique data with different trend to the others was found at the point of GL-3.5m of CASE2, this was considered as caused by the curve fitting and also the measured ground acceleration at this point. The coefficients of dynamic subgrade reaction (K_{he2}) calculated for the points of GL-2.0m and GL-3.5m, which the dynamic behavior of the pile foundation is supposed to be strongly affected, are shown in TABLE 7. It is clear that the K_{he2} changes with not only the ground conditions but also the depth of the ground.

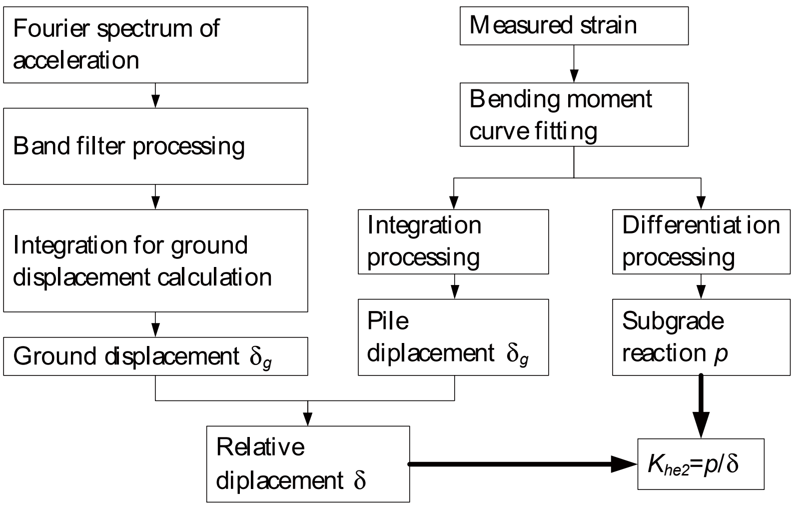

FIGURE 9. FLOWCHART OF *p*-*δ* METHOD.

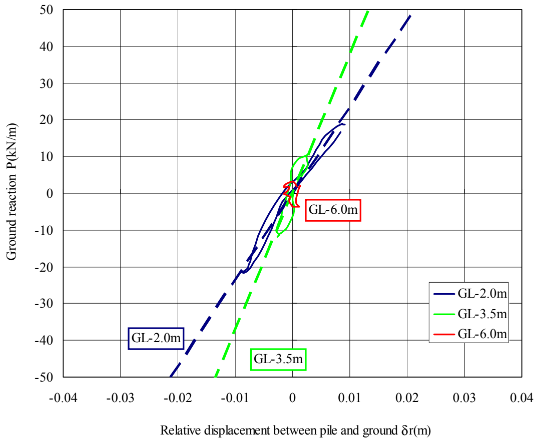

FIGURE 10. RELATIONSHIP BETWEEN p AND δ FOR CASE1.

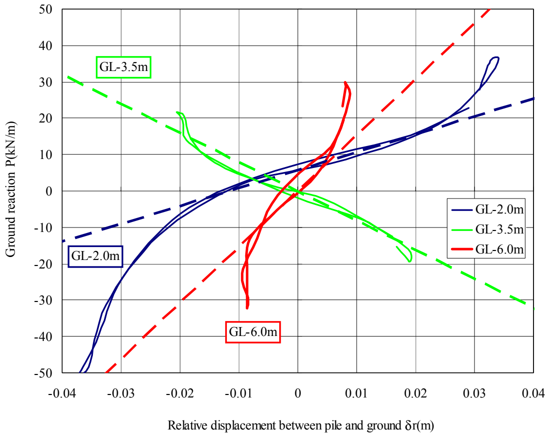

FIGURE 11. RELATIONSHIP BETWEEN p AND δ FOR CASE2.

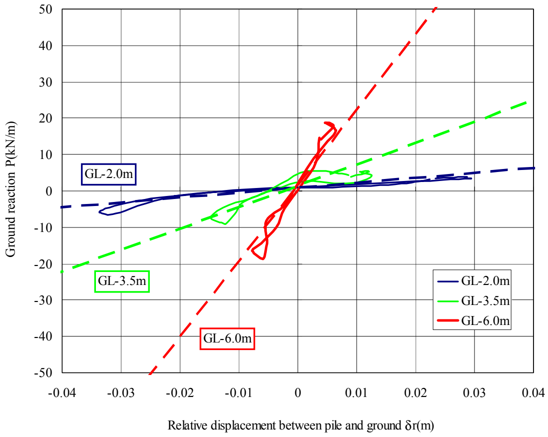

FIGURE 12. RELATIONSHIP BETWEEN p AND δ FOR CASE3.

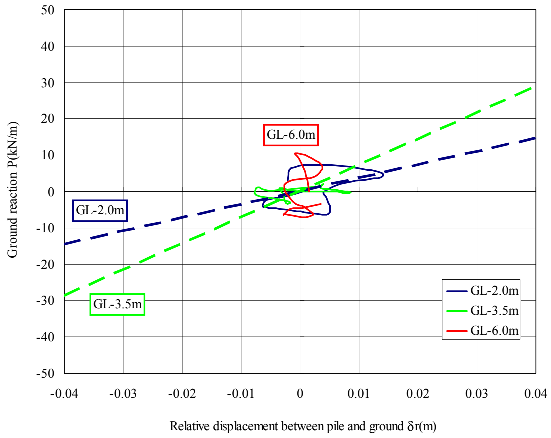

FIGURE 13. RELATIONSHIP BETWEEN p AND δ FOR CASE4.

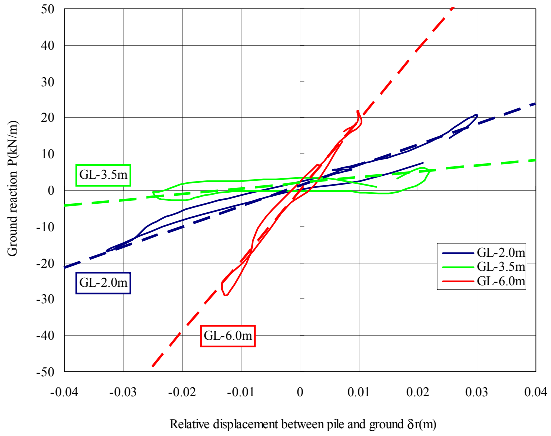

FIGURE 14. RELATIONSHIP BETWEEN p AND δ FOR CASE5.

TABLE 7. COEFFICIENT OF DYNAMIC SUBGRADE REACTION K_{he2}.

Test case		CASE1	CASE2	CASE3	CASE4	CASE5
Ground material		Kaolin	Peat			
Moisture content W_0 (%)		-	200	150	150	150
Pre-consolidation surcharge p_0 (kN/m^2)		-	0	0	25	50
K_{he2} (kN/m^2)	GL-2.0m	2350	493	135	365	565
	GL-3.5m	3745	803	587	720	156

DISCUSSION

Comparison between K_{he} and K_h

TABLE 8 illustrates the results of the coefficients of both dynamic and static subgrade reaction calculated for all the test cases together with the correction factor . It is clear that the coefficients of both dynamic and static subgrade reaction drawn from this study do not agree with that prescribed in the Specifications for Highway Bridges. The changes in K_{he} and K_h along the depth of the ground, which have not been specified in the Specification, should also be considered for the seismic design of the pile foundation.

TABLE 8. COMPARISON BETWEEN K_{he} AND K_h.

Test case		CASE1	CASE2	CASE3	CASE4	CASE5
Ground material		Kaolin	Peat			
Moisture content W_0 (%)		-	200	150	150	150
Pre-consolidation surcharge p_0 (kN/m^2)		-	0	0	25	50
K_{he1} (kN/m^2)		8318	4093	3508	4140	3811
K_{h1} (kN/m^2)		5367	2200	2625	3010	3750
$\alpha = K_{he1}/K_{h1}$		1.550	1.860	1.336	1.375	1.016
K_{he2} (kN/m^2)	GL-2.0m	2350	493	135	365	565
	GL-3.5m	3745	803	587	720	156
K_{h2} (kN/m^2)	GL-2.0m	2879	1379	134	297	72
	GL-3.5m	7182	615	371	715	1638
$\alpha = K_{he2}/K_{h2}$	GL-2.0m	0.816	0.358	1.007	1.229	7.847
	GL-3.5m	0.521	1.306	1.582	1.007	0.095

Effect of moisture content of peaty ground

TABLE 9 illustrates the test results of the case where the moisture content of the peaty ground was changed from 150% to 200%. The unit weight was higher when W0 = 200% than that when W0 = 150%. No significant differences were, however, observed in these two test cases.

TABLE 9. TEST RESULTS OF THE CASE WITH DIFFERENT MOISTURE CONTENT.

Test case	CASE2	CASE3
Ground material	Peat	
Moisture content W_0 (%)	200	150
Unit weight γ_t (kN/m^3)	9.582	7.551
Natural frequency f_p (Hz)	0.60	0.55
K_{he1} (kN/m^2)	4093	3508
K_{h1} (kN/m^2)	2200	2625

Effect of pre-consolidation surcharge of peaty ground

TABLE 10 illustrates the results of the case where pre-consolidation surcharge p0 was changed to 0, 25 and 50 kN/m^2. The static and dynamic coefficients of subgrade reaction of the piles tended to increase with the increase of p0. Effects were insignificant, however, and improvements in the coefficient of subgrade reaction could not be expected from the pre-consolidation surcharge on peaty ground.

TABLE 10. TEST RESULTS OF THE CASES WITH DIFFERENT PRE-CONSOLIDATION SURCHARGE.

Test case	CASE3	CASE4	CASE5
Ground material	Peat (W_0=151%)		
Pre-consolidation surcharge p_0 (kN/m^2)	0	25	50
Unit weight γ_t (kN/m^3)	7.551	7.551	7.551
Natural frequency f_p (Hz)	0.55	0.65	0.60
K_{he1} (kN/m^2)	3508	4140	3811
K_{h1} (kN/m^2)	2625	3010	3750

CONCLUSIONS

On the basis of the test results, the following findings were obtained concerning the characteristics of dynamic horizontal subgrade reaction of the pile foundations constructed in the peaty ground:

(1) Through a series of dynamic centrifuge model tests, the fundamental dynamic behavior of pile and ground were clarified for different ground condition.

(2) The coefficient of dynamic subgrade reaction was dependent on the natural frequency of the pile foundation, and the value calculated using the eigenvalue analysis method (K_{he1}) exhibits different relationships depending on the vibration mode of the ground and the natural frequency of pile in different ground condition.

(3) The coefficient of subgrade reactions calculated using p-δ method (K_{he2}) changes with not only ground condition but also the depth of the ground. Such characteristics of the coefficients of both dynamic and static subgrade reaction drawn from this study do not agree with that prescribed in the current design specification. The data

obtained from this study should be the useful information for future studies.

(4) Tests were carried out by changing the moisture content and pre-consolidation surcharge for peaty ground, no significant differences in coefficients of subgrade reaction were found under the test conditions.

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