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A STUDY ON THE CHARACTERISTICS OF DYNAMIC HORIZONTAL SUBGRADE REACTION FOR DIFFERENT TYPES OF GROUND BY CENTRIFUGE MODEL EXPERIMENTS USING SINGLE PILE MODELS

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SUMMARY

In pile foundation seismic design, it is necessary to appropriately evaluate the response of dynamic interaction of piles and the ground and vibration characteristics (natural period) depending on ground conditions. In this study, static horizontal loading and dynamic vibration tests of single pile models were conducted using centrifuge model tests in a 50 G field for sandy soil ground, as well as for clayey soil ground and volcanic ash ground. Accordingly, basic earthquake-proof evaluation focused on the pile ground spring constant was conducted. The p-δ method, which focuses on the relative displacement of piles and ground during earthquakes, and the eigenvalue analysis method for calculation of dynamic subgrade reaction from the natural frequency of piles were used as analysis methods. Results showed that the dynamic coefficient K_{he} of the horizontal subgrade reaction of piles must be properly determined by comprehensive evaluation based on differences in strength characteristics and other earthquake performance for each ground type rather than only determining K_{he} from the relationship with the static coefficient K_h of horizontal subgrade reaction ($K_h = \alpha K_{he}$), or from shear elastic waves and other foundation strength constants.

INTRODUCTION

In pile foundation seismic design methods[1), 2), 3)], the characteristics of dynamic horizontal subgrade reaction during earthquakes, including nonlinearity and other complex factors, must be accurately predicted depending on the ground properties. For pile behavioral analysis during earthquakes, verification by the seismic horizontal strength method and the dynamic analysis

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method is provided in addition to the conventional seismic intensity method. These seismic design methods are thought to have several commonalities primarily from the structural standpoint of ensuring a certain level of deformability on the pile body against seismic action. In earthquake-proof evaluation of the ground, however, the dynamic coefficient of horizontal subgrade reaction is principally determined from the static foundation strength constants, although there are rough divisions by foundation strength based on the results of ground surveys for pile foundation seismic design.

In this study, static horizontal loading and dynamic vibration tests of single pile models were conducted using centrifuge model tests in a 50 G field for sandy soil ground as a base, as well as for clayey soil ground and volcanic ash ground, to simulate peat, which is a special type of soil widely distributed throughout Hokkaido. Based on the test results, basic earthquake-proof evaluation was conducted concerning the characteristics of the dynamic coefficient K_{he} of the horizontal subgrade reaction of piles from the relationship with the static coefficient K_h of horizontal subgrade reaction for each ground type.

OVERVIEW OF THE CENTRIFUGE MODEL TEST

In the centrifuge model test, a steel model container with inner dimensions of 700 mm x 200 mm x 350 mm was used, and model ground and piles on a scale of 1:50 of the actual size were placed inside it. To satisfy the law of similarity for the soil stress level, static horizontal loading and dynamic vibration tests of single piles were conducted by applying a centrifugal acceleration of 50 G (Fig. 1).

The model piles, which were prepared by extending and specially processing steel pipes, were 10 mm in outer diameter, 0.2 mm in thickness and 400 mm in pile length. Since the experiments were conducted by generating 50 G with a centrifuge, the similarity rate (Table 1) was adjusted to simulate the actual size of commonly used steel-pipe piles (D= 500 mm, thickness: t = 10 mm).

When installing model piles, pile ends equivalent to three times the diameter of the pile were buried in soil cement to satisfy the pile end fixation conditions. To measure the stress generated on the model piles, strain gauges were installed on the pile bodies, and acceleration sensors were placed on the pile bodies and in the ground for measurement purposes during vibration. At the time of the vibration test, 800-gram weights (P = 100 ton = 0.8 kg x 50^3 in actual size) were installed on the pile heads to simulate the substructure of a bridge. In the dynamic vibration test, a performance test using white noise was conducted prior to the actual test for the purpose of measuring the natural frequencies of the vibration table and model tank. The white noise ROM was prepared according to the specifications using the phase difference spectral method[4)].

Figure 1 also shows a conceptual diagram of the models. For analysis, it was assumed that the discrete spring was a dash-pot type. Silica sand as sandy soil, kaolin clay to simulate peaty soft ground and Shikotsu volcanic ash[5)] as a typical example of volcanic ash were used for model ground to verify the characteristics of subgrade reaction for each ground type. While all of the samples were mixed samples, kaolin clay was leveled and compacted in multiple layers of 20 mm in mean layer thickness, and the uniformity of silica sand and volcanic ash was ensured by pouring them down as a flow from a certain height at the time of ground preparation. Table 2 presents the results of the test for physical soil properties for each ground type. As the strength characteristics of each ground type, the results of a cone penetration test in a 1 G field were presented.

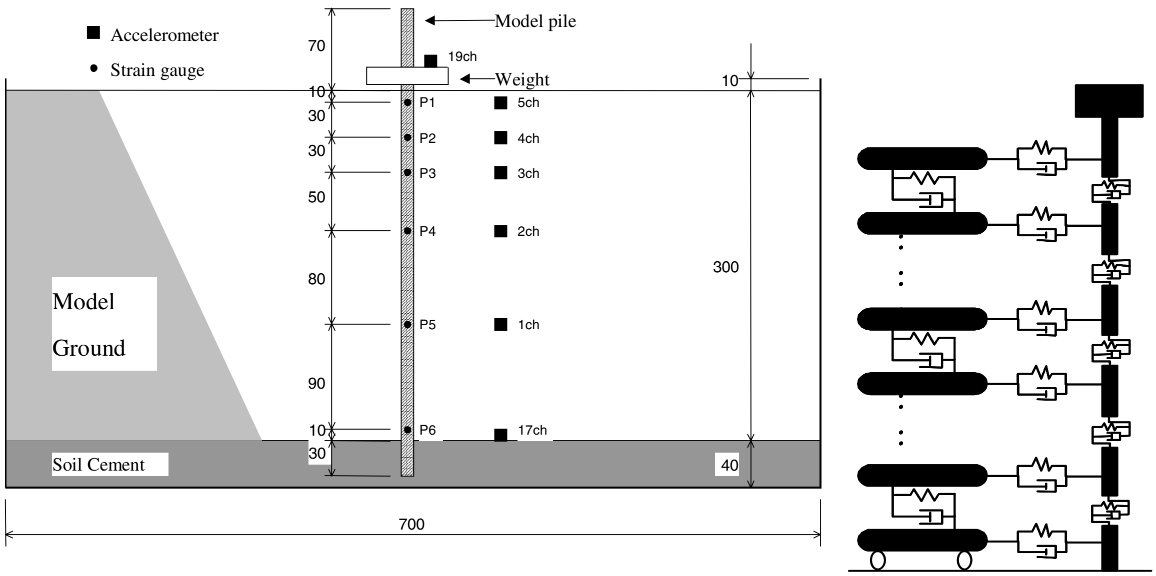

Fig. 1 Test models

Table 1 Similarity rule

		Notation	Unit	Scale	Experimental size	Real size
Ground	Thickness	H_{g1}	m	$1/\lambda$	0.300	15.000
	Bearing ground thickness	H_{g2}	m	$1/\lambda$	0.040	2.000
Pile	Embedding depth	L	m	$1/\lambda$	0.320	16.000
	Outer diameter	D	m	$1/\lambda$	0.010	0.500
	Plate thickness	t	m	$1/\lambda$	0.002	0.010
	Modulus of elasticity	E	Tf/m^2	1	$2.1\text{x}10^7$	$2.1\text{x}10^7$
	Geometrical moment of inertia	I	m^4	$1/\lambda^4$	$7.3952\text{x}10^{-11}$	$4.6220\text{x}10^{-11}$
	Cross-sectional area	A	m^2	$1/\lambda^2$	$6.1575\text{x}10^{-6}$	0.01539
Structure	Weight	M_S	Tf	$1/\lambda^3$	$0.4\text{x}10^{-3}$	50.0
	Height	H_S	m	$1/\lambda$	0.015	0.75
Vibration acceleration		α	g	λ	(1)	(0.020)

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

Table 2 Model ground

			Silica sand	Kaolin	Volcanic ash
Soil particle density		g/cm^3	1.36	1.17	1.11
Grain size distribution	Sand content	%	92.2	-	65.8
	Silt content	%	7.8	45.1	29.4
	Clay content	%	-	54.9	4.8
Cone index		MN/m^2	15.5	1.6	11.7

Table 3 Static coefficient of subgrade reaction K_h

		Silica sand	Kaolin	Volcanic ash
Static K_h	kN/m^2	12,000	8,000	7,000

STATIC HORIZONTAL LOADING TEST (50 G)

The static horizontal loading test of piles was conducted using the multi-cycle strain control method, in which load is applied to the heads of model piles at the speed of 0.25 mm/min using a horizontal loading device. Pile displacement was measured using a laser displacement gauge and the pile stress was measured using a strain gauge. The surface displacement of piles was considered to be approximately y = 0.3 mm (15 mm/50 G) from the permissible displacement of piles in actual size, and the load retention time was 15 minutes for the initial load in accordance with the criteria specified by the Japanese Geotechnical Society[6)].

Using the static horizontal loading test, the relationship among the pile head horizontal load, ground surface displacement and the pile bending moment was determined. The static coefficient K_h of horizontal subgrade reaction was calculated inversely as Winkler's spring model based on the elasticity theory. The static coefficient K_h of horizontal subgrade reaction, which was equivalent to 1% of the pile diameter or the standard displacement of 0.1 mm (50 G field), was in the elastic region, and the K_h of silica sand, kaolin clay and volcanic ash was 12,000 kN/m/m, 8,000 kN/m/m and 7,000 kN/m/m, respectively, as shown in Table 3.

DYNAMIC HORIZONTAL SUBGRADE REACTION

P-δ analysis method

As a method for calculating the coefficient of subgrade reaction through interaction between the ground and piles, a method for determining the dynamic coefficient of subgrade reaction (K_{he1}) by calculating the force of interaction P and relative displacement δ and dividing the force by the displacement (P/δ) was employed. The vibration level was tested by minute displacement on the assumption that the plasticising of the piles and ground was not taken into account.

The relative displacement and force of interaction in the calculation of the dynamic coefficient of horizontal subgrade reaction change with the frequency. Thus, as a method for calculating the dynamic coefficient of subgrade reaction, analysis was conducted at the natural frequency of the pile foundation, for which the relative displacement of piles and the ground became most remarkable, and the dynamic and static coefficients of horizontal subgrade reaction were compared. Figure 2 illustrates the relationship between the Fourier amplitude and the frequency after transfer function curve fitting of the pile foundation in a vibration test using sine waves. The natural frequency of the pile foundation was determined to be 52.50 Hz for silica sand ground, 45.0 Hz for kaolin clay ground and 62.5 Hz for volcanic ash ground, respectively.

Pile displacement was determined by calculating the bending moment distribution from the pile strain value and conducting curve fitting. The functions used for curve fitting were approximated with the polynomials of a cubic function because there were four measurement points. While the subgrade reaction can be found by using a second-order differential equation from the approximating curve function, it was thought to be possible to approximate the function of subgrade reaction using a cubic function curve. As for the boundary conditions for the indefinite constants generated by the second-order integral equation of polynomials, the deflection angle θ and displacement δ at the pile ends were supposed to be zero because the pile ends were fixed with soil cement. Displacement in the ground was calculated by the second-order Fourier integral of ground acceleration because it was difficult to directly measure displacement due to the test equipment. The calculation was made by conducting bandpass processing as a method for correcting the imperfect alignment of displacement. The pile displacement, ground displacement and subgrade reaction were calculated using the calculation method described above, and the dynamic coefficient K_{he1} of subgrade reaction was determined. Figure 3 shows the relationship of relative displacement between piles and ground for each type of ground. The approximating curve was set from the distribution of the coefficients of subgrade reaction, the dynamic coefficient K_{he1} of subgrade reaction was estimated from the mean value, and the values of 33,000 kN/m/m, 18,500 kN/m/m and 16,000 kN/m/m were found for silica sand, kaolin clay and volcanic ash ground, respectively, as shown in Table 4. As a result, the dynamic coefficient K_{he1} of subgrade reaction was silica sand > kaolin clay > volcanic ash (K_{he} / K_h = 2.8 : 2.4 : 2.3), which was larger than the static coefficient K_h of subgrade reaction for these samples.

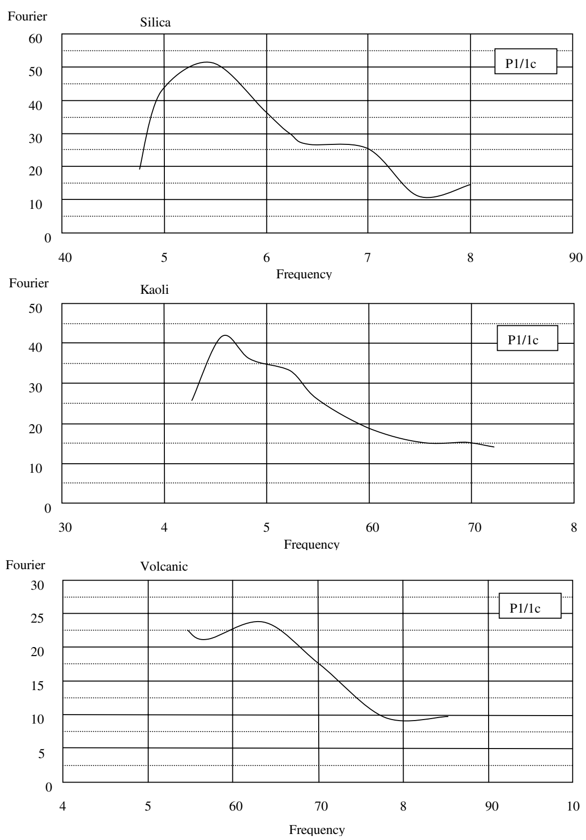

Fig. 2 Sine wave transfer function

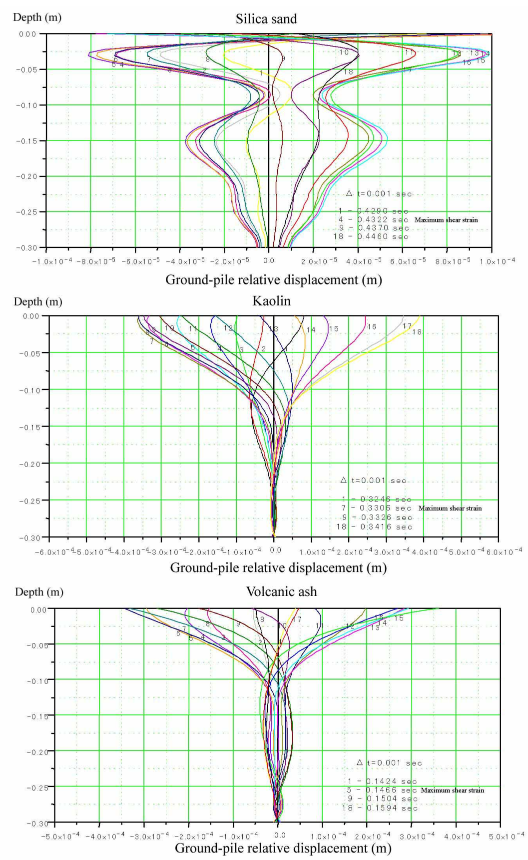

Fig. 3 Ground-pile relative displacement

Table 4 Dynamic coefficient K_{he1}

		Silica sand	Kaolin	Volcanic ash
Dynamic K_{he1}	kN/m^2	33,000	18,500	16,000
K_{he} / K_h		2.8	2.4	2.3

Eigenvalue analysis method

While numerous experiments and analyses have been conducted with a focus on dynamic interaction between piles and ground, verification in many studies has been carried out using two- and three-dimensional FEM analyses, Penzien models and other means. Therefore, in this study, the dynamic coefficient of subgrade reaction was evaluated using eigenvalue analysis (mode analysis with free vibration) by diverting the analysis model used for the analysis of the static coefficient of subgrade reaction. The dynamic coefficient (K_{he2}) of subgrade reaction at the natural frequency of piles was calculated for verification. As a result, the dynamic coefficient (K_{he2}) of subgrade reaction found using the eigenvalue analysis method was 55,500 kN/m/m, 13,700 kN/m/m and 18,000 kN/m/m for silica sand, kaolin clay and volcanic ash ground, respectively, as shown in Table 5. Figure 4 presents the analysis diagram.

Table-5 Dynamic coefficient K_{he2}

		Silica sand	Kaolin	Volcanic ash
Dynamic K_{he2}	kN/m^2	55,500	13,700	18,000
K_{he} / K_h		4.1	1.0	1.3

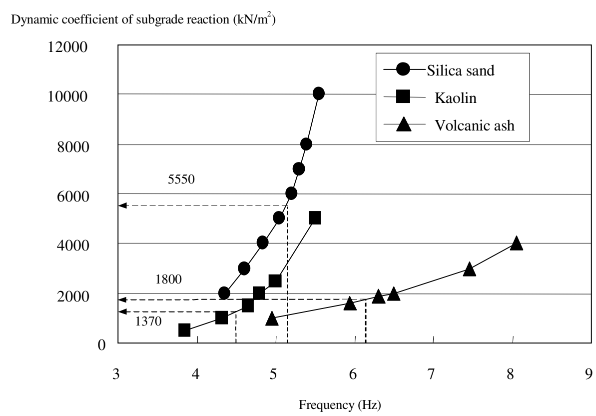

Fig. 4 Dropper value analysis

CONCLUSION

Under the conditions of this test, the following basic data were obtained concerning the characteristics of dynamic horizontal subgrade reaction in the seismic behavior of piles:

(1) With a sinewave vibration test conducted using a centrifuge, the basic dynamic characteristics of ground and piles were roughly determined for each type of ground.

(2) The dynamic coefficient $K_{he1}$of subgrade reaction calculated using the P-δ method was 33,000 kN/m^2 for silica sand, 18,500 kN/m^2 for kaolin clay and 16,000 kN/m^2 for volcanic ash ground, and the ratio of the dynamic coefficient to the static coefficient of subgrade reaction (K_{he1}/K_h) was 2.8, 2.4 and 2.3, respectively. The difference in results was presumed to be due to the ground strength characteristics.

(3) The dynamic coefficient of subgrade reaction was dependent on strain and frequency, and the dynamic coefficient K_{he2} of subgrade reaction calculated using the eigenvalue analysis method exhibits different relationships depending on the vibration mode of the ground and the pile frequency (eigenvalue) according to the type of ground.

By analyzing a series of dynamic centrifuge model tests, the difference in frequencies by the type of ground was found for sandy soil, clayey soil and volcanic ash. Ground characteristics exhibited a variety of relationships depending on dynamic interaction between the piles and ground. For evaluation of the characteristics of dynamic horizontal subgrade reaction, therefore, it is considered necessary to consider the pile-ground response [7), 8)] in pile foundation design.

AFTERWORD

The results here were found through basic research for obtaining knowledge on the characteristics of dynamic subgrade reaction. The characteristics of dynamic subgrade reaction were therefore calculated on a trial basis using two methods to show the necessity of future verification, and a comparison with static subgrade reaction was made at the same deformation level. These subgrade reactions, however, did not take non-linearity into account, and were intended for the standard displacement of infinitesimal pile head deformation. To reflect these basic data as actual design methods, it will be necessary to develop considerable verification efforts and make further accurate research approaches concerning the detailed relationship between the pile foundation strength characteristics and the cone strength value and between the pile foundation strength characteristics and dynamic subgrade reaction, as well as the dependency of the strain rate, among other factors.

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