Estimate of dynamic stiffness and damping by forced excitation test of foundation on bedrock (Part 1)

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ABSTRACT

To clarify the characteristics of the dynamic interaction between foundation and bedrock, forced excitation tests of model foundations have been made at many nuclear power sites in Japan. Dynamic stiffness and damping of bedrock were extracted from these experiments by applying the same method to all experiments, and the characteristics of dynamic stiffness and damping common to all sites were examined. Moreover, the applicability of the half-space elastic theory[1)] was also examined. It has been found that as for the dynamic stiffness of bedrock, the value estimated by using the physical constants determined by seismic prospecting and applying the half-space elastic theory is generally appropriate. Further, the damping of bedrock has a tendency to increase with the increase in frequency, as indicated by the half-space elastic theory.

1 INTRODUCTION

Remarkable progress has been made in the study of soil-structure interaction, which is important in examining the seismic behaviour of the building. Up to the present, however, these results have not been fully reflected in the design. For bedrocks on which important structures such as nuclear power plants are to be erected, values on the safer side have been applied partly due to insufficient accumulation of demonstration data. With such a background, in-situ forced excitation tests on large-sized model foundations have been made at many sites in recent years. The present research was conducted to integrate these demonstration data and prepare a basic data which will be reflected in the future design.

2 OUTLINE OF EXPERIMENTS

The ground conditions of the sites examined in the present research are shown in Table 1. As shown in the table, kinds of rock were varied, and there were two types of site; site of which ground could be regarded as uniform, and stratified site. Most of the sites, however, were of hard rock except the loose thin surface layer. The forced excitation tests were made by placing large-sized model foundations (Table 2) on these hard bedrocks. The foundations were rectangular in plane, except one at the site B, which was circular. At three sites A, E, and G, excitation tests were also made on smaller-sized model foundations to analyze the scale effect. Measurement was made on the behaviour of the foundation and the contact pressure distribution. Fig. 1 shows an example of the arrangement of measuring points for the foundation behaviour.

From response curves obtained from the experiments, those which were appropriate for the estimation of dynamic stiffness and damping of bedrock were selected. Fig. 2 shows an example of the response curve for horizontal excitation. In the case of horizontal excitation, the criteria of selection were that the amount of torsion was small, that the oscillation was a clear coupling of horizontal and rotational motions, and that the first natural frequency was included. In the case of the vertical excitation, the criterion was that the rocking of the foundation was small. As for the contact pressure distribution, the items measured at several sites included the normal stress distribution and the shearing stress distribution under horizontal excitation, and the normal stress distribution under vertical excitation. The measurement, however, did not reveal clear distribution patterns such as those usually assumed in theory. If they were assumed to be remotely comparable, the approximation by uniform distribution (triangular distribution for rotation) was the best one (Fig. 3). The strain in the ground was approximated from $\dot{U}/V_s$ (where $\dot{U}$: measured velocity amplitude; V_s: shear wave velocity of bedrock). Such data was obtained by velocity seismographs installed in the bedrock directly beneath the foundation. The range was from 5×10^{-8} to 7×10^{-6}, which may be regarded as an elastic range.

3 METHODS FOR ASSESSING DYNAMIC STIFFNESS AND DAMPING OF BEDROCK FROM EXPERIMENTAL RESPONSE CURVES

In assessing the dynamic stiffness and damping of bedrock from the experimental response curves, the following formulas were used (Fig. 4). The formulas take into consideration the uniform shear deformation of the foundation since the bedrocks of many sites were considerably hard and the foundation was not necessarily assured to behave as a rigid body.

$$K_H = [P + M\omega^2\{U_B + s(\theta_B + \theta_e)\}]/U_B \quad \ldots\ldots \quad (1)$$

$$K_R = [(s+\ell)P + Ms\omega^2 U_B + \omega^2\theta_B(I_G + Ms^2\omega^2) + \frac{4}{3}Ms^2\omega^2\theta_e]/\theta_B$$

$$K_V = (P + M\omega^2 V_B)/V_B$$

$$h_L = \mathrm{Im}(K_L)/\{2\mathrm{Re}(K_L)\} \qquad (L = H \text{ or } R \text{ or } V)$$

where

K_H, K_R, K_V: horizontal, rotational, and vertical complex spring coefficients of bedrock;
P, ω: amplitude and circular frequency of the exciting force;
M, I_G: mass and rotational moment of inertia of the foundation;
U_B, θ_B, V_B: horizontal, rotational and vertical displacements of the bottom of the foundation;
θ_e: rotational displacement corresponding to the elastic deformation of the foundation;
s: distance between the bottom and the center of gravity of the foundation;
ℓ: distance between the center of gravity of the foundation and the exciting center;
h_H, h_R, h_V: horizontal, rotational, and vertical damping of bedrock.

4 APPLICATION OF HALF-SPACE ELASTIC THEORY

The half-space elastic theory[1)] was applied, and the dynamic reactive complex spring coefficients of the bedrock were obtained and compared with the measured values. As for the ground stiffness which was required in the application of the elastic theory, a method for determining the equivalent shear wave velocity ($V_{s,eq}$) so that the experimental natural frequency agrees with the theoretical one was used. This value was also used in determining the non-dimensional frequency (a_0) and the like. In applying the theory, the contact pressure distribution was assumed to be of three types; uniform, rigid base, and parabolic.

5 DYNAMIC STIFFNESS AND DAMPING OF BEDROCK

(1) Table 3 shows the values of $V_{s,eq}$ obtained by the above-mentioned method for all the sites considered. The table also shows the eccentric moment and natural frequency of each experiment to identify all of the experiments. Fig. 5 shows the relationships between $V_{s,eq}$ obtained from the experiments and V_s obtained from the seismic prospecting. When the ground was a stratified one, Tajimi's stratification correction method was used. They agreed well with each other irrespective of the presence of stratification. Thus, as for the dynamic stiffness of bedrock, it would be appropriate to use the shear wave velocity distribution obtained from the seismic prospecting.

(2) The dynamic reactive complex spring coefficients of bedrock were calculated from the above-mentioned $V_{s,eq}$ according to the half-space elastic theory, and the response of the foundation under forced excitation was analyzed. The results were compared with the response curves obtained from experiments. (Fig. 6 shows examples of comparison between experimental and theoretical response curves.) The teoretical values including amplitude and phase lag generally agreed well with the experimental values, indicating the applicability of the elastic theory. Generally speaking, the degree of approximation when the contact pressure distribution was assumed to be uniform was higher than others.

(3) The dynamic reactive complex spring coefficients K_H, K_R, K_V and damping h_H, h_R, h_V of bedrock obtained from experiments according to the formulas (1) were plotted against the non-dimensional frequency $a_0 = \omega\sqrt{A}/V_{s,eq}$. a_0 was introduced to express the differences in bedrock elastic modulus, dimensions and configuration of the foundation, and presence of stratification of the sites according to a common measure. The damping constant obtained from the elastic theory is a function of a_0 alone.

The results were as follows:

1) The horizontal damping h_H increased with the increase in frequency, and tended to substantially agree with the theoretical value and tendency. In particular, it agreed well with the theoretical value based on the assumption of uniform contact pressure distribution at sites which could be regarded as a half-space ground. h_H of the stratified grounds generally tended to be smaller than h_H of the half-space grounds. Detailed examination of the effect of stratification on damping will be made in Part 2 of the present study. At the site G, h_H was fairly large although the site was a stratified ground. The explanation was as follows: the rock quality of the site G was relatively soft than other sites, and the measured contact pressure distribution was close to a rigid base distribution (Fig. 7 (1)).

2) The rotational damping h_R also increases with the increase in frequency. When compared with theoretical values, however, they were fairly larger and showed a large dispersion. h_R of the stratified grounds were generally lower than h_R of half-space grounds except the site G (Fig. 7 (2)).

3) The vertical damping h_V also increases with the increase in frequency. Measured values were approximately equivalent to theoretical ones, but showed a large dispersion (Fig. 7 (3)).

(4) Experimental analyses of the scale effect revealed the following:

1) The equivalent shear wave velocity ($V_{s,eq}$) of bedrock increased with the increase in the dimensions of the foundation. When the dimension of the foundation exceeded a certain value, the equivalent shear wave velocity of bedrock can be regarded equivalent to that of a full-scale foundation. The decrease in $V_{s,eq}$ with the decrease in the dimensions of the foundation was greater for the stratified grounds (Fig. 8 (1), (2)).

2) When expressed by a_0, both h_H and h_R showed almost identical curves irrespective of the dimensions of the foundation. Thus, as for damping, the scale effect can be neglected (Fig. 9).

REFERENCES

1) H. Tajimi, "Basic Theories on Aseismic Design of Structures", Journal of Institute of Industrial Science, Univ. of Tokyo, Vol. 8, 1959.

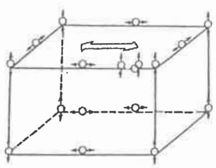


Fig. 1 Example of Measuring Point Arrangement for Horizontal Excitation

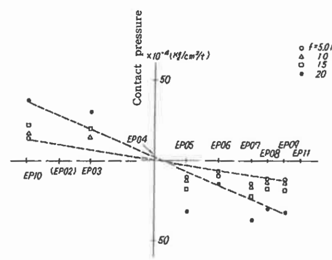
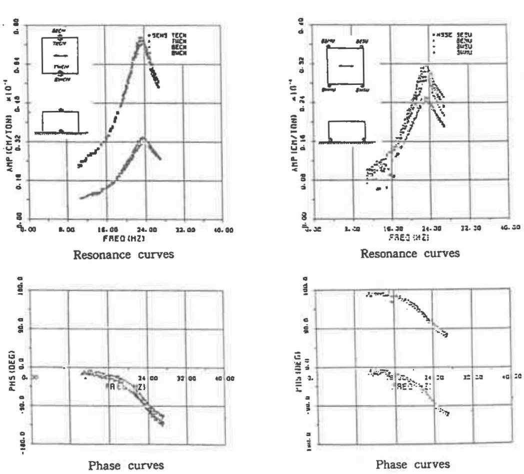


Fig. 3 Example of Measured Normal Stress Distribution under Horizontal Excitation



(1) Displacements of the top and bottom of the foundation in the direction of excitation

(2) Vertical displacements of the four corners of the foundation bottom

Fig. 2 Examples of Horizontal Excitation Response Curves

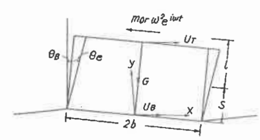


Fig. 4 Calculation of the Dynamic Stiffness and Damping of the Bedrock from the Measured Behaviour of the Foundation

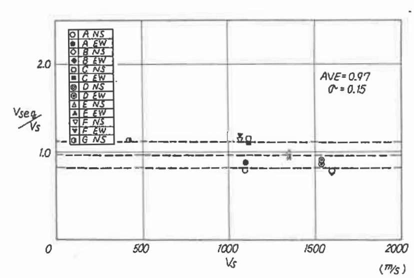
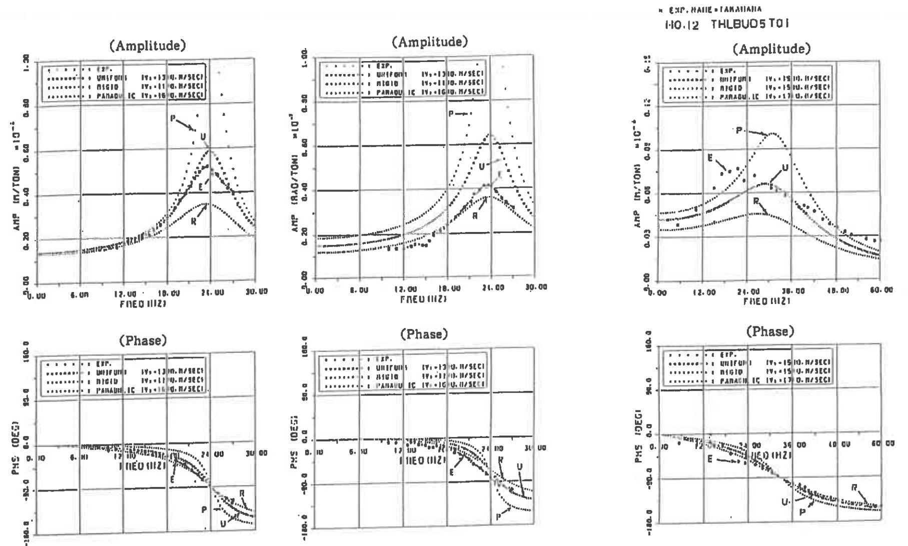


Fig. 5 Equivalent Shear Wave Velocity (Vs,eq) of the Ground Obtained from Excitation Test and Shear Wave Velocity (Vs) Obtained from Seismic Prospecting



(i) Horizontal displacement of the center of gravity of the foundation

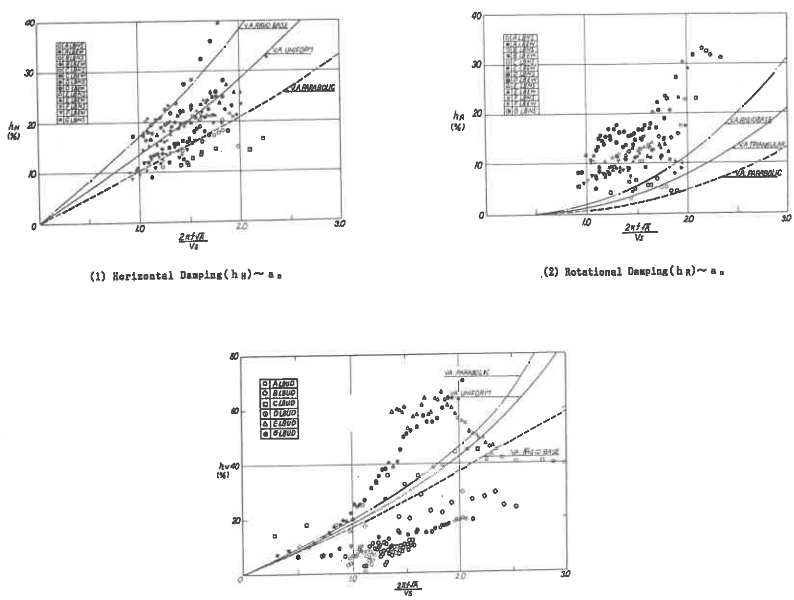
(ii) Angle of rotation of the center of gravity of the foundation

Vertical displacement of the foundation

(1) Horizontal Excitation at the Point E

(2) Vertical Excitation at the Point C

Fig. 6 Comparison of Theoretical and Measured Response Curves



(1) Horizontal Damping(h_H)~a_0

(2) Rotational Damping(h_R)~a_0

(3) Vertical Damping(h_V)~a_0

Fig. 7 Relationship between Damping and Non-dimensional Frequency (a_0) (All Sites Plotted)

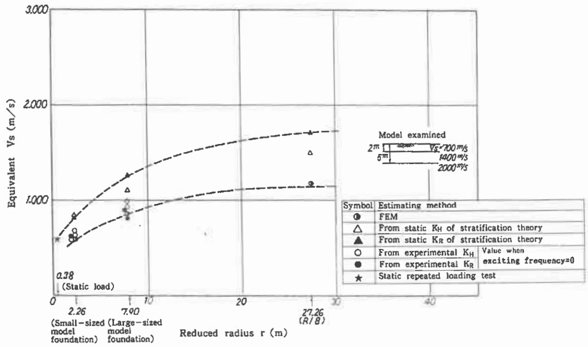


Fig. 8 Relationship between Equivalent Shear Wave Velocity (Vs,eq) and Dimensions of the Foundation

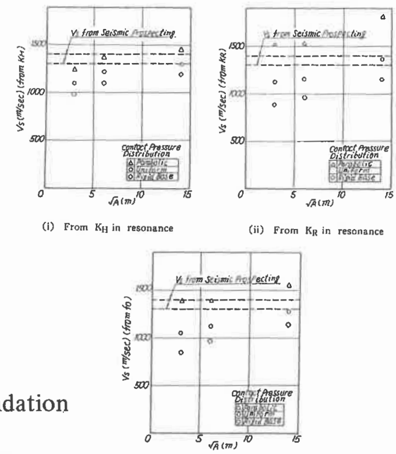


Fig. 8(2) Example at Point B

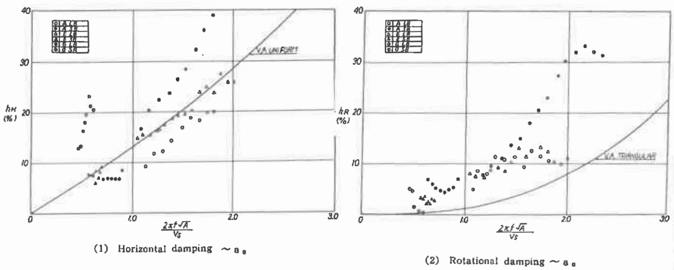


Fig. 9 Effect of Foundation Size on Damping

Table 2 Particulars of Model Foundations

Site	Foundation	Dimensions (m) (Plane×height)	Weight (tf)
A	Large	14×14×7.33	3.406×10^3
	Small	4×4×4.29	1.664×10^2
B	Large	φ 12×5	1.360×10^3
C	Large	15×15×9	4.658×10^3
D	Large	10×10×7	1.610×10^3
E	Large	14×14×7.5	3.380×10^3
	Medium	6×6×4	3.310×10^2
	Small	3×3×4	8.280×10
F	Large	15×15×12.5	6.469×10^3
G	Large	14×14×7	3.293×10^3
	Small	4×4×6	2.300×10^2

Table 1 Ground Conditions of All Sites

Site		Kind of rock	Shear wave velocity Vs obtained from seismic prospecting: Depth (m)	Velocity (km/s)
A		Alternate layers of sandstone and shale	0–2 2–5 5–	0.7 1.4 2.0
B		Conglomerate, sandstone, and slate	(Uniform ground)	1.9–2.0 (From seismic prospecting) 1.4–1.8 (From surface elastic wave survey)
C		Rhyolite	0–1.0 1.0–2.5 2.5–5.0 5.0–	0.5 1.0–1.7 1.7–2.4 2.4
D		Granite	0–2 2–	1.3–1.4 1.7
E		Tuff breccia	(Uniform ground)	1.3–1.4
F		Tuff and tuff breccia	0–1.5 1.5–8.0 8.0–14.0 14.0–18.0 18.0–24.0 24.0–30.0	0.6 1.55 2.0 1.6 2.0 1.6
G	Large-scaled	Alternate layers of mudstone and sandstone	0–1.5 1.5–4.4 4.4–10.5 10.5–12.8 12.8–20.0 20.0–37.0 37.0–50.0 50.0–65.0 65.0–92.0 92.0–	0.3 0.49 0.61 0.37 0.55 0.62 0.77 0.9 0.77 0.77
	Small-scaled	Alternate layers of mudstone and sandstone	0–2.0 2.0–4.5 4.5–10.0	0.42 0.37 0.63

Table 3 Equivalent Vs Obtained from Experiment

Site Foundation Direction of excitation.	Eccentric moment (kg·m)	Natural frequency fo (Hz)	Equivalent Vs (m/sec): fo ↓ Uniform	Rigid	Parabolic	K_H↓ (or K_V↓ in Vertical) Uniform	Rigid	Parabolic
A LB NS	(20t, constant)	15.9	870	760	1070	890	830	1010
A LB EW	ditto	17.8	970	850	1190	1000	930	1130
A LB UD	5.6–89.4	(19.9)	–	–	–	1130	1070	1250
A SB NS	0.9679	20.43	640'	520	820	660	590	750
A SB EW	0.9679	19.41	600	500	780	640	580	730
A SB UD	4.156	(21.17)	–	–	–	730	650	820
B LB NS	0.33–1.00	34.33	1240	1110	1500	1230	1150	1230
B LB EW	0.30–1.00	34.04	1230	1100	1480	1230	1150	1380
B LB UD	0.30–1.00	(50.0)	–	–	–	1650	1620	1780
C LB NS	0.34	19.48	1280	1080	1580	1550	1410	1750
C LB NS	10.20	17.50	1140	970	1420	1400	1270	1580
C LB NS	1.00	16.74	1090	930	1360	1320	1200	1490
C LB EW	0.34	18.9	1240	1060	1550	1410	1290	1600
C LB UD	0.34	32.0	1580	1540	1710	1640	1600	1780
D LB NS	0.34	28.6	1390	1190	1740	1420	1300	1600
D LB EW	0.34	27.55	1340	1130	1680	1330	1210	1500
D LB UD	0.34	53.45	1770	1720	1930	1770	1720	1930
E LB NS	4.156	23.81	1340	1170	1640	1350	1250	1530
E LB EW	4.156	22.6	1270	1120	1560	1300	1210	1470
E LB UD	2.235	32.52	1370	1350	1480	1390	1360	1500
E MB NS	0.0651	38.01	1100	940	1370	1150	1050	1300
E MB EW	0.0651	38.63	1120	940	1390	1220	1100	1370
E MB UD	0.107–0.521	39.74	–	–	–	1050	980	1170
E SB NS	0.1622	36.41	1050	860	1380	1100	1010	1240
E SB EW	0.1622	35.58	1040	850	1370	1100	1000	1250
E SB UD	–	–	–	–	–	–	–	–
F LB NS	(10t, constant)	14.81	1220	1030	1540	1270	1150	1430
F LB EW	ditto	15.41	1260	1060	1600	1290	1170	1480
F LB UD	0.203–0.621							
G LB NS	(20t, constant)	8.90	490	430	590	460	430	520
G LB UD	(5t, constant)	12.8	540	530	580	540	530	580
G SB NS	2.0	11.8	580	470	770	730	650	830
G SB UD	(5t, constant)	28.6	590	540	660	590	540	660

Note) Figures in ( ) of the column fo indicate the maximum excitation frequency when natural frequency is not determined in the excitaion range.