DYNAMIC CHARACTERISTICS OF SOIL-FOUNDATION INTERACTION DETECTED FROM FORCED VIBRATION TEST

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SUMMARY

This paper presents the results on the following subjects:
(1). The experimental radiation damping of soil-foundation interaction vs. nondimensional frequency $a_0(=\omega r/V_s)$ was evaluated by the equivalent damping ratio, h_H and h_R, which were defined by complex stiffness K_H and K_R as; $h_H=K'_H/2K_H$, $(K_H=K_H+iK'_H)$, $h_R=K'_R/2K_R$, $(K_R=K_R+iK'_R)$.
(2). The comparative studies of experimental and theoretical results were made. The theoretical results were obtained from Dr. H. Tajimi's vibrational admittance theory [Ref. 3].
(3). The semi-empirical equation to estimate the equivalent S-wave velocity for elastic half-space model was proposed here considering the effects of layered media.

INTRODUCTION

It is very important problem to estimate the characteristics of soil-foundation interaction, especially radiation damping, when nuclear power facilities are built on a base rock in Japan. But accurate consideration cannot be made because of the insufficient in-situ tests on base rock, so far. From this point of view, the methodical in-situ forced vibration tests on base rock at four sites were carried out.

The distinction of the experiments are; (1). the large model foundation made of concrete were used, (2). the 150-ton vibrator owned by Central Research Inst. of Electric Power Industry (CRIEPI) was used to generate the large force, (3). the earth pressure was measured.

SUMMARY ON FORCED VIBRATION TEST

Large Model Foundation and Soil Condition

Model foundation were made of concrete, and their scales were; 5m x 5m x 7m (TSU) [Ref. 1], r=6m, height=5m (SDA) [Ref. 2], 14m x 14m x 7.33m, 4m x 4m x 4.33m (OGA), 14m x 14m x 7.5m, 6m x 6m x 4m (H-A) as shown in Fig. 1.
Each model foundations was settled on the base rock at four sites which has different base rock conditions as shown in Fig. 1.

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150-ton Vibrator

In each experiments, both small vibrator which can make force in high frequency and 150-ton vibrator of CRIEPI were used. 150-ton vibrator was designed to shake a nuclear power plant to estimate the dynamic characteristics of it. If it will be necessary, three 150-ton vibrators can be synchronized (in this case, muximum generated force is 450 tf at 13Hz). The generated force-frequency relation is shown in Fig. 2 (solid line is for horizontal and dotted line is for vertical vibration). According to frequency-force relations shown in Fig. 2, the experiments were carried out at each sites.

COMPLEX STIFFNESS OF BASE ROCK

Soil (base rock)-foundation interaction system was equalized by a simple model (Sway and rocking model: SR-model) as shown in Fig. 3. It was assumed that the model foundation was a rigid body, and the characteristics of the interaction system was evaluated by the horizontal and rotational complex stiffness of base rock, that is, $K_H=K_H+iK'H$ for horizontal, and $K_R=K_R+iK'R$ for rotational.

According to the SR-model of rigid body, we botained the following equation under the harmonic excitation.

$$\begin{bmatrix} M & 0 \\ 0 & I_G \end{bmatrix} \begin{Bmatrix} \ddot{U} \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} K_H & -SK_H \\ -SK_H & K_R+S^2K_H \end{bmatrix} \begin{Bmatrix} U \\ \theta \end{Bmatrix} = m_o r\omega^2 \begin{Bmatrix} 1 \\ \ell \end{Bmatrix} e^{i\omega t} \tag{1}$$

Substituting $u=Ue^{i\omega t}$ and $\theta=\theta_e{}^{i\omega t}$ into eq. (1), we get

$$\left.\begin{aligned} K_H &= \frac{m_o r\omega^2 + M\omega^2 U}{U - S\theta} \\ K_R &= \frac{(\ell+S)m_o r\omega^2 + \omega^2(SMU+I_G\theta)}{\theta} \\ h_M &= K'_H/2K_H, \qquad h_R = K'_R/2K_R \end{aligned}\right\} \tag{2}$$

where, s is a distance from the center of foundation to the ground surface. ℓ is a distance from the center of gravity of foundation to the point of force application. U and θ are complex values containing the term of phase lag against periodic disterbing force. From eq. (2), we can estimate the complex stiffness, K_H and K_R, as shown in Fig. 5 and equivalent radiation damping of base rock by knowing the transfer function U and θ. Fig. 4 indicate the example of observed U and θ. The measured values were obtained with good accuracy.

Fig. 5 indicates that the K_H, K'_H, K_R, and K'_R are the function of frequency. The real part of complex stiffness decreases monotonously with frequency, and imaginary part of complex stiffness increases monotonously with frequency.

EARTH PRESSURE

Fig. 6 indicates the example of measured earth pressure of rotational component by using earth pressure cell during horizontally forced vibration. Although the accuracy of absolute value of it was still problem, the qualitative tendency of earth pressure will be clarified. In case of H-A-experiment, the spatial distribution of earth pressure seems to be approximately triangular shape, and this shape was not changed with frequency. In case of OGA, it seems that the spatial distribution of earth pressure approximately changed from triangular shape to parabolic one as the frequency is changed from low to high frequency.

EQUIVALENT DAMPING, h_H AND h_R

The experimental results of h_H and h_R are indicated in Fig. 7. These values were plotted vs. non-dimensional frequency a_o ($=\omega b/V_s$ for square foundation, $=\omega r/V_s$ for circular foundation). So, the theoretical equivalent damping h_H and h_R calculated from vibrational admittance theory based on elastic half-space medium can ce represented only by the function of a_o. We can see from this figure that experimental h_H increases monotonously with frequency. The theoretical values agree well with the observed results estimated by using equivalent s-wave velocity, and it seems to be an average of observed ones. The results of h_R indicates that the dissipative damping of base rock is much larger than the radiation damping in low frequency range because of small value of theoretically estimated values. Although experimental value of h_R seems to have the general tendency of increasing monotonously with frequency, the rate of increasing of each experimental h_R vs. a_o is different to each other. Especially, in case of OGA-experiment, the increasing rate is slightly small (almost flat with frequency). The theoretical value of h_R seems to be a minimum value of experimental ones. So, in order to estimate the h_R of soil-foundation interaction system rationally, the dissipative damping of base rock should be considered.

ESTIMATION OF EQUIVALENT S-WAVE VELOCITY

A soil is generally composed of layered media. In order to estimate approximatelly the characteristics of soil-foundation interaction system by using an simple elastic half-space model, it is necessary to replace equivalently the layered media by the elastic half-space model as shown in Fig. 8.

The horizontal displacement and rotational angle of elastic half-space model considering the effects of layered media is given as eq. (3) and eq. (4) under the assumption that the stress distribution in layered media and elastic half-space are same.

$$U = U_1[1-F_H(Z_1/a)+\frac{G_1}{G_2}\left\{F_H(Z_1/a)-F_H(Z_2/a)\right\}+\frac{G_1}{G_2}\left\{F_H(Z_2/a)-F_H(Z_3/a)\right\}+\cdots] \qquad (3)$$

(for Horizontal)

$$\Omega = \Omega_1[1-F_R(Z_1/a)+\frac{G_1}{G_2}\left\{F_R(Z_1/a)-F_R(Z_2/a)\right\}+\frac{G_1}{G_3}\left\{F_R(Z_2/a)-F_R(Z_3/a)\right\}+\cdots] \qquad (4)$$

(for Rotational)

where, U_1, Ω_1 is a displacement and rotational angle of foundation on elastic half-space which have a rigidity G_1 of first layer shown in Fig. 9, and the values Z, G_1, G_2 and function F(z/a) are shown in Fig. 9.

Otherwise the displacement U_{xo} and rotational angle Ω_{yo} of the center of bottom surface of a foundation are given as follows:

$$U_{xo} = \frac{Q}{2\pi Ga}(2-\nu), \qquad \Omega_{yo} = \frac{1-\nu}{2G}\cdot\frac{M_y}{J_y}a \tag{5}$$

where, ν is a poisson's ratio, G is a rigidity of soil, Q and M are shear force and moment, respectively. From eq. (5), we can get U/U_1 and Ω/Ω_1, considering the relations, $U=U_{xo}(G_{est}, \nu_{est})$, $U_1=U_{xo}(G_1, \nu_1)$, $\Omega=\Omega_{yo}(G_{est}, \nu_{est})$ nd $\Omega_1=\Omega_{yo}(G_1, \nu_1)$.
Where $G_{est}(=\rho_{est}V^2{}_{est})$ are a equivalent rigidity. It can be replaced easily by equivalent s-wave velocity V_{est}.

From eqs. (3) and (4), we also get U/U_1 and Ω/Ω_1. Assuming the relation $\nu_e \doteqdot \nu_1$, $\rho_1 \doteqdot \rho_e$, we get the following approximate relations:

$$V_{est} \doteqdot V_1/\sqrt{\left[1-F_H(Z_1/a)+\frac{G_1}{G_2}\left\{F_H(Z_1/a)-F_H(Z_2/a)\right\}+\frac{G_1}{G_2}\left\{F_H(Z_2/a)-F_H(Z_3/a)\right\}+\cdots\right]} \tag{6}$$

(for Horizontal)

$$V_{est} \doteqdot V_1\sqrt{\left[1-F_R(Z_1/a)+\frac{G_1}{G_2}\left\{F_R(Z_1/a)-F_R(Z_2/a)\right\}+\frac{G_1}{G_3}\left\{F_R(Z_2/a)-F_R(Z_3/a)\right\}+\cdots\right]} \tag{7}$$

(for Rotational)

Fig. 10 shows the relationship between estimated V_{est} with experimental V_{obs} (●: horizontal forced ○: rotational forced vibration). Eq. (8) represent the average relationship between V_{est} and V_{obs} estimated by using the least square methods.

$$V_{obs} = 1.05\,V_{est}^{0.97}\ \text{(Horizontal)}, \qquad V_{obs} = 1.49\,V_{est}^{0.91}\ \text{(Rotational)} \tag{8}$$

From eqs. (6), (7) and (8), the first order estimation of equivalent s-wave velocity of elastic half-space model can be done concidering the effect of layered media.

REFERENCE

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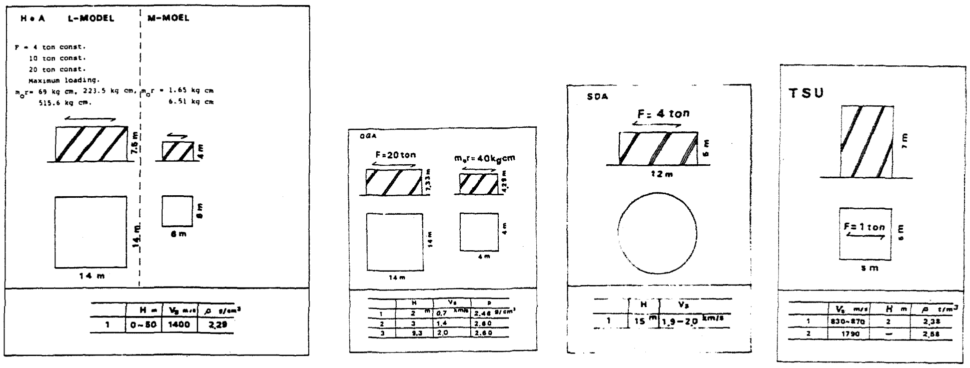
(2) Kisaki, N., M. Siota, et. al., Forced Vibration Test of a Model Foundation on Rock Ground, 6th Japan Earthq. Eng. Symp., pp.1657 ~ 1664 (in Japanese).

(3) Tajimi, H., Basic Theories on Aseismic Design of Structures, Journal of Inst. of Ind. Sci., Univ. of Tokyo, Vol. 8, 1959.



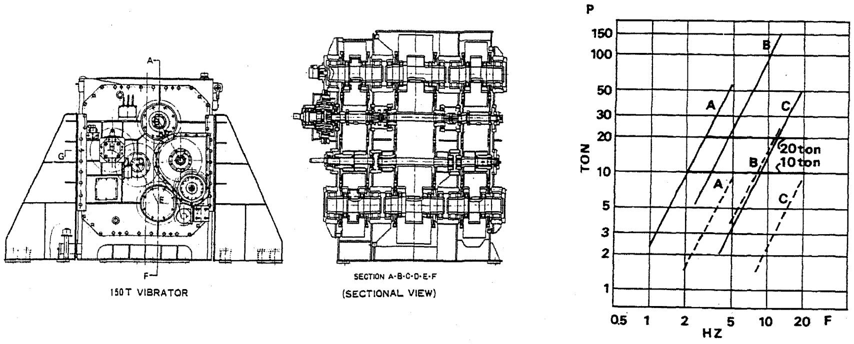
	H m	V_s m/s	ρ g/cm³
1	0 – 50	1400	2.29

	H	V_s	ρ
1	2 m	0.7 km/s	2.46 g/cm³
2	3	1.4	2.60
3	9.3	2.0	2.60

	H	V_s
1	15 m	1.9 – 2.0 km/s

	V_s m/s	H m	ρ t/m³
1	830~870	2	2.38
2	1790	–	2.58

Fig.1 Large model foundations made of concreat and soil(base rock) conditions of each experiments. these models were settled on the surface of base rock at each sites.


150T VIBRATOR

SECTION A-B-C-D-E-F (SECTIONAL VIEW)

Fig.2 150-ton vibrator owned by Central Research Inst. of Electric Power Industry, and its generated force-frequency relations. Solid line is for horizontal and dotted line is for vertical vibration.

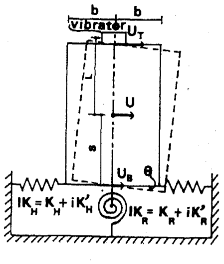
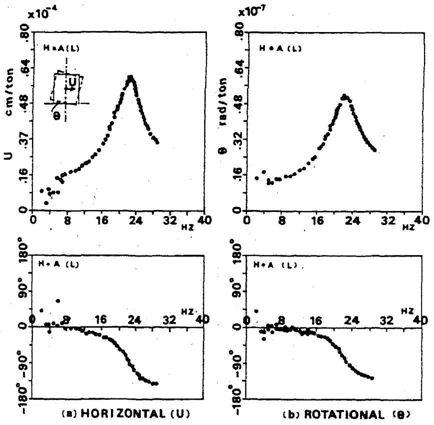


Fig. 3 Sway and rocking model of rigid body (SR-Model).



(a) HORIZONTAL (U)

(b) ROTATIONAL (θ)

Fig. 4 Response of horizontal displacement *U* and rotational angle θ .

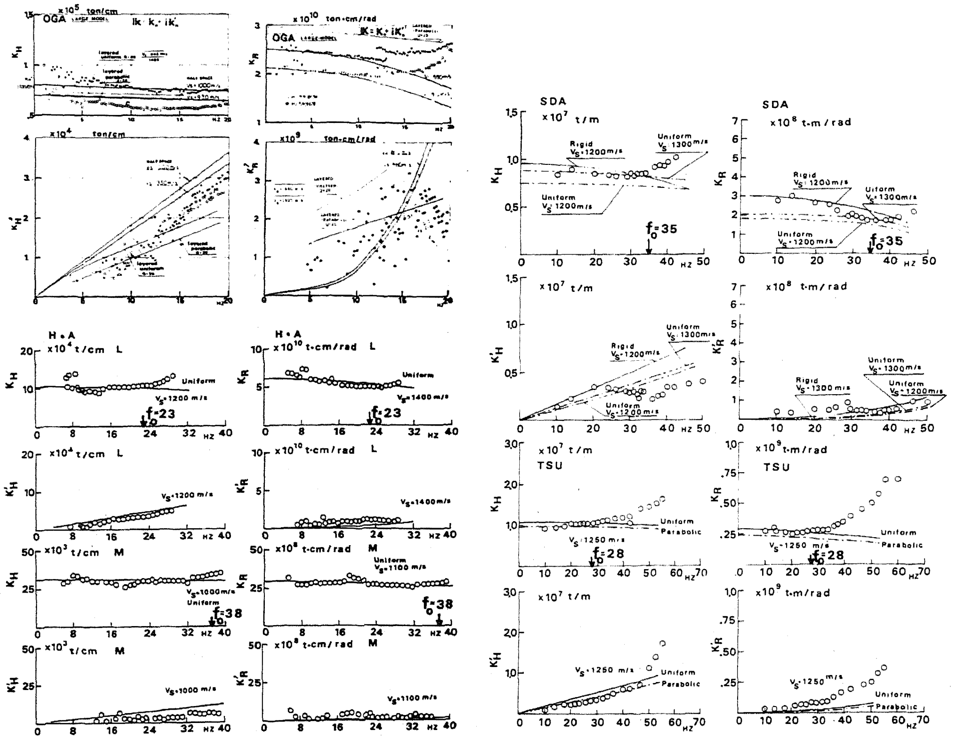


Fig.5 Comparison of observed and theoretical complex stiffness of base rock at four sites. The theoretical results are obtained by vibrational admittance theory(H.Yajimi,1959) based on elastic half-space model. S-wave velocity(V_s) indicated in each figures was estimated by fitting the observed resonance frequency and theoretical one of soil-foundation interaction system.

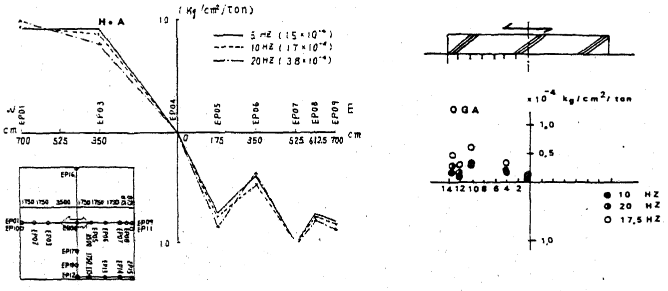


Fig.6 Spatial distribution of observed normal earth pressure(H・A experiment and OGA experiment) for horizontal forced vibration.

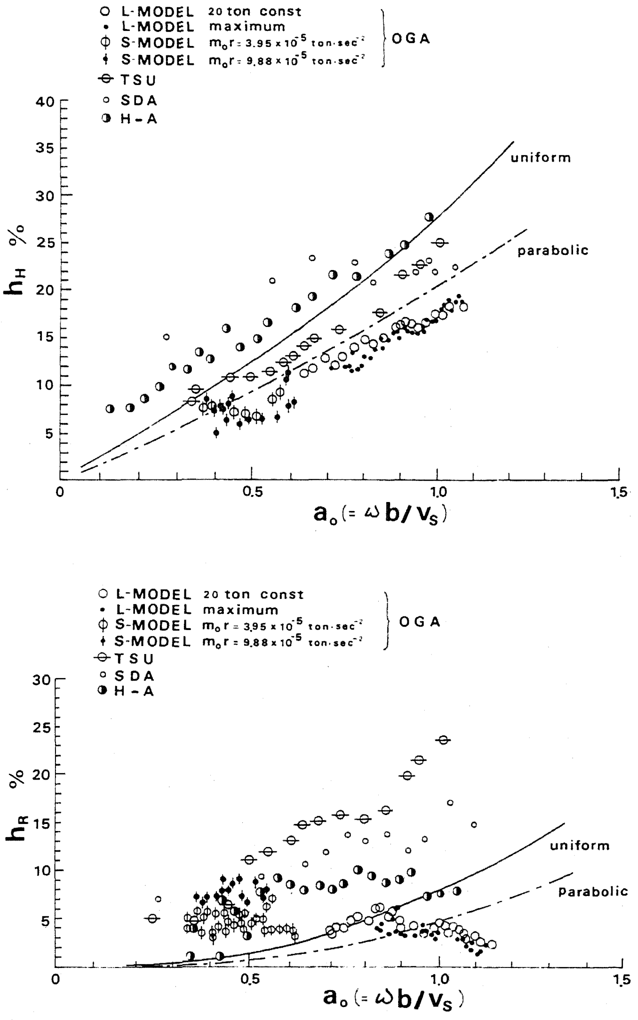


Fig. 7 Equivalent damping of base rock, $h_H(=K'_H/2K_H)$ and $h_R(K'_R/2K_R)$, vs. non-dimensional frequency a_0. The theoretical results are obtained by the vibrational admittance theory(H.Tajimi,1959) under two kinds of stress distributions(solid line is for uniform and dashed line is for parabolic stress distribution). The theoretical results are estimated only by the function of non-dimensional frequency a_0.

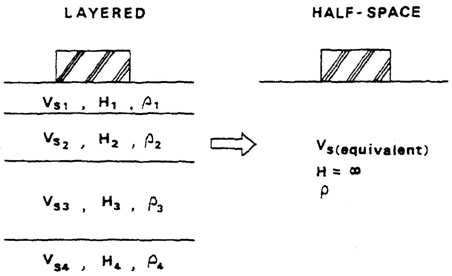


Fig.8 Equivalent replacement of layered media by elastic half-space model.

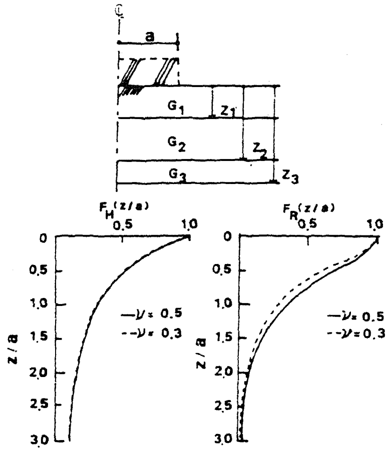


Fig.9 Correction coefficient $F_H(z/a)$ and $F_R(z/a)$ for equivalently replacing the layered madia by elastic half-space model.

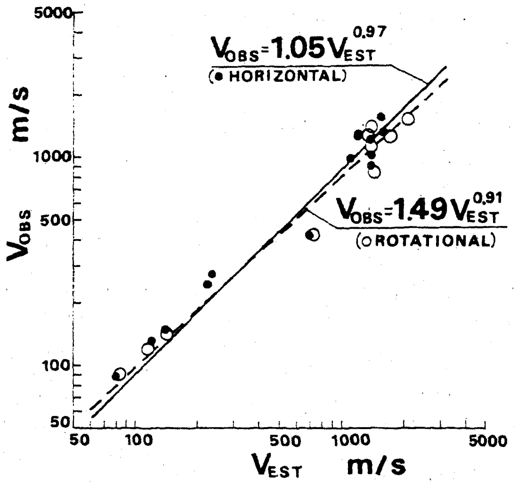


Fig.10 Relations between observed equivalent S-wave velocity, V_{obs}, and estimated equivalent one, V_{est}, by the eqs.(7) and (8). The data on soft-soils were obtained by other experiments. The strain levels of these experiments were 10^{-9}- 10^{-5}.