VIBRATION TEST OF FOUNDATIONS ON BEDROCK

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SUMMARY

Vibration test of foundations on bedrock in nuclear power site was carried out. From the response of the foundation dynamic stiffness was calculated and its characteristics and size effect of the foundation were made clear. Experimental results were compared with half-space theory and numerical simulation by axisymmetric finite element analysis, and applicability of both methods to soil-structure interaction problem on the bedrock was examined.

INTRODUCTION

It is considered that field vibration test of foundation has an important meaning in the following respects. One is to investigate the dynamic interaction characteristics of the actual foundation-ground system, another is to examine the applicability of analysis methods in the interaction problem. From this point of view field vibration test of foundation was carried out. And experimental results were examined by half-space theory and finite element analysis. As distinctive features of the experiment the following may be pointed out. (1) Vibration test was carried out on the bedrock shear wave velocity of which is about 1300 m/s ~ 1400m/s. (2) Three foundations, large-sized, medium-sized and small-sized, were made in the test yard to examine size-effect on dynamic interaction characteristics of the foundation-ground system. (3) For large-sized foundation vibrator which generates maximum force of 150 ton was used.

EXPERIMENTAL OUTLINE

As is shown in Fig. 1 three concrete foundations, large-sized, medium-sized and small-sized were made in the test yard. Test yard was created excavating until bedrock outcropped. Rock material is tuff breccia, and material properties are shown in Table 1. Rock profile under large-sized foundation is shown in Fig. 2, and also value of Vs (S-wave velocity), Vp (P-wave velocity) obtained by seismic prospecting (velocity logging). Also seismic prospecting by direct arrival survey was carried out in the test yard, and Vs and Vp obtained by this method are 1300 m/s ~ 1400m/s and 3000 m/s ~ 3200 m/s respectively, which correspond well to those obtained by velocity logging. From both methods of seismic prospecting layered stratum of the bedrock in the test yard was not perceived and the bedrock can be regarded as uniform.

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Size of the foundations is as follows, large-sized; 14 m X 14 m in plane, 7.5 m in height, medium-sized; 6 m X 6 m in plane, 4 m in height, small-sized; 3 m X 3 m in plane, 4 m in height. For small-sized and medium-sized foundation rotating mass vibrator which generates maximum vibrating force of 1 ton and frequency range 1~40 Hz was used, for large-sized foundation rotating mass vibrator which generates maximum vibrating force of 10 ton and frequency range 1~40 Hz, and also rotating mass vibrator which generates maximum vibrating force of 150 ton and frequency range 1~20 Hz [1] were used. Foundations were vibrated horizontally in two directions (NS and EW direction) and vertically. In this paper result of horizontal vibration test is reported. In the case of horizontal vibration, velocity seismographs were set on each foundation as shown in Fig. 3. In measuring and prcessing of data, digital computer was used, and time series data transformed by FFT, amplitude and phase lag (against vibrating force) at each measuring point were obtained.

EXPERIMENTAL RESULTS

Response of Foundation

In Fig. 4 displacement response at the top of foundation (measuring point TCSE in Fig. 3) in the case of EW-direction vibration test is shown. In each case eccentric moment of vibrator is as follows, for large-sized foundation (experiment name; LBSEEWD901) $m_o r = 0.424$ kg sec^2, for medium-sized foundation (experiment name; MB1TEWDR01) $m_o r = 6.64 \times 10^{-3}$ kg sec^2, for small-sized foundation (experiment name; SB1TEWD101) $m_o r = 1.66 \times 10^{-2}$ kg sec^2. In the case of medium-sized foundation owing to disorder of the vibrator reliable data was acquired only at high frequency. In Fig. 5 displacement response of large-sized foundation for various level of vibrating force and one case for NS-direction vibration is shown, in which case ratio of vibrating force is as follows; LBSEEWD901:LB<u>LE</u>EWD102 ("LE" denotes "150 ton vibrator") :LB<u>LE</u>EWD103:LB<u>LE</u>NSD103 (NS-direction) = 2.8 : 10 : 20 : 150 : 150 at 13 Hz, and at 20 Hz , = 6.7 : 10 : 20 : 50 : 50. It can be seen that the difference of response by force level and direction is very small and experimental results for smaller vibrating force can be applied to the case of larger vibrating force (to large input motion).

Dynamic Stiffness of Foundation

Dynamic stiffness of foundation can be calculated from its swaying and rocking motion in the following way. In the case where foundation can be regarded as a rigid body, the motion of it is described by equation below.

$$\begin{bmatrix} M & M s \\ M s & I_G + M s^2 \end{bmatrix} \begin{Bmatrix} \ddot{u}_B \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} K_H & 0 \\ 0 & K_R \end{bmatrix} \begin{Bmatrix} u_B \\ \theta \end{Bmatrix} = m_o r\, \omega^2 \begin{Bmatrix} 1 \\ s + 1 \end{Bmatrix} e^{i\omega t} \tag{1}$$

in which M = the mass of the foundation; I_G = the moment of inertia of the foundation about its center of mass; s = vertical distance from the line of action of vibrating force to the center of mass; u_B and $\ddot{u}_B$ the horizontal displacement and acceleration at the bottom; θ and $\ddot{\theta}$ the rocking angle and its acceleration; $\mathbf{K}_H (= K_H + iK'_H;\ i = \sqrt{-1})$ and $\mathbf{K} (= K_R + iK'_R)$ the dynamic stiffness of the foundation for swaying and rocking motion; $m_o r$ = eccentric moment of the vibrator; ω = angular frequency of vibrating force and $e^{i\omega t}$ denotes harmonic vibration. Putting harmonic response $u_B = U_B e^{i\omega t}$, $\theta = \Theta e^{i\omega t}$ and substituting in eq. (1), dynamic stiffness of foundation is obtained as follows.

$$K_H = \frac{m_o r \omega^2 + M \omega^2 (U_B + s \Theta)}{U_B}$$
$$K_R = \frac{(s+1) m_o r \omega^2 + M s \omega^2 U_B + \omega^2 \Theta (I_G + M s^2)}{\Theta} \qquad (2)$$

And damping ratio is defined as follows.

$$h_H = K_H'/2 K_H, \quad h_R = K_R'/2 K_R \qquad (3)$$

in which h_H and h_R damping ratio for swaying and rocking motion and proportional to the energy ratio (ratio of energy dissipated per cycle to maximum energy stored in the spring). In the case where elastic deformation of the foundation cannot be negliged, equation above cannot be applied. When shear deformation excesses and uniform as shown in Fig. 6, which is the case with this experiment, considering inertia force by shear deformation eq. (2) is modified as follows.

$$K_H = \frac{m_o r \omega^2 + M \omega^2 (U_B + s \Theta_B + s \Theta_e)}{U_B}$$
$$K_R = \frac{(s+1) m_o r \omega^2 + M s \omega^2 U_B + \omega^2 \Theta_B (I_G + M s^2) + 4 M s^2 \omega^2 \Theta_e / 3}{\Theta_B} \qquad (4)$$

in which Θ_B = complex amplitude of rocking angle measured at the bottom of the foundation; Θ_e = complex amplitude of rotational angle by shear deformation. In Fig. 7 dynamic stiffness of large-sized foundation is shown. For swaying and rocking motion frequency dependece of dynamic stiffness in its real part is not noticeable and may be regarded as constant. As for imaginary part of dynamic stiffness its dependence on frequency is apparent. For swaying motion it increases nearly proportionally to frequency, and for swaying motion it increases at first but from halfway it shows tendency of flat. In Fig. 8 and Fig. 9 dynamic stiffness of medium-sized and small-sized foundation is shown. For small-sized foundation the same also holds true as that for large-sized foundation.

THEORETICAL INVESTIGATIONS

Comparison with Half-Space Theory

Dynamic stiffness of the foundation obtained from experiment was compared with half-space theory. Here as half-space theory vibrational admittance theory by Tajimi, H. [2] was used, and here it is so modified to apply to square foundation and for the assumption of contact pressure distribution, uniform (triangular for rocking), rigid base (displacement constant) and parabolic. In the application of half-space theory rigidity (or Vs) of the bedrock was determined in the following way; (1) Determine from K_H at resonance frequency, (2) Determine from K_R at resonance frequency, (3) Determine from resonance frequency by experiment and calculated response by half-space theory. Vs obtained in this way (hereafter called "equivalent Vs" or (Vs)eq) is shown in Table 2. (Vs)eq increases according as the size of the foundation increases, and for large-sized foundation under assumption of contact pressure distribution uniform (Vs)eq amounts to 1300 m/s ~ 1400 m/s and coincides with that obtained by seismic prospecting. It can be considered the difference of Vs by seismic prospecting and (Vs)eq results mainly from looseness of the bedrock in its surface layer and as the size of the foundation increases the difference may be considered to get smaller. In this case Vs and (Vs)eq coincided well for large-sized foundation, and for the foundation of larger size the same will hold true. Using (Vs)eq, dynamic stiffness of each foundation was calculated by half-space theory, and theoretical value is shown in Fig. 7 ~ Fig. 9 with experimental value. As for dynamic stiffness of large-sized foundation, for swaying motion experimental and theoretical value agreed well assuming contact pressure distribution uniform. For rocking motion, in the imaginary part of dynamic stiffness difference between experimental and theoretical value is observed, and experimental value is larger than theoretical one. As for medium-sized foundation, similar tendency can be observed, but in this case on the assumption of contact pressure distribution parabolic. As for small-sized foundation, experimental and theoretical value agreed well for swaying motion, but for rocking motion discrepancy is observed in imaginary part. In Fig. 4 response of foundations calculated by half-space theory is shown. For large-sized foundation theoretical result agreed well with experimental one. For medium-sized and small-sized foundations discrepancy is perceived, which results from the difference of damping ratio for rocking motion between experimental and theoretical value, and for these foundations rocking motion is dominant comparatively.

Size-Effect of Foundation on Dynamic Stiffness

In Fig. 10 (a) relation of dynamic stiffness to the size of the foundation for swaying motion at resonance frequency is shown. In this figure also theoretical solution, adopting Vs = 1300 m/s and 1400 m/s. Experimental value increases nearly proportionally to the size (side length) of the foundation similar to that by theoretical result. And in Fig. 10 (b) dynamic stiffness for rocking motion. In this case experimental value increases nearly in proportion to the cube of side length, similar to theoretical value. For both swaying and rocking motion, size-effect of the foundation on the dynamic stiffness is noticeable and agrees well with theoretical result. As for contact pressure distribution, reliable data was not acquired in the experiment, but distribution shape is supposed to be ruled mainly by relative stiffness of ground material to foundation structure, and therefore it may be proper to consider that (Vs)eq increased in accordance with the size of the foundation because of looseness of bedrock in its surface thin layer. In Fig. 11 relation of damping ratio to non-dimensional frequency (= $\omega\sqrt{A}/Vs$, A; area of foundation) is shown, in which as Vs "equivalent Vs" obtained from K_H, K_R was applied to h_H, h_R respectively. For swaying motion damping ratio corresponds well to non-dimensional frequency, and for the foundation of larger size and for arbitrary frequency it can be estimated from experimental result and also from theoretical solution within certain limit of non-dimensional frequency. For rocking motion variation of damping ratio with non-dimensional frequency is not so noticeable and discrepancy between theoretical solution is perceived.

Numerical Simulation by Finite Element Analysis

Behavior of the foundation was simulated by axisymmetric finite element analysis with computer program named "TB3D-1" developed by one of the authors [3] in which transmitting boundary for azimuthal direction and viscous damper on base boundary are attached. At first, simulation was carried out with ground properties shown in Table 1. In this case resonance frequency of the foundation by simulation was higher than that by experiment, which indicates rigidity of the bedrock should be lowered than that estimated by seismic prospecting. Assuming that lowering of bedrock rigidity mainly results from looseness, various irreguralities of surface thin layer estimation of which is difficult, following measure was taken. Rigidity of the bedrock in the surface layer of 1.5 m depth was lowered from that shown in Table 1. Rate of rigidity lowering and depth of surface layer were taken the same for three foundations, since the bedrock in the test yard could be regarded as uniform. After several times of trial behavior of the foundation could be simulated fairly well as shown in Fig. 12. As to the accuracy of the simulation, the extent was almost the same for three foundations. And about the following items, result of the simulation was compared with experimental result; the resonance frequency, the peak value, the modal damping, the radius of rocking and so on.

CONCLUSIONS

From the experiment dynamic interaction characteristics for model foundations and its size-effect were made clear. In the analysis by half-space theory evaluation of material properties of ground, especially its rigidity, proved to be an important factor and also the assumption of contact pressure distribution, and in the numerical simulation rigidity of ground material and layered stratum. And for both analysis methods evaluation for rocking motion is difficult compared with swaying motion. In accordance with the size of the foundation, dynamic interaction characteristics could be estimated more accurately by analytical method with material properties of the bedrock obtained by seismic prospecting. And for the foundation of larger size such as that of nuclear reactor building, dynamic interaction characteristics would be evaluated with sufficient accuracy by analytical methods applied herein.

REFERENCES

[1] Tsutsumi, H., Hanada, K., "Development of 450 tons Mechanical Vibrator and Data Acquisition" CRIEPI Report No. E377011, AUGUST 1978

[2] Tajimi, H., "Basic Theories on Aseismic Design of Structures" Journal of Institute of Industrial Science Univ. of Tokyo, Vol. 8, 1959 (in Japanese)

[3] Ueshima, T., et al., "Development of a Computer Program for 3-D Complex Response Analysis of Soil-Structure Interaction Problem with Transmitting Boundaries" CRIEPI Report No. 382009, July 1982 (in Japanese)

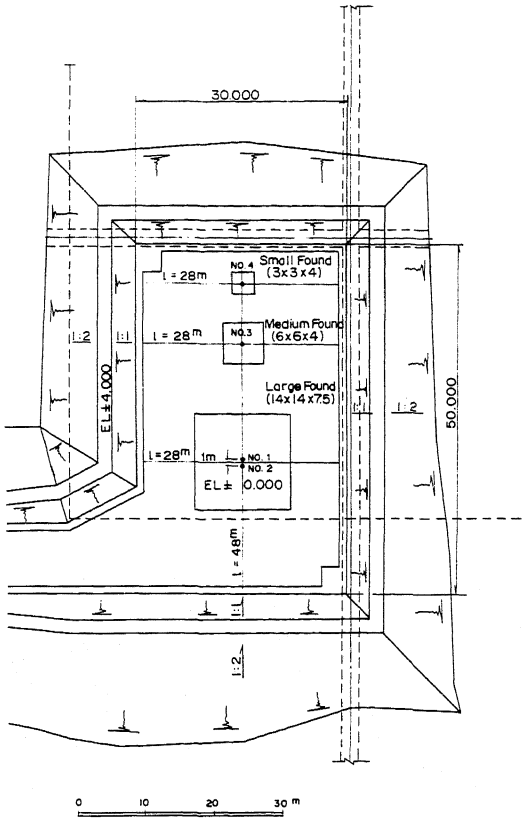


Fig. 1 Location of Foundations

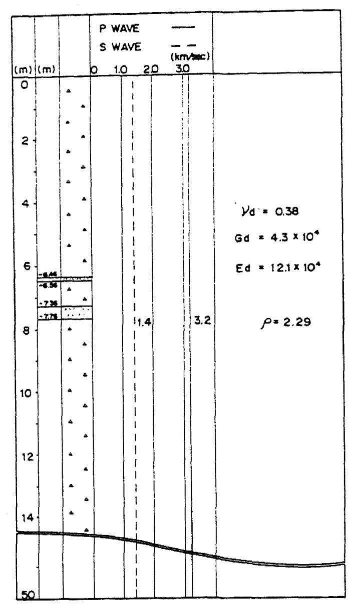


Fig. 2 Rock Profile

Table 1. Material Prorerties of Bedrock under each Found.

	LARGE	MEDIUM	SMALL
Vs(km/s)	1.4	1.3	1.3
Vp(km/s)	3.2	3.0	3.0
ν	0.38		
$\gamma(ton/m^3)$	2.29		

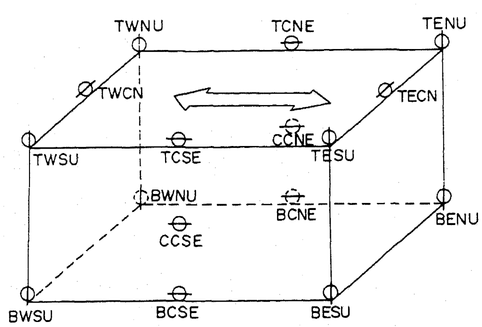
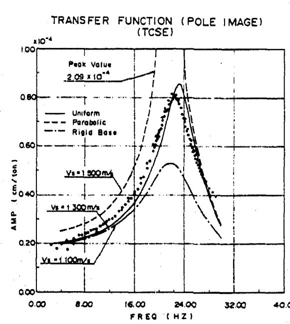
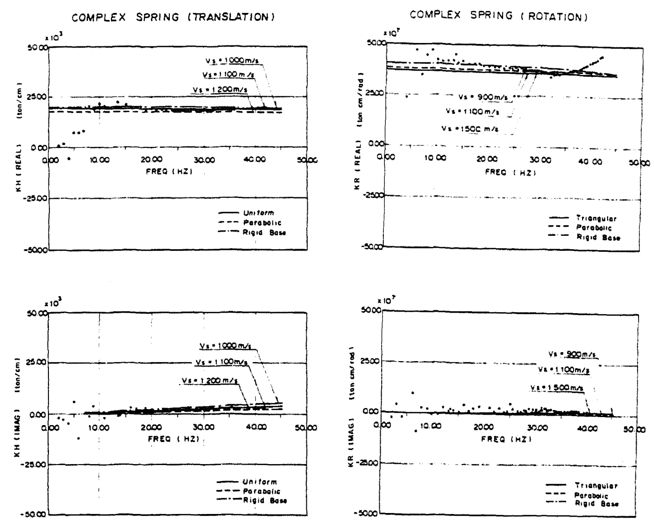


Fig. 3 Location of Seismographs



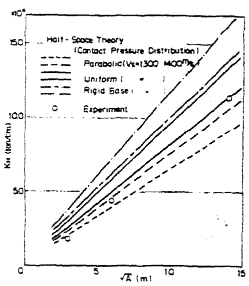
(a) Large-Sized Found.

Fig. 4 Displacement Response

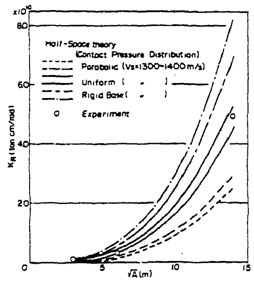


(a) Swaying Motion (b) Rocking Motion

Fig. 9 Dynamic Stiffness of Small-Sized Found.

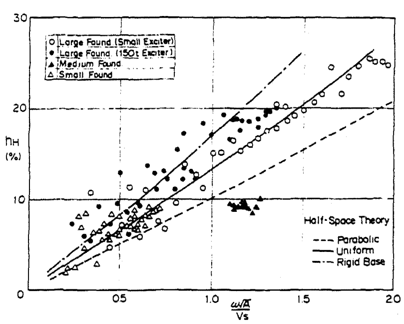


(a) $K_H \sim \sqrt{A}$

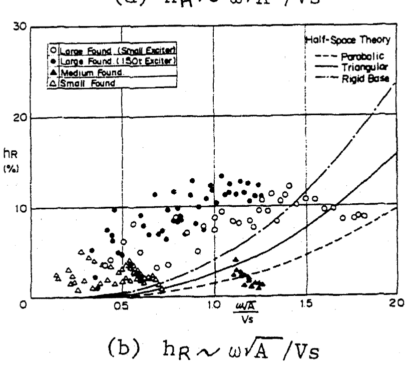


(b) $K_R \sim \sqrt{A}$

Fig. 10 Size-Effect on Dynamic Stiffness of Foundation

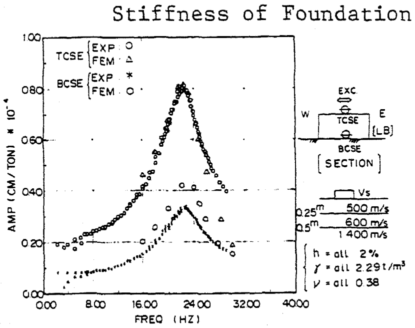


(a) $h_H \sim \omega\sqrt{A}\,/Vs$

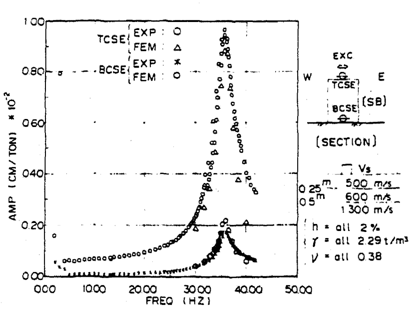


(b) $h_R \sim \omega\sqrt{A}\,/Vs$

Fig. 11 Relation between Damping Ratio and Non-Dimensional Frequency

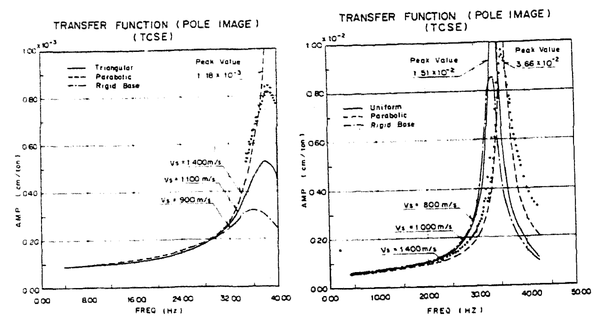


(a) Large-Sized Foundation



(b) Small-Sized Foundation

Fig. 12 Comparison between Experiment and FEM



(b) Medium-Sized Found. (c) Small-Sized Found.

Fig. 4 Displacement Response

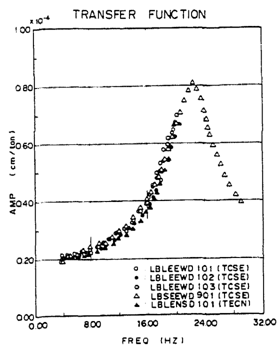


Fig. 5 Difference of Response by Force Level and Direction

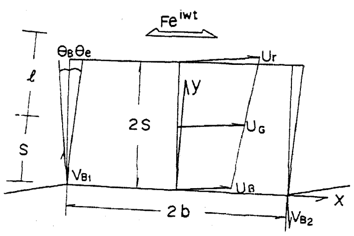
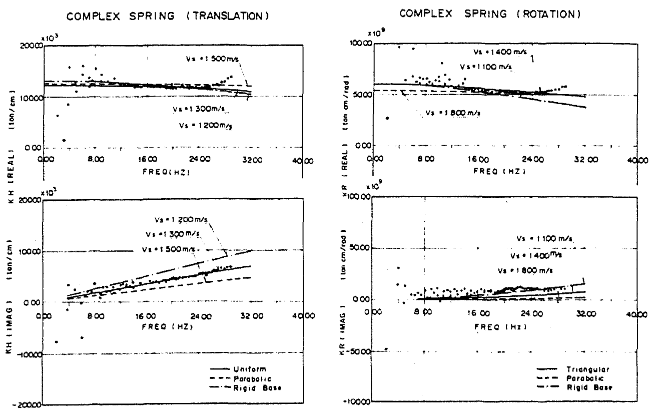


Fig. 6 Coupled Sway and Rocking Motion

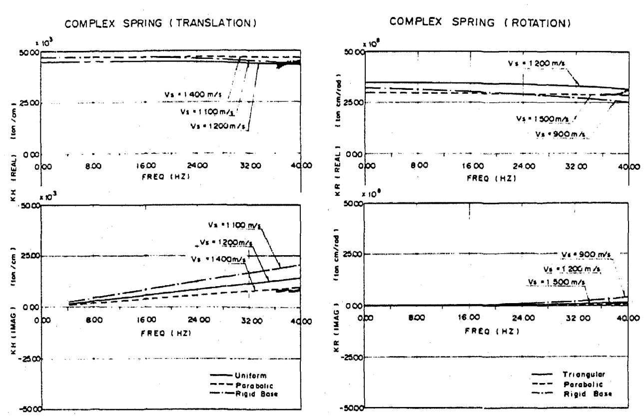
Table 2. (Vs)eq for each Foundation

CONTACT PRESSURE	EQUIVALENT Vs (m/sec) LARGE FOUND.	MEDIUM FOUND.	SMALL FOUND.	ESTIMATE METHOD
UNIFORM	1300	1200	1100	← K_H
	1400	1200	1100	← K_R
	1300	1100	1000	← f_o
RIGID BASE	1200	1100	1000	← K_H
	1100	900	900	← K_R
	1100	900	800	← f_o
PARABOLIC	1500	1300	1200	← K_H
	1800	1400	1500	← K_R
	1500	1400	1400	← f_o



(a) Swaying Motion (b) Rocking Motion

Fig. 7 Dynamic Stiffness of Large-Sized Found.



(a) Swaying Motion (b) Rocking Motion

Fig. 8 Dynamic Stiffness of Medium-Sized Found.