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SYNOPSIS On dynamic analyses of rockfill dams, dynamic deformation characteristics of rockfill materials such as shear moduli and damping ratios must be known to make analysis more accurate. In this study, large-scale cyclic triaxial tests were carried out using rockfill materials of actual dams, and the results were compared with the dynamic deformation characteristics obtained by in-situ geophysical explorations and response analyses of earthquake motions observed at dams. Furthermore, the radiation damping ratio was estimated from response analyses and laboratory tests, and then the frequency and strain dependency characteristics of the radiation damping were evaluated.

1. INTRODUCTION

In Japan, rockfill dams are designed using a seismic coefficient method and a modified seismic coefficient method. Seismic forces acting on the dams are estimated by dynamic analyses for the modified seismic coefficient method. On more accurate dynamic analyses, hence, it is important to investigate dynamic deformation characteristics, including the shear moduli and damping ratios of dam materials, over wide shear strain and frequency ranges. Dynamic deformation characteristics of rockfill materials obtained by laboratory tests have been used for dynamic analyses of rockfill dams. However, deformation characteristics from laboratory tests have rarely compared with those from in-situ tests. In this study, we conducted large-scale cyclic triaxial tests using rockfill materials transported from quarry sites and compared the results with the dynamic deformation characteristics obtained by in-situ geophysical explorations and observed earthquake motions at dam bodies. Radiation damping by dissipation of wave energy into base rock from the dam body has not been determined quantitatively even though it has more affect to the behavior of the dam during earthquakes than internal damping. We, hence, estimated radiation damping from the total damping of the dam body by response analyses and hysteresis damping of rockfill materials by laboratory tests. We compared the estimated radiation damping ratio with that from various ground models by other researchers.

2. GENERAL DESCRIPTION OF TEST AND ANALYSIS

2.1 Object Dams

This study was made on two existing dams: the Miho Dam and the Oya Dam. These are zoned rockfill dams with a central core of 95 m and 56.5 m heights. Figures 1(a) and (2) show the standard cross sections of each dam.

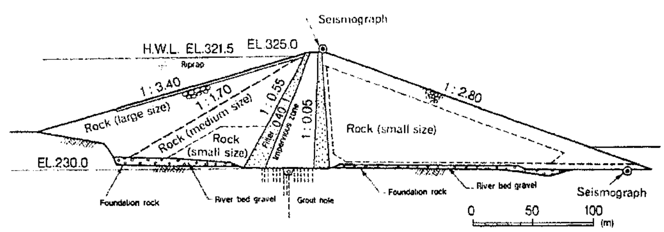

Fig. 1 (a) Standard cross section of the Miho Dam

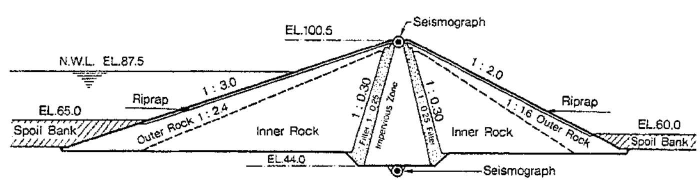

Fig. 1 (b) Standard cross section of the Oya Dam

2.2 Laboratory Test

We transported rockfill materials from the quarry site of each dam. The materials were inner small grain sized rock for the Miho Dam, and inner and outer rock for the Oya Dam. We conducted large-scale cyclic triaxial laboratory tests using the materials. Specimens were 30 cm in diameter and 60 cm in height. We sieved the rockfill materials for a maximum grain size of 63.5 mm and for similar grain size distribution with the banking materials at each dam. Using eddy current gap sensors or differential transformer type displacement gauges, the shear modulus was obtainable in the strain level of 10^{-5} or less.

2.3 In-Situ Geophysical Exploration

We conducted geophysical explorations in the downstream side body of the Miho Dam by means of PS logging and refraction method. For PS logging, blasting was executed in the open-standpipe piezometer within the dam body, and reception of S-wave was taken on the downstream surface of the dam.

2.4 Analysis of Observed Earthquake Motions

For the Miho Dam seismographs have been installed at the crest and downstream toe as shown in Fig. 1 (a), and for the Oya Dam seismographs have been installed at the crest of the dam, at the lowest level of the inspection gallery and in the limb tunnel on the left abutment as shown in Fig. 1 (b). The main features of the used earthquakes are listed in Tables 1. We estimated the natural frequencies of the dam bodies from the frequency response functions at the dam crest against the foundation in the upstream-downstream direction. We smoothed the functions using a Parzen window of 0.6 Hz in band width.

Table 1(a) Main features of the earthquakes for the Miho Dam

No.	NAME OF EARTHQUAKE	DATE	DISTANCE (km)	DEPTH (km)	MAGNITUDE
①	IZU PENINSULA OFF	JUN 29, 1980	57	10	6.7
②	EAST YAMANASHI PREF.	APR 14, 1981	13	40	4.5
③	WEST KANAGAWA PREF.	AUG 8, 1983	12	30	6.0
④	EAST CHIBA PREF. OFF	DEC 17, 1987	131	58	6.7
⑤	HAKONE	AUG 5, 1990	24	14	5.1
⑥	TOKYO BAY	FEB 2, 1992	73	90	5.7

Table 1(b) Main features of the earthquakes for the Oya Dam

No.	NAME OF EARTHQUAKE	DATE	DISTANCE (km)	DEPTH (km)	MAGNITUDE
①	NOTO PENINSULA OFF	FEB 7, 1993	31	25.0	6.6
②	NOTO PENINSULA OFF	FEB 8, 1993	37	25.7	4.9
③	NOTO PENINSULA OFF	FEB 16, 1993	28	24.8	5.0
④	EAST ISHIKAWA PREF.	FEB 22, 1993	9	26.5	4.8
⑤	NOTO PENINSULA OFF	DEC 8, 1993	42	21.0	5.0

3. S-WAVE VELOCITY BY LABORATORY TEST AND IN-SITU GEOPHYSICAL EXPLORATION

Using the result of the laboratory tests of the rockfill materials of the Miho Dam, the relationships between shear modulus G_0 at infinitesimal strain, $\gamma = 10^{-6}$, void ratio e and mean effective principal stress σ'_m are expressed by:

$$G_0 = 551\, P_{at} \frac{(2.17 - e)^2}{1 + e} \left(\frac{\sigma'_m}{P_{at}}\right)^{0.94} \quad (K = 1.0) \qquad (1)$$

$$G_0 = 834\, P_{at} \frac{(2.17 - e)^2}{1 + e} \left(\frac{\sigma'_m}{P_{at}}\right)^{0.73} \quad (K = 0.5) \qquad (2)$$

where, P_{at} is the atmospheric pressure and K is the principal stress ratio. G_0 and σ'_m have the following relationships respectively.

$$G_0 = \rho_D V_s^2 \qquad (3)$$

$$\sigma'_m = \frac{1}{3}(1 + 2K)\,\sigma'_v \qquad (4)$$

$$\sigma'_v = \rho_D \cdot g \cdot D \qquad (5)$$

where, ρ_D is the wet density of the rockfill, Vs is the S-wave velocity, σ'_v is the effective vertical stress expressed by (5) and D is the depth from the dam surface.

If (3), (4) and (5) are substituted for (1) and (2), and if $\rho_D = 2.3$ t/m^3 and e = 0.25 on the basis of the results of quality control tests on banking, Fig. 2 shows the distribution of Vs with D in the cases of K=1.0 and 0.5. The result of in-situ geophysical explorations conducted in the downstream side of the Miho Dam is also shown in this figure. The distribution of Vs from the laboratory tests agreed with that from the in-situ geophysical exploration. The shear modulus of the rockfill dam body can be estimated by laboratory tests on the rockfill materials, since rockfill dams are constructed in a similar process to that for preparing specimens of laboratory tests

4. SHEAR MODULUS BY LABORATORY TEST AND EARTHQUAKE MOTION ANALYSIS

We calculated the shear moduli of the two dams for each shear strain level during the earthquakes listed in Tables 1. In accordance with shear beam theory, the shear modulus G is

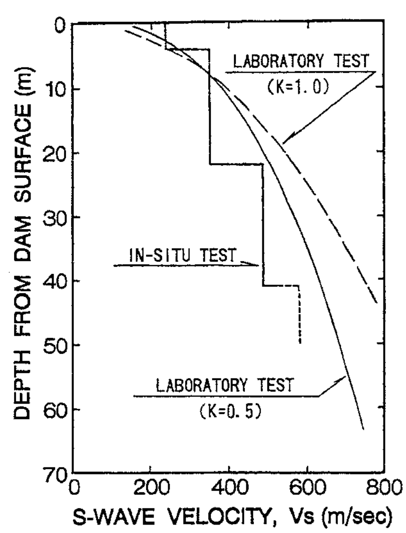

Fig. 2 Distribution of S-wave velocity for the Miho Dam

in proportion to the square of the i-th natural frequency f_i. When the first natural frequency and shear modulus of a dam body at very small shear strain are f_{1*} and G_* respectively, the normalized shear modulus G/G_* is expressed by:

$$\frac{G}{G_*} = \left(\frac{f_1}{f_{1*}}\right)^2 \quad (6)$$

The first natural frequency and the shear modulus at the smallest shear strain level of a dam body among the observed earthquake motions were assumed to be f_{1*} and G_*. The mean shear strain caused in the dam body during each earthquake motion for the Miho Dam was calculated by the three processes shown below — and the shear strain for the Oya Dam was calculated by the process 2) only.

1) The average of maximum shear strains for each layer of the dam body was obtained using the one-dimensional dynamic analysis, SHAKEM (Chugh, 1985).
2) The shear strain was calculated from the maximum displacement d_{max} by two times integration of the time history of acceleration at the crest.
3) The shear strain was calculated from the maximum acceleration a_{max} at the crest, as expressed by:

$$\gamma = \frac{d_{max}}{H} = \frac{a_{max}}{(2\pi f_1)^2 \cdot H} \quad (7)$$

where, H is the height of dam.

Figures 3 (a) and (b) show the dependency of G/G_* with γ during the earthquakes for the Miho Dam and the Oya Dam respectively. Normalized shear moduli G/G_* decrease as the shear strains γ increase for both the dams. These figures show also the normalized shear moduli G/G_0 obtained by laboratory tests for various confining pressures σ'_c. The G/G_* obtained by earthquake motions is slightly larger than G/G_0 by laboratory tests, for G_* and G_0 were defined at the different shear strains. The reductive tendency of G/G_* with γ for each dam agreed with that of G/G_0. As a result, the strain dependency of the shear modulus for rockfill dam bodies during earthquakes can be estimated from laboratory tests.

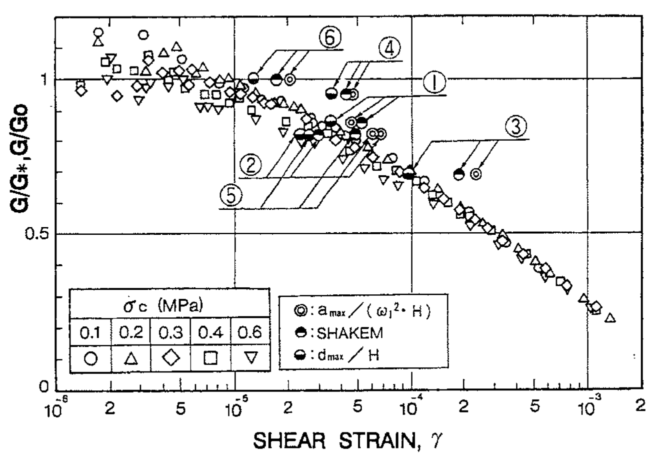

Fig. 3 (a) Normalized shear modulus G/G_*, G/G_0 versus shear strain γ relationships for the Miho Dam

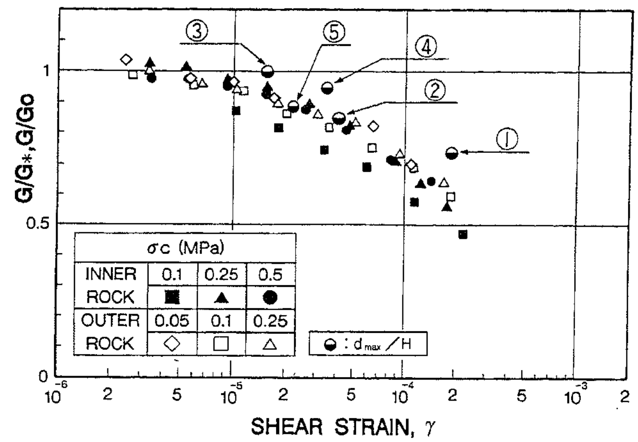

Fig. 3 (b) Normalized shear modulus G/G_*, G/G_0 versus shear strain γ relationships for the Oya Dam

5. QUANTITATIVE ESTIMATION OF RADIATION DAMPING RATIO

We obtained the damping ratios of dams for the first to third resonance frequencies from frequency response functions of observed earthquake motions by half power method. Figure 4 shows damping ratios from response analyses of observed earthquake motions and hysteresis damping ratios h_h of the rockfill materials from laboratory

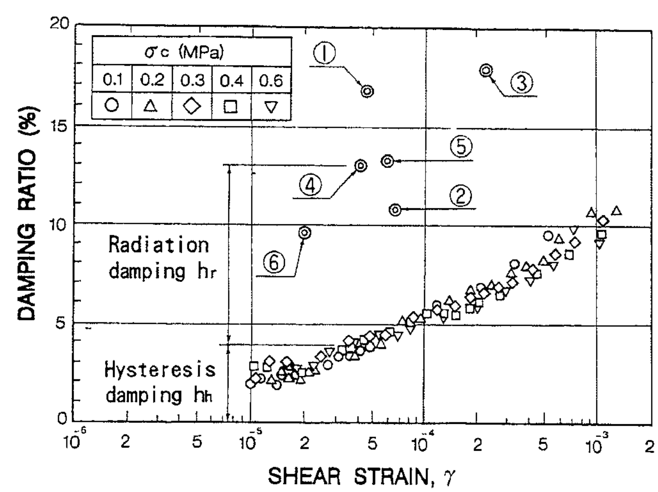

Fig. 4 Hysteresis damping ratio obtained by laboratory tests and total damping ratio of the first vibration mode by observed earthquake analyses versus shear strain relationships for the Miho Dam

tests, with shear strains for the Miho Dam.

The damping ratios from analyses of observed earthquake motions are total damping ratios ht, which consist of both internal damping — it is almost covered by hysteresis damping for earth structures — and radiation damping. In response analyses, the accelerations observed at the downstream toe of the dam were input to the foundation for the Miho Dam, and those observed in the limb tunnel were input for the Oya Dam, for the accelerations at these points had little effect on the vibration of the dam body itself during earthquakes. As shown in Fig. 4, the value at each strain level obtained from the difference between the ht for each vibration mode and the hh is equivalent to the radiation damping ratio hr. Figures 5 (a) and (b) show the hr for each earthquake motion with the first to third natural frequency of the dam body. We theoretically calculated the radiation damping ratio by the model of triangle-shaped elastic body on elastic foundation after Ohmachi (1981) and by the models of two-layer ground after Toki (1982) and Sato (1983). We add the theoretical radiation damping ratios with a parameter γ in Figs. 5 (a) and (b). In these figures, the hr of the two dams

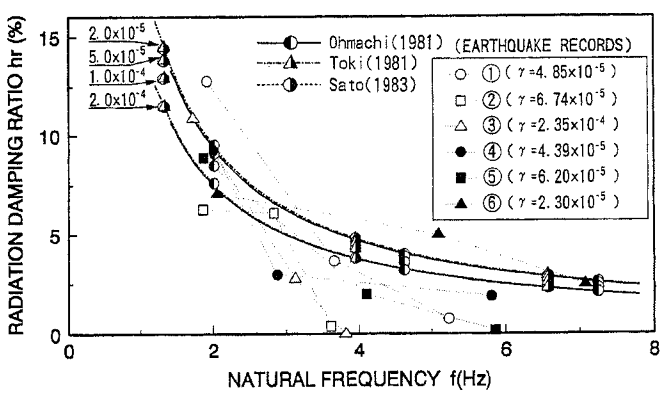

Fig. 5 (a) Radiation damping ratio with natural frequency for the Miho Dam

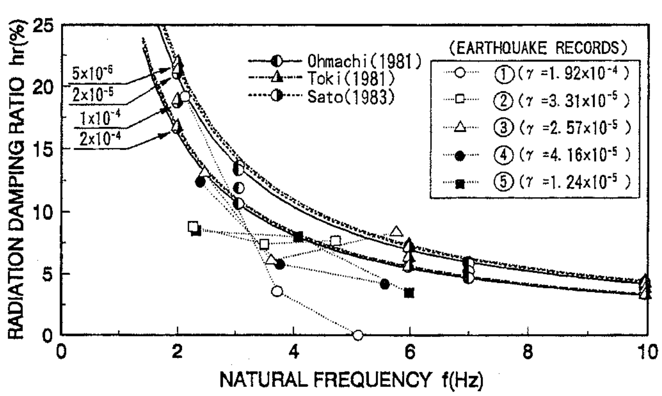

Fig. 5 (b) Radiation damping ratio with natural frequency for the Oya Dam

from response analyses and laboratory tests decrease as the vibration mode frequency increases. In the calculation of the hr, we deducted the same value of the hh from the ht for each vibration mode. Since the shear strain of the dam body for over the second vibration mode can be considered much smaller than that of the first vibration mode, it is assumed that we have reduced excessive hh in the calculation for over the second mode. Thus, the reduction rate of the hr for over the second vibration mode by our method was larger than those by Ohmachi, Toki and Sato. The radiation damping ratio hr should theoretically become slightly smaller as γ increases, but the values of the hr from analyses of observed earthquake motions varied widely and the shear strain dependency of the hr was not noted.

6. CONCLUSIONS

We examined the dynamic deformation characteristics of rockfill materials from cyclic triaxial laboratory tests, in-situ explorations and response analyses of observed earthquake motions.

The distributions of S-wave velocities in the direction of depth obtained by laboratory tests and in-situ explorations were in agreement. The reduction of the normalized shear moduli with shear strains from laboratory tests and response analyses of earthquake motions was also in agreement. Therefore, the shear moduli of man-made banking structures such as rockfill dams can be estimated accurately by laboratory tests.

We estimated the radiation damping ratio of rockfill dams by deducting the hysteresis damping ratio by laboratory tests from the total damping ratio calculated by the half power method from the frequency response function of observed earthquake motions. Thus, we obtained the frequency characteristics where the radiation damping ratio decreased as a higher vibration mode.

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