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IN-SITU MEASUREMENT OF RADIATION DAMPING OF EXISTING ROCKFILL DAMS

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SUMMARY

A practical method for in-situ measurement of radiation damping is proposed and applied to three existing rockfill dams. In the method, use is made of ambient vibration of dams because of its extremely small level of vibration amplitude. Transfer functions resulting from the ambient vibration measurement reveal the damping ranging from 4 % to 10 % of the critical. These values look fairly consistent with analyitical estimation.

INTRODUCTION

It is generally believed that vibration damping of earth- and rockfill-dams are made up of two factors. One is material damping and the other is radiation damping. In comparison with the former, present knowledge on the latter which has stemed only from analytical approach (Refs. 1 and 2) is quite limited in both quality and quantity. Up to the present little effort has been made for experimental evaluation. But, in order to improve reliability or at least to check validity of dynamic analysis on such dams, more knowledge on the radiation damping should be accumulated through in-situ measurement on actual dams. By extending a previously proposed method (Ref. 3), radiation damping is experimantally evaluated for rockfill dams existing in Japan.

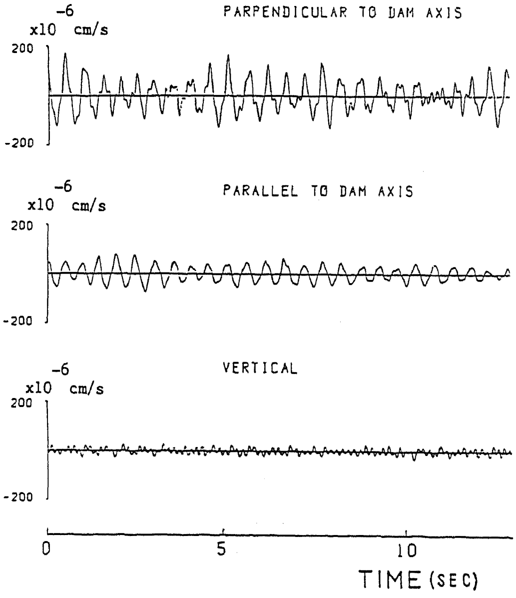


Fig. 1 Ambient Vibration of a Dam

MEASUREMENT PROCEDURE

As is well known, soil tends to show negligibly small damping of vibration in a low level of strain for itself. Strain level induced by ambient vibration (or microtremor) is extremely low, as shown in Fig. 1

which is observed near the center of the crest of a rockfill dam. In this context, it seems reasonable to assume that damping characteristics of a rockfill dam associated with ambient vibration can be practically attributed to the radiation damping. If this holds, the damping can be evaluated from in-situ measurement of ambient vibration of a dam in principle.

Fig. 2 shows a flowchart of the present procedure to evaluate radiation damping of existing dams, which follows.

1) Using a F. E. program, three-dimensional modes of vibration of a dam concerned is analyzed for planning the in-situ measurement.

2) Ambient vibration is observed at many points along crest of the dam as well as at the foundation. This serves for selecting reference points in 3) as well as for mode identification in 6).

3) At reference points selected on the crest and at the foundation, ambient vibration is simultaneously observed and transformed into Fourier spectra.

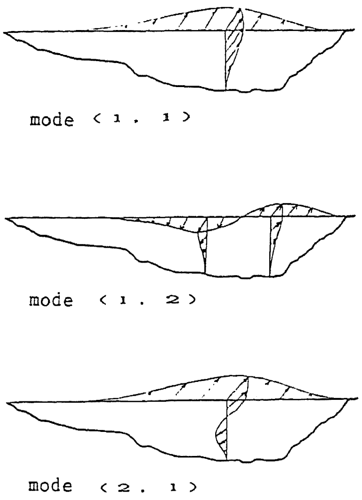
4) A transfer function is calculated in terms of a spectral ratio between the crest and the foundation.

5) From the transfer function, the several lowest natural periods and their associated damping ratios are evaluated.

6) The lowest few modes of the dam are iteratively analyzed by a 3-D F.E.M. until their natural periods become identical to the observation.

7) With shear wave velocity resulting from the above iteration, an impedance ratio is estimated for the dam and foundation system.

8) The impedance ratio obtained above is compared with an observation to check validity of the damping evaluated in 5).


mode < 1 . 1 >

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1) Measurement Planning
by Use of 3-D F. E. M.
↓
2) Ambient Vibration Measurement
for Reference Point Selection
↓
3) Ambient Vibration Measurement
Followed by Spectral Analysis
↓
4) Calculation of Spectral Ratio
Leading to Transfer Function
↓
5) Evaluation of Natural Frequency
and Damping of Fundamental Mode
↓
6) Mode Identification of Dam
by Use of 3-D F. E. M.
↓
7) Estimation of Impedance Ratio
of Dam-foundation System
↓
8) Check of Observed Damping
by Theoretical Estimation

Fig. 2 3-D Vibration Modes and a Flowchart of the Present Procedure to Evaluate Radiation Damping

TRANSFER FUNCTIONS

The proposed procedure was applied to three rockfill dams in Japan.

1. Kassa Dam

The Kassa Dam is a center core rockfill dam with the maximum height of 90 m and the crest length of 487 m. It was built in 1977. Hard dacite (Da) is exposed over the entire right-bank side of the dam, but on the left bank side uncemented deposits mainly of volcanic mud flows (Vm) thickly cover the basement rock of the dacite, as shown in Fig. 3 which also shows location of observation stations. The reservoir was fully impounded with water during the interval of the in-situ measurement.

Fig. 4 shows the Fourier amplitude spectra of three components of ambient vibration observed at the point C1 which are partly shown in Fig. 1. From the spectra, the frequency component around 2 Hz is predominant on the crest, suggesting the fundamental mode of vibration at around the frequency. A frequency component of 6.25 Hz is due to power generation about 5 km distant from the dam.

As for a component perpendicular to the dam axis, amplitude at G3 and C1 is on an average 2 and 10 times larger than that at G4. Meanwhile ambient vaibration at G4, G5 and G6 are almost the same in both amplitude and phase. On this basis, reference points of this dam were selected at C1 and G4.

Fig. 5 shows transfer functions calculated from Fourier spectra of the ambient vibration. Two curves in Fig. 5 were resulted from two observations conducted at different time. It should be noticed that the function appears steady only in a frequency range associated with the fundamental mode of vibration, while unsteady at higher frequency.

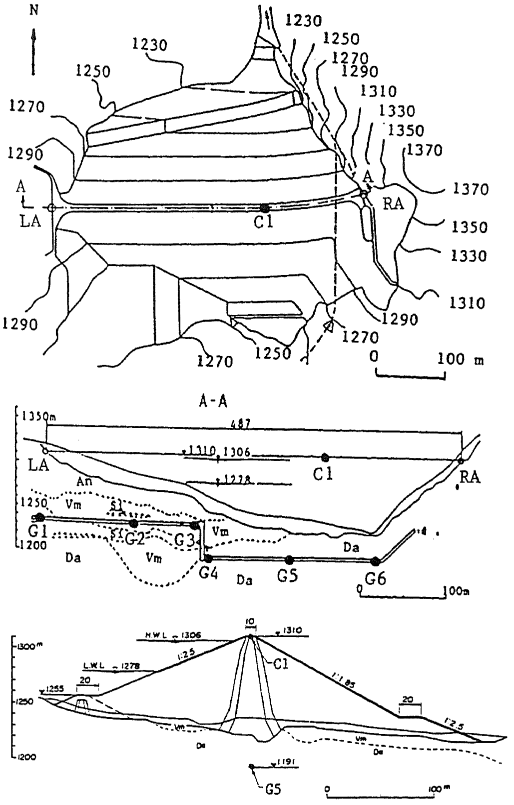

Fig. 3 Outline of the Kassa Dam and Location of Observation Points

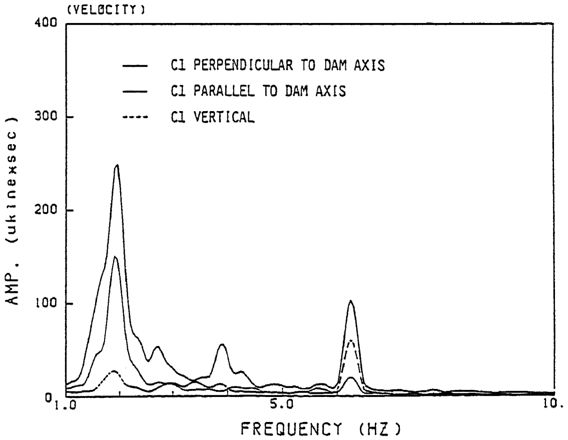

Fig. 4 Fourier Amplitude Spectra of Ambient Vibration Observed at C1 of the Kassa Dam

2. Miboro Dam

The Miboro Dam which is 131 m high and 405 m long along the crest having an inclined clay core. It was built in 1960. The foundation is symmetrical across the valley and covered with granite. Reference points for this dam were selected at the center of the crest and in the outlet tunnel as shown in Fig. 6.

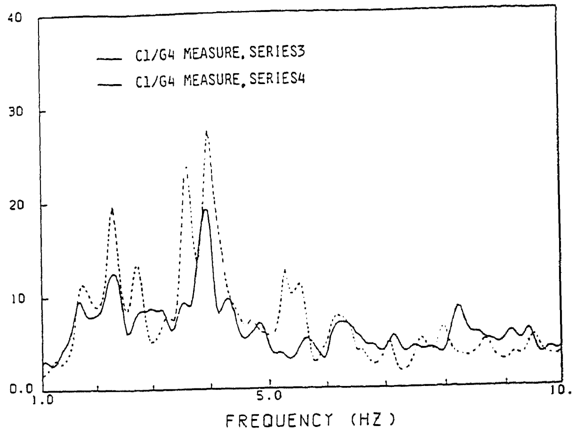

Fig. 5 Transfer Functions of the Kassa Dam

Transfer functions derived from the aforementioned procedure are simply shown in Fig. 7. The reservoir water was almost at the high water level of the dam during the measurement.

3. Ouchi Dam

The Ouchi dam is 102 m high and 340 long along the crest, and has a central clay core. It was built in 1986. On both upstream and downstream sides, it is provided with large weighting zones to secure slope stability as shown in Fig. 8. Tuff is distributing at the foundation as a whole, but hardness or soundness of the tuff on the right bank side is different from that of the left.

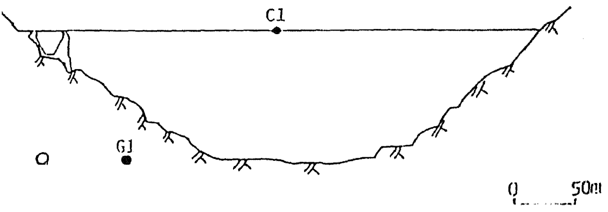

Fig. 6 Outline of the Miboro Dam and Location of Reference Points

Transfer functions of this dam are shown in Fig. 9. Reference points for the function are shown in Fig. 8. The ambient vibration was measured before the reservoir became impounded with water.

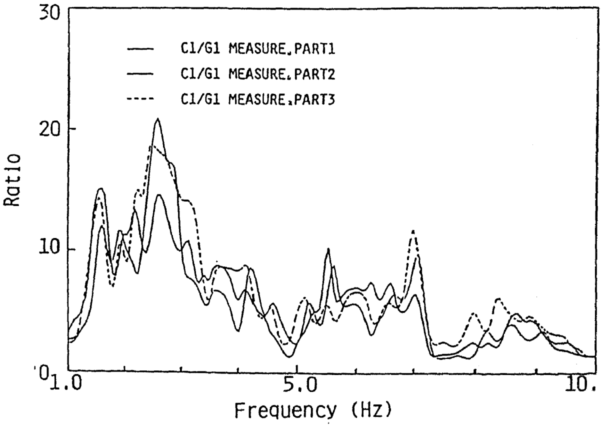

Fig. 7 Transfer Functions of the Miboro Dam

RADIATION DAMPING

As described previously, the transfer functions derived from the ambient vibration measurement appear unsteady at higher frequency, but rather steady at around the fundamental frequency of each dam. The unsteadiness is partly due to a less reliable S/N ratio of the ambient vibration with small amplitude at higher frequency, as can be suspected from Figs. 1 and 4. In addition, at higher frequency any peak amplitude has considerable amount of contribution from many modes of vibration because of close spacing of many natural frequencis as shown in Table 1.

For these reasons, radiation damping can be evaluated only for the fundamental mode from the transfer function. The simplest way of the evaluation is given by the formula

$$M = p/2h \quad \text{or} \quad h = p/2M$$

where M, p and h are an amplification factor, a participation factor and a damping ratio, respectively. The factor M of the fundamental mode can be read from the figures of the transfer functions, and p is given by the 3-D F. E. analysis (cf. Table 1). Some examples of natural frequencies and associated participaction factors of the Kassa Dam computed by the simplified 3-D F.E.M. (Ref. 4) are shown in Table 1.

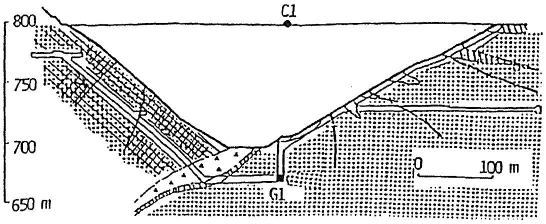

Fig. 8 Outline of the Ouchi Dam and Location of Reference Points

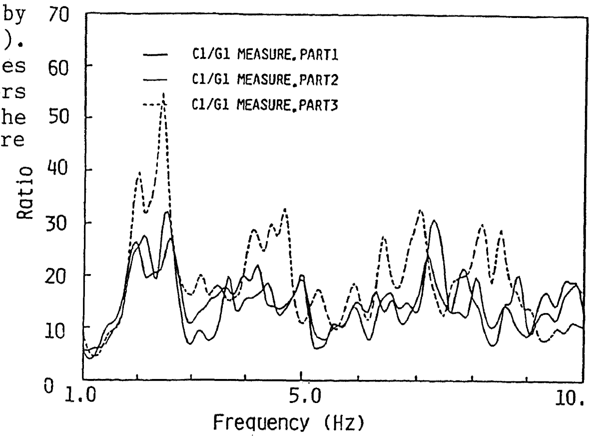

Fig. 9 Transfer Functions of the Ouchi Dam

Table 1 Natural Frequencies and Participation Factors Calculated for the Kassa Dam

MODE	V_s = const.(V_s =360m/s)		$V_s = k_o z^{1/3}$ (k_o = 97m/s)	
(V, H)*	FREQUENCY (Hz)	PARTICIPATION FACTOR	FREQUENCY (Hz)	PARTICIPATION FACTOR
(1, 1)	1.80	2.06	1.80	2.58
(1, 2)	2.29	0.10	2.15	0.13
(1, 3)	2.84	0.98	2.52	1.51
(1, 4)	3.30	0.39	2.78	0.63
(1, 5)	3.63	1.13	2.97	1.36
(1, 6)	3.95	0.19	3.19	0.11
(1, 7)	4.32	0.56	3.42	0.71
(1, 8)	4.68	0.00	3.66	0.07
(1, 9)	5.07	0.39	3.90	0.56
(2, 1)	3.78	1.40	3.40	2.61
(2, 2)	4.18	0.22	3.70	0.31
(2, 3)	4.71	0.56	4.10	1.12

*) Note:
A few mode shapes of the Kassa Dam are exemplifed at the top of Fig. 2.

The radiation damping ratios thus obtained are summarized in Table 2.

Table 2 Summary of Results

Dam Name	Kassa	Miboro	Ouchi
Compl. Year	1977	1960	1986
Height (m)	90	131	102
Length (m)	487	405	340
Found. Rock	Dacite	Granite	Tuff
Reservoir Water	full	full	empty
1st Mode Freq. (Hz)	1.80	1.65	1.90
1st Mode Rad. Damp.	0.10	0.10	0.04
Impedance Ratio	0.23 (0.13-0.32)	0.31 (0.27-0.34)	0.08 (0.20-0.33)

DISCUSSION

According to the simple analytical formulation (Refs. 2 and 3), the radiation damping for the fundamental mode is expressed as

$h = 0.43R$; for a dam with Vs being uniform.

$h = 0.32R$; for a dam with Vs increasing with 1/3 power of depth.

where Vs and R are shear wave velocity and the impedance ratio at the interface of the dam and the foundation. Either model of the shear wave velocity is selected by the iterative mode identification based on the 3-D F. E. analysis. For the Miboro Dam, the second model was found to give a better fit, and for the remaining two dams the first one was found to give a better fit. Once the damping ratio is determined, then the impedance ratio is evaluated by using either of above relations.

Although measured shear wave velocity at the foundation is lacking for each dam, rough estimation is available based on rock classification. Using the shear wave volocities calculated by the F. E. M. for the dams and the rough estimation for their foundations, impedance ratios of the three dams were estimated and listed in parentheses at the bottom of Table 2.

CONCLUSION

The present procedure for in-situ measurement of radiation damping of rockfill dams has proved to be practical and valid, providing 4 to 10 % of the critical damping for the fundamental mode of vibration. The measurement results suggested that the damping should be increased by water impoundment in the reservoir.

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