A CONSIDERATION ON THE SEISMIC COEFFICIENTS OF ROCK AND EARTH FILL DAMS THROUGH OBSERVED ACCELEROGRAMS AND MODEL TESTS

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SYNOPSIS

The experiments of vibration are performed on six dam models of sand containing gravel which are constructed in a testing box of steel fixed on the shaking table. With the experimental results the interrelation between the behavior of models and that of actual dams during earthquakes is discussed. On the other hand 77 earthquake records at the bases of 14 dams are collected. With these data an empirical formula concerning the predominant periods of accelerograms at dam bases is deduced. Together with all these results the magnification factors of accelerations at dam crests are estimated against three earthquakes of which magnitudes are 7, 7.5 and 8 respectively and of which peak accelerations at dam bases are just 200 gals. The values of 1.6 for rock fill dams and 1.94 for earth fill dams are obtained as the mean values of these factors.

INTRODUCTION

According to the design criteria of large dams by Japanese National Committee on Large Dams, we can adopt a seismic coefficient of dam body equal to a design ground acceleration in the fill type dams. But some of the reports on the observations of earthquakes on earth fill dams (Okamoto, S. et al, 1966; Kawakami, F. et al, 1967) and on the experiments of vibration on models performed so far (Davis, R.E., 1952; Clough, R.W. et al, 1956; Minami, I., 1960; Ishizaki, H. et al, 1962; Krishna, J. et al, 1969) showed that the accelerations in dam bodies are considerably larger than those on the bases. The observed earthquakes on fill type dams, however, did not include such strong motion earthquakes as could be applied to design except the recent data on the San Fernando Dams (Seed, H.B. et al, 1973). So, the validity of the seismic coefficient of dam body is not confirmed.

In this paper the author would like to estimate the seismic coefficients of dam bodies through observed accelerograms and model tests. The author would like to show first the results of the experiments of vibration on models of sand containing gravel applying periodic base motions. With these results the author would like to discuss about the distribution of acceleration in models, the frequency characteristics of acceleration magnification factor, the effects of material non-linearity, the irregularity of earthquake waves and reservoir water on the behavior of models during vibration, and above all the interrelation between the behavior of models and that of actual dams during earthquakes. On the other hand, with 77 earthquake records on the bases of 14 dams the author would like to deduce an empirical formula concerning the predominant periods of the earthquakes on dam bases. Together with all these data mentioned above the magnification factors of acceleration at dam crests will be estimated.

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EXPERIMENTS OF VIBRATION ON MODELS

An objective dam of the experiments has the height of 175 meters and has slopes of 1 : 2.6 in the up stream side and 1 : 2.1 in the down stream side. The material of models was sand containing gravel of which grain size accumulation curve is given in Fig. 1 as a curve of X (-63.5). According to Japanese Industrial Standard the optimum water content and maximum dry density of the material are 6.3% and 2.1 gr/cm^3 respectively. Models were filled with the sand moistened to near optimum water content in the testing box of steel, compacting layer by layer incrementally of which thickness was about 20 cm.

The testing box was fixed on the shaking table and had 2.0 meters width, 10.0 meters length and 3.0 meters depth in inside measurement. On each layer density and water content were measured at several points. The average dry density and water content of whole models were 1.68 gr/cm^3 and 6.54 % respectively. The experiments were performed along the keynote that the general characteristics of vibration of models should be examined firstly, then these results should be applied to actual fill type dams considering into the law of similitude. So that following six models were tested, that is, two homogeneous models of reduced scale of 1/200, three more homogeneous models of reduced scales of 1/150, 1/100 and 1/70 respectively and one zoning type model of reduced scale of 1/100. In order to measure the vibration of models, 23 acceleration meters of unbonded wire strain gauge type were arranged and set over the cross section of models in maximum case. The location of gauges is shown in Fig. 2. The shaking table has 6.0 meters width and 6.5 meters length. Loading capacity is 120 tons. The capacity of exciting force is such one as can excite the model of 100 tons up to 400 gals in the frequency range of 2.0 to 20.0 Hz. Each model was subjected to 7 or 8 series of sinusoidal ground motions. In each one of series the amplitude of ground acceleration was kept constant and the frequency was changed stepwise in the range of 5.0 Hz to 30.0 Hz. These 7 or 8 series of above mentioned excitations were performed with 7 or 8 different values of amplitude of ground acceleration in the range of about 20 gals to 200 gals. Summarizing these results following conclusions are obtained.

(1) The resonant curves of each measuring point are similar through all the models. The horizontal response acceleration at near crest decreases rapidly as the period of ground motion comes apart from the fundamental predominant period of model dam as shown in Fig. 3. From this resonant curve a digital relation between response acceleration at dam crest and the period of ground motion may be obtained. An example is shown in Table 1.

(2) Because of material non-linearity the magnification factor of response acceleration at every point in the model dam decreases exponentially as the amplitude of ground acceleration increases as shown in Fig. 4. This relation may be expressed in the following formula,

$$M^* = M_0 \exp\ (-\beta a_0) \qquad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where M* represents the magnification factor, a_0 represents the amplitude of ground acceleration, M and β are constants.

(3) In spite of the fact that all homogeneous models are made from same material and filled in the same condition of compaction, following size effect is recognized, that is, the magnification factor of response acceleration decreases as the scale of model becomes larger as shown in Fig. 5. It may be caused by non-elastic properties of material.

(4) From the results of F.E.M. analysis it is proved that when the ground motion is that of earthquake the magnification factor of response acceleration at the crest is reduced to 57% of the factor when the ground motion is sinusoidal one with resonant period because of irregularity of earthquake wave. An example is shown in Fig. 6.

(5) No evident difference is recognized between the behavior of homogeneous model and that of zoning type model. But it is recognized that the response acceleration of the model with full reservoir water is considerably smaller than that with no reservoir water. For example the amplitude of the response acceleration with full reservoir water is reduced to about 66% of that with no reservoir water in the fundamental mode.

(6) With all the results from these experiments mentioned above, we may estimate the earthquake responses of any other fill type dams. When average shear modulus, average density and height of a dam are known, the reduced scale of the similar model of that dam, which model has the same material properties as those models in these experiments, may be determined from the law of similitude that both ratio of acceleration and ratio of strain are unity. In the case that the size of that model thus determined is within the range of sizes of the models in these experiments, the results from these experiments mentioned above may be applied to it approximately under several assumptions. For example we assume that the material non-linear properties in these models may be applied approximately to the actual dams and that small changes in slopes of dams do not affect much more the response accelerations at near the crests of dams. In this manner the author estimates the magnification factors of horizontal response accelerations at the crests of several actual dams with no reservoir water when predominant periods are known. Table 2 shows the constants M_0 and β in Eq. (1) thus estimated for those dams.

With Table 1 and 2 the following results may be obtained. That is, in the cases when the maximum ground acceleration is 200 gals and the predominant periods of ground motions are just identical with the fundamental predominant periods of dams, the magnification factors of horizontal accelerations at the crests of dams become 3 or 4. In the cases when the predominant periods of ground motions are 20% longer, however, those factors become 2.6 in the maximum, and in the cases when the predominant periods are shorter to the extent of 85% of fundamental periods of dams, there is no magnification factor larger than 2.0. Moreover, in the cases when the predominant periods become much shorter to the extent of 57% of fundamental periods of dams, all the values of magnification factors become under unity. From above mentioned results it may be said that when a fill type dam is struck by severe earthquake of which predominant period is identical with the fundamental period of the dam, it is expected that the dam will vibrate sympathetically for the first, however, because of material non-linear properties the predominant period of dam will be lengthened, and so vibration at the crest will decrease rapidly.

PREDOMINANT PERIODS OF ACCELERATIONS AT BASES OF DAMS

There are only a little records of accelerograms at bases of dams in Japan. Among them there are records of Sannokai dam (Okamoto, S. et al, 1966), Ainono dam, Ushino dam (Kawakami, F. et al, 1967, 1973), Miboro dam, Kuzuryu dam, Yanase dam, Numappara dam (Baba, K., 1974) and Kisenyama dam (Niwa, T., 1974) of which predominant periods are known. And there are also those records of which maximum accelerations only are known but not the predominant periods, such as the records of Susobana dam, Tonoyama dam, Shimokotori dam, Muromaki dam, Kurobe dam and Tagokura dam. It may be that among some of these records the predominant periods are known though they are not published. Of course the epicenters and magnitudes of them all are known.

The latter records are classified into three groups corresponding to the magnitudes in the levels of 4.5 ~ 5.7, 5.9 ~ 6.6 and 6.9 ~ 7.8 respectively. In each group letting the abscissa be the distance from the focus of the earthquake, letting the ordinate be the logarithmic scale of the maximum acceleration at base of dam and plotting all of the above mentioned data on it, then such relation as shown in Fig. 7 may be obtained. In Fig. 7 a curve remarked "after Kanai" is drawn after Kanai's empirical formula (Kanai, K. et al, 1966) with the average values of magnitude and distance from the focus of earthquake of this group. Thus three predominant periods corresponding to above mentioned three groups are obtained from the latter records which are plotted in Fig. 8.

From the former records of which predominant periods are known, the relation between predominant period and distance from focus of earthquake may be obtained as shown in Fig. 9. With Fig. 8 and 9 following empirical formula may be obtained,

$$T_p = (1.28 \times 10^{-3} M - 7.02 \times 10^{-3})\, X + 0.211 \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where T_p represents the predominant period, M represents the magnitude in the range of 5.5 ~ 7.8 and X represents the distant from focus of the earthquake in the range of 59 ~ 762 (km). Fig. 10 shows the relations between T_p, M and X plotted from Eq. (2) and superimposed on the similar relations by Seed (Seed, H.B. et al, 1968).

ESTIMATION OF SEISMIC COEFFICIENTS OF ROCK AND EARTH FILL DAMS

In the case when a_0 is kept equal to 200 gals and three levels of magnitude such as 7.0, 7.5 and 8.0 are taken into account of, letting the maximum velocity for each level of magnitude after Kanai's empirical formula be multiplied by $(2\pi / T_p)$ and letting the resultant be equal to 200 gals, we may obtain the simultaneous equations together with Eq. (2) concerning T_p and X. Thus, for each level of magnitude we may obtain the predominant period of the ground motion of which maximum acceleration is 200 gals at dam base. These values are shown in Table 3. As for the actual dams given in Table 2, Eq. (1) is applied to them with constants M_0 and β and with a_0 equal to 200 gals. Then the spectrum given in Table 1 is applied to those results with the predominant periods of corresponding magnitude of earthquakes given in Table 3. After all we may obtain the magnification factors of accelerations which may be expected in several actual dams as shown in Table 4. From Table 4 the values of 1.6 for rock fill dams and 1.94 for earth fill dams are obtained as the mean values of the magnification factors of accelerations at dam crests.

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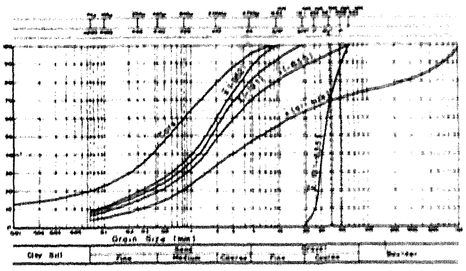
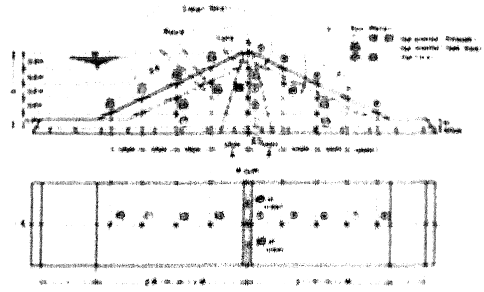


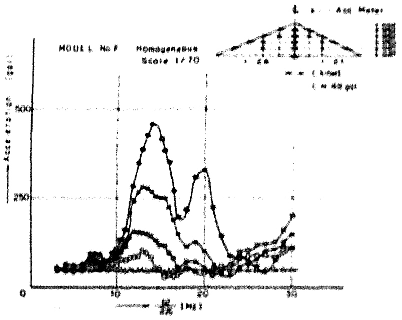
Grading Curves of Materials of Model Dams

Fig. 1



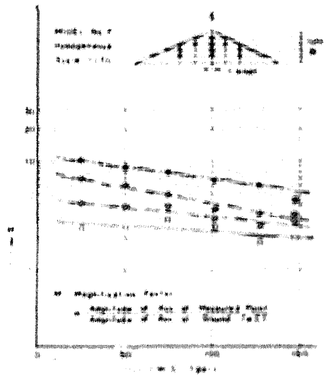
Arrangement of Acceleration Meters

Fig. 2



Resonant Curves of Measured Points along Center Line

Fig. 3

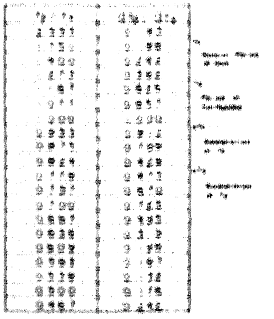


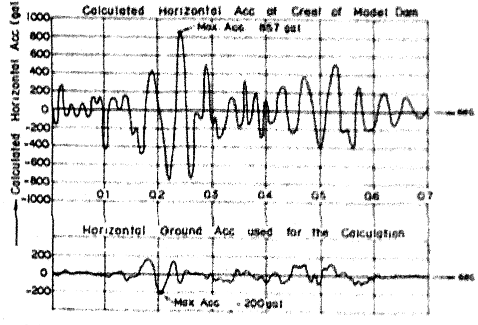
Non-linearity of Acceleration Magnification Factor (Center Line)

Fig. 4

Table. 1

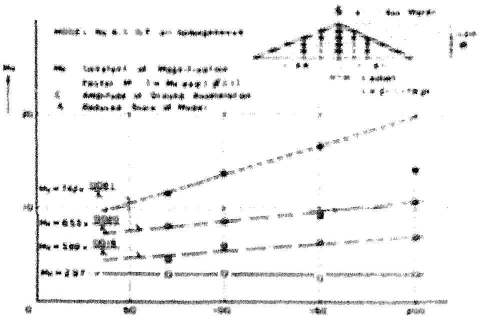
Relation between Response Acceleration in the vicinity of Dam Crest and Period of Ground Motion





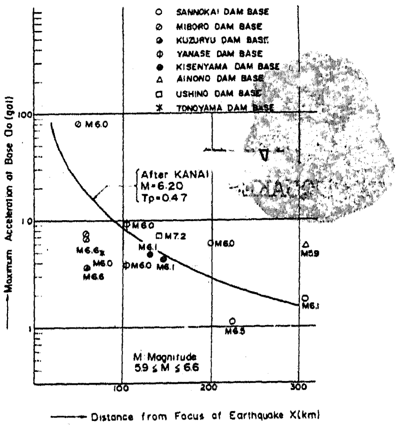
Calculated Horizontal Acceleration at Crest of Model Dam due to Ground Motion of Earthquake

Fig. 6



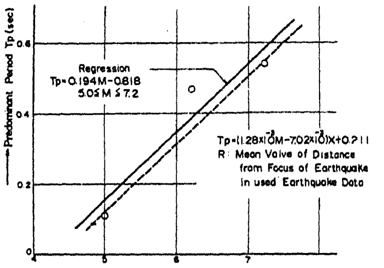
Relations between Mo and 1/λ

Fig. 5



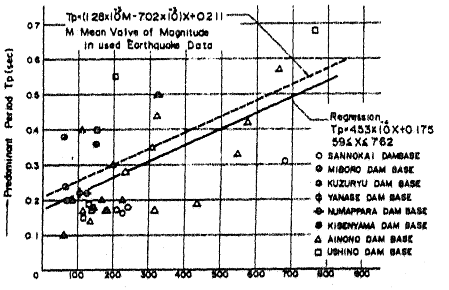
Relation between Acceleration at Dam Base and Distance from Focus of Earthquake

Fig. 7



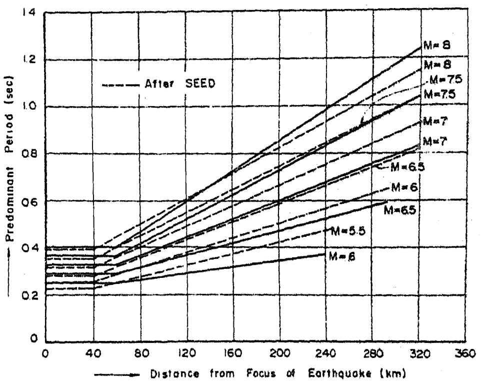
Relation between Predominant Period and Magnitude in Earthquake Records at the Bases of Rock and Earth Fill Dams

Fig. 8



Relation between Predominant Period and Distance from Focus of Earthquake in Earthquake Records at the Base of Dams

Fig. 9



Predominant Period for Maximum Acceleration in Rock Foundations of Dams

Fig. 10

Table. 4

Ratio of The Highest Peak Acceleration at Dam Crest to that at Dam Base during Earthquakes

Name (Sorts)	Height m	To sec	M	$\frac{Tp}{To}$	$\frac{Oc}{Oo}$
Samokai (Earth Fill)	37	0.42	7.0 7.5 8.0	0.64 0.78 1.00	0.97 1.34 2.85 Average 1.72
Ainono (Earth Fill)	41	0.40	7.0 7.5 8.0	0.68 0.83 1.05	1.89 1.51 2.93 Av. 2.11
Miboro (Rock Fill)	135	0.59	7.0 7.5 8.0	0.46 0.56 0.71	1.05 0.69 3.09 Av. 1.61
Kisenyama (Rock Fill)	95	0.50	7.0 7.5 8.0	0.54 0.66 0.84	0.57 1.94 2.29 Av. 1.60
Bouquet Canyon (Earth Fill)	62	0.45	7.0 7.5 8.0	0.60 0.73 0.93	0.71 2.48 3.30 Av 2.16
Tōgō (Earth Fill)	31	0.40	7.0 7.5 8.0	0.68 0.83 1.05	1.58 1.26 2.44 Av 1.76
A (Rock Fill)	175	0.875	7.0 7.5 8.0	0.31 0.38 0.48	— — 0.65

Remarks:

Oc	The Highest Peak Acceleration at Dam Crest
Oo	The Highest Peak Acceleration at Dam Base (assumed to be 200 gal)
To	Natural Period of Dam
Tp	Predominant Period of Acceleration at Dam Base
M	Magnitude of Earthquake

Table. 2

Average Shear Moduli of Actual Fill Type Dams Estimated from Shear Wedge Theory

Name	Height (m)	Natural Period T₀ (sec)	Average Shear Modulus (kg/cm²)	Mo	β	0.57M₀
Sannokai	37ᵐ	0.42	1,080	14.60	5.35×10^{-3}	8.32
Ainono	41	0.40	1,460	16.18	5.25×10^{-3}	9.22
Miboro	135	0.59	7,300	20.72	4.97×10^{-3}	11.81
Kisenyama	95	0.50	5,000	20.36	4.99×10^{-3}	11.61
Bouquet Canyon	62	0.45	2,650	17.93	5.15×10^{-3}	10 22
Tōgō	31	0.40	820	13.92	5.39×10^{-3}	7.93
A	175	0.875	6,200	15.30	$5.31\ 10^{-3}$	8.72

Table. 3

Estimated Values of Predominant Period of Acceleration at Dam Base

M	X (km)	Tp (sec)
7.0	30.5	0.27
7.5	45.5	0.33
8.0	63.5	0.42

Remarks:

Tp	Predominant Period of Acceleration at Dam Base
X	Distance from Focus
M	Magnitude

The highest peak acceleration at dam base was assumed to be 200gal