On Behaviors Of An Arch Dam During Earthquakes

By Shunzo Okamoto* and Tadashi Takahashi†

1. Preface

The seismic force is one of the main external loads which acts upon the body of an arch dam together with its own weight, hydrostatic pressure due to stored water and the thermal effects. It also affects the stability of the foundation supporting the dam body. The stability of an arch dam should, therefore, be viewed from the twofold aspects, the dam itself and the underlying foundation.

In practice, however, when a dam is going to rest on an exceedingly sound rock, it is usually assumed that the foundation is stable enough to withstand any earthquake shock. The stability of a dam body against an earthquake is usually examined by analysing the internal stresses on the assumption that during an earthquake the dynamic water pressure as well as the distributed mass force which is a product of the seismic factor and the weight of the mass, act statically upon the dam as a horizontal force.

This procedure, though simple and practical, should be used carefully, since much of the actual behaviors of an arch dam during an earthquake remain unknown today. The present authors have been engaged for the past few years in the studies including both laboratory and field investigations on the nature of vibration of an arch dam with special emphasis on the dams of Kamishiiba and Tonoyama, Japan. The characteristics of these dams are shown in Table 1. The results of the studies and related considerations are briefly described in this paper. Readers are referred to the references (1), (2) and (3) for further details.

2. Observation of earthquakes at dam sites

At the dam sites of Kamishiiba and Tonoyama the vibration characteristics of the dams due to earthquakes were observed by using the seismometers of mechanical and electromagnetic types installed on the dams and their foundations, and thus numerous records of small earthquake motions of several gals in acceleration were obtained. Some of the focal distances of these earthquakes were far and others near.

The predominant periods of vibration which were detected from the accelographs recorded at the center of the crest of the Tonoyama dam are tabulated in Table 2. Figures 4 - 8 show some examples of the earthquake records obtained with electromagnetic pick-ups installed on the dams and their foundations at Kamishiiba and Tonoyama. No record of an intensive earthquake agitation has yet been obtained, and the observation is continued today.

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The observations yielded the following results:

1) Corresponding to the characteristics of the earthquake motion, various modes of vibration may develop in the arch dam.

2) Several predominant periods of vibration occured to the dam body during an earthquake, which are supposedly the periods of the normal vibrations of the dams. Such remarkable development of normal vibrations evidently indicates that the damping effect of the vibration of an arch dam is not so large.

3) The vibration of an arch dam caused by an earthquake may frequently be accompanied by normal vibrations of a fairly higher order as well as those of a lower order. The highest frequencies ever recorded of the predominant normal vibrations due to an earthquake were approximately 26 cps at Tonoyama and 8 cps at Kamishiiba.

4) When the earthquake motions were very slow, the dam body moved in a concerted action with the foundation as if they constituted a sole rigid body.

5) At Tonoyama, a resonance action was in evidence against vertical as well as horizontal vibrations, where the accelerations were sometimes approximately of the same magnitude.

6) From the earthquake records obtained, the damping constant of a dam could be determined by means of several methods, namely by Takahashi-Fushimi's method, by frequency analysis or by reading the records of the damped free vibration of a dam after the earthquake ended. The resulting calculations gave the damping constant of a few percentage of the critical damping value of the dam.

3. Vibration tests of arch dams

The results of the earthquake observation conducted at the dam sites seemed to suggest the impotance of a study on the normal vibrations of a dam. Accordingly, a series of experimental tests were performed at both dam sites. A vibration exciter which was designed to produce a sinusoidal exciting force was installed on the crest or in the inspection gallery of the dam in order to start normal vibrations artificially in the dam. The resonant vibration curve of a dam was obtained by changing the frequencies of the exciting force gradually.

Some of the resonance curves and the modes of the predominant vibrations of the Kamishiiba dam due to horizontal exciting force are shown as examples in Figures 9 - 13 and Figures 14 - 17, respectively. Similar results were also obtained at Tonoyama dam.

The experiments yielded the following results:

1) Frequencies and modes of the predominant vibrations of a dam are independent from either the position of the exciting machine or the direction of the exciting force. This fact indicates that the predominant vibrations are the normal vibrations of the dam.

2) The periods of the predominant vibrations of a dam are related to the water level of the reservoir. As the level was raised, they tended to be somewhat longer. However, in case of the Kamishiiba dam, such lowest frequency as 230 cpm which seems to be the first mode of vibration, was observed

only when the reservoir was full.

3) The damping behavior of the vibration of an arch dam are also related to some extent to the water level in the reservoir. At Kamishiiba the damping constant slightly increased with rise of the water level in the reservoir, whereas at Tonoyama no material change occured to this value although the water level rose by 13 meters in the reservoir.

The resonance curves depend naturally on the positions of the vibration exciter and the pick-up. Accordingly, it is presumed that the normal vibrations mentioned above resulted from a large deflection amplitude occurring at the position of the pick-up, and further that there could be other types of normal vibrations which the pick-up may not detect due to its position. Compared to a 1-dimensional structure, a 2-dimensional structure such as an arch dam shows a rather complicated pattern of a resonance curve, where there are often two normal vibrations possessing nearly equal periods and quite different modes. Therefore, it is difficult to arrange the normal vibrations in a definitely classified order. The order appointed here by the authors should be interpreted purely as a matter of convenience.

Moreover, the exciting test of a vertical vibration was performed at the Tonoyama dam, since the resonances to the vertical vibration were recognized in its earthquake records. The relationship between the amplitude of vibration and the frequencies of the exciting forces are shown in Figure 18. Although the scatter of the observed values are comparatively large, three peaks are vaguely distinguished. Two of the peaks, each representing the frequencies of approximately 6 and 10 cps respectively, coincide with the symmetric horizontal normal vibrations both in frequencies and modes. It is supposed that the symmetrical horizontal normal vibrations were produced by the vertical exciting force because the dam is a dome type. The remaining peak representing the frequencies of approximately 13 cps is presumably the resonance of a pure vertical vibration.

From the resonance curves the damping constants of a dam was calculated as shown in Table 3. It is noticed here that the rate of energy dissipation of an arch dam is comparatively smaller than generally believed.

In the preceding discussions the continuity of the dam body was assumed. In reality, however, the longitudinal joints are apt to open at the upper part of the dam. This was confirmed during the field test at Kamishiiba from a time distance curve obtained by transmitting elastic waves along the crest arch. Therefore, it will be necessary to take into account the effect of the discontinuity of the dam body in order to enable a more refined treatment of an arch dam.

4. Vibration test of a model dam

The model test has proved an exceedingly useful method to find characteristics of the vibration of an arch dam. The conventional test procedure consisted of rocking a platform which carries a model dam. By means of this procedure, it is difficult to reproduce the vibrations of a higher order in a model scale, since the driving and frequency capacities of a shaking machine are limited. In our test, therefore, a model dam was placed on a fixed floor and the seismic forces were applied by a group of electromagnetic exciting units which were attached directly to the model.

The model of the Tonoyama dam, 1.2 m in height, was made of plaster mixed with diatomearth. 10 units of electromagnetic exciters were placed in such a manner that each unit may govern one of the adjoining segments of the model possessing an equall mass, as shown in Figure 19. The exciter is capable of inducing a normal vibration of a higher order in the model. The modes and the stress patterns of an order which is too high to obtain by a field test or a numerical calculation, can be determined by this arrangement.

Figure 20 shows the resonance curves of the horizontal and vertical vibrations of the model and Figures 21 - 23 show some examples of the mode and strain pattern of the horizontal and vertical normal vibrations. The frequencies and modes obtained from the model tests agree fairly well with those obtained by field tests within the range of normal vibrations of not so much higher order. This fact shows that the model test procedure described above are useful enough to serve the engineering purposes.

The normal vibrations being thus obtained, the forced vibration induced in the structure due to an earthquake can be determined by a simple procedure superposing various normal vibrations through a computor. If further a model can be designed as to possess the same value of damping constant with the prototype, the stresses due to an earthquake may be read directly off the model by applying an electromagnetic force which is proportional to the ground acceleration. The damping constant of our model is 0.05 for the lowest symmetrical normal vibration. Since this value was fortunately approximate to that of the prototype, an earthquake force was tentatively applied to the model dam considering the similitude of time.

The results are shown in Figure 24. In this figure, 'A' represents the exciting voltage converted from the electric current which is similar in wave form to the earthquake acceleration and 'B' and 'C' represent the horizontal tangential strains each measured on the upstream surface at the center of the crest and on the down stream surface at the quartile point of the crest, respectively. The stresses derived from 'B' and 'C' are larger than those at other points. Therefore, they have an important meaning to the stability of an arch dam against an earthquake. It would be very convenient for engineering purposes if direct estimation of the stresses induced by an earthquake is always possible. However, our knowledge to date on the model materials concerning with the time effects on their deformations is insufficient. Therefore, further studies on the materials for a model dam are necessary in order to develop the above described procedure.

5. Conclusions

From this series of experiments, then, it may be concluded:

1) In vibrations of an arch dam produced by an earthquake, the normal vibrations of the lowest order and a few more higher orders frequently predominate.

2) The damping constant of an arch dam is considered to be of an order of a few percentage. Therefore, the arch dam will be endangered by a resonance action when the predominant period of an earthquake motion coincides with the period of the normal vibration of the dam.

3) Dynamical properties of an arch dam can be estimated within the accuracy allowable for engineering purposes by a model test described in Section 4.

4) For a dome type dam a resonance action can also result from a vertical agitation due to an earthquake. Dynamical properties of the dam against a vertical agitation due to an earthquake are also obtained by a model test.

5) Once the modes and natural frequencies of the normal vibrations are obtained by model tests and the value of the damping constant determined by referring to the values of other dams, the forced vibration of a dam during an earthquake can also be determined by a computor. However, if a definite improvement is made as to the model materials in the future, the stresses induced by an earthquake may be read directly off the model without resorting to the calculation procedure.

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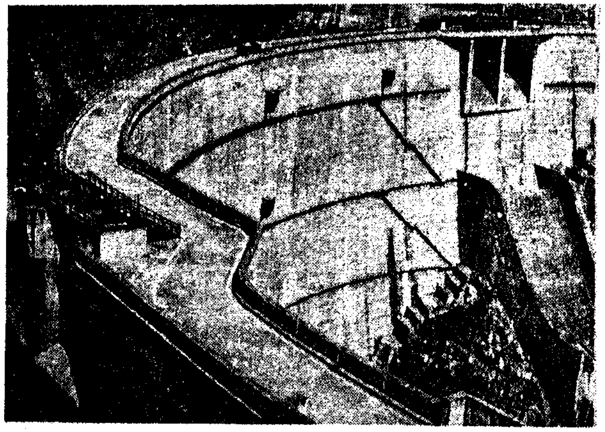


Fig.1 General View Of Kamishiiba Dam

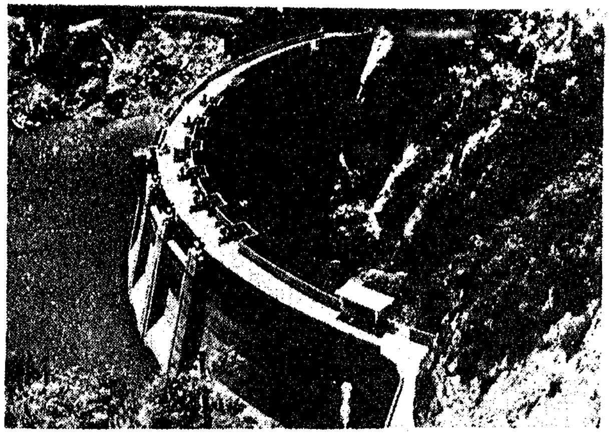


Fig.2 General View Of Tonoyama Dam

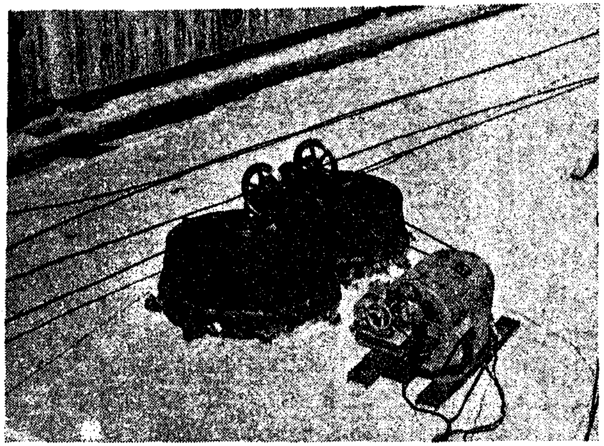
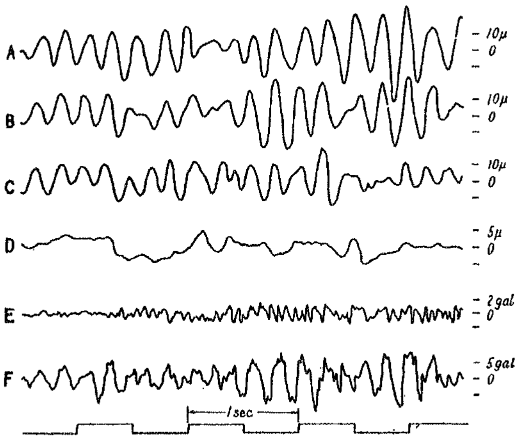


Fig.3 Vibartion Exciter



A : Displacement in radial direction at B_5
B : Displacement in radial direction at B_8
C : Displacement in radial direction at B_{12}
D : Horizontal displacement in stream direction on foundation rock
E : Horizontal acceleration in stream direction on foundation rock
F : Acceleration in radial direction at A_8

Fig.4 Seismograph At Kamishiiba Dam

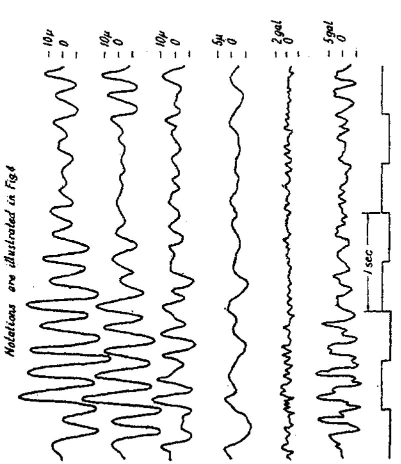


Fig.5 Seismograph At Kamishiiba Dam

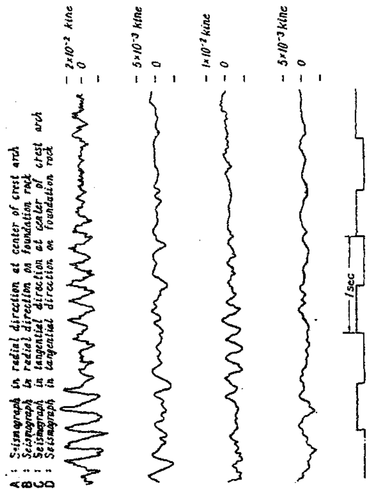


Fig.6 Seismograph (Velocity) At Tonoyama Dam

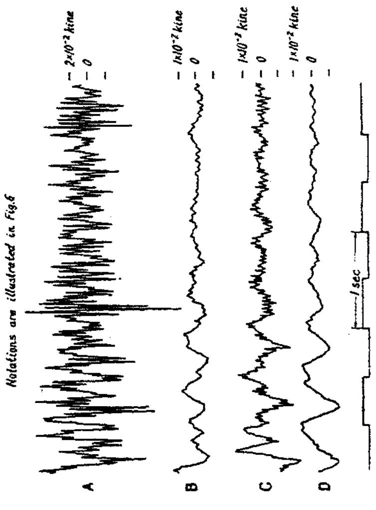


Fig.7 Seismograph (Velocity) At Tonoyama Dam

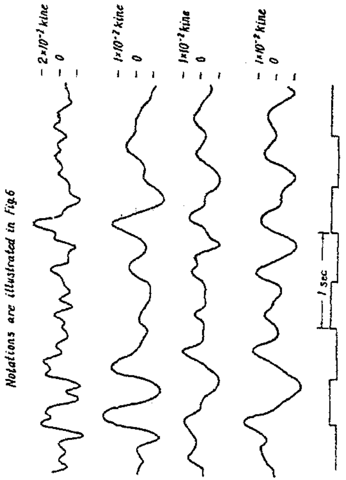


Fig.8 Seismograph (Velocity) At Tonoyama Dam

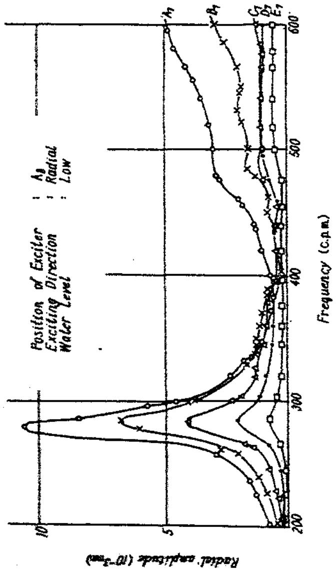


Fig.9 Responce Curves : Kamishiiba Dam

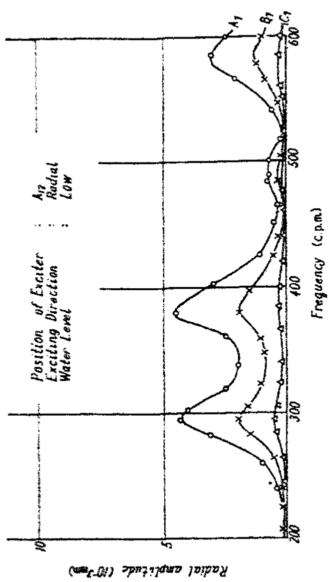


Fig.10 Responce Curve : Kamishiiba Dam

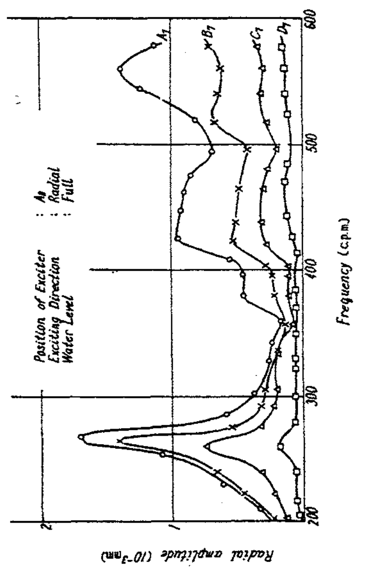


Fig.11 Responce Curve : Kamishiiba Dam

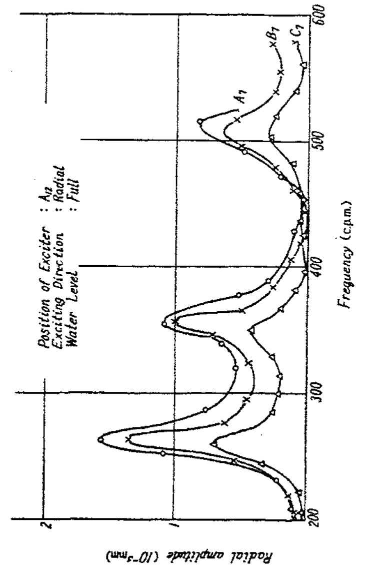


Fig.12 Responce Curve : Kamishiiba Dam

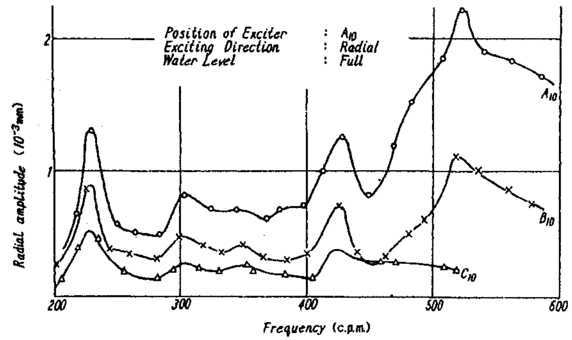


Fig.13 Responce Curve : Kamishiiba Dam

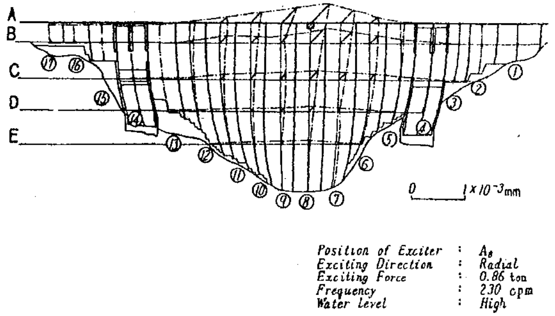


Fig.14 Mode Of Vibration : Kamishiiba Dam

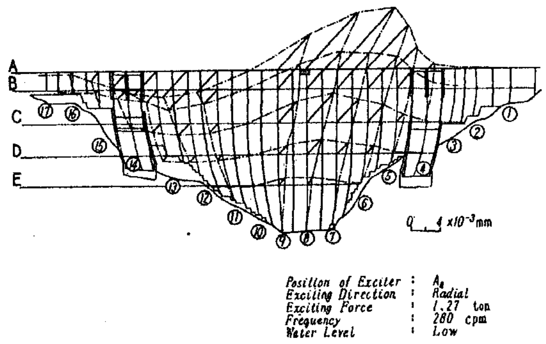


Fig.15 Mode Of Vibration : Kamishiiba Dam

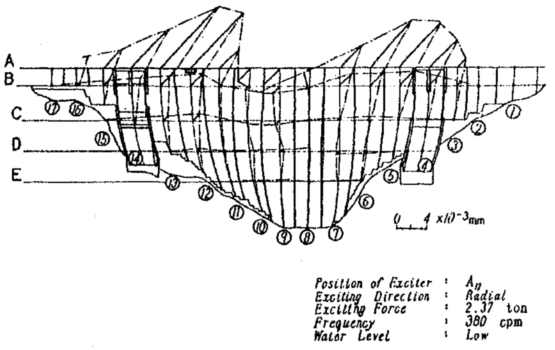


Fig.16 Mode Of Vibration : Kamishiiba Dam

Table 1 Characteristics of the dams

	Kamishiiba dam	Tonoyama dam
River	Mimi-kawa	Hiki-gawa
Location	Miyazaki-ken	Wakayama-ken
Foundation rock	Hard sand stone	Congromerate
Type	Nearly symmetrical arch	Symmetrical arch (dome)
Height (m)	110	64.5
Crest length (m)	310	129
Radius of crest arch (m)	142.4	63.8
Crest width (m)	7.0	4.3
Base width (m)	27.7	12.4
Space betw. joints (m)	20.0	10.0 - 14.7
Perimetral joints	None	In existence
Design seismic factor (Full reservoir)	0.12	0.15

Table 2 Earthquake accelerations at Tonoyama dam

Date	Vertical	Radial	Tangential	Water level
1958 12.15	11 cps	- cps	5.5 cps	El. 119.77
1959 1. 3	10	5.5	5.0	124.97
3. 3	11	6.0	6.5	111.64
5.22	-	5.5	5.0	125.23
5.26	-	5.5	5.0	125.87
5.28	-	6.0	5.0	124.97
6.28	-	6.5	5.5	116.60
6.28	9	6.0	5.5	116.60
7.12	9	6.0	5.5	118.45
7.29	11	6.0	-	123.23
7.30	11	5.5	5.0	122.76
8. 5	-	6.0	5.0	121.02
8.12	11	10	11	124.82
8.12	11	11	-	124.82
8.23	11	5.5	-	122.85
11.26	11	5.5	-	124.71
11.27	5	5.0	5.0	124.80
12.25	11	-	6.0	124.48
1960 1.31	9	6.0	5.0	121.70
2. 8	12	6.0	-	119.55
2.17	11	6.0	5.0	117.15
3.17	11	-	5.6	111.48

Table 3 *Damping constants*

		Tonoyama dam				Kamishiiba dam				
Water level		Full		-13 m		Full			-30 m	
Normal vibration		cps	h%	cps	h%	N.V	cps	h%	cps	h%
Symmetrical	2nd	5.6	3 - 4	6.3	3 - 4	1st	3.8			
Symmetrical	4th	9.8		10		3rd	5.3	3.5 - 4.5	6.3	3.5 - 4.5
Antisymmetrical	1st	5.2	6 - 7	5.9	4 - 6	2nd	4.3	4 - 5	4.7	3.5 - 4.5