NON-LINEAR BEHAVIORS OF THE EARTH DAM DURING EARTHQUAKES

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1. Introduction

In recent times, the progress of the construction techniques, the advance in soil mechanics and the elevation of the economicity of the construction works resulted from the use of big construction machines have made sometimes the fill type be adequate to even extremely high dams. Therefore, in the seismic active zones, the stability of the fill type dams during earthquakes becomes important problem to be investigated strictly and a large body of literature concerned with this problem have been already presented. Since 1963, the observation of earthquakes at the Sannokai dam has been carried out by authors(1) (Fig. 1 and 2). During this time, more than 70 earthquakes have been recorded. In these data, there are such strong earthquakes as the Off-Tokachi or the Niigata earthquakes, such a moderate one as the Akita earthquake and many local small earthquakes. Characteristics of major earthquakes are shown Tab. 1.

2. Descriptions of the Sannokai dam

The Sannokai dam is an earth dam for irrigation purpose and was completed in 1952. It is 37 m high, 145 m long and 194 m thick at the base. The direction of the dam axis is N 69° E and the side slope of the up-stream face is 1 : 2. 9 and that of the down-stream face is 1 : 2. 5 at the upper part and 1 : 2. 7 at the lower part of the dam. The dam is consisted of four zones. Density, grain size and mechanical properties of soil are shown in Tab. 2 and Fig. 3. Values tabulated in Tab. 2 are of course average values.

The stability of the dam is examined by the sliding surface method with circular slip line and the permeatic line is determined by the Casagrandes method.

The foundation is consisted of green tuff and it crops out at the river bed and the hillside. Lava agglomerate crops out at the right bank. Rock is not homogeneous but is generally hard except the weathered zone of its surface. Rock is jointed 15 m in depth.

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3. Dynamic characteristics of the Sannokai dam

The dynamic properties of the dam have been studied by the model tests as well as the analysis of the earthquake records obtained at the site.

The frequencies and the modes of 1st and 2nd order natural vibration perpendicular or parallel to the dam axis are shown in Tab. 3 and in Fig. 4. Those of the 1st order vibration in vertical direction are also shown in Tab. 3 and in Fig. 5. And it was noted by model tests that in the vertical vibration the 2nd or more higher order natural vibrations did not come out and that by the horizontal exciting, besides horizontal vibration, vertical vibration were generated at the face of the dam especially in the upper part of the dam.

4. Records of earthquakes

As examples of earthquake records, a small earthquake whose epicenter is not so far from the dam site (M = 4.8, △ = 62 km), an after shock of the Akita earthquake (M = 6.5, △ = 220 km), the main-shock of the Niigata earthquake (M = 7.5, △ = 204 km) and the main-shock of the Off-Tokachi earthquake (M = 7.9, △ = 250 km) are picked up and are shown in Fig. 6 ~ 9.

Notations in the Figures are defined as follows.

Notation	Location		Seismometer		
	Position	Elevation	Direction	Out put	Period
DCS	Top	288.1^{m}	Horizontal(S69^{o}E)	Acceleration	0.33^{sec}
DCS-M	Slope	279.2	"	"	"
DCS-L	"	268.3	"	"	"
DCS-B	"	259.2	"	"	"
RLS	Left bank	288.1	"	"	"
RRS	Right bank	"	"	"	"
DCU-α	Top	"	Vertical	"	"
RLU-α	Left bank	"	"	"	"
OTA'	Intake tower	c.a.288.1	Horizontal(N16^{o}W)	"	"

5. Non-linear behaviors of the dam during earthquakes

More than 70 earthquakes ranging from small intensity to considerable large intensity have been recorded by this time.

After close examination of records, it was found that predominant periods and magnification factors of the vibration of the dam depend on the acceleration of shocks.

Table 1. Characteristics of Major Earthquakes

Name of earthquake	Date	Magnitude	Hypocenter			Epicentral distance	Included angle between dam axis and direction to epicenter (degree)
			N (degree)	E (degree)	H (km)		
Akita earthquake	1964. V-7	6.9	40.5	138.6	40	230	7
Niigata earthquake	1964. VI-16	7.5	38.4	139.2	40	204	58
Off-Tokachi earthquake	1968. V-16	7.9	40.7	143.6	20	250	53.5

Table 2. Mechanical Properties of Fill Material

Mechanical property	D	G	M	A
Real density of soil	2.65	2.71	2.69	2.57
Liquid limit	50.5	50.0	41.0	41.0
Plastic index	29.1	30.7	7.5	3.5
Field moisture equivalent	44.0	44.0	38.3	40.0
Optimum moisture content (%)	20.0	35.0	25.0	15.0
Moisture content of actual fill (%)	20 ~ 30	35 ~ 50	25 ~ 35	15 ~ 25
Permeability coefficient k(cm/s)	2.91×10^{-7}	4.15×10^{-6}	9.24×10^{-6}	1.24×10^{-5}
Angle of internal friction ϕ	7°59'	9°00'	21°00'	21°07'
tan ϕ	0.140	0.158	0.384	0.652
Cohesion c	1.2	1.2	0.8	0.3

Table 3. Natural Frequencies

Natural vibration		Frequency	Mode
Horizontal vibration parallel to dam axis	1st order	2.88	Fig. 4-1
	2nd order	4.07	Fig. 4-2
Horizontal vibration perpendicular to dam axis	1st order	2.80	Fig. 4-3
	2nd order	4.03	Fig. 4-4
Vertical vibration	1st order	4.07	Fig. 5

This is as followings.

1) The relationship between predominant period of the dam and the hight of water level of the reservoir.

In the case of the small earthquakes in which the maximum acceleration at the top of the dam is 20gal or less, the relationship between the period of the predominant vibration of the dam and the height of water level of the reservoir, is shown in Fig. 10.

From this, it is noted that when the water level is drawn down from the highest water level by 10 m, the predominant period is some-what reduced. This trend of the decrement of the predominant period against the descent of the water level may be of interest and further investigations must be carried out for clarification of this fact.

2) Ratio of the maximum acceleration at the top of the dam to that at the base. The maximum acceleration at the base and at the top of the dam are shown in Fig. 11 ~ 13. The figures show that magnification factors (ratio of the maximum acceleration of the top of the dam to that at the foundation) are not constant but decrease with the increase of the acceleration of earthquakes. Empirical equations showing magnification factor are as follows,

$$M_p = 5.4\,\alpha_{gp}^{-0.25} \quad \text{(perpendicular to dam axis)}$$

$$M_a = 3.5\,\alpha_{ga}^{-0.11} \quad \text{(parallel to dam axis)}$$

$$M_v = 3.2\,\alpha_{gv}^{-0.14} \quad \text{(vertical)}$$

where

M: magnification factor

α_g: maximum acceleration at the base

3) Period of the predominant vibration

Sometimes, nearly stational vibrations are found in the records of earthquakes obtained at the top of the dam. As it is considered that the stational vibrations will be associated with the natural vibration of the dam, the relationship between the natural period and the acceleration can be obtained from the records.

In case of the vibration perpendicular to the dam axis natural period is 0.38 sec. for small earthquakes. In case of the Niigata earthquakes, natural period is 0.4 ~ 0.41 sec at and around the maximum acceleration 107 gals. In case of the Off-Tokachi earthquake, natural period is 0.385 sec for about 60 gals, 0.41 sec for 80 ~ 100 gals, and 0.43 ~ 0.44 sec for about 140 gals. From these data, natural period for the acceleration 50 gals or more at the top of the dam differ from that for the small earthquakes and lengthens as the acceleration increases (Fig. 14). In case of the vibration parallel to the dam axis, the natural period is 0.345 sec on the average for small earthquakes. However, in case of the Off-Tokachi earthquakes, the natural period is 0.35 sec in the section where acceleration at the top is 50 ~ 70 gals and 0.38 sec at and around the maximum acceleration 151 gals. In this case, increment of the period is smaller than that in the case of the vibration perpendicular to the dam axis in spite of the maximum acceleration in both cases are nearly equall in case of the Off-Tokachi earthquakes (Fig. 15).

In case of the vertical vibration, the natural period for small earthquakes is 0.245 sec on the average, but it is 0.265 sec at and around the maximum acceleration 75 gals in case of the Off-Tokachi earthquakes. Furthermore, in case of the Niigata earthquakes, maximum acceleration at the top is 40 gals or more and the natural period is nearly 0.245 sec at and around the maximum acceleration. Comparative large variation in the period of the 1st order verical vibration at the top may be due to the fact that especially in the upper paer of the dam a part of the vertical motions is caused by the horizontal ground vibration (Fig. 16).

6. Mode of the natural vibration

By analysing of the records, obtained at the top and the mid height of the slope, the natural mode of the dam can be estimated. In Fig. 17, the 1st order natural mode of vibration perpendicular to the dam axis is shown. In this figure, the corresponding modes obtained by the model tests as well as those calculated by Prof. Chopra are also shown for comparison. It is evident that the observed deformations at the face of the slope of the dam fairly differ from those of the theoretically expected. This difference may be due to the variable stiffeness of the dam. The stiffeness of the dam is generally considered to be larger in the lower part of the dam.

7. Conclusions

The observation carried out at the Sannokai dam lead to the conclusion that earth dams will generally behave non-linearly and their characteristics for strong earthquakes will somewhat different from those for weak earthquakes. This result should be accounted for the dynamic design of earth dams.

Reference

(1) S. Okamoto, C. Tamura, K. Kato and M. Otawa: Dynamic Behavior of Earth Dam during Earthquakes, Report of the Institute of Industrial Science, the University of Tokyo. vol. 16, No. 14, 1966.

Fig. 1 View of the Sannokai Earth Dam

Fig. 2 Standerd Cross Section of the Dam and Location of Seismometers

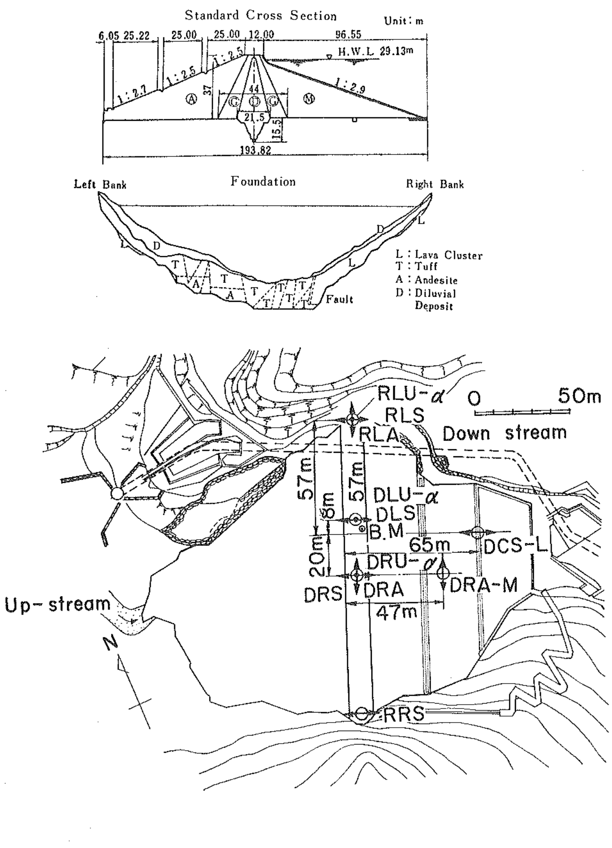
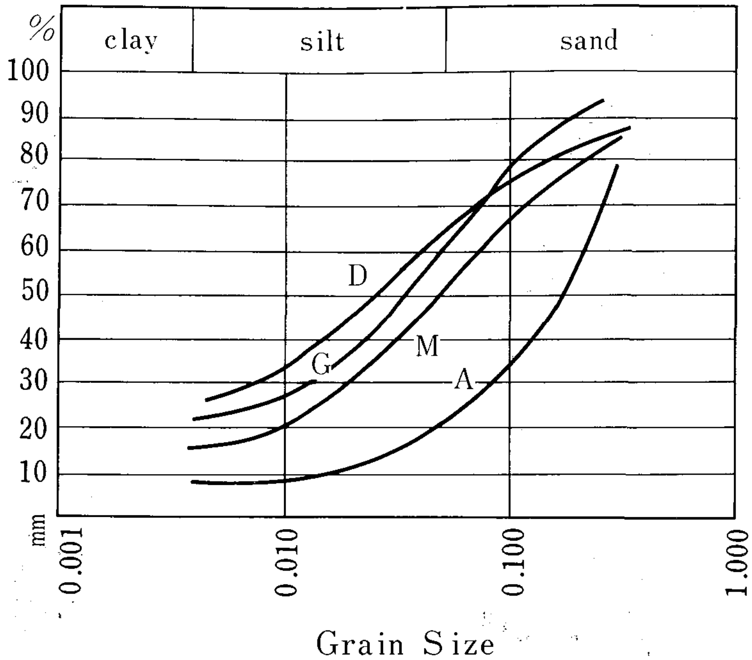


Fig. 3 Grain Size and Density of the Fill Material



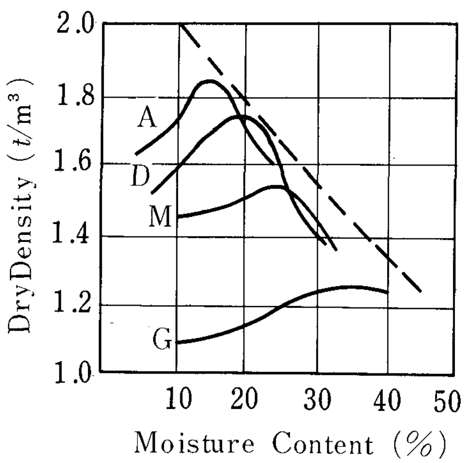


Fig. 4-1 Mode Shape of 1st order Horizontal Vibration parallel to Dam Axis (Model Test)

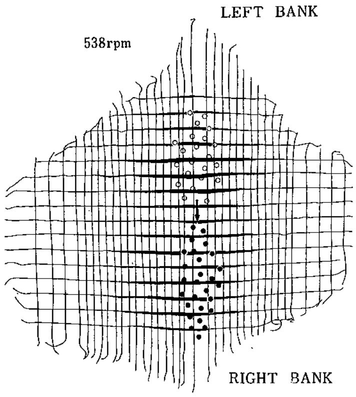


Fig. 4-2 Mode Shape of 2nd order Horizontal Vibration parallel to Dam Axis (Model Test)

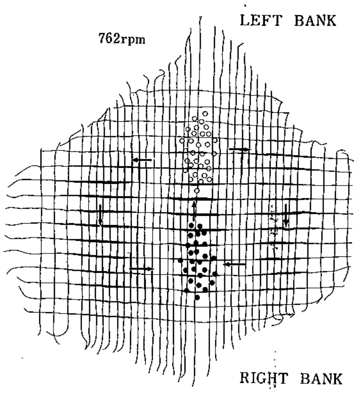


Fig. 4-3 Mode Shape of 1st order Horizontal Vibration perpendicular to Dam Axis (Model Test)

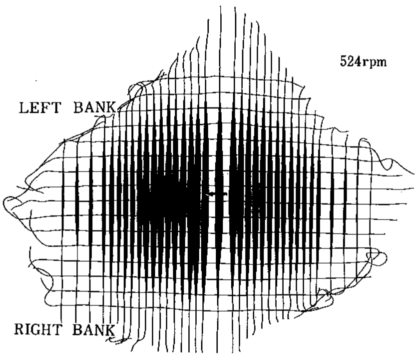


Fig. 4-4 Mode Shape of 2nd order Horizontal Vibration perpendicular to Dam Axis (Model Test)

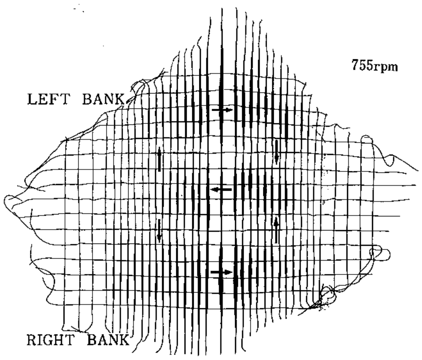


Fig. 5 Mode Shape of Vertical Vibration (Model Test)

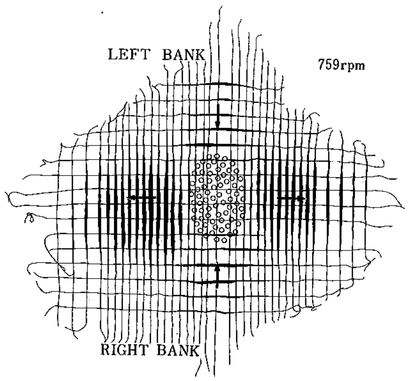


Fig. 6 Records of a small earthquake

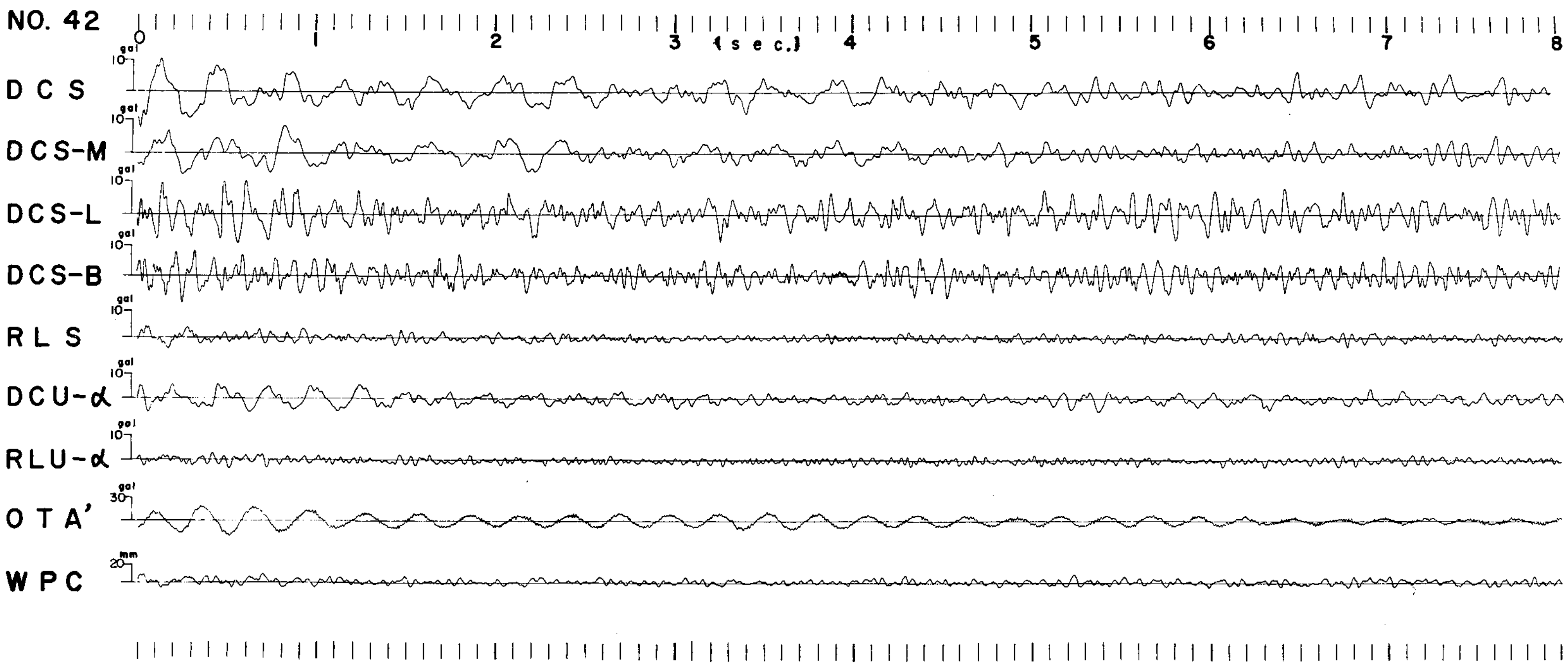


Fig. 7 Records of a after-shock of the Akita Earthquake

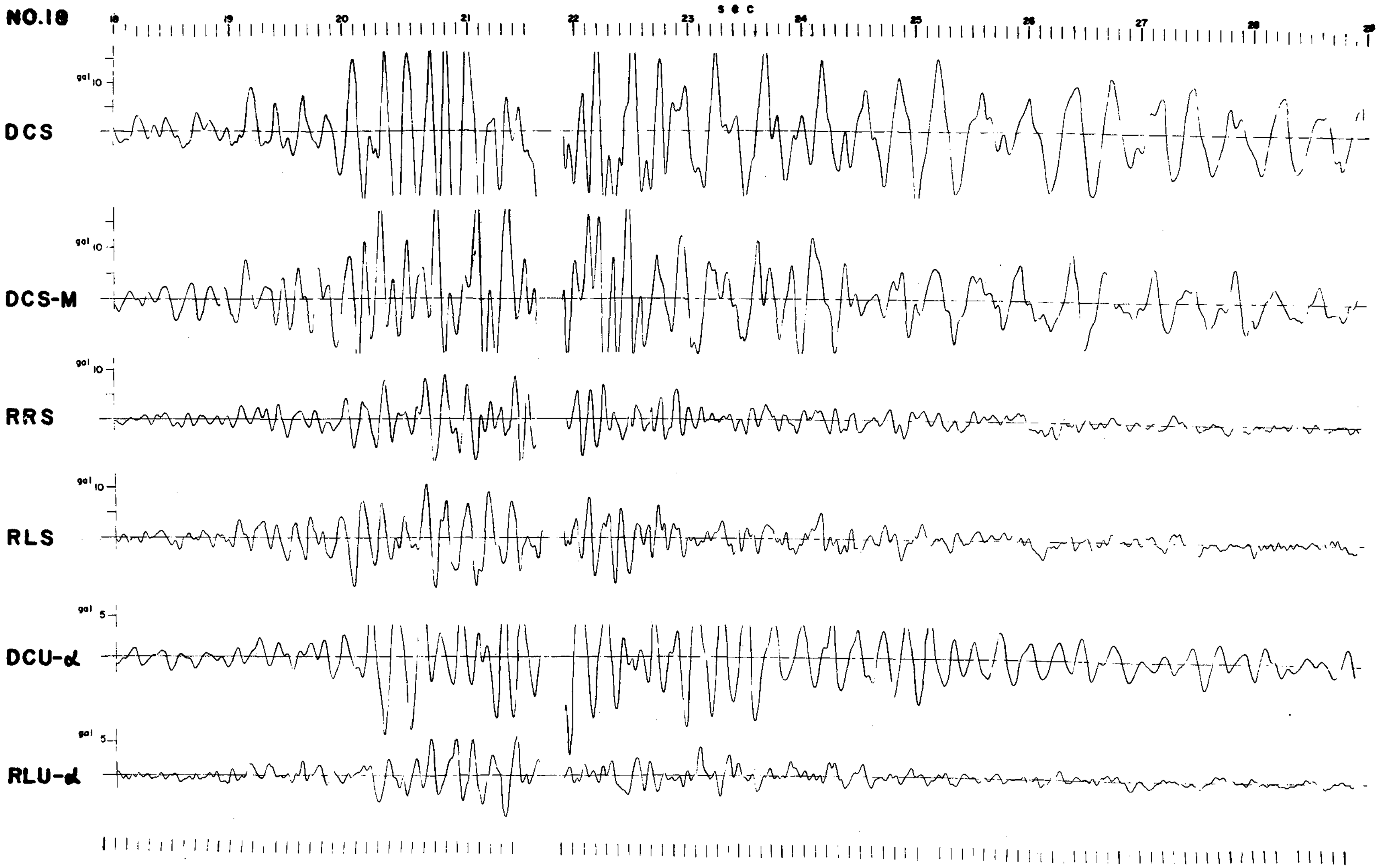


Fig. 8 Records of the Niigata Earthquake

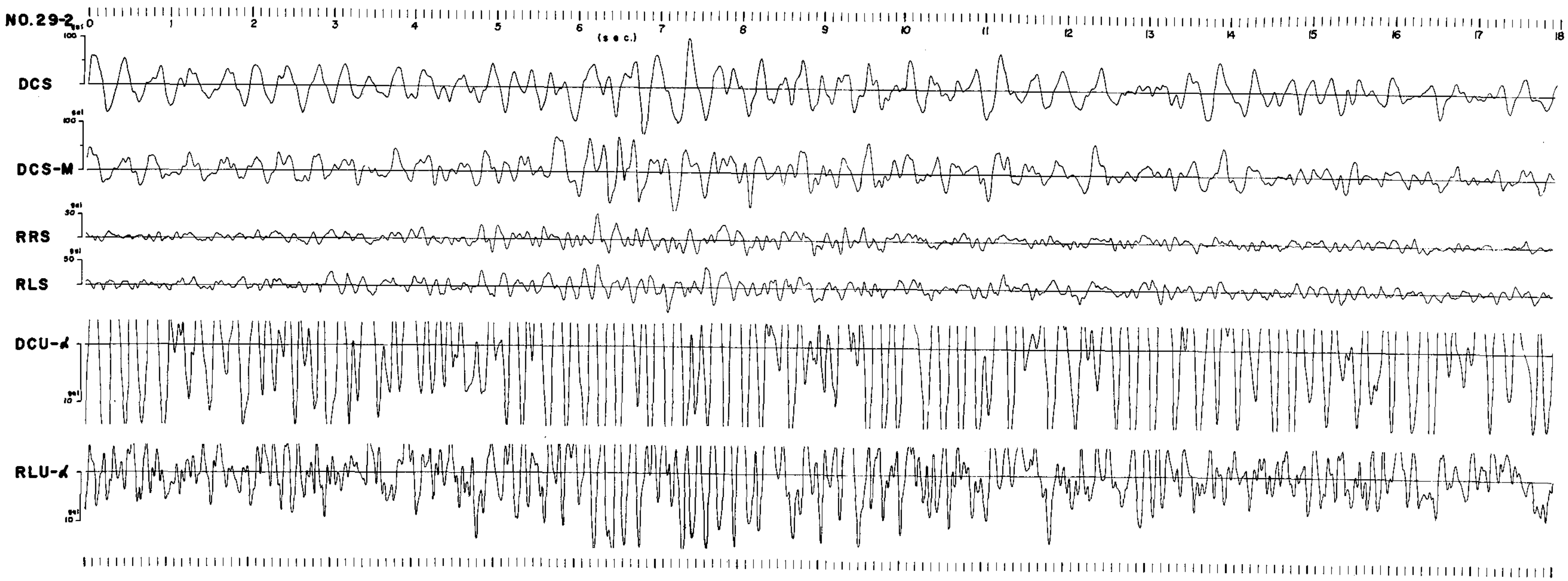


Fig. 9 Records of the Off-Tokachi Earthquake

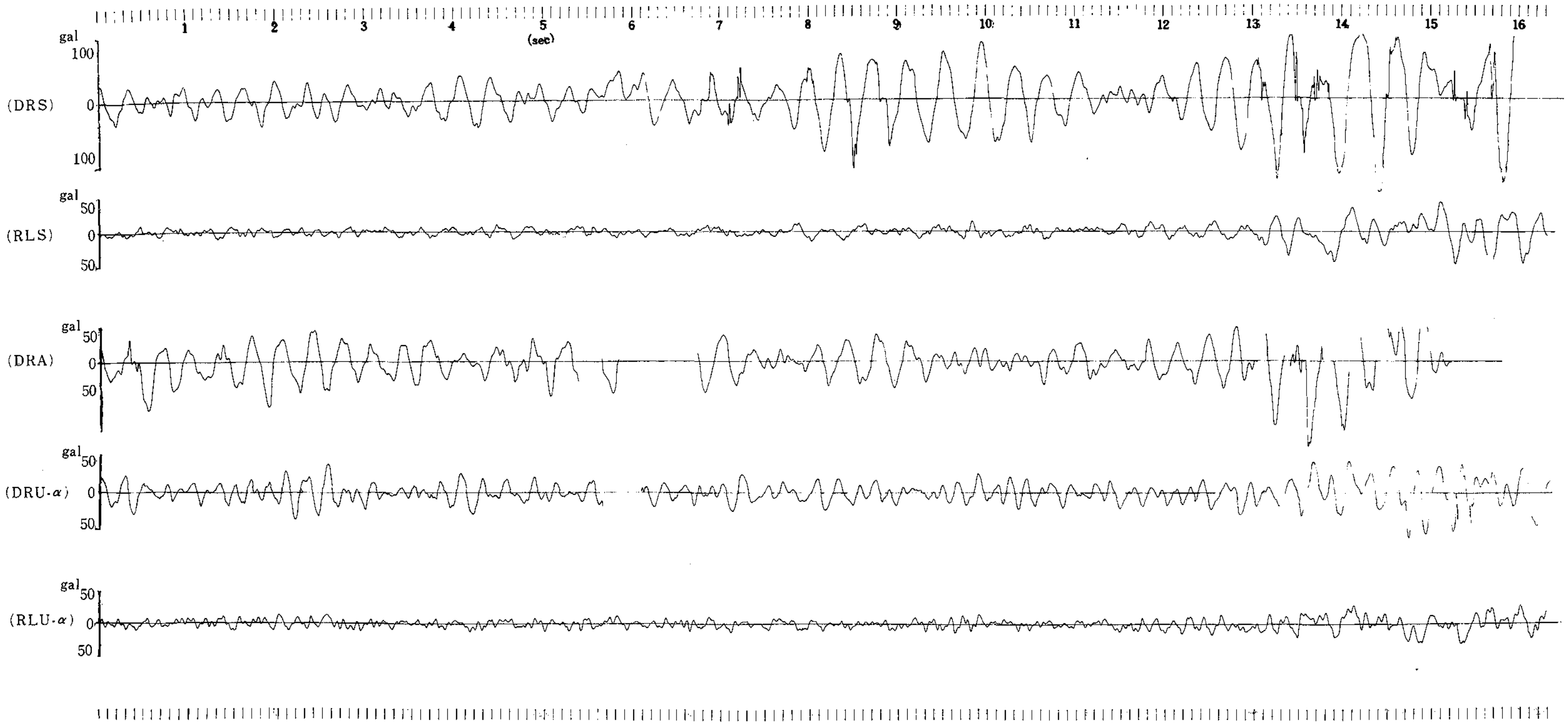


Fig. 10 Natural Period (sec)

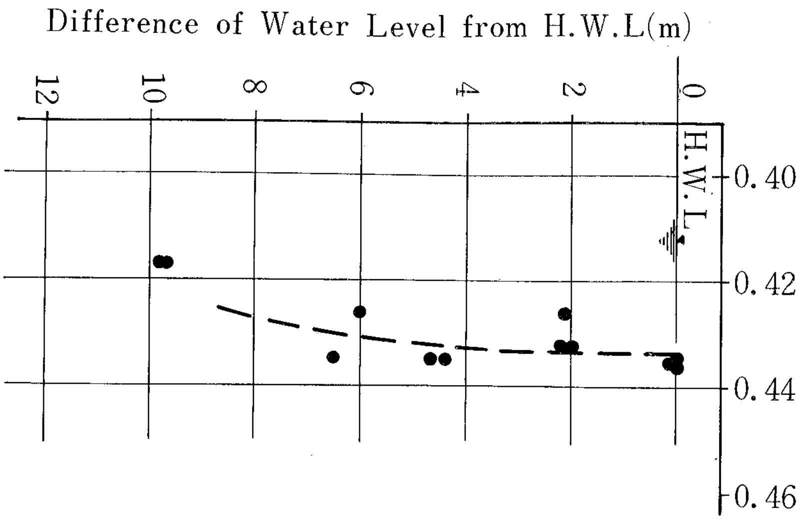


Fig. 11 Relation between Max. Acc. at the Top of the Dam and that on the Ground perpendicular to the Dam Axis

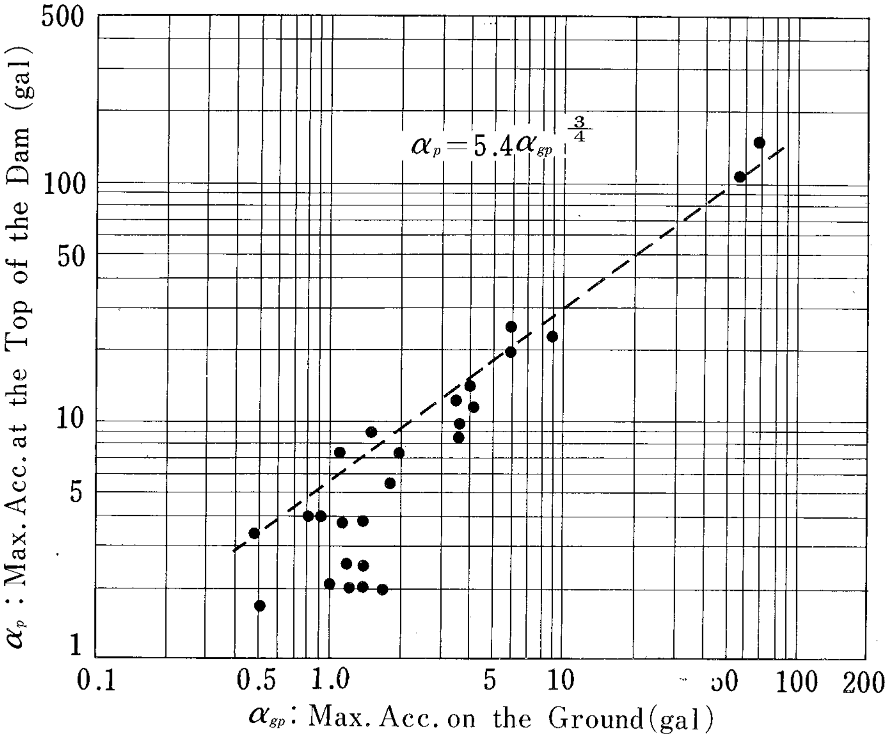


Fig. 12 Relation between Max. Acc. at the Top of the Dam and that on the Ground parallel to the Dam Axis

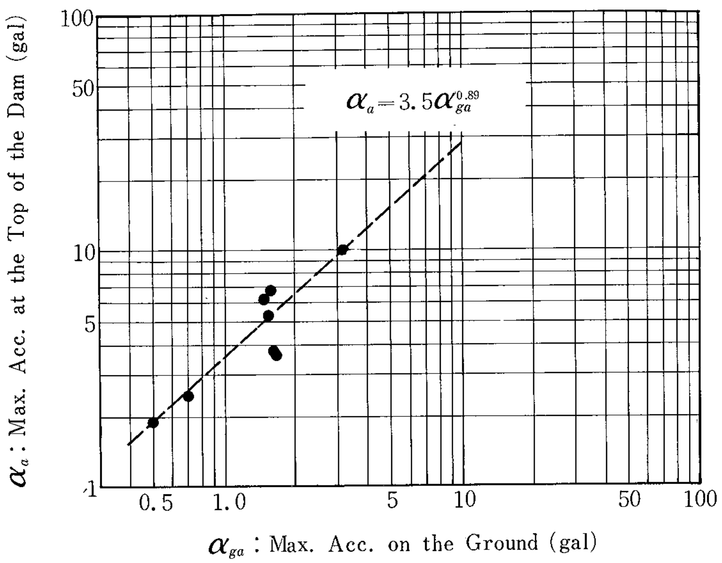


Fig. 13 Reletion between Max. Acc. at the Top of the Dam and that on the Ground in vertical Direction

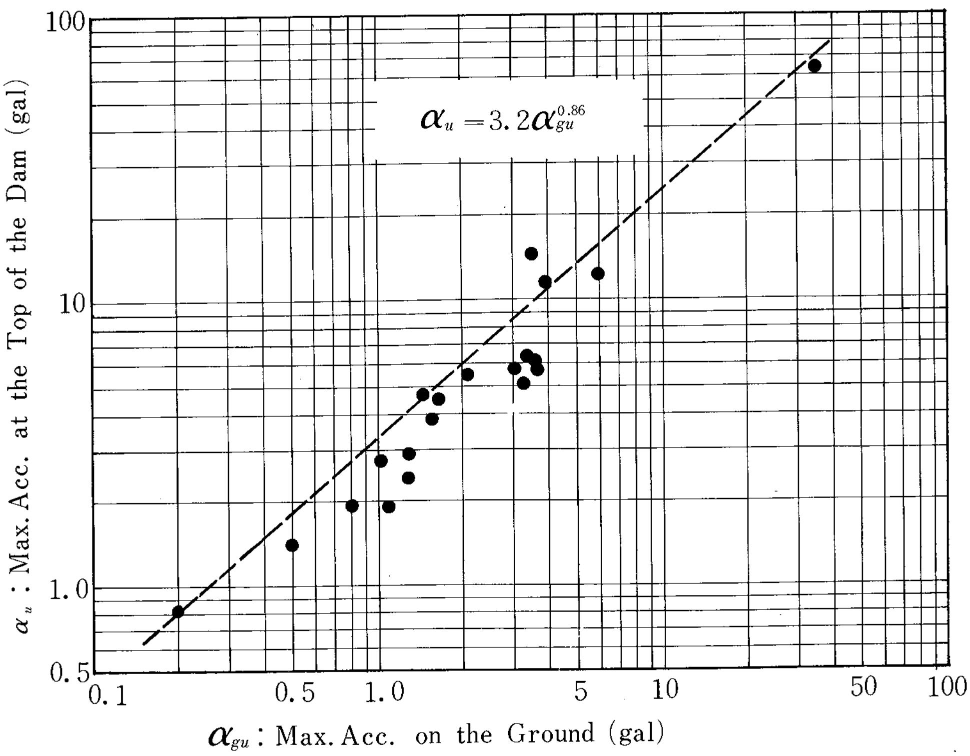


Fig. 14 Relation between 1st order period and Max. Acc. at the Top of the Dam pependicular to the Dam Axis.

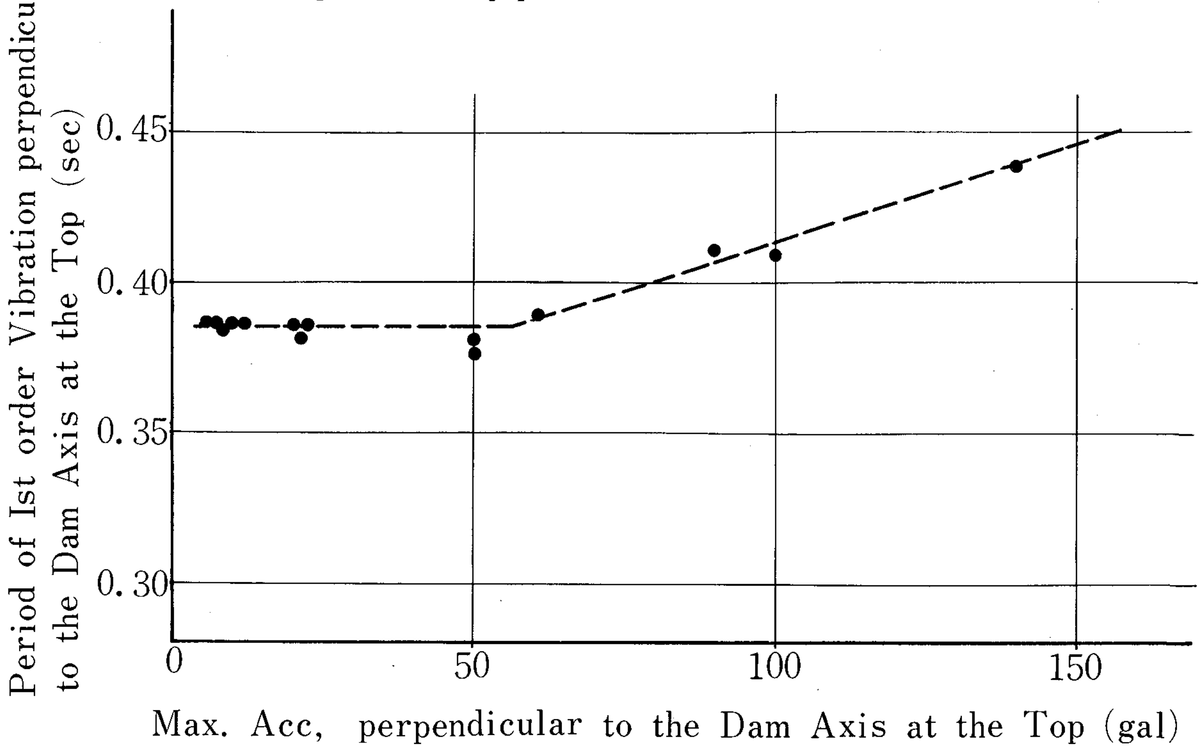


Fig. 15 Relation between Period of 1st order Vibration and Max. Acc. parallel to the Dam Axis at the Top of the Dam

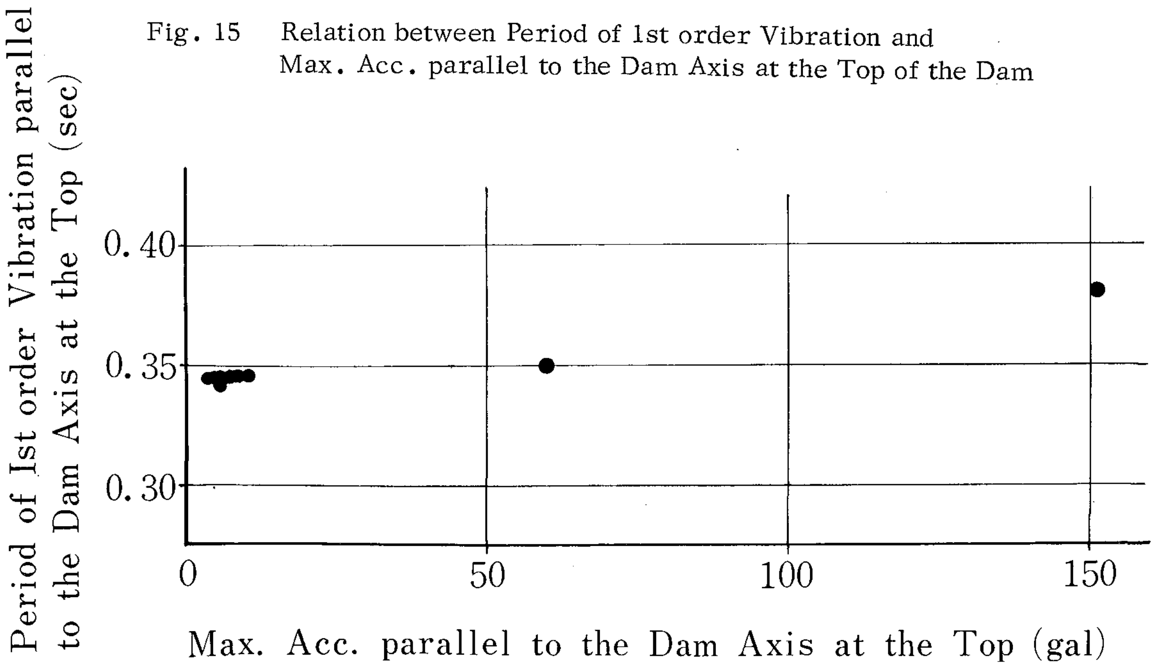


Fig. 16 Relation between Period of 1st order Vibration and Max. Acc in vertieal Direction at the Top of the Dam

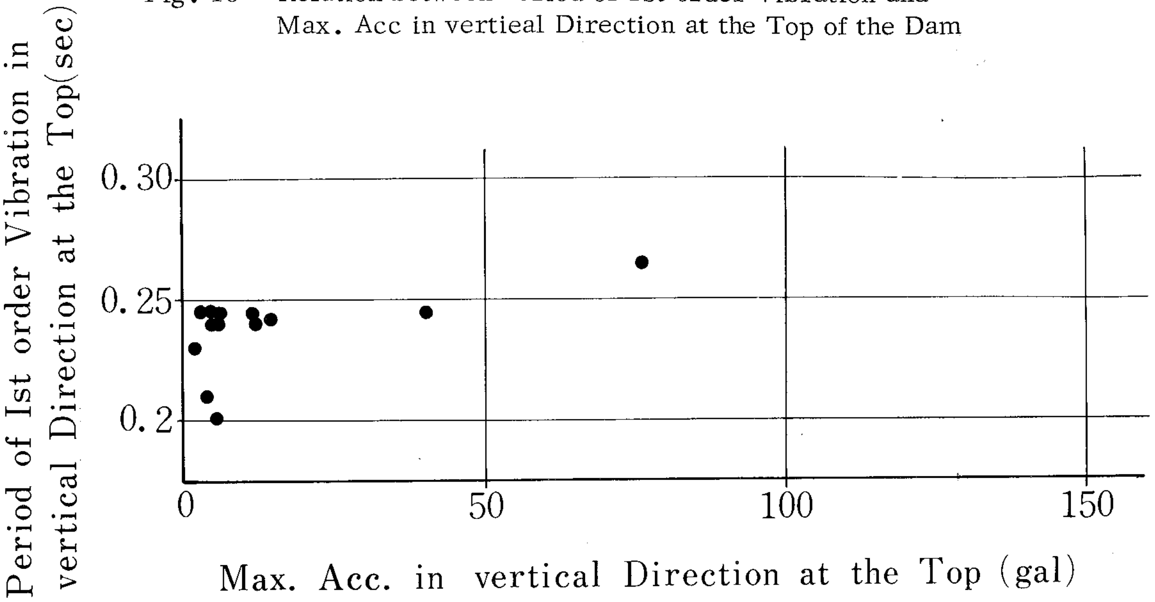
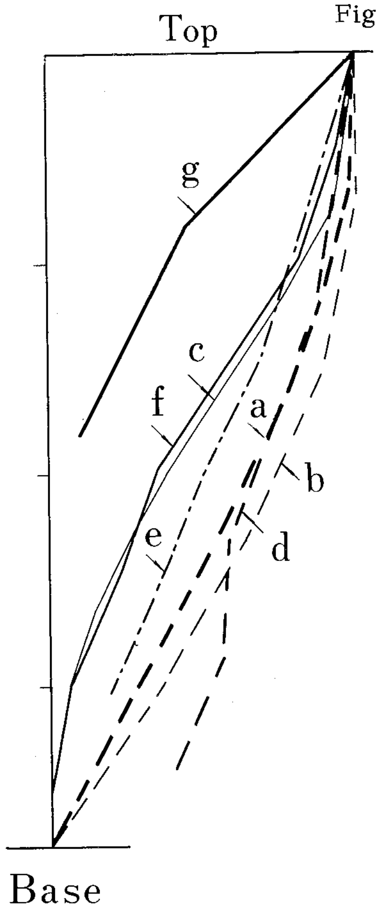


Fig. 17 Mode Shape of the Dam



Calculation
a : Shear wedge solution
b : Center line SS 3 : 1 (by Chopra)
c : Face SS 3 : 1 (by Chopra)

Model test
d : Center line
e : Up stream face
f : Down stream face

Sannokai dam
g : Down stream face