ON THE DYNAMICAL BEHAVIOR OF AN EARTH DAM DURING EARTHQUAKE

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Authors distributed eight seismometers on an existing earthdam, 37m in height and observed the dynamic behavior of the dam during earthquakes. It is seen that two kinds of the natural vibration are excited in the seismic response of the earthdam. Some of the dynamical properties, frequencies, damping coefficient, etc., of these natural vibrations are disclosed by the Fourier analysis of the earthquake records.

§ 1. Introduction

Experience has repeatedly proved that earth dams are affected by seismic shocks and Ambraseys(1) made the extensive references on this subject at the 2nd World Conference on Earthquake Engineering in 1960. Recently, a remarkable progress of soil mechanics and construction technique made it possible to build high earth dams and then the criteria of its seismic stability comes to be an important problem.

The current method of the aseismic design of earthdam in Japan is based on the seismic coefficients procedure. This procedure usually consider only a horizontal seismic force and specify the design seismic coefficient as in the range of 0.12 - 0.20 at full reservoir and 0.06 - 0.20 at empty, depending on the seismicity and the geological features at the dam site. The stability of the dam body against the earthquake is examined by the circular sliding surface method and the safety factor is specified in this case usually to be more than 1.2.

Many research works have been done to this day related to the earthquake resistant problems of earth dams. In the theoretical works, Mononobe, Takada and Matsumura evaluated the shear vibration of two dimensinal truncated wedge in 1936(2) and Yoko-o, Ishizaki and Hatakeyama(3) treated of the coupled vibration of two kinds of motion, vertical extensional type and shear type of the wedge. Recently Hatanaka(4) and ambraseys(5) evaluated the three dimensional shear vibration of the truncated wedge, respectively.

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In the experimental works, Mononobe and Matsumura conducted vibration experiments on models made of agar-agar to check the results of their theoretical studies in 1936. Later, Davis and many others(6,-.9) tried to make clear the features of the dynamical damage to the model dam which is made of sand or the similiar granular materials, by shaking it on the vibration table. Besides these model studies, a field investigation was carried out recently by keightley in U.S.A. Keightley(10) set the synchronized shakers at the crest of earth dam 60ft in height and rocked it. The response curves on some points of dam surface were obtained and the damping coefficients for several modes were estimated.

§ 2. Earthquake observation on an existing earthdam

Authors also paied attention to an importance of disclosing the dynamic behaviors of earthdams during earthquakes and tried to observe the seismic response of an existing earthdam.

The name of the dam where the observations were carried out is the Sannokai Earth Dam. It is located in the north-eastern part of Japan Island and is 37m in height, 140m in crest length, 12m in crest width and 194m in base width as shown in Fig.1. The geology at dam site consists of mainly green tuff, partially of andesite and lava cluster and a thin layer of dilluvial deposit lies on it. Dam body is divided into 4 zones,A, M, D and G as shown in Fig.1, whose mechanical properities are shown in Tab.1.

Authors distributed eight seismometers at the center of the crest, at the mid-slope of the downstream surface and at the both sides of the bank. Their locations, measured directions of earthquake motion and other properties are shown in Fig.2 and Tab.2.

Earthquake acceleration at the intake tower were also obtained but they are not reported here.

The natural frequency of accelerometers is 3 cps and is in the state of over-damping. The natural frequency of the galvanometers of a oscillograph is 50 cps and the output of the whole system of the instrument shows the constant sensitivity for acceleration in the frequency range of 1 cps - 10 cps. The natural period of velocity type seismometers is 1.5 sec. and the output of it is also of constant sensitivity for velocity in 1 cps - 10 cps.

Some of the records obtained in this way are shown in Figs.3 - 7. Characteristics of earthquakes concerned are shown in Tab.3. The records shown in these figures are those of main part of earthquakes except the records of Earthquake No.12. In the case of the Earthquake No.12, records of the main shocks at the crest of the dam scaled out so that the vibration in Fig.6 are those which were recorded after the main shock elapsed.

In order to derive the dynamical properties of the earthdam, main parts of the record of 5 sec long are Fourier analysed by following formula,

$$G\left(\frac{2n\pi}{To}\right)=\frac{2}{To}\sqrt{\left(\int_0^{To} f(t)\cos\frac{2n\pi}{To}t\,dt\right)^2+\left(\int_0^{To} f(t)\sin\frac{2n\pi}{To}t\,dt\right)^2} \quad \ldots.(1)$$

Where, T_o : analized length of the record, 5 sec.
n : positive integar, 1, 2, 3 $\cdots$.
$f(t)$: amplitude of earthquake.

Figs.8 - 15 show the frequency components, $G\left(\frac{2n\pi}{T_o}\right)$, at each section of the dam.

From these figures it is seen that at the crest of the dam frequency components of about 2.8 cps and about 4.2 cps are predominant in horizontal direction and that of about 4.2 cps in vertical direction as well.
The ratio of components at the crest or at the mid-slope of the dam to those at the right bank is given in Fig.16.

§ 3. Discussions

1) On the predominant period.

Two predominant frequencies, 2.6 - 2.8 cps and 4.2 - 4.7 cps are recognized in the spectrum of the horizontal vibration at the crest of the dam during earthquakes. On the other hand, the spectrum of the vertical response of the vibration at the crest shows that the vibration of 4.2 - 4.7 cps is remarkably magnified in No.12-2 and No.13 records.

From these results, it is considered that the predominant vibration at the crest of 2.6 - 2.8 cps and of 4.2 - 4.7 cps show the excitation of the natural vibrations of the earthdam. The natural vibration of frequency about 2.8 cps is appeared to be composed mainly of the horizontal deformation of the dam body whereas the natural vibration of 4.2 - 4.7 cps is appeared to be composed of the horizontal deformation accompanied by the vertical component. Natural vibration of the latter type is supposed to be excited only in the case when the ground motion has a large vertical component.

For the main part of the record of shock No.12, which scaled out as mentioned above, amplitude can not be estimated but the predominant period of the vibration can be estimated by drawing its hystogram. According to its hystogram the predominant period is also in the range of 2.6 - 3 cps and, therefore, any elongation of the natural period of the dam is not expected to such a large shocks, whose maximum acceleration is of 23 gals at the bank and may be of 90 gals on the crest.

The natural period of the shear vibration of the wedge is given theoretically by the following formula

$$J_o\left(\frac{2\pi H}{T}\sqrt{\frac{\rho}{G}}\right) = 0 \qquad \cdots\cdots(2)$$

where

H : height of dam
ρ : density of dam body
G : shear modulus of the dam body
T : natural period of the shear vibration
J : Bessel function of zero order

In this case ρ and H are

$$\rho = 2.0 \times 10^{-6} \text{ Kg sec}^2/\text{cm}^4$$

$$H = 3.7 \times 10^3 \text{ cm}$$

If the vibration of the frequency of 2.6 - 2.8 cps is assumed to be 1 st order natural vibration of the dam, the value of G computed from the eq.(2) is 1360 kg/cm^2. Whereas, if it is assumed to be 2 nd order natural vibration, the computed value of G is 260 kg/cm^2. The latter value of G is more acceptable than the former one so that it is considered that the predominant vibration of the dam during earthquakes may be 2 nd order natural vibration.

2) On the magnification of the ground motion at the crest.

Table,4 shows the ratio of the maximum acceleration amplitude at the crest to that at the right or left bank. From these results, it is quite probable that the acceleration at the crest can be at least 3 to 5 times that at the base. The ratios of the frequency component of the earthquake records at the crest and at the mid-slope of the dam to the component at the right bank are shown in Fig.16. The ratio is about 25 in the frequency of 2.8 cps and about 1.8 in 1 cps. Then the apparent damping coefficient h is calculated for the natural vibration of 2.6 - 2.8 cps by the following way.

$$\frac{1}{2h} = \frac{25}{1.8} = 13.9$$

$$\therefore h = 0.04 \qquad \text{------------} \qquad (3)$$

This value is nearly half of the value 0.1 obtained from the vibration test of the actural earthdam carried out by keightley (10).

The vertical vibration is frequently magnified at the crest in the frequency of about 4.5 cps and its maximum magnification ratio is about 4.

3) Mode of natural vibration

Authors picked up the acceleration amplitudes of the crest, of the mid-slope and of the bank in a phase and plotted the mode of vibration of the dam. From the pattern of the mode, the predominant oscillation of 2.8 cps is appeared to be the shear vibration of the 2 nd order rather than the 1 st.

This is also supposed by comparing the observed natural frequency of the dam with the theoretical one as mentioned above and authors are going to investigate it in more details by increasing the measuring apparatus at the dam site.

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Figure caption

Fig. 1 : Section of the dam.

Fig. 2 : Location of Seismometers.

Fig. 3-7 : Earthquake records.

Fig. 8-5 : Fourier components of the records.

Fig. 16 : Ratio of Fourier components on the dam to those on the foundation.

Table caption

Tab. 1 : Mechanical Properties of materials of the dam.

Tab. 2 : Characteristics of seismometers.

Tab. 3 : Characteristics of earthquakes;

Illustration of Notation

D C S	: Horizontal Acceleration (S69°E)	at Center of Crest
D C S - M	: Horizontal Acceleration (S69°E)	at Center of Mid Slope
D C U - v	: Vertical Velocity	at Center of Crest
D C U - α	: Vertical Acceleration	at Center of Crest
R R S	: Horizontal Acceleration (S69°E)	at Right Bank
R L S	: Horizontal Acceleration (S69°E)	at Left Bank
R L U - α	: Vertical Accleration	at Left Bank
O T A'	: Horizontal Acceleration (N16°E)	at Outlet Tower
R L A'	: Horizontal Acceleration (N16°E)	at Left Bank

Tab. 4 : Ratio of Maximum acceleration on the dam crest to that on the fundation.

Mechanical Properties of Materials of Dam

Sort of Filled Soil	D	G	M	A
Real Density of Soil ($^g/_{cm^3}$)	2.65	2.71	2.69	2.57
Plastic Limit	38.5	42.5	37.5	30.9
Liquid Limit	50.5	50.0	41.0	60.0
Plastic Index	12.0	7.5	3.5	29.1
Field Moisture Equivalent	44.0	44.0	38.3	40.0
Shrinkage Limit	32.0	24.4	26.0	18.0
Optimum Moisture Content(%)	20.0	35.0	25.0	15.0
Moisture Content of the actual Fill(%)	20 30	35 50	25 35	15 25
Moisture Content in Borrow Pit(%)	21	52	—	22

Table — 1

Characteristics of Seismometers

Location	Measurinf Direction	Output of Seismometers	Nutural Period of Sesmometer	Natural Frequency of Galvanometer	Notation of Earth-quake Records
I	Vertical	Velocity	1.5 sec	30 cps	R L U - v
I	Vertical	Acceleration	0.33	30	R L U - α
I	Horizontal(S69°E)	Acceleration	0.33	50	R L S
I	Horizontal(N16°E)	Accelerarion	0.33	50	R L A'
II	Horizontal(S69°E)	Acceleration	0.33	50	R R S
III	Vertical	Velocity	1.5	30	D C U - v
III	Vertical	Acceleration	0.33	30	D C U - α
III	Horizontal(S69°E)	Acceleration	0.33	50	D C S
IV	Horizontal(S69°E)	Acceleration	0.33	50	D C S - M
V	Horizontal(N16°E)	Acceleration	0.33	50	O T A'

Table — 2

Characteristics of Earthquakes

Earthquakes	Time of Occurence	Epicenter	Distance of Epicenter	Magnitude	Water Level*
No. 4	11^h59^m, Jan. 9,1964	N41.1°,E=142.7° h=40km	230^{km}	—	19.30^m
No. 5	13^h51^m, Jan.10,1964	N41.8°,E=143.0°	300	—	19.20
No. 7	$22^h\ 0^m$, Feb. 7,1964	N39.7°,E142.8°	150	—	22.25
No.12	16^h58^m, May. 7,1964	N40.5°,E138.6° h=40km	240	7.2	29.13
No.13	After Shocks of No.12				

* High water level is 29.13^m

Table - 3

Ratio of Maximum Acceleration on the Crest to that on the Foundation

Earthquakes	Max.Acc.of Ground		Max.Acc. of Crest	Ratio		
	Right Bank	Left Bank		Right B.	Left B.	Average
No. 4	0.75^{gal}	$—^{gal}$	3.9^{gal}	5.2	—	5.2
No. 5	1.75	—	5.4	3.1	—	3.1
No. 7	0.83	0.67	3.75	4.5	5.6	5.1
No.12-2	5.4	6.0	19.5	3.6	3.3	3.5
No.13	1.6	2.6	7.0	4.4	2.7	3.5

Table - 4

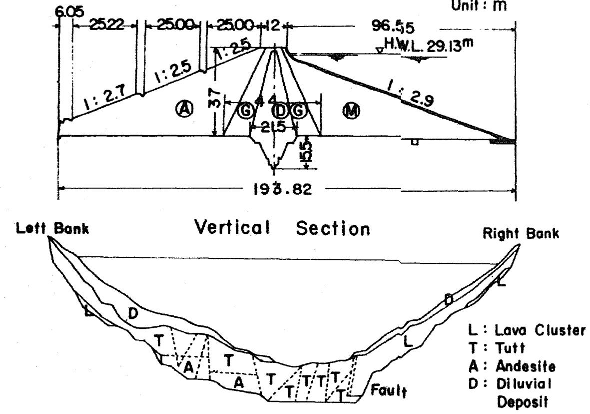


Fig. 1

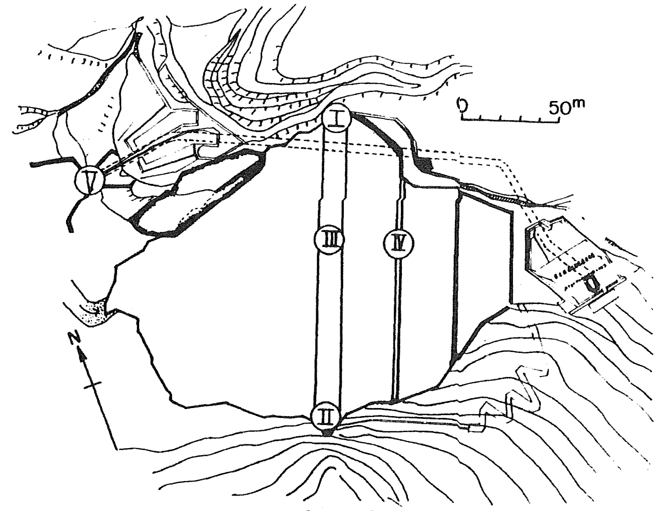


Fig. 2

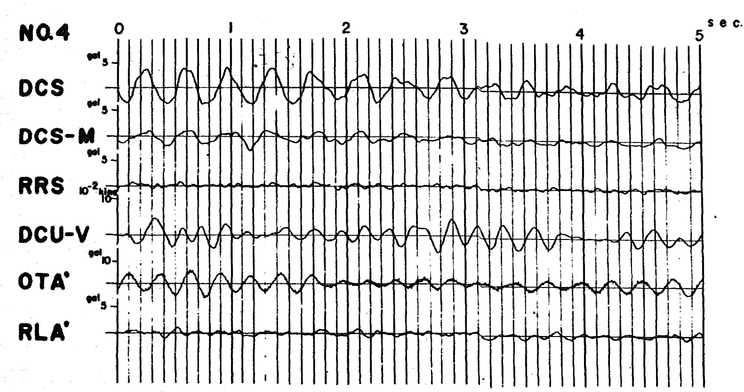


Fig. 3

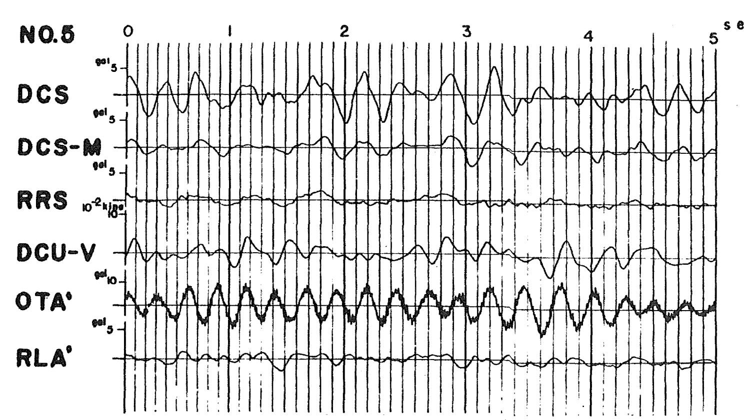


Fig. 4

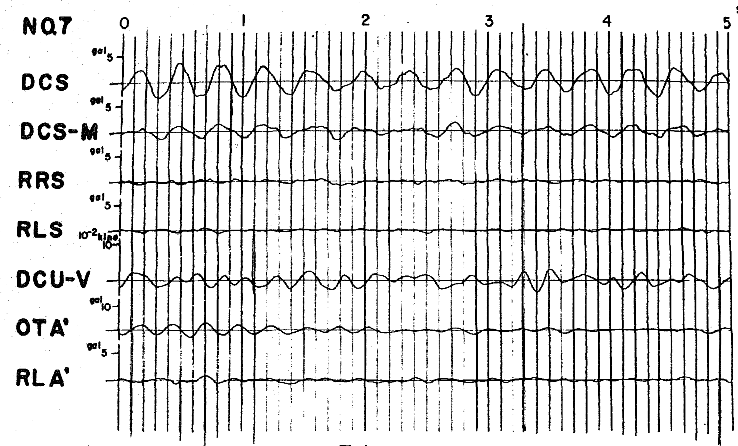


Fig.5

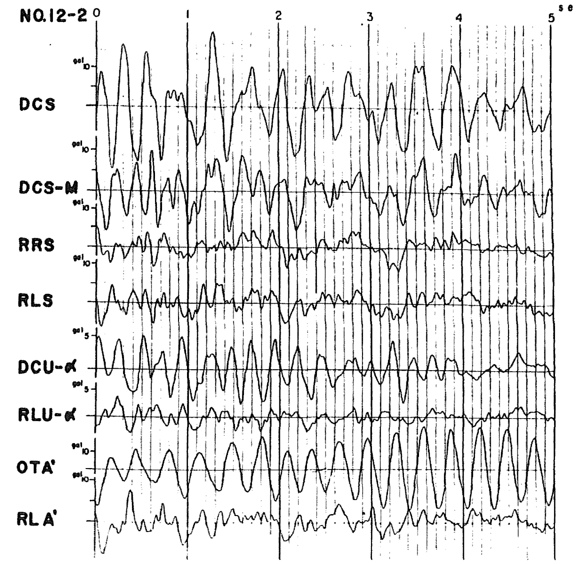


Fig.6

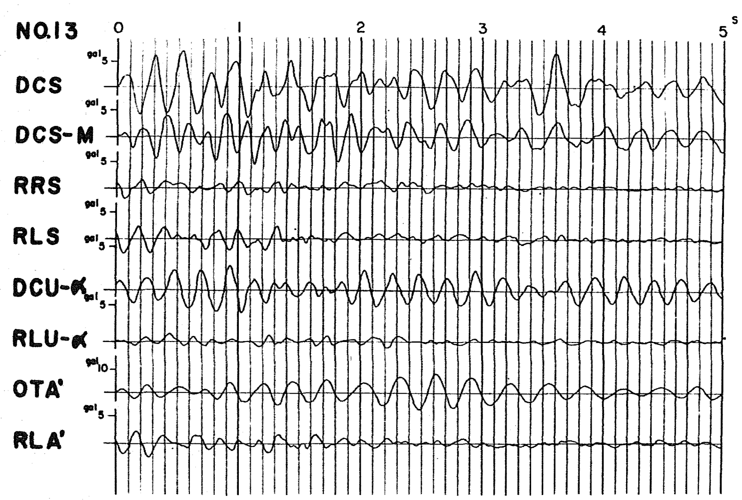


Fig.7

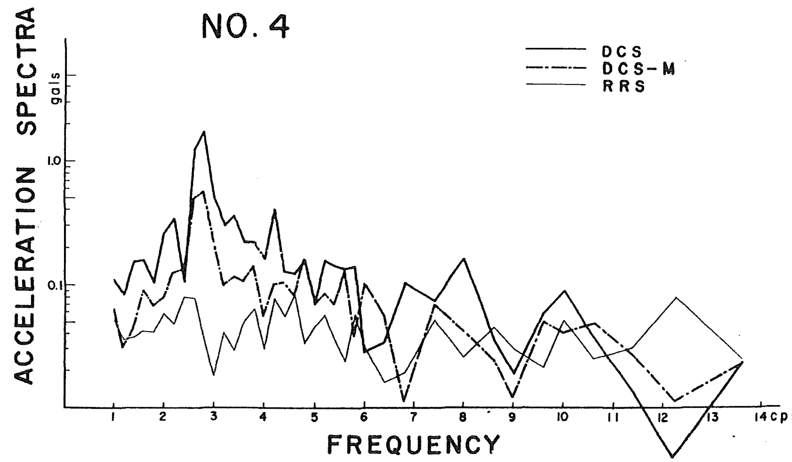


Fig.8

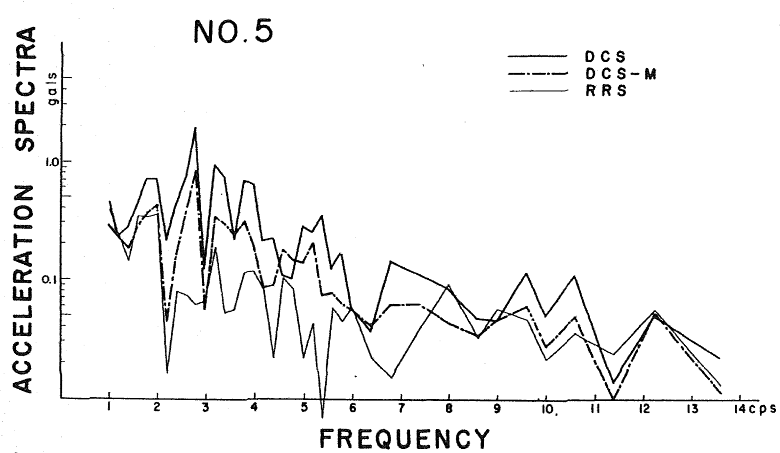


Fig.9

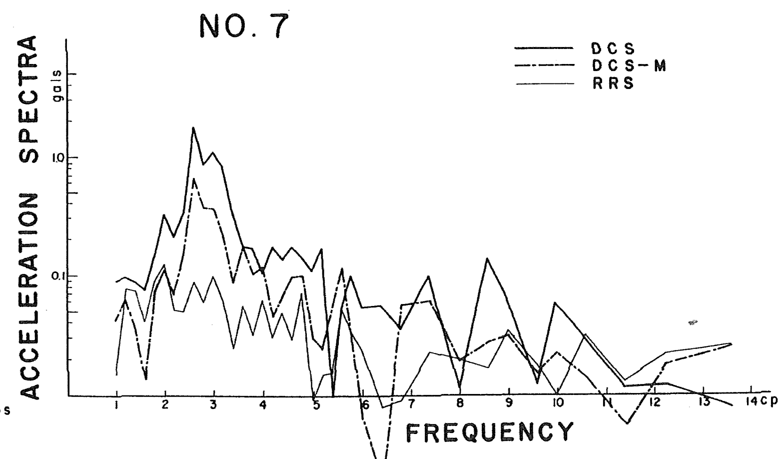
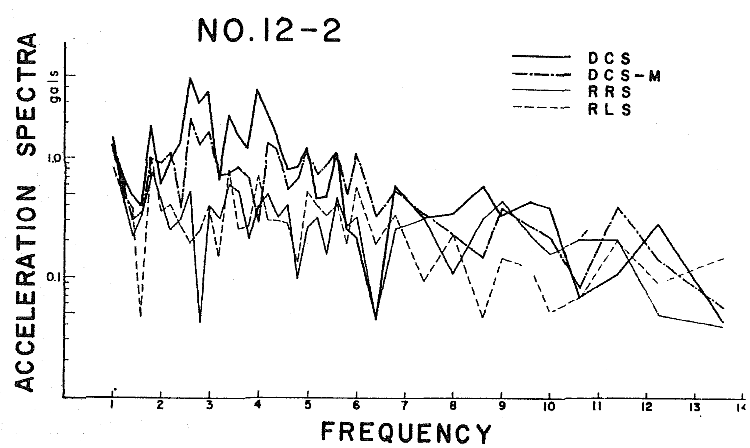


Fig.10



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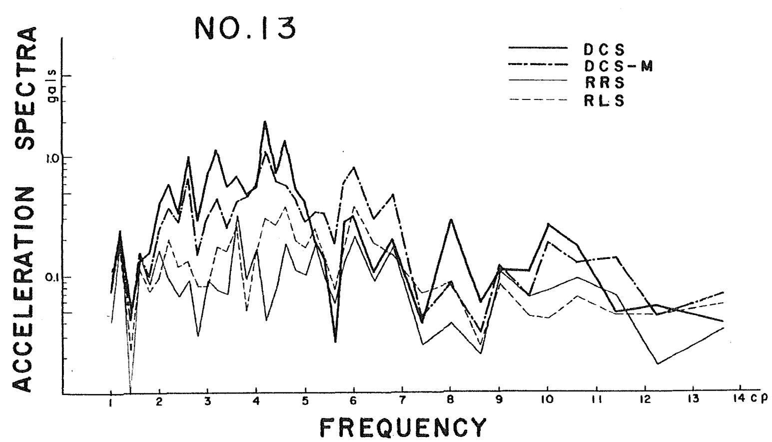

Fig.12

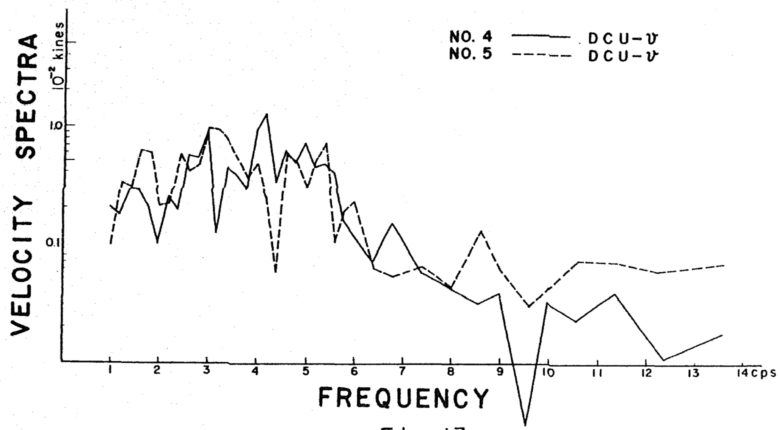

Fig.13

NO.12-2

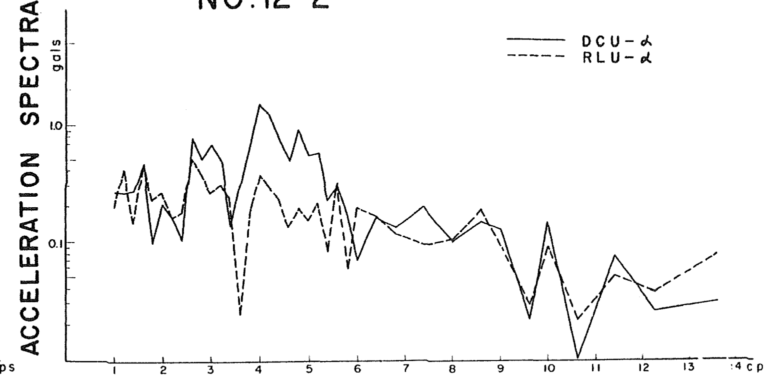

Fig.14

NO.13

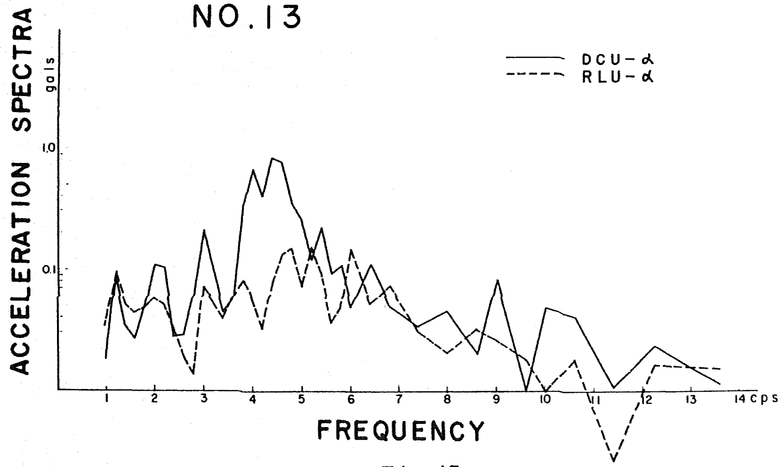

Fig.15

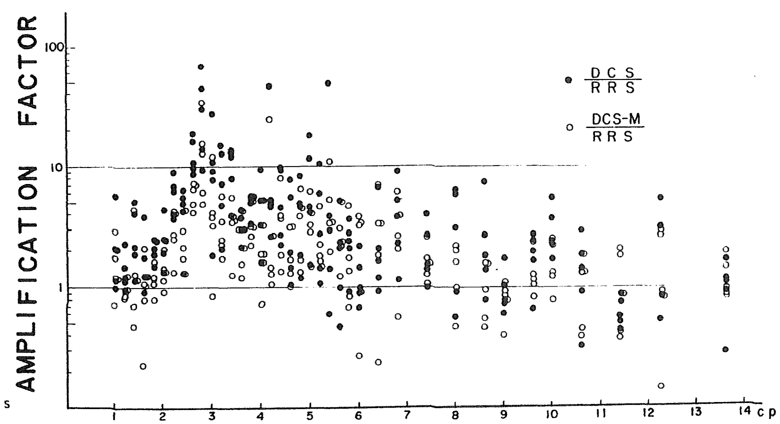

Fig.16

ON THE DYNAMICAL BEHAVIOUR OF AN EARTH DAM DURING EARTHQUAKE

BY S. OKAMOTO, M. HAKUNO, K. KATO, F. KAWAKAMI.

QUESTION BY: V.A. MURPHY - NEW ZEALAND.

It is noted that model tests were made and recorded and also it is noted that the actual earthquake of Niigata was recorded. Would the authors please state, if the records showed satisfactory agreement?

QUESTION BY: J. KRISHNA - INDIA.

How far away was the dam from the epicentre of the Niigata shock?

AUTHORS' REPLY: Further development of the research is as follows.

1) After the paper had been sent out, several earthquakes took place and were recorded. One of them was the Niigata Earthquake on 16th June, 1964. Maximum acceleration during the Niigata Earthquake at the dam site, 210 km distant from the epicenter, was 55 gals. on the ground and 107 gals. on the crest of the dam (Figs. A, B and C.).
Since the records of small earthquakes have already been obtained, the characteristic behaviours of the dam during the strong earthquakes can be compared with those during the slight earthquakes.

Results are as follows.

a) Between them, no marked difference of prominent frequencies of the dam is found.

b) Ratio of the maximum acceleration on the crest and that on the ground (amplification in popular sense) is 2. The amplification seems to decrease with the increase of the ground acceleration.

2) Some seismometers have been added on the slope in order to obtain the more detailed data and it has been disclosed that the vibration of 2.8 cps is the first mode. (Our guess described at the end of the paper should be amended).

3) The first mode, which has been observed during the recent small earthquake, is different from the mode which is assumed in theoretical calculation (equation 2), and this seems to be one of the reasons why the observed natural period is different from the theoretical one. The observed first mode shows satisfactory agreement with that obtained by the model test which is the mode of agar-agar. However, the

observed mode is that of the small earthquake which occurred after the Niigata earthquake. At the time of the Niigata earthquake, only a seismometer had been located on the slope except those on the crest and the ground, therefore the mode could not be determined.

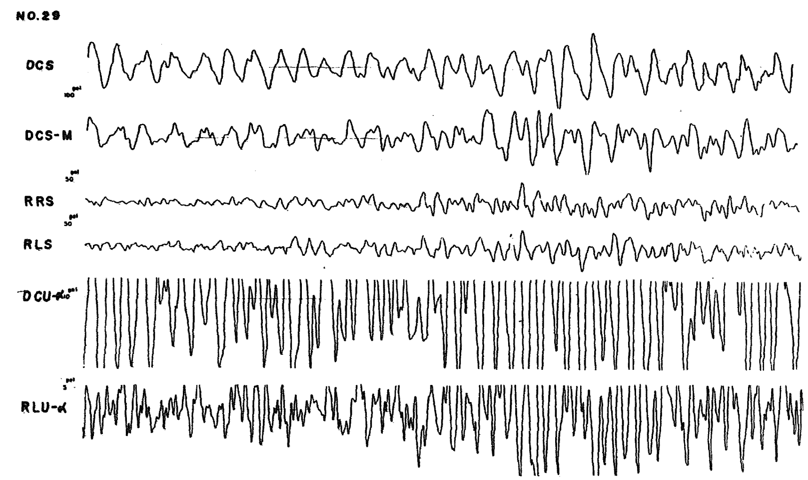

Fig. A

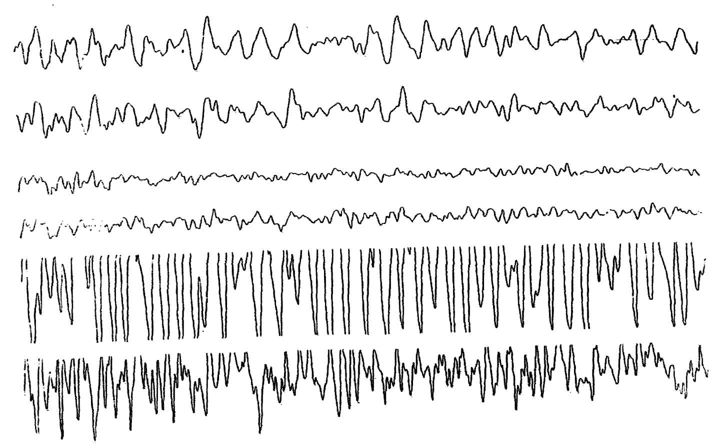

Fig. B

ACCELERATION SPECTRA

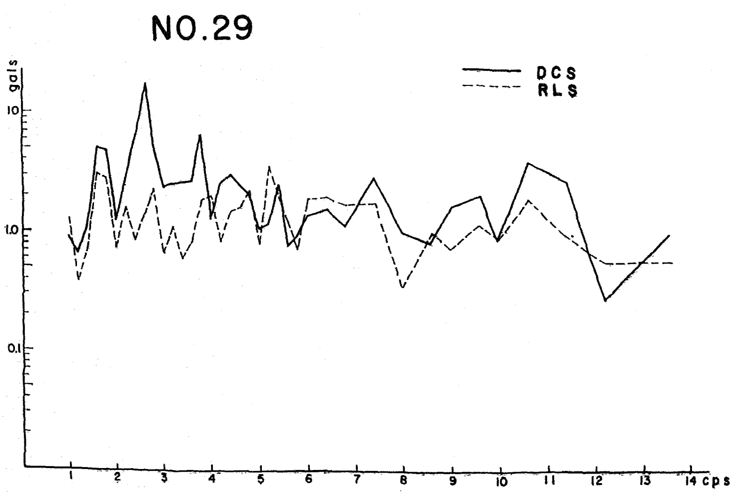

Fig. C