Dynamic Response of Dams

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Abstruct. Electric Power Development Co., Ltd., (EPDC) establishsd in 1960 the seismological engineering laboratory on dams, which is specially operated for study aseismic design of various types of dams.

This paper describes the dynamic behaviors of the dam subject to earthquakes, especially arch dams, obtained by the dynamic model tests, field hynamic tests on prototype dams vibrated by artificial exciting force and earthquake observations on the dams for research of their responses during natural earthquakes.

I. Seismological Engineering Laboratory on Dams

This description is concerning to the aseismic engineering laboratory established by EPDC for obtaining the useful data for aseismic design of dams.

This laboratory is situated in the Central Research Institute of Electric Power Industry in Tokyo.

In this laboratory, we are studying some special works as follows;

1. Earthquake observations at the proposed dam site. Ths works are including in scheduling, preparing, adjusting of the apparatus for operation and analysis of its records or its response spectrum.
2. Material tests for model dams to improve the similarity of model test and for prototype dams to study the dynamic characteristics of their materials.

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These tests are operated with small shaking table (max. load; 500kg, frequency range; 2 — 20 cps, max. Acc.; 0.5 g) and pulsating load generator (capacity 100 ton) etc.

3. Model tests

The model tests are studied using two different type shaking apparatus by case by case.

i) Large shaking table (See Photo-1)

The characteristics of this table are as follows;

Size of table	5m x 5m
Max. load	22 Ton
Frequency Range	7 — 50 cps (unbalanced mass drive)
Max. exciting force	56 Ton
Direction of exciting	on the vertical plane including each 4 exciters, able to shake either horizontal or vertical.

The special features of the table are as follows;

a) Enable to continuously change the frequency, displacement and shaking direction during operation.

b) The table is supported with 4 air springs for reduce the warps of the wave forms.

c) On horizontal vibration, the moment of gyration in vertical plane is able to prevent.

d) Collapse test is practicable.

ii) Okamoto type shaking installation (See Photo-2)

This installation was applied the method indicated by Dr. Okamoto, Professor of the Institute of Industrial Science, Tokyo University. The method is that a model is situated on a fixed floor and only a model is shaked by small magnetic exciters with sinusoidal and any random wave forms. Its mainly characteristics of the exciters are as follows;

Max. load	250 kg	(horizontal)
Frequency range	5 — 500 cps	
Max. acceleration	20 g	(no load)
Max. displacement	30 mm	(")
Wave forms	Sinusoidal and Random	

4. The estimation of design stress distributions under seismic conditions and studies of safety factor against collapse of dam by analytical methods applying the results of items 1 and 3, are studied by means of frequency analyzer, analog computer, FM and PWM data recorders etc.

5. Field vibration tests on prototype dams by artificial exciting force to presume their responses during earthquakes.

6. Earthquake observations on the dams and their foundations have been made systematically after the completions of the dams to compare these data with designed its value of the dam.

Upper mentioned works are a application of the aseismic engineering theory to the plactical engineering at the present state, but we are making efforts to obtain more rational theories and techniques of the aseismic designs for dam constructions.

II. Dynamic Model Tests of Futatsuno Arch Dam

Futatsuno Arch Dam is 76 m height, 210 m crest length and has a center overflow type large spillway (120 m in width, 9,600 m^3/sec. over flow capacity)

The tests were performed on the large shaking table in 1961.

1. Similarity

The similarities for the tests either in or out of elastic limit, are shown in Table-1.

2. Materials of the model

The plaster, diatomite and others were selected for the materials of the model dam. The mixture and physical characteristics are shown in Table-2.

The stress-strain curve of this material is nearly similar to the concrete in the elastic limit.

3. Model and Measurement

The dam body and a part of its surrounding abutment in scale 1:50 were molded on a steel frame, then the loaded steel frame (total weight 18 ton) fixed on the large shaking table.

The displacement measurements of the model dam were made by means of special gauges. The measurements of the strains were used 3 compornents bonded wire strain-gauges.

4. The results of the test in the elastic limit.

i) Predominant period of the dam

The frequency-displacement curve measured at the center of the top arch at ± 0.1 g, are shown in Fig.-2. The predominant periods of the prototype dam are presumed as follows;

1st symmetric vibration	0.2 seconds
1st antisymmetric vibration	0.28 "
damping constants (model dam)	0.02 -- 0.05

ii) Vibration modes

Fig.-3 shows the modes of 1st symmetric vibrations measured at 5 points on the top arch in radial direction.

iii) Stress distributions

The stress distributions are shown in Fig.-4 obtained by analysing the results of strain measurements (damping constant 0.05).

iv) Estimation of dynamic stress in prototype dam during earthquakes.

A ground motion during earthquakes is idealized as a stationary random wave and to comply statistically with Gaussian law. Otherway, assuming a dam to linear transfer element, a ratio which is a standard deviation of a ground motion to a coresponded standard deviation of a dam, is regarded to be equal to a ratio of each maximum value.1)

Then the maximum acceleration of earthquake adopted to the calculation is 0.06 g at empty reserved or 0.12 g at full, and the predominent frequency of the foundation rock at the dam site is 0.2 sec., that is obtained by analysis of the records observed at the dam site before construction by Ishimoto type seismographs.

Fig.-3 and 4 show the calculated dynamic stress on the condition that the dam is a vibration system of one degree freedom and its mode is 1st symmetric.

5. Collapse test

It has very rare chance that a prototype dam is breaked down due to a resonance, but if a collapse of a dam happens, it can be assumed that a process of a collapse is similar to it of a model dam by resonance at low order normal mode vibration. Therefore, the model test was done to examine qualitatively a process of resonant collapse at empty reserved.

The first crack appeared at the base of the spillway pier when vibrated the table with ± 0.27 g and 32 cps in the model. With ± 0.38g and 32 cps, the crack arised at the perimeter and it grew all over. The first crack developed to abutment at the center of the dam vertically with ± 0.41 g and 30 cps. At last, the dam showed a collapsed aspect as a result of growing all cracks with ± 0.69 g and 17 cps. Photo.-3 shows the aspect of this state.

6. Consideration

The dynamic behaviors presumed by the results of upper mentioned model tests, are as follows.

The predominant frequencies are 0.2 sec. at 1st symmetric mode, and 0.28 sec. at 1st antisymmetric mode. It is considered the predominant frequency of the foundation rock at the dam site and the dam itself with empty or full reserved, is nearly equal. Moreover it is unfortunately expected to occur the comparatively large repetitive stress in the center of the top arch and the bottom of the crown cantilever with 1st symmetric vibration.

Then, it must be designed an arch dam with considerations of the results of model tests not only static but also dynamic.

III. Dynamic Model Tests of Ikehara Arch Dam.

Ikehara Arch Dam is 111 m height, 460 m crest length. This dam has the characteristics of the large crest length for its height and of the antisymmetric special 4 centered arch in its plan.

The tests were carried out in 1962 at the condition with empty and full reserved by means of Okamoto type shaking installation which is able to shake a model with random waves. (See Photo.-2)

1. Model

The model made of the mixture with mainly plaster, and formed by cut out method on a fixed floor in scale 1:150. The length of the reservior is 1.5 times as its depth.

2. Exciting apparatus

Only the dam body was excited by several small magnetic exciters which were installed on the fixed arms.

A exciter was arranged on the model dam in proportion to equivalent mass. When the model was shaked in direction of right or left bank, two exciters were installed at one point with an angle between them, so to erase a force of stream direction and to put one force upon another.

3. Test by sinusoidal wave

i) At empty reserved

The predominant periods were obtained as follows;

	model	prototype
1st symmetric	143 cps	0.34 -- 0.4 sec.
2nd "	184 "	0.26 -- 0.31 "
1st Antisymmetric	120 "	0.26 -- 0.31 "
2nd "	215 "	0.20 -- 0.24 "

damping constant of model dam

1st symmetric	0.02
2nd "	0.01

Fig.-5 shows the vibration modes (displacement) at 0.1 g and Fig.-6 shows the strain modes (horizontal and vertical) at same vibrating condition.

ii) At full reserved

On this test, the water was stored upstream face of the dam covered with 0.4 mm thin rubber membrane, and shaked the model in same way as item i).

The resonance curve showed not so predominant but could be recognized the 1st normal vibration was only predominant (76 cps).

Comparing the modes of this test with its of test i), the former showed similar to the latter except the modes at the top arch appeared slightly near the both abutment on the latter test.

4. Test with natural earthquake wave forms.

The tests were done with two waves at empty reserved.

Wave-A; The acceleration records observed at the dam site, changed its period by similitude law to 52 times as real.

Wave-B; The predominant period of Wave-A is pretty higher than the 1st and 2nd symmetric vibration period of the model dam to make a resonance, so the period of Wave-B changed to 26 times as real.

Both Wave-A and Wave-B had two predominant frequencies (143 cps; 1st symmetric and 184 cps; 2nd symmetric for model), but only 1st symmetric vibration mode in model dam was remarkable.

5. Consideration

Owing to a seismological consideration for past activity, it is expected that the proposed earthquakes, given max. acceleration at Ikehara Dam site, have comparatively near epicenter.

The periods of these earthquakes are assumable to 0.1 - 0.2 secons, and are shorter than the period of Ikehara Dam at 1st predominant period (0.5 sec.) with full reserved. Therefore there is little chance to occur the resonance of the dam during these earthquakes. And as the repetitive stress, which is caused by only dynamic load at the perfect resonance, is small too, so the worry tensile stress in the dam body is not expected.

IV. Field Vibration Test on Sakamoto Arch Dam.

Sakamoto Arch Dam is 103 m height, 256 m crest length and one of the thinest dome type arch dam in Japan.

The dynamic behaviors of this dam were studied in 1964 by field vibration test cooperated with Dr. T.Takahashi of Central Research Institute of Electric Power Industry.

1. Exciter and measuring equipments

A exciter with unbalanced mass (max. 600 rpm, 5 HP) was fixed on the top of the dam.

The measurements of acceleration and displacement were made by several high sensitivity magnetic seismographs.

2. Results

The resonance curve is shown in Fig.-7. Fig. 8 and 9 show the vibration modes. These data are converted to vibrate the dam with exciting force of 10 ton.

3. Consideration

As Sakamoto Dam is situated at same region of upper mentioned Ikehara Dam, so it must be expected the dam is suffered the earthquakes having fairly near epicenter.

But it is considerable that there is a chance of resonance as little as Ikehara Dam, because Sakamoto Dam has a different predominant period (about 0.5 sec.) from its of these earthquakes.

The damping constant are obtained by calculation of the resonance curve as 0.02 -- 0.04.

V. Earthquake Observations on dams

EPDC performs itself the earthquake observations on some type of dams. After completions of these dams, several magnetic seismographs with starter have been installed on dam body and its foundation rock for observation of comparatively small earthquakes which are expected to occur once or twice a month. At Tagokura Gravity Dam, so many useful data have been obtained by recording small earthquakes during past several years, then the seismographs on this dam site were changed down their sensitivities to catch strong motion earthquakes.

The follows show the list of dams installed the seismographs.

Name of dam	Height(m)	Region	Numbers	Remarks
Tagokura (G)	145	Tohoku	14	5 Hydro-dynamic pressure meters
Futatsuno (A)	73	Kinki	12	
Ikehara (A)	111	"	10	
Miboro (R)	131	Chubu	11	
Yanase (R)	115	Shikoku	9	

(G) : Gravity
(A) : Arch
(R) : Rock-fill

VI. Conclusion

The systematic studies in our laboratory for aseismic design of dams are going to more advanced and accurate by means of the dynamic model tests, field vibration tests of prototype dams and earthquake observations of the dams to analyze their responses.

In this paper we mentioned only about behaviors of arch dams but we are studying aseismicity of fill type dams or other type dams, too.

The studies for aseismic design of dam performed by EPDC, are promoted with many instructive suggestions by Dr. S. Okamoto, professor of Tokyo University, Dr. T. Hatano of Central Research Institute of Electric Power Industry, and Dr. M. Yoshikoshi, Mr. K. Nakayama of civil engineer of EPDC.

The authors take this opportunity of expressing their thanks to Dr. S. Okamoto, Dr. T. Hatano, Dr. M. Yoshikoshi and Mr. K. Nakayama.

Reference

1) H. Tajimi: Basic Theories on Aseismic Design of Structures.
(Report of the Institute of Industrial Science,
University of Tokyo)

2) Okamoto & others: Observations of Dams during Earthquakes.
(Paper of the 8th Congress on ICOLD)

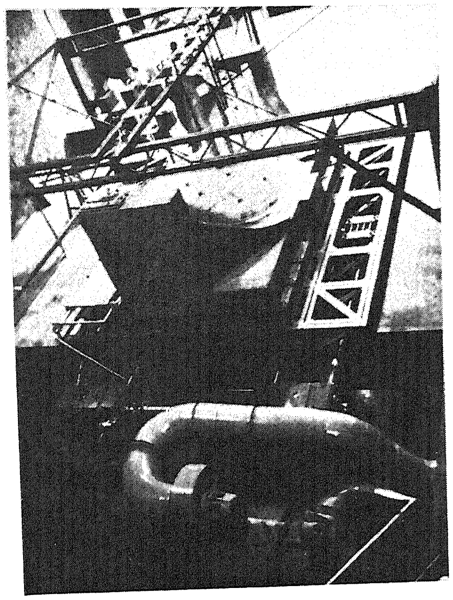


Photo-1

Large shaking table

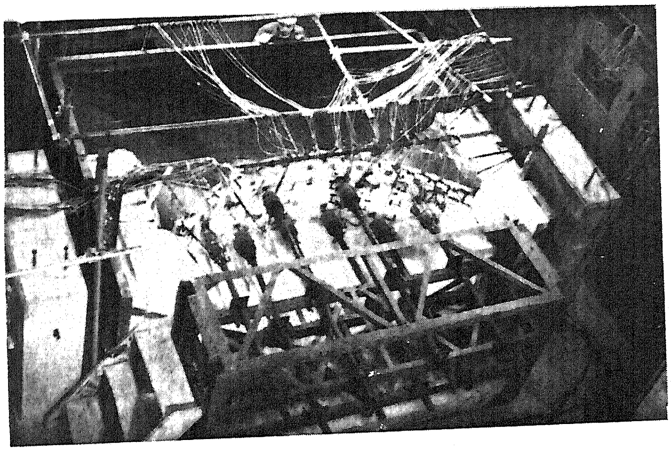


Photo-2

Okamoto type
shaking installation

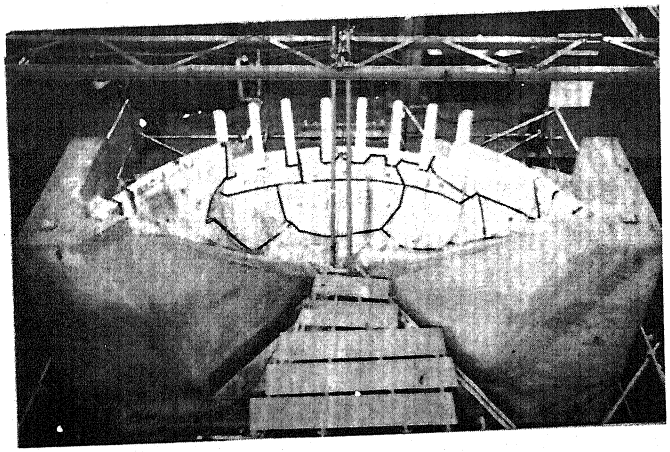


Photo-3

Collapse test

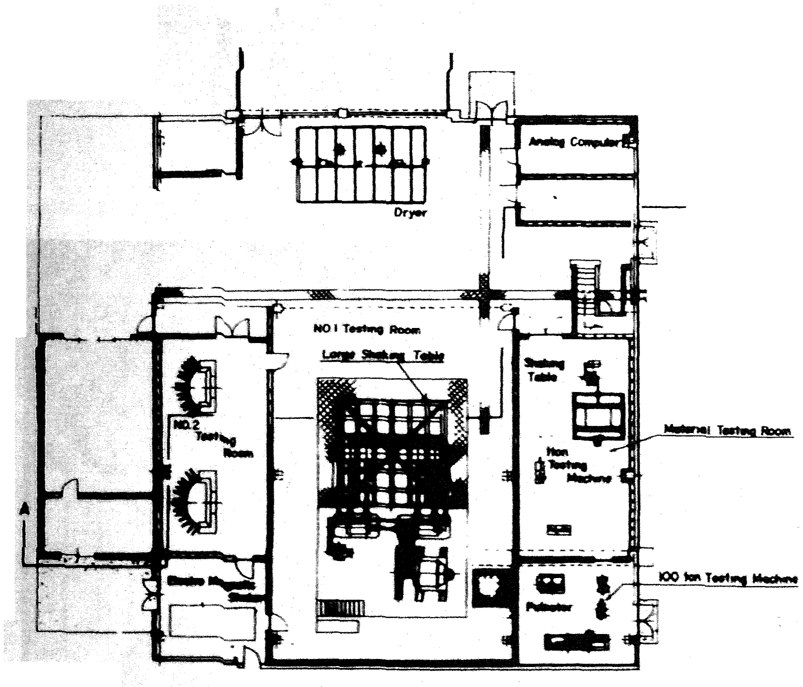
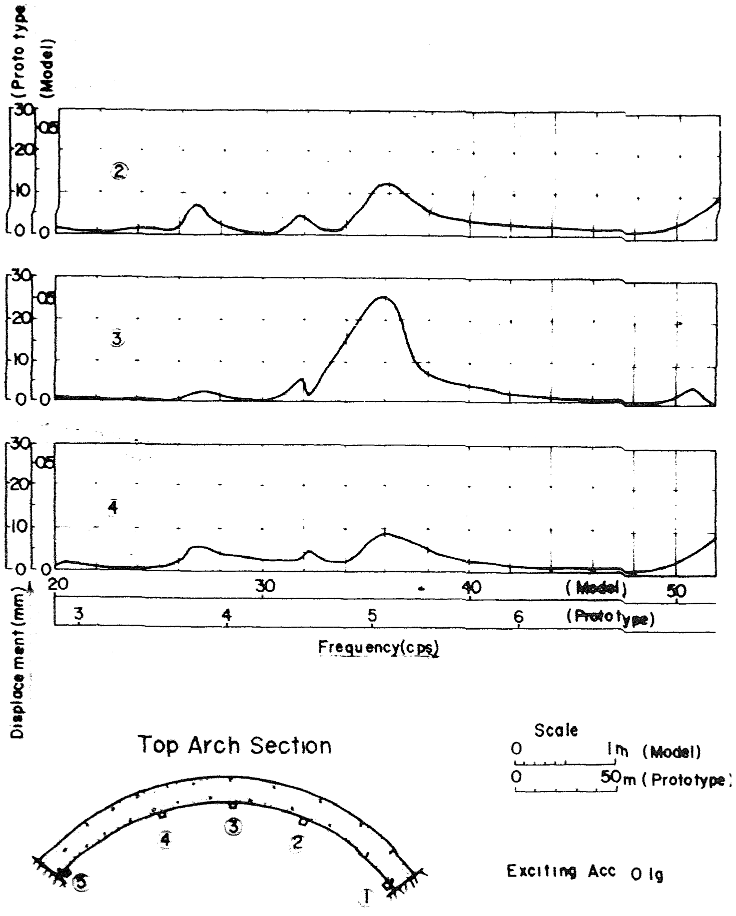


Fig.-1 Plan of Laboratory



Fiq-2 Frequency- Displacement curve
(Futatsuno Dam)

	Notation	Ratio of Proto Type and Model	Value in $n=50$ and $\rho_p = \rho_m$
Length	ℓ	$\ell_p/\ell_m = n$	50
Time	T	$T_p/T_m = n^{1/2}$	7.07
Weight in Unit Volume	ρ	ρ_p/ρ_m	1
Acc. of Gravity	g	1	1
Inertia Force	I	$I_p/I_m = \rho_p/\rho_m \cdot n^3$	1.25×10^5
Young's Modulus	E	$E_p/E_m = \rho_p/\rho_m \cdot n$	50
Elastic Limit	S	$S_p/S_m = \rho_p/\rho_m \cdot n$	50
Strength of Failure	γ	$\gamma_p/\gamma_m = \rho_p/\rho_m \cdot n$	50
Coeff of Viscosity	K	$K_p/K_m = \rho_p/\rho_m \cdot n^{3/2}$	352
Poison's Ratio	μ	1	1
Strain	s	1	1
Displacement	d	$d_p/d_m = n$	50
Stress	σ	$\sigma_p/\sigma_m = \rho_p/\rho_m \cdot n$	50
Natural Period	To	$T_{op}/T_{om} = n^{1/2}$	7.70

Suffix . p : Proto Type , m : Model

Table - 1 Similitude

	Mix				ρ (t/m³)	E (kg/cm²)	⑤	⑥	μ
	①	②	③	④					
Abutment	1.0	1.5	4.0	0	0.53	4,540	9.60	—	0.20
Dam Body	1.0	1.5	4.0	11.5	2.35	5,790	10.40	1.30	0.21

Note ① : Plaster ④ Lead Powder

② Diatomite ⑤ Compressive Strength (kg/cm²)

③ Water ⑥ Tensile Strength (kg/cm²)

Table - 2 Model Materials

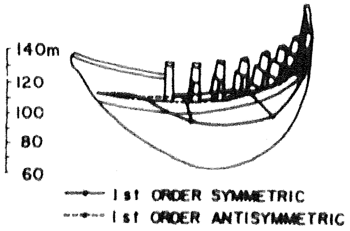


Fig.-3 Displacement Mode
(Futatsuno Dam)

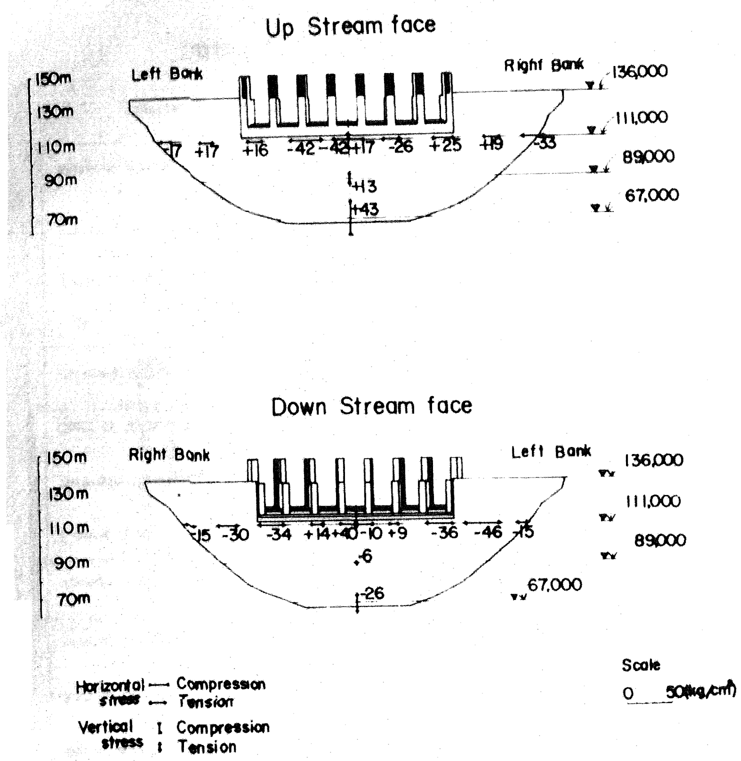


Fig.-4 Stress Distribution (Ist Order Symmetric)
(Futatsuno Dam)

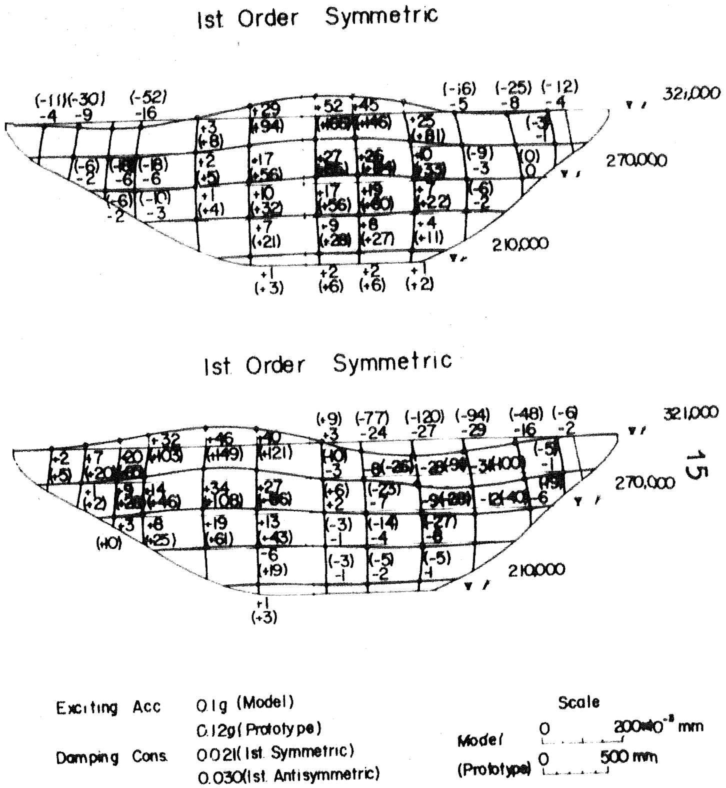


Fig-5 Vibration Models (Radial Disp.)
(Ikehara Dam)

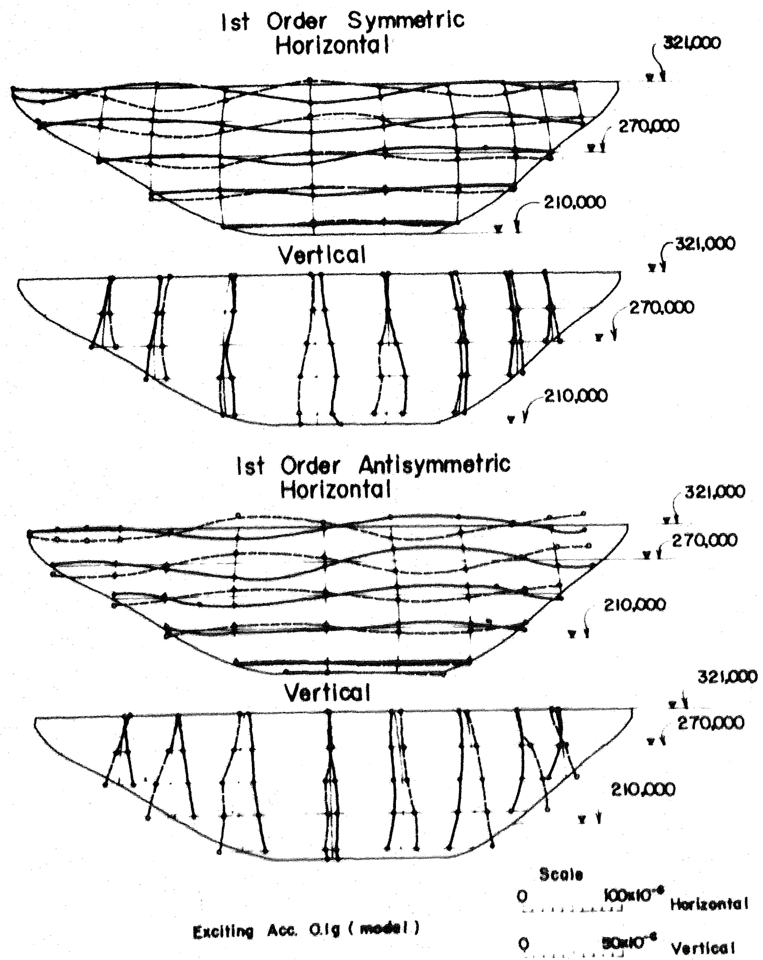
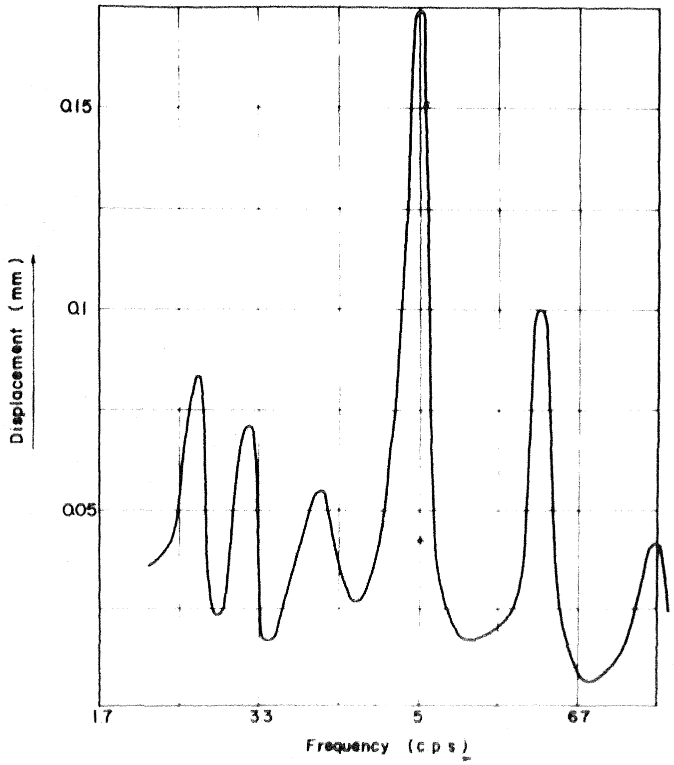


Fig-6 Vibration Modes (Strain)
(Ikehara Dam)



Exciting Direction : Radial
Exciting Force : 10 ton

Fig.-7 Frequency - Displacement Curve
(Sakamoto Dam)

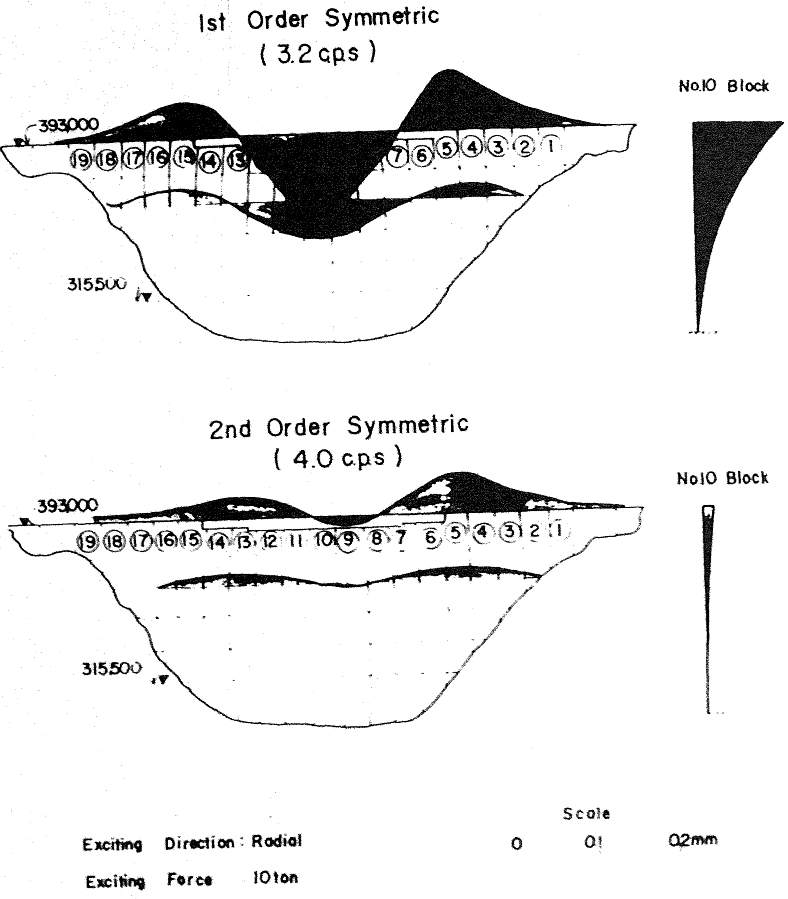


Fig.-8 Vibration Modes (Displacement)
(Sakamoto Dam)

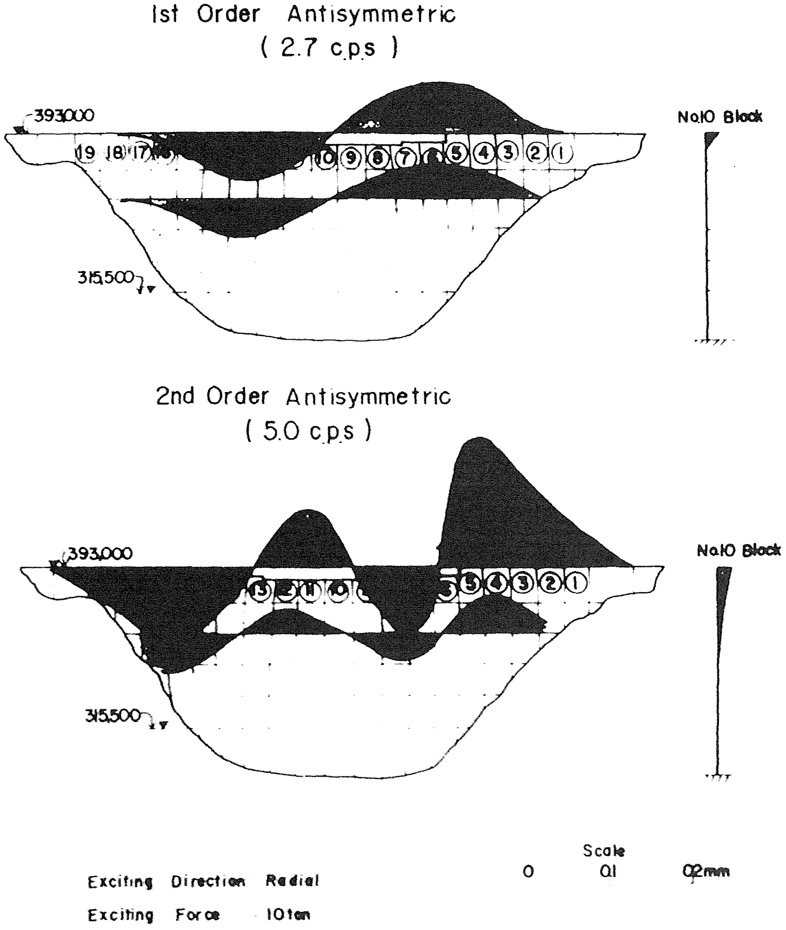


Fig.-9 Vibration Modes (Displacement)
(Sakamoto Dam)