VIBRATION STUDIES OF AN ARCH DAM

by

Tadashi Takahashi(i)

Synopsis

The steps to be followed in determining earthquake effect on the arch dam in design are discussed basing on the results of vibration field tests of actual dams. These involve the dynamic shapes of the dam structure, hydrodynamic water pressure due to earthquakes, the natural frequencies of arch dams, and damping constants in the first two modes. A method of earthquake design on an arch dam is presented.

Introduction

This report is referred to seismic studies of arch dams out of seismic studies of concrete dams which the author has worked on for many years.

In Japan, the construction of high arch dams dates from post war days, meanwhile, since Kamishiiba Dam was constructed, many high arch dams have been already constructed and also are under construction. As is well-known, in Japan where strong earthquakes are frequent thorough studies have been made regarding each dam so that dams and their foundation rocks may be enough free from danger of earthquakes.

Now in Japan, earthquake effect on an arch dam is estimated by calculations and studied by model tests, in designing all important arch dams.

Since shapes of dams vary with geographical and geological features, and also structures are complicated, it is important to make sure whether assumption in designing are correct or not. Then, after completion of dams vibration field tests on many dams were conducted and studies on vibration characteristics of actual dams have been made. Furthermore, observations of response of dams due to earthquakes have been made. Basing on the results of these studies, the methods of earthquake-proof design have been gradually improved.

Some of the results of these studies have been already published, but some of them unpublished yet. In this report, the achievement related to the seismic design of arch dams basing on the results of these field tests, are presented.

Arch dams involved in this report are as follows: (1) Kamishiiba Arch Dam, max. height 110m, on the Mimi River in Miyazaki prefecture;

(i) Fellow Research Engineer, Supervisor, Earthquake Engineering Section, Structure Dept., Technical Laboratory, Central Research Institute of Electric Power Industry.

(2) Sazanamigawa Arch Dam, max. height 67m, on the Sazanami River, in Yamaguchi prefecture; (3) Hitotsuse Arch Dam, max. height 130m, on the Hitotsuse River, in Miyazaki prefecture; (4) Kurobe Dam, max. height 180m, on the Kurobe River in Toyama prefecture; (5) Sakamoto Arch Dam, max. height 103m, on the Kumano River in Nara prefecture; (6) Ikehara Arch Dam, max. height 111m, on the Totsu River in Nara prefecture; (7) Takane Arch Dam, max. height 130m, on the Masuda River in Toyama prefecture, under construction; (8) Nagawado Arch Dam, max. height 155m, on the Azusa River in Nagano prefecture, under construction.

Field vibration tests and model tests have been conducted for the dams of (1) to (7), model tests for the dams of (1),(2),(8) and (9), and together with field tests, earthquake observations have been made for the dam of (1) to (4) and (6).

Vibration field tests and earthquake observations.

There are various kinds of methods of vibration field tests on structures. A method of vibration tests with a vibration machine which is one of the best method among them has been used for the purpose of examing vibration characteristics of dams. In this method, the vibration machine is installed on the top of a dam to give vibrations to the dam. The vibration displacement of the dam is measured by gradually changing the frequency of the vibration machine and from the results of this measurement the relations between vibration displacement of the dam and frequencies of applied force are obtained. The relations thus obtained are resonance curves. The fequencies which are signified by peaks of these curve show natural frequencies of the dam. The vibration shapes of the dam at the frequencies show the natural vibration modes. Furthermore, a damping ratio to critical damping can be obtained from a shape of a resonance frequency.

The vibration machine used in this test is an mechanical one with 2 eccentric weights and the maximum output power is about 60 ton at 10 c/s. The output power of vibration machine can be changed by variation of eccentric weight and eccentric distance.

The vibration meters used in our field tests were designed and trially produced by the author for this purpose. This principle is that vibrations are recorded by connecting a moving coil type pick-up directly with a galvanometer of an electric-magnetic oscillograph. Now that electromotive force of the moving coil type pick-up is proportional to the velocity of motion of a pendulum, the electromotive force is proportional to the velocity of the pendulum if the pendulum is a displacement type. Therefore, it is a velocity meter. If much damping is given to a galvanometer, it turns into a displacement meter. On the other hand, if the pendulum is a velocity type, it is an accelerometer. As the sensitivity of the vibration meter which is produced on the principle, in the case of displacement type, maximum sensitivity is 1mm/1μ on recording paper, and frequency range is 1-60 c/s; in the case of velocity type, maximum sensitivity is 0.78 volts/kine, frequency range is 1-70 c/s; in the case of an accelerometer, maximum sensitivity is 24μA/gal and frequency range is 0.2 - 20 c/s. With the recent improvement of these pick-ups, displacement, velocity, and acceleration can be measured with use of only one. As known above, our these vibration meter are highly sensitive and precision of the measured value is very high because an amplifier is not used. Besides, as there is no limit to the distance between a pick-up and a recorder, they are good for the field tests.

In order to measure the dynamic stress while a dam is vibrating, Carlson strain and stress meters embedded in a dam are used with amplifiers.

Hydro-dynamic water pressure acting on up stream face of a dam during earthquakes has a great influence on the vibration of a dam, so thst it is essential for earthquake-proof design of dams to measure hydro-dynamic water pressure on an actual dam and to study the effect on the vibration of a dam. For this purpose, a new hydro-dynamic water pressure meter applied the principle of a moving coil type pick-up has been developed for field tests and earthquake observations.

Earthquake observation apparatus consists of moving coil type vibration-meters, hydrodynamic pressure meters described above and a trigger to perceive ground motion at the beginning of earthquake at the site and make a recorder into operation. Now in Japan, the apparatus similar to this specification are being used for earthquake observations of dams.

Vibration characteristics of an arch dam.

As already reported,(1)-(6) the vibration shapes of an arch dam are similar to the vibration shapes of an arch. Following after the designation of vibration modes of an arch, it is natural that symmetric one to the central axis of an arch dam is called a symmetric vibration, and anti-symmetric one is called an anti-symmetric vibration. The former vibration is excited due to earthquakes in the stream direction and the latter is excited by the earthquake force at a right angle to the stream direction. During earthquakes both vibrations are generally exited because earthquakes act on any direction. Considering from the viewpoint of seismic study the lowest order vibration of these vibrations is most important. As a matter of course, the vibration in a cantilever direction is similar to cantilever transverse vibration in shape.

The vibration shapes of an arch dam somewhat vary with the shape of the valley. If the shape of the valley is symmetric, the central axis of vibration is in the center of the arch, and if it is not symmetric, the central axis slides into a deeper trough.

Fig. 3 shows a symmetric and anti-symmetric modes of vibration.(2)

In order to prevent from cracks by calorification of concrete and by drying and shrinking of concrete, an arch dam has vertical construction joints. It is natural to consider that at these joints dynamic stress distribution is disturbed. Accordingly it is conceivable that owing to the influence of these joint the stress distribution in the dam body is different from the case that a dam is assumed to be a homogenous structure.

As the result of having examined propagation of elastic wave at the top of a dam, it was proved that elastic waves were not propagated at the upper part of joints of a dam. And the dynamic stress measured in the vibration field(3) test of Sazanamigawa Dam showed discontinuity of stress at the upper part of vertical construction joints. Of course, the length of this discontinuous part varies with reservoir water level. However, as will be mentioned later on, in the case of the vibration within the limits of vibration displacement measured, natural periods which were calculated in assuming that an arch dam is an homogeneous structure are well in accord with the measured values, and the results of a model test on the same assumption are also in accord with the measured values. Judging from these results, earthquake effect on an arch dam can be estimated approximately on the assumption that the dam is regarded as an homogeneous structure in earthquake-proof designing.

An example of stress distribution obtained from a model test(4) is given in Fig. 4. These figure show that the stress distribution of symmetric 1-st mode of vibration is similar to the stress distribution due to static water pressure and the stress distribution of anti-symmetric 1-st mode of vibration is similar to the one due to bending moment.

It is important to measure dynamic elastic constant of concrete with pertinent method. There are two measurement methods for dynamic elastic constant of concrete now being used as to dams completed. The one is to obtain it from propagation velocity of an elastic wave using a supersonic method. It is known to all that there are some doubts wheter the obtained by these methods are correct or not. In order to make clear this problem, in addition to determining elastic constant with use of the above methods dynamic strain and stress were measured by strain and stress meters which were embedded at the same place in the dam structure in case of vibration field test on Sasanamigawa Dam(3) and Youngs modulus was drived from the measurement values. Then, the value was 3×10^5 kg/cm^2. On the other hand, the value obtained from propagation velocity of elastic waves was 3.7×10^5 kg/cm^2. As a result of having calculated natural vibration frequencies of this dam with use of respective value, it was revealed that the one calculated with the former value was in accord with the measured value better than with the latter.

It has been already shown by the results of measurement that an arch dam has many natural vibration frequencies within the frequency range of earthquake ground motion. The examples given in Fig. 5 are resonance curves of the vibrations of Hitotsuse Dam. The natural vibration which are important so far as earthquake design of structures is concerned, are lower order vibrations among them. In the case of arch dams these are symmetric 1-st mode and anti-symmetric 1-st mode of vibration. Accordingly, if natural vibration frequency of optional arch dams can be easily obtained, it is very convenient in earthquake-proof designing.

Therefore, natural frequencies of symmetric 1-st mode and anti-symmetric 1-st mode of vibration which were obtained from the results of our tests on seven arch dams are shown in Fig. 6 and Fig. 7. In Figure. 6, symmetric 1-st mode of vibration is expressed on the relation with the radious of the top arch and in Fig. 7, anti-symmetric 1-st mode of vibration frequency is expressed on the relation with the height of the cantilever placed in the position where a top arch shows the maximum displacement in this vibration mode. The marks in these figures are measured values in the full water level of the reservoir. These figures point out that the natural frequencies of symmetric 1-st mode of vibration is almost in inverse proportion to the radius of a top arch, and the natural frequency of anti-symmetric 1-st mode of vibration is almost in inverse proportion to the height of a cantilever.

Hydrodynamic water pressure during earthquake has much influence on vibration characteristics of a dam and acts on the dam as an external force. To make clear this influence, it is necessary to measure the hydrodynamic water pressure workings on up-stream face when a dam is vibrating and to known the change in vibration characteristics of dam corresponding to the change in the reservoir water level. Hydrodynamic water pressure, has been measured on the occasion of a vibration test on Fujiwara Gravity Dams, (maximum height 94.5m)(1). The measured value was well in accord with the calculated one by theoretical formula derived on the assumption that water is in-compressible fluid. Furthermore, vibration tests on Kamishiiba Dam, Sazanamigawa Dam and Sakamoto Dam (1)(3)(5) were conducted respectively when the water was at high level and at low level. The measured natural vibration frequencies at different water levels agreed with the theoretical values basing on the above-mentioned assumption. In this calculation, the energy method was applied, using the measured dynamic shapes, on the base of the shell theory. It may be said that the above mentioned treatment appoximately was proved by these results.

And the most part of the vibration strain potential energy of symmetric 1-st mode of vibration was caused by expansion and contraction of horizontal arch and on the other hand the most part of the vibration strain potential energy of anti-symmetric 1-st mode of vibration was caused by bending moment of horizontal arch and vertical cantilever. It is evident that this explains the relation showed in the above figure.

The ratio of the change of natural vibration frequency to the change of the reservoir water level depends on a vibration mode. Symmetric 1-st mode of vibration is affected more than anti-symmetric 1-st mode of vibration by water level.

Since a damping constant has a great deal of influence on the response of a dam during earthquake, it is important to measure this value of an actual dam. From the results of our field tests, damping constants of symmetric 1-st and anti-symmetric 1-st modes of vibration obtained from resonance curve using an ordinary method were about 2-5%. And it is better to think these values have no connection with the variation of the water level of a reservoir.

At Kamishiiba Arch Dam, Sazanamigawa Arch Dam, Hitotsuse Arch Dam and Kurobe Arch Dam, the earthquake observation apparatus were installed on the dam foundation grounds (both banks and river bed) and dam bodies and earthquake observations are being made from the dams completed. Generally speaking, the wave form of acceleration of ground motion is a shape as that a high frequency vibration superposes on the vibration less than several cycles/sec. In case of weak earthquake, the earthquake intensity I or II, high frequency vibration predominated. On the other hand, in case of strong earthquake low frequency vibration predominated. As to the response of a dam due to earthquakes, symmetric 1-st and anti-symmetric 1-st mode of vibration were predominantly excited. Sometimes higher order vibrations were predominantly excided due to weak earthquakes.

Aseismic design of an arch dam.

In view of the results so far achieved, it is not too much to say that vibration characteristics of arch dams have been almost made clear. In these, natural vibration frequencies of almost all arch dams are revealed to be within the limits of the frequency of ground motion. Consequently, it should be reated dynamically in seismic design of an arch dam. . A procedure determining earthquake effect for an dam is as follows. (1) Earthquake history of the dam site is investigated to select moderate strong earthquakes, generally using an existing design intensity (0.1g - 0.15g in Japan). (2) Strong motion earthquake response spectrum at the dam site is studied to determine average maximum magnification factor. Natural vibration frequencies and damping constants of the designed arch dam necessary for this purpose are easily obtained from the results mentioned in the previous chapter. (3) Determining load distribution from the vibration shape and the distributed mass of a dam, base shear effectiveness factor on each vibration is obtained. The vibration shape of arch of symmetric 1-st mode and anti-symmetric 1-st mode of vibration may be approximated respectively by cosine and sine functions. It is so much better that the vibration shape of a cantilever is approximated so as to be proportional to the height squared or cubed. According to the result of the calculation approximated so as to accord the vibration shape of a dam with the measured, base shear effectiveness factor was less than about 0.5 in any mode, in high water level. (4) Dynamic distributed load is adjusted to equalize total earthquake loads to effective base shear. (5) Earthquake loads to stress of a dam for the load distribution thus decided is calculated. This calculation is made with use of an electronic compute basing on Arch and Cantilever method.

Conclusions.

An arch dam is an elastic structure of which lower order natural vibration frequencies are within the frequency range of earthquake ground motion and can be excited to resonance due to earthquakes, thus developing dynamic loadings in the dam. In consequency, the consideration should be paid to a seismic design.

Using the results presented here, earthquakes effect on an arch dam can be more easily and correctly obtained.

However, the results presented here are the one by studies on small vibration of an arch dam due to weak earthquake. It is essential to study the vibration of an arch dam due to strong earthquakes and furthermore to develope a method of dyanamic earthquake proof-design.

Bibliography.

(1) Takahashi, T. "Results of vibration tests and earthquake observations on concrete dams and their considerations." Report No. 14, Question 29: Eighth Congress on Large Dams, Edinburgh, 1964.

(2) Takahashi, T. Tsutsumi, H. Masuko, Y. and Hashimoto, K. "Vibration Studies of Hitotsuse Arch Dam. "Report of Central Research Institute of Electric Power Industry, Tokyo, Dec. 23th, 1965 No.66019, 1966. April. (in Japanese)

(3) Takahashi, T. Tsutsumi, H. and Masuko, Y. "Vibration characteristics of Sazanamigawa arch dam. "Report of C.R.I.E.P.I. No. II-6007. 1960. June (in Japanese)

(4) Takahashi, T. Masuko, Y. "Vibration model test of Takane No.1 Arch Dam" Report of C.R.I.E.P.I. No. 66134. 1967. April March. (in Japanese)

(5) Takahashi, T. etc. "Vibration studies of Sakamoto, Futatsuno and Ikehara arch dam" 1966. Oct. Report of 6th meeting of Civil engineering Section, Central Research Institute of Electric Power Industry, Nov., 1963. (in Japanese)

(6) S. Okamoto and T. Takahashi "On Behaviours of an Arch Dam During Earthquakes." Proceeding of the 2-nd world Conference on Earthquake Engineering, 1960.

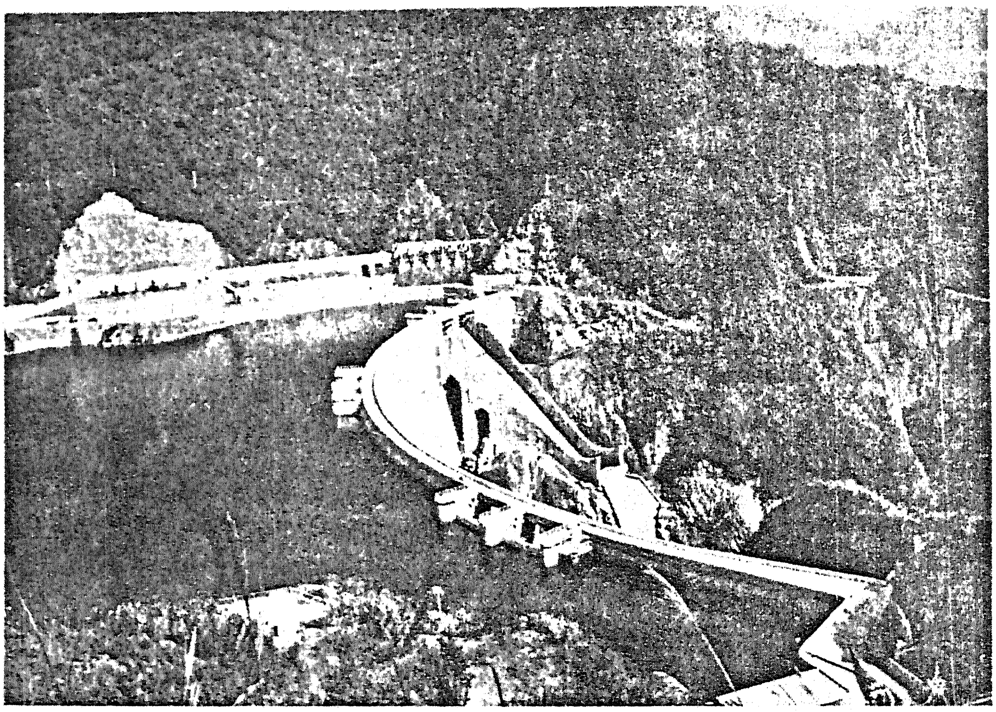

Fig. 1. Hitotsuse Arch Dam

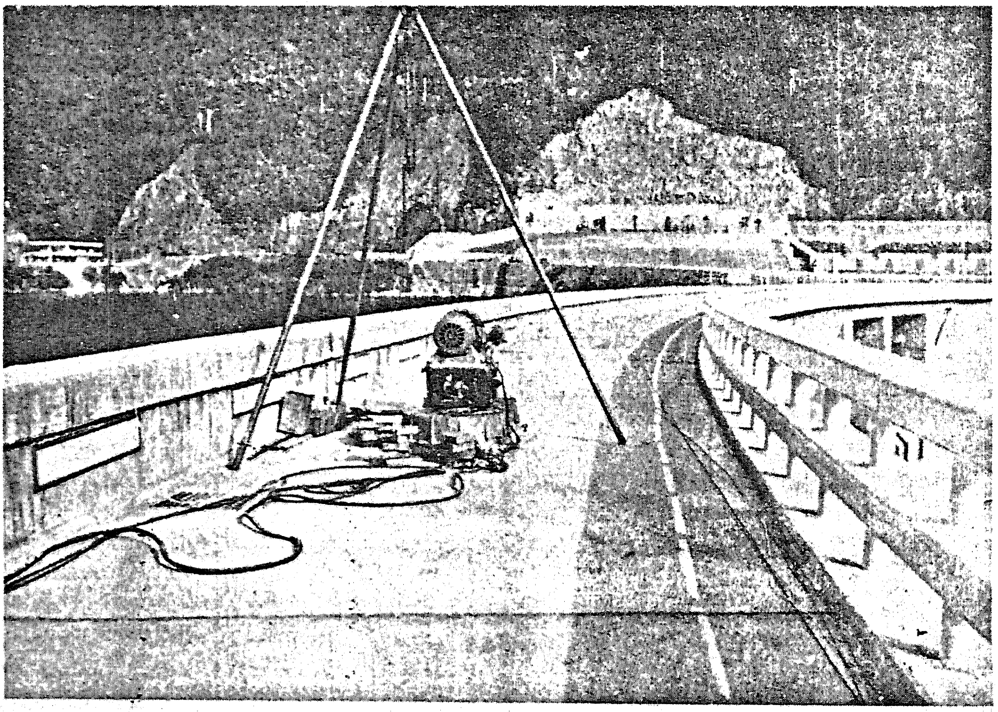

Fig. 2. Vibration machine in position

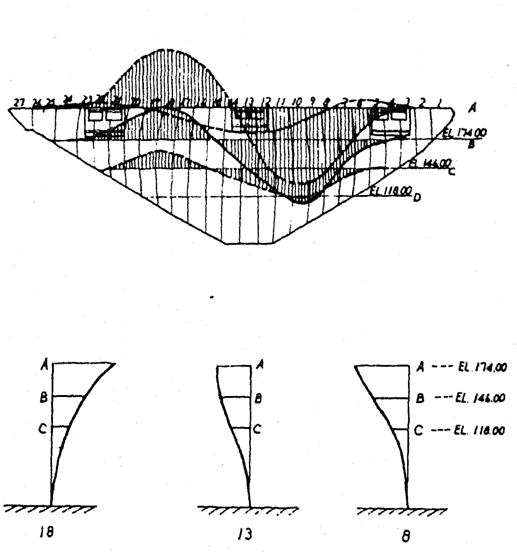

Fig.3. (a) Anti-symmetric 1-st mode of vibration
Exciting position   A 20
" direction   radial
Radial displacement
Frequency   134 c.p.m.

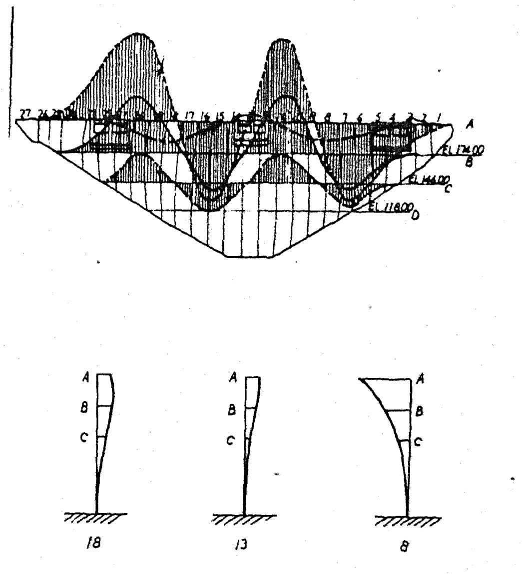

Fig.3. (b) Anti-symmetric 2-nd mode of vibration
Exciting position   A 20
" direction   radial
Radial displacement
Frequency   268 c.p.m.

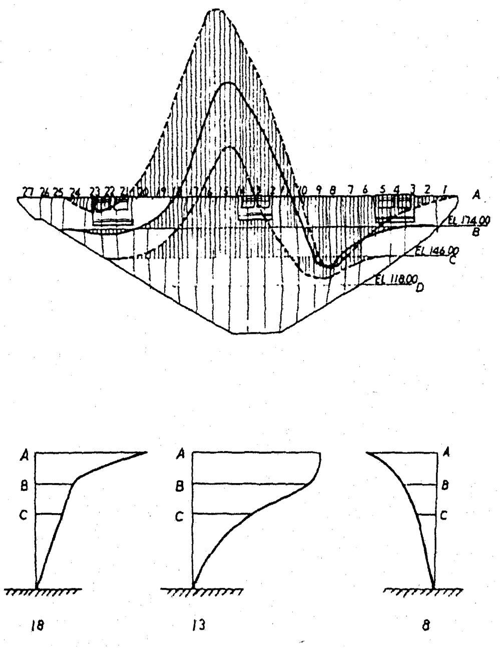

Fig.3. (c) Symmetric 1-st and Anti-symmetric 1-st mode of Vibration
Exciting position   A 14
" direction   radial
Radial displacement
Frequency   136 c.p.m.

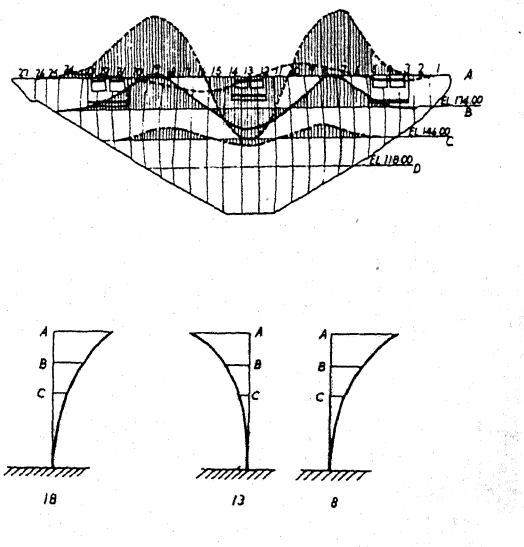

Fig.3. (d) Symmetric 2-nd mode of vibration
Exciting position   A 20
" direction   radial
Radial displacement
Frequency   204 c.p.m.

Fig. 3. Modes of Vibration (Hitotsuse Dam)

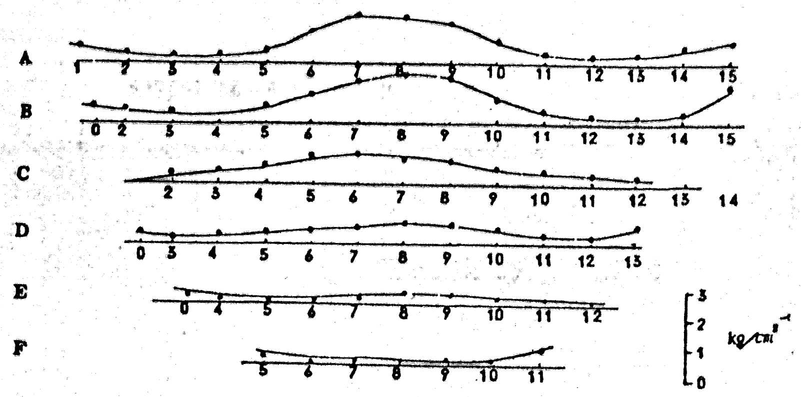

Fig.4. (a) Symmetric 1-st mode of vibration Up-Stream face

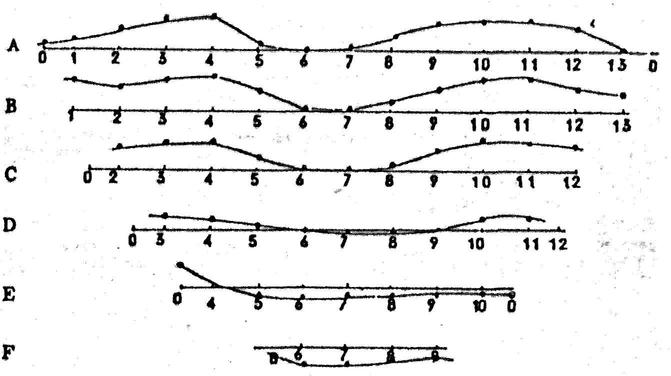

Fig.4. (b) Symmetric 1-st mode of vibration
Down-stream face

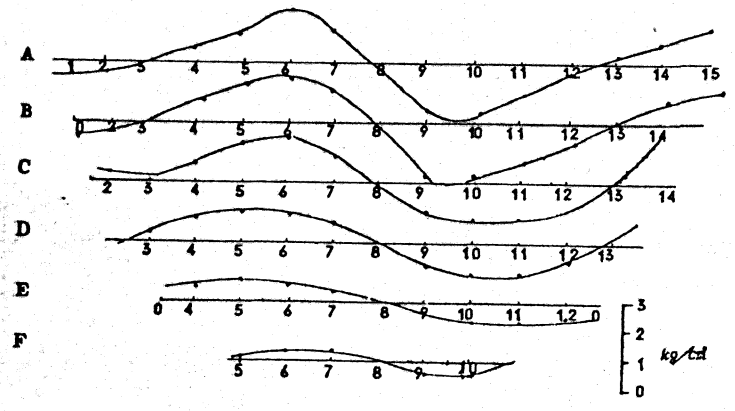

Fig.4. (c) Anti-symmetric 1-st mode of vibration
Up-stream face

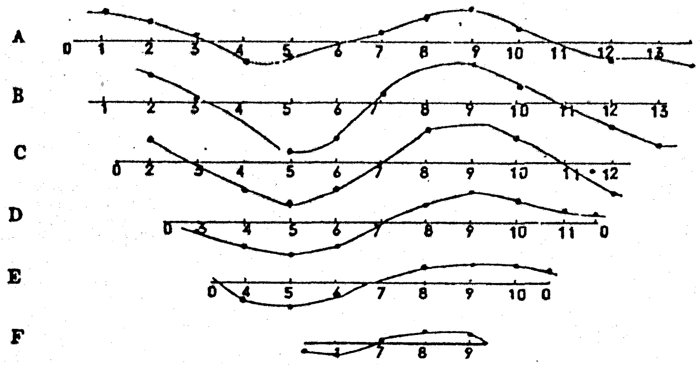

Fig.4. (d) Anti-symmetric 1-st mode of vibration
Down-stream face

Fig. 4. Horizontal arch stress pattern

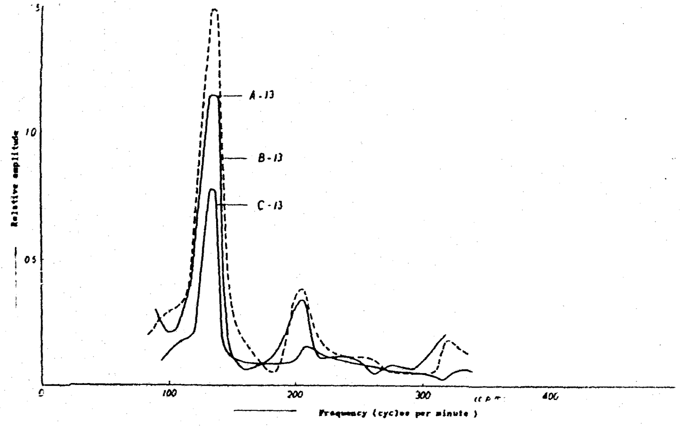

Fig. 5(a) Vibration Position A_{14}

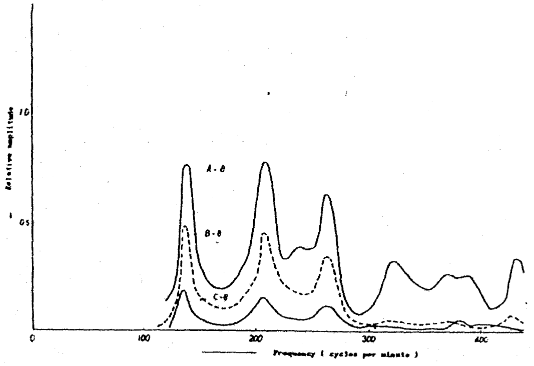

Fig. 5(b) Vibration Position A_{20}

Fig. 5. Resonance Curve

Vibration Direction radial direction
Vibration Displacement radial direction

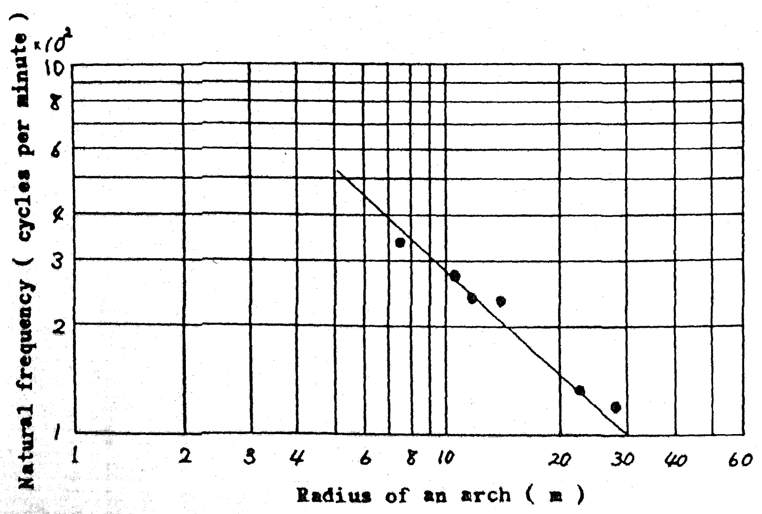

Fig. 6. Radius of an arch v.s. Natural frequency

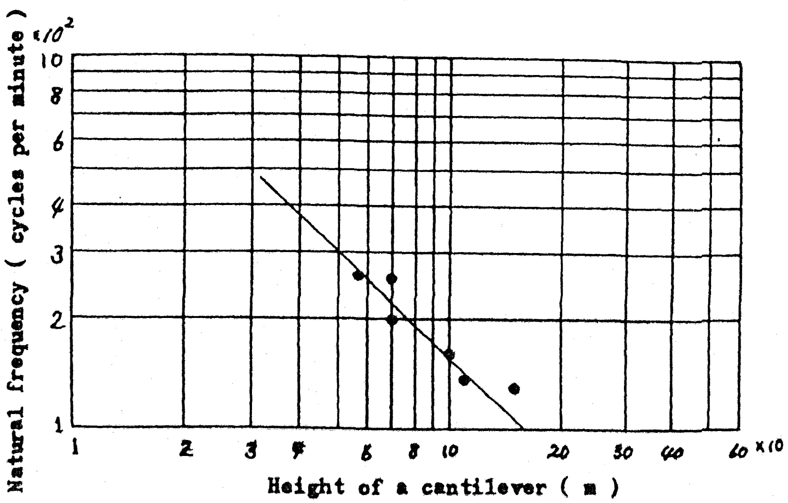

Fig. 7. Height of cantilever v.s. Natural frequency