ON A VIBRATION CHARACTERISTICS OF FILL DAMS IN EARTHQUAKES

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This is a fundamental study for a practical estimation of the distribution of seismic force toward the fill dams. Among many factors relating to dam vibration, an apparent viscosity has newly been presumed to compare with the shearing vibration theory and the observed vibration data of Makio dam and Togo dam. The increase of the apparent viscosity of the dam material due to a large acceleration is checked by the field observations, and this mechanism has been understood by means of considering the non-linear characteristics of prototype dam in vibration. But the assumptions presented in this paper should be checked in future investigations for stronger earthquakes to prototype dams.

A = amplitude
Amax = amplitude on dam crest
Ao = amplitude of the ground motion
Aco = horizontal acceleration on the ground
Ac = horizontal acceleration
Acmax = maximum acceleration on the top of the dam
a = experimental constant for an apparent viscosity of the material
B = length of the check line in dam
b = experimental constant for an apparent viscosity
Co = shearing wave velocity (m/s)
Cl = parameter for apparent viscosity of the dam materials ($m/s^{1/2}$)
D = displacement of neutral line in the dam
Do = displacement of the ground
Es = integral constant
g = acceleration of the gravity
H = dam height
Jo = zero ordered Bessel function
Jl = first ordered Bessel function
kl = horizontal seismic coefficient
m = dam slope
n = exponent
R = rigidity of the dam material
S = shearing force on the check line
Snon = shearing force owing to the non-linear effects
s = order of the terms using the Bessel function
T = period of vibration
t = time
V = Voigt type viscosity
Va = apparent viscosity
Vnon = viscosity owing to the non-linear effects
x = perpendicular coordinate to the dam axis
Y = parallel coordinate to the dam axis
z = depth from the dam crest
d = density of the dam material
λs = root of Jo(z)

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1. Preface

In the earthquake proof design of the fill dams, we usually estimate the maximum earthquake forces acting on the dam by vibration analysis of it. The displacement of dam in vibration is effectively controlled by viscosity, though this is not effective for natural period of dam. When there is a strong earthquake, a shrinkage and an expansion would occur in the dam, and this creates an elastic deformation and small plastic displacements of particles. The partial displacement of the soil particles in the dam will yield the partial transport of the momentum and this will yield an apparent shearing resistance along the check line shown in Fig.3. The observations of X- and Y components in prototype dams show that there are zig-zag motions in the horixontal plane as shown in Fig.7 and Fig.8. Then by these zig-zag motions, non-linear energy dissipation would be generated. To know vibration behaviours of the fill dams, two dimensional analysises had been performed by Prof. Hatakeyama 1), Prof. Medevdev 2), Prof. Clough 3) and Dr. Hatano 4) according to the elastic theory, and the other groupe, Dr. Matsumura 5), Prof. Hatanaka 6), Prof. Ambraseys 7), Prof. Seed 8) and Prof. Okamoto 9) had analyzed one dimensional shearing vibration of the dams.

But the observation and analysis of the vibrations of the prototype dams become most essential for this problem. For example, according to the results of observations of Makio dam and Togo dam, the apparent viscosity of the dam materials have been increased with seismic coefficient of the ground motions. The ratio of the maximum acceleration on the top of dam to it on the ground is larger in feeble earthquakes and smaller in strong earthquakes, and the shearing wave velocity is faster in the lower part of the dam and slower in the upper part of the dam comparing the vibration data of the two dams.

There are many unknown factors for the practical design of the fill dams, but the main problems seem to depend on how to estimate the proper values of the elastic rigidity, viscosity and strength of the prototype dam when there are strong vibrations. In this paper, the author wishes to present an estimation method for distributions of the seismic coefficient of the fill dams considering increase of the apparent viscosity. To verify that formula, observed vibration data of the Makio rock fill dam and the Togo earth fill dam were used.

2. An assumption for apparent viscosity of the dam materials

By analyzing mechanical behaviours of the shearing vibration of the prototype dams at the time of earthquakes, we can learn that there are Voigt type viscosity and the non-linear type viscosity especially there are large deformations. Though it is easy to get proper value of rigidity, density and Voigt type viscosity of material but it is difficult to know an apparent viscosity of prototype dam. The origin of the non-linear vibration would depend on the following two reasons.

(i) momentum flow by plastic deformations of material in prototype dam

(ii) characteristics of the soils at the time there are dynamic motions

When there is a small earthquake, the motion of the soil particles is perfectly elastic and periodic and it becomes linear visco-elastic vibration. The shearing resistance is yielded by the elastic rigidity and Voigt type viscosity. When there is a strong earthquake, the shearing resistance will depend on the elastic rigidity, Voigt type viscosity and the non-linear viscosity yielded by the partial momentum transport perpendicular to the check line in Fig.3 during unit time and by original characteristics of dam materials.

This phenomenon would vary according to the scale of the dam, strength and frequency of the earthquake and the kind of the dam materials.

This fact was seen in experiments in laboratory and in all vibrations of the prototype dams.
Then viscosity of the dam for the strong vibration should be obtained by a sum of Voigt type viscosity and non-linear viscosity as shown in Eqs.(1).

$$Va = V + Vnon \qquad (1)$$

Where Vnon is the non-linear viscosity, and the apparent shearing force Sa is obtained by the Eqs.(2) when the same consideration is given.

$$Sa = Sv + Snon \qquad (2)$$

Where Snon is the non-linear shearing force. The apparent viscosity is fundamentally very complicated. So the author wishes to give a relation of the Eqs.(3) for apparent viscosity considering vibration characteristics of the prototype dams at a time of the earthquakes.

$$Va = V + f(kl,T,Co) \qquad (3)$$

The shearing wave velocity Co which depends on the rigidity of the dam materials was regarded as nearly constant in all grade of the vibration, and period T and seismic coefficient kl on the ground will be given as a design condition. An example of form of function f(kl,T,Co) is assumed in the following paragraph as shown in Eqs.(8).

3. Fundamental differential equation of the shearing vibration of the fill dams

Considering shearing force along the check line of depth z from top of the dam, as shown in Fig.3, the total shearing force along QP is:

$$S = B\left\{R\frac{\partial D}{\partial z} + (V + f(kl,T,Co))\,\frac{\partial^2 D}{\partial z \partial t}\right\}.$$

Shearing force along RW is:

$$S + \Delta S = B\left\{R\frac{\partial D}{\partial z} + (V + f(kl,T,Co))\,\frac{\partial^2 D}{\partial t \partial z}\right\} + \frac{\partial}{\partial z}\left\{BZ\frac{\partial D}{\partial z} + B(V + f(kl,T,Co))\,\frac{\partial^2 D}{\partial z \partial t}\right\}dz.$$

The increment of the shearing force for the small depth dz is:

$$\Delta S = \frac{\partial}{\partial z}\left\{ mzR\frac{\partial D}{\partial z} + mRz\frac{\partial^2 D}{\partial z^2} + mz(V + f(kl,T,Co))\,\frac{\partial^2 D}{\partial z \partial t}\right\} dz$$

where B = mz

Considering the balance between inertia force and total resistance shearing force on the check line, the fundamental differential equation for the non-linear shearing vibration at a time there is a strong vibration can be obtained from Eqs.(4).

$$dmz\frac{\partial^2 D}{\partial t^2} = mR\frac{\partial D}{\partial z} + mRz\frac{\partial^2 D}{\partial z^2} + mz\{V + f(kl,T,Co)\}\frac{\partial^2 D}{\partial z^2 \partial t} + \{mV + mf(kl,T,Co)\}\frac{\partial^2 D}{\partial z \partial t} \tag{4}$$

As the theoretical form of f(kl,T,Co) is unknown, the author wishes to use a proper value of f(kl,T,Co) which matches with the design conditions.

Periodic vibration is considered in the following studies. Generally, the seismic coefficient for the ground motion is obtained as a design condition, and it is shown in Eqs.(5).

$$kl = \left(\frac{2\pi}{T}\right)^2 Ao \frac{1}{g} \tag{5}$$

Considering the facts which are presumed from the vibration observation of the two dams, as shown in Fig. 9,12 and 13, the assumption is used that the parameter of apparent viscosity Cl is proportioned to the shearing wave velocity Co and Co/Cl also has close relation with the horizontal seismic coefficient kl on the ground. Then equation (6) is obtained as a experimental formula.

$$Cl/Co = a + b(kl - klcr)^n \tag{6}$$

or

$$Cl = Co\{a + b(kl - klcr)^n\} \tag{7}$$

where T = 0.38∿0.4 seconds and n = exponent.

Where klcr is critical value of the horizontal seismic coefficient for Voigt type viscosity. Using the Eqs.(13) instead of Co and Eqs.(14) instead of Cl, the Eqs.(8) is obtained for apparent viscosity.

$$Va = R\{a + b(kl - klcr)^n\}^2 \tag{8}$$

The experimental constant a and b would be determined by the comparison between Eqs.(8) and observed vibration data of Makio dam and Togo dam. As the apparent viscosity is assumed as a function of the depth Z, the averaged apparent viscosity Vam through the dam height is:

$$Vam = \frac{1}{H}\int_0^H Va\, dz$$

When vibration is small, the apparent viscosity would coincide with the Voigt type viscosity.

$$\begin{aligned} Vam &= V \\ &= a^2 R \end{aligned} \tag{9}$$

When vibration is strong, Voigt type viscosity would become negligible and small to compare with the non-linear viscosity. Then apparent viscosity is:

$$Vam = Rb^2(kl - klcr)^{2n} \tag{10}$$

Then the equation of the shearing vibration become as Eqs.(11) using averaged apparent viscosity Vam.

$$\frac{\partial^2 D}{\partial t^2} = \frac{R}{d}\left(\frac{\partial^2 D}{\partial z} + \frac{1}{z}\frac{\partial D}{\partial z}\right) + \frac{Vam}{d}\left(\frac{\partial^3 D}{\partial z^2 \partial t} + \frac{1}{z}\frac{\partial^2 D}{\partial z \partial t}\right) \tag{11}$$

4. Harmonic vibration analysis of the fill dam

The displacement at the arbitrary height of the dam can be solved by the analysis of the Eqs.(11) under given initial conditions and given boundary conditions. Owing to get convenient equation for deducing an apparent viscosity of prototype dam, harmonic response of vibration of the dam body against the ground motion is presented here. The boundary conditions for the harmonic vibration are:

$$\begin{aligned} &z = o, \quad \frac{\partial D}{\partial z} = o \qquad &&\text{(on the top of the dam)} \\ &z = H, \quad D = Ao \cos\frac{2\pi}{T}t \qquad &&\text{(on the ground)} \end{aligned} \tag{12}$$

Where

$$P = \frac{2\pi}{T}$$

The shearing wave velocity is:

$$Co = (R/d)^{1/2} \qquad \text{m/s} \tag{13}$$

The parameter for the apparent viscosity is:

$$Cl = (Vam/d)^{1/2} \qquad \text{m/s}^{1/2} \tag{14}$$

To solve the harmonic shearing vibration, the Eigen function

$$D = \sum Es\ Jo\left(\frac{\lambda s}{H}z\right) \tag{15}$$

are used.
Then the displacement of neutral line of the fill dam is:

$$D = Ao\left[\cos\frac{2}{T}t + \sum_{s=1}^{\infty} \frac{\dfrac{2P^2}{Co^2}}{\sqrt{\left\{\left(\dfrac{P}{Co}\right)^2 - \left(\dfrac{\lambda s}{H}\right)^2\right\}^2 + \left(\dfrac{\lambda s}{H}\right)^4 P^2 \left(\dfrac{Cl}{Co}\right)^4}} \frac{Jo\left(\dfrac{\lambda s}{H}z\right)}{\lambda s J1(\lambda s)} \cos\left\{\frac{2\pi}{T}t - \tan^{-1}\frac{\left(\dfrac{\lambda s}{H}\right)^2 P \left(\dfrac{Cl}{Co}\right)^2}{\left(\dfrac{P}{Co}\right)^2 - \left(\dfrac{\lambda s}{H}\right)^2}\right\}\right] \tag{16}$$

The distribution of the horizontal acceleration Ac is:

$$Ac = -\left(\frac{2\pi}{T}\right)^2 D. \tag{17}$$

The horizontal seismic coefficient is:

$$kl = -\frac{1}{g}\left(\frac{2\pi}{T}\right)^2 D. \tag{18}$$

The ratio of displacement of top of the dam against the displacement of the ground is:

$$\frac{D}{Do} = 1 + \sum_{s=1}^{\infty} \frac{\dfrac{2P^2}{Co^2}}{\sqrt{{(\frac{P}{Co})^2 - (\frac{\lambda s}{H})^2}^{2} + (\frac{\lambda s}{H})^4 P^2 (\frac{Cl}{Co})^4}} \; \frac{Jo(\frac{\lambda s}{H}z)}{\lambda s J1(\lambda s)}$$

$$\frac{\cos\left(\frac{2\pi}{T}t - \tan^{-1} \dfrac{(\frac{\lambda s}{H})^2 P\ (Cl/Co)^2}{(P/Co)^2 - (\frac{\lambda s}{H})^2}\right)}{\cos \frac{2\pi}{T}t} \qquad (19)$$

$$= \frac{Ac}{Aco} \qquad (20)$$

The ratio D/Do and Ac/Aco become a function of depth z, time t and other many factors. The maximum value of D/Do depends on the value of Cl/Co, $\lambda s/H$ and P/Co. The relation between the max $(D/Do)_{z=o}$ and (Cl/Co) is shown in Fig.9 which is calculated by Eqs.(19) by adapting the mechanical property deduced from Makio dam and Togo dam.

5. Vibration characteristics and proper apparent viscosity of Makio rock fill dam and Togo earth fill dam

Observing the vibration characteristics of Makio rock fill dam and Togo earth fill dam, the maximum acceleration on top of the dam and on the ground is obtained as shown in Tables 2 and 4, and the following interesting items are found from these data. The positions of the pick-up part of the measuring apparatus are shown in Figs.1 and 2 and in Tables 1 and 2. During the period of observation, the maximum acceleration on the ground were 33 gals for Makio dam and 52 gals for Togo dam.

(i) Structures used at Makio and Togo dams

The cross sections of the two dams are shown in Figs.1 and 2. The Makio dam was made as the rock fill with clay center core on the rock foundation as shown in Fig.1, while Togo dam was made as the earth fill with inclined core on the alluvial soil foundation as shown in Fig.2. The height of the Makio dam is 105 meters from rock foundation and 85 meters from the ground surface. The height of Togo dam is 31 meters from the ground surface. Fig.4 shows the grading of material of Togo dam.

(ii) Design seismic coefficient of Makic and Togo dams

The designed seismic coefficient for Makio dam was 0.15 in the horizontal component and the minimum stability coefficient was 1.35 in the critical condition according to calculation by using slip circle method. The designed seismic coefficient for Togo dam was 0.2 in the horizontal component and the minimum stability coefficient was 1.2 in the critical conditions by using slip circle method. These designed seismic coefficients were determined according to the standard for the large dam design in Japan and the vertical distribution of the seismic coefficient was regarded as uniform throughout the dam height. The earthquakes which had the scale of acceleration so strong as the designed seismic coefficient have not been experienced yet. Figs.5 and 6 are examples of the recorded papers on vibrations of Makio and Togo dam.

(iii) Observed hysteresis of the resultant accelerations in the dams over the horizontal planes during the quaking motion.

The displayed paths of vector of the resultant acceleration during one cycle of Makio dam is shown in Fig.7 and those of resultant accelerations of Togo dam during one cycle is as shown in Fig.8. In earthquakes, the dam did not move along a simple straight line which is perpendicular to the dam axis, but the motion was very complicated having three dimensional characteristics as explained in Figs.7 and 8. By these observed facts, we came to find that all theoretical results of the vibration analysis are surely simplified solutions. The zig-zag paths of particles in the dam has drawn complicated loops and it becomes clear that there exists much energy dissipation due to those non-linear effects.

(iv) Vertical distribution of the acceleration

Generally, the vertical distribution of the seismic coefficient through the dam is not uniformed. The maximum acceleration was seen on the top of the dam and it is much greater than the values on the ground. According to field observations, ratios of the maximum accelerations of the crest of dam to the maximum acceleration of the ground increased in small earthquakes and decreased in strong earthquakes. These characteristics show that we must treat the vibration problems considering possibility of increase of apparent viscosity. The same tendency for acceleration distribution was reported by Prof. Okamoto and others for the Sannokai dam. The important fact is that the non-linear effects will produce the earthquake proofness of the fill dam owing to decrease the amplitude in the big earthquakes. This is very interesting fact for economic design of the high dams. Table 3 shows the observed data of the horizontal acceleration of Makio dam. The ratio of crest acceleration to it of the ground was 2.3 in strong earthquake with 33 gals on the ground and 4.0 in feeble earthquake with 1.5 gals on the ground. Table 4 shows the relation of the horizontal accelerations for the Togo dam. The ratio of the crest acceleration to the ground acceleration was 1.6 in the large earthquake having 44 gals on the ground and 2.8 in the feeble earthquake having 10 gals on the ground. Fig.10 shows the relation between that ratios and ground seismic coefficient of Makio dam and Fig.11 shows a relation between that ratio and ground seismic coefficient of Togo dam.

(v) Shear wave velocity and rigidity

By comparing time lags among wave in front of the vibration curves on recorded papers, the shearing wave velocity was estimated as follows:

(a) Makio dam

Co = 350 m/s (near the top of the dam)
Co = 1000 m/s (near the ground)
Co(mean) = 680 m/s
then $R = dCo^2 = 7.85x10^5$ ton/m^2

(b) Togo dam

Co = 125 m/s (near top of the dam)
Co = 250 m/s (near the ground)
Co(mean) = 187 m/s
then $R = 6.0x10^4$ ton/m^2

The data show that the shearing wave velocity is larger near the base of the dam and smaller near the top of the dam and the wave velocity is a function of the dam height.

(vi) Observed vibration periods

The average observed vibration period which is measured from recorded vibration curves is as follows:

(a) Makio dam

T = 0.38 seconds

(b) Togo dam

T = 0.4 seconds

The average period on all observations were nearly constant at Makio dam, but at Togo dam, a few examples in all observed earthquakes were scattered among 0.3 seconds to 1.0 seconds.

(vii) Apparent viscosity of Makio and Togo dams

Though there are many unknown factors for earthquake proof design of the fill dam, the important item would estimate the behaviours of the apparent viscosity of the dam in strong earthquakes. Rigidity of two dams was determined from the average values of measured shearing wave velocity. The period of vibration and the amplitude of the ground vibrations are gotton from the observed data. The shearing wave velocity of Makio dam was 680 m/s as an average value and for Togo dam was 187 m/s. Voigt type viscosity is assumed from the field observation at the feeble vibrations having 5 gals on the ground. The behaviour of apparent viscosity of the fill dam in every earthquakes is decided from the systematical analysis of observed ratio of the acceleration at the top of the dam and the ground by using equation (19). Fig.12 shows the relation between deduced C1/Co and seismic coefficient on the ground of Makio dam, then C1 which is comparable to Voigt type viscosity is assumed as 102 m/s$^{1/2}$. Fig.13 shows the relation between deduced C1/Co and seismic coefficient of the ground of Togo dam, and C1 comparable to Voigt type viscosity is assumed as 32 m/s$^{1/2}$. In Fig.12 and Fig.13, the author selected the critical seismic coefficient for Voigt viscosity as k1cr = 0.005. Then the apparent viscosity will be presented by an experimental equations of Eqs.(22) and (23).

For Togo dam $Cl/Co = 0.17 + 0.318(k - 0.005)^{0.6}$ (20)

For Makio dam $Cl/C\dot{o} = 0.15 + 0.105(k - 0.005)^{0.7}$(21)

For Makio dam:

$$Va = 0.60(0.17 + 0.318(k - 0.005)^{0.6})^2 \times 10^5 \qquad (22)$$

For Togo dam:

$$Va = 0.785(0.15 + 0.105(k - 0.005)^{0.7})^2 \times 10^6 \qquad (23)$$

where $T = 0.38 \sim 0.4$ second

But we had never experienced earthquakes larger than 52 gals for the ground motion, then the extrapolation by Eqs.(22) and (23) for the larger earthquake will inevitably contain small errors.

In future investigations, when we catch larger earthquakes, the author want to reform the two equation, Eqs.(22) and (23), for more general form.

6. Conclusion

To presume the proper distribution of the seismic force on the fill dams, the observed vibration data of Makio rock fill dam and Togo earth fill dam were analyzed as a harmonic shearing vibration, and an experimental equation for the behaviours of the apparent viscosity of the prototype dam was presented as an approximate equation. This relation would be important for the earthquake proof design of the fill dams against the larger earthquakes.

7. Bibliographys

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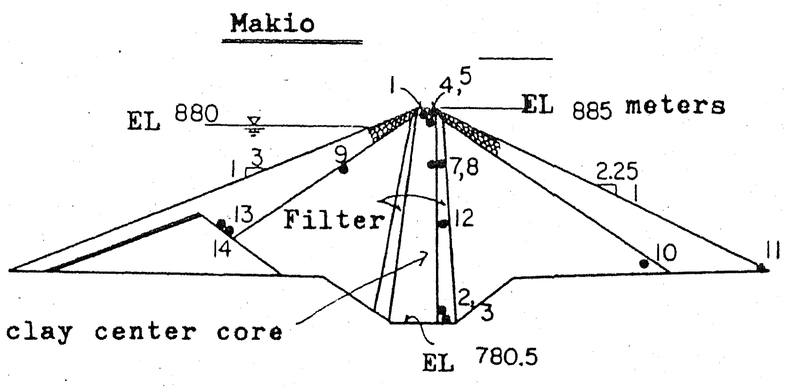

Fig.1 Cross section of Makio rock fill dam and locations of pick-ups

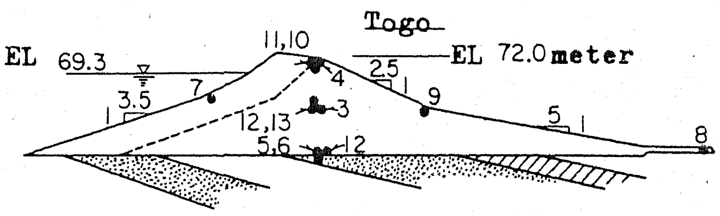

Fig.2 Cross section of Togo earth fill dam and location of pick-ups

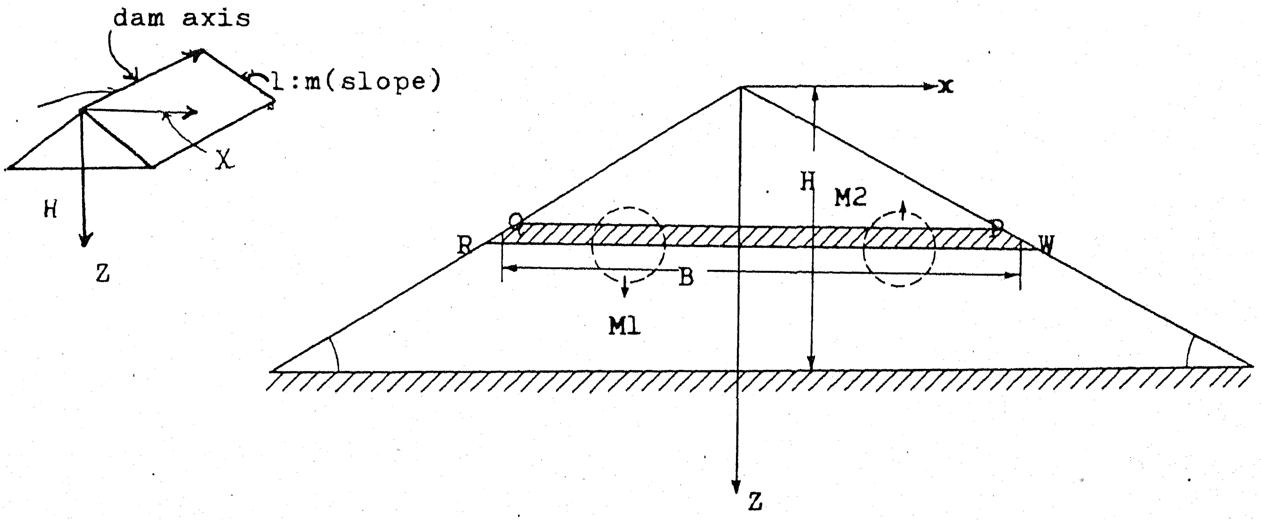

Fig.3 Cross section of fill dam model

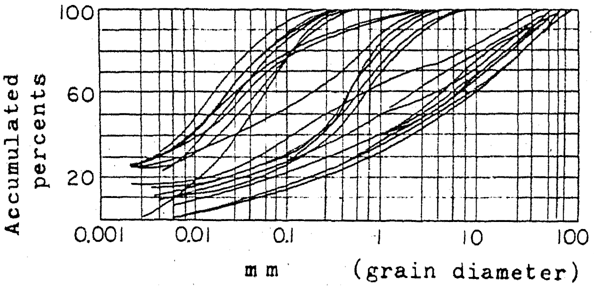

Fig.4 Accumulated curves of the grain size of the dam materials (Togo dam)

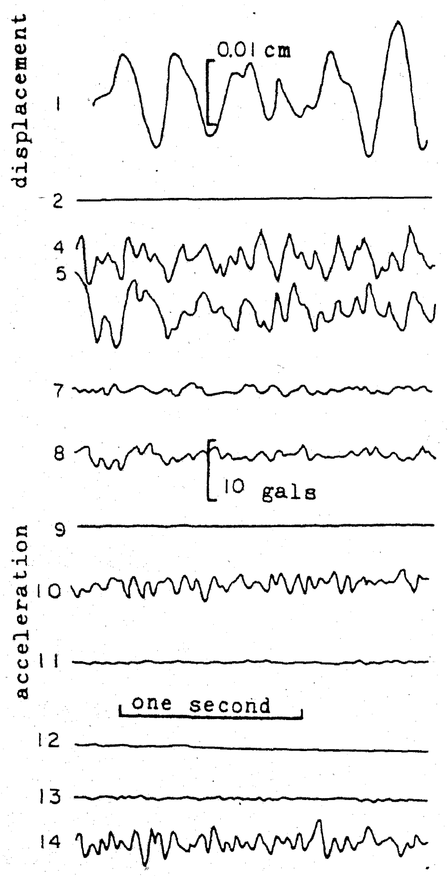

Fig.5 a record paper of displacement and acceleration of Makio rock fill dam

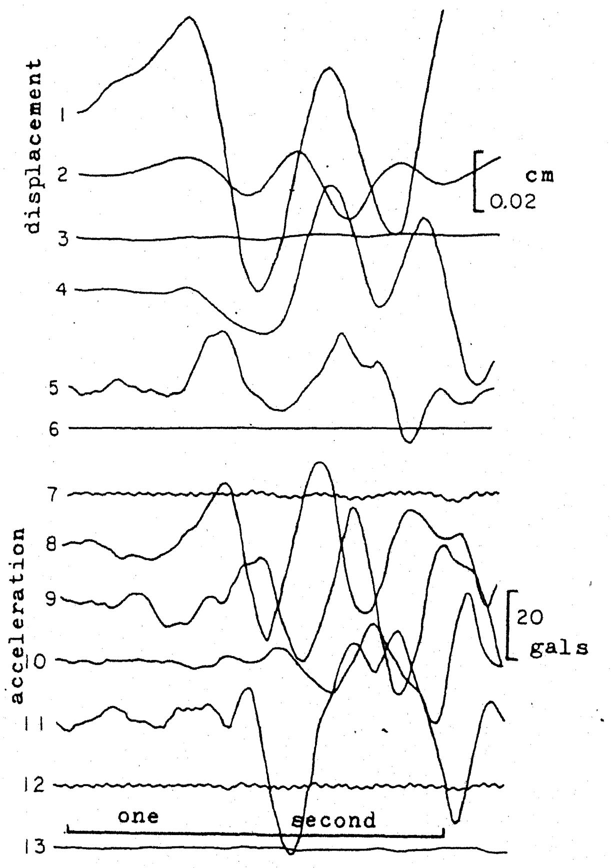

Fig.6 a record paper of displacement and acceleration of Togo earth fill dam

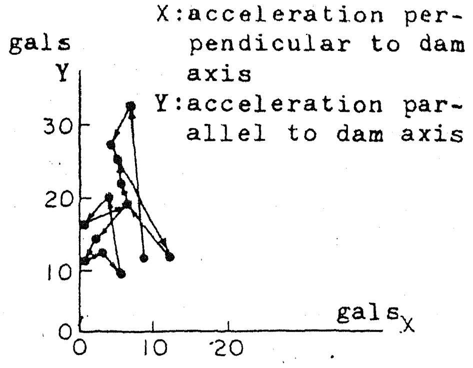

Fig.7 An example of variation of resultant vector of acceleration during one cycle of motion of Makio rock fill dam (crest)

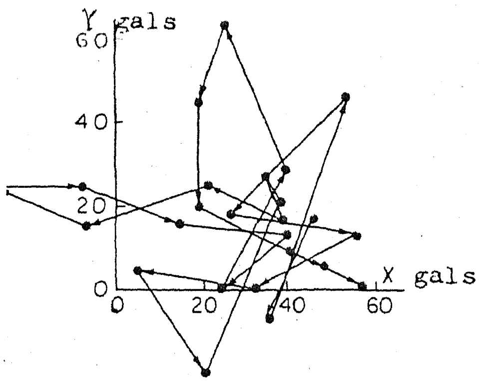

Fig.8 An example of variation of resultant vector of acceleration during one cycle of motion of Togo earth dam (crest)

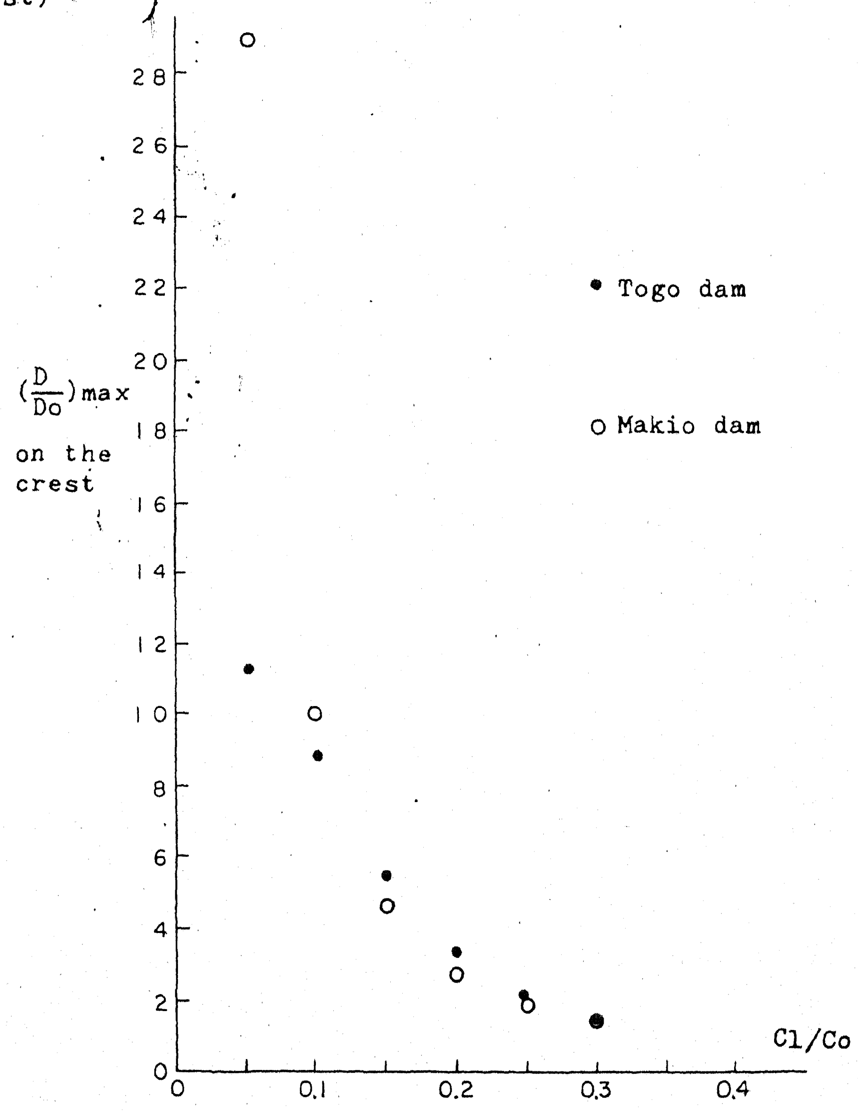

Fig.9 Relation between max.(D/Do) on the crest and (Cl/Co) which calculated by Eqs.(19)

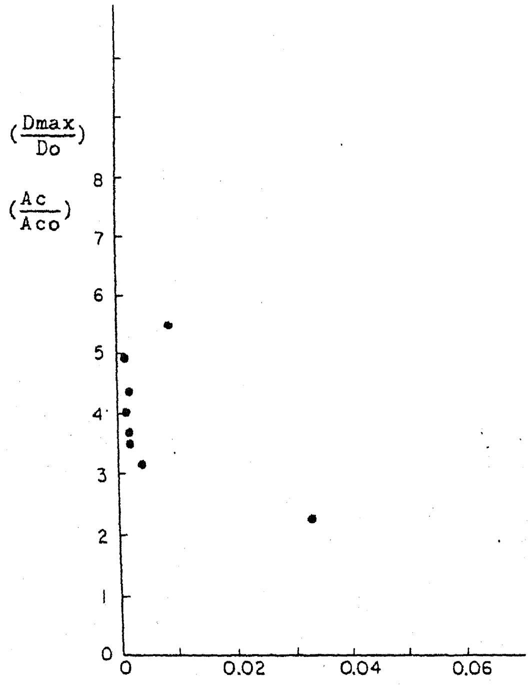

Fig.10 Relation between max.(D/Do) on the crest and seismic coefficient of dam base (observed data of Makio dam)

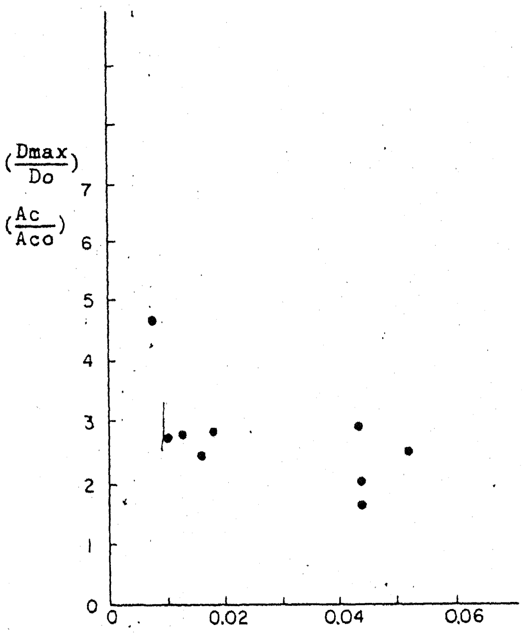

Fig.11 Relation between max.(D/Do) on the crest and seismic coefficient of dam base (observed data of Togo dam)

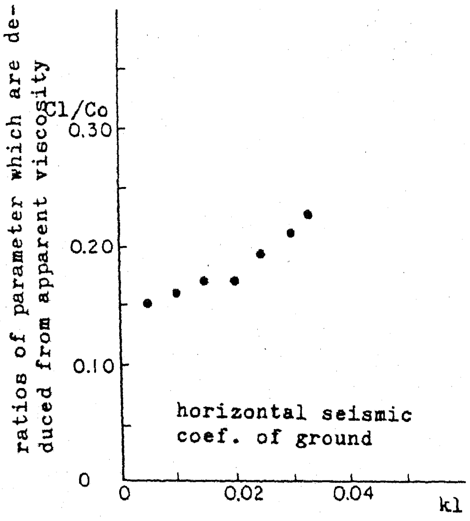

Fig.12 The optimum parameter of apparent viscosity (Cl/Co) and seismic coefficient on the base of Makio dam

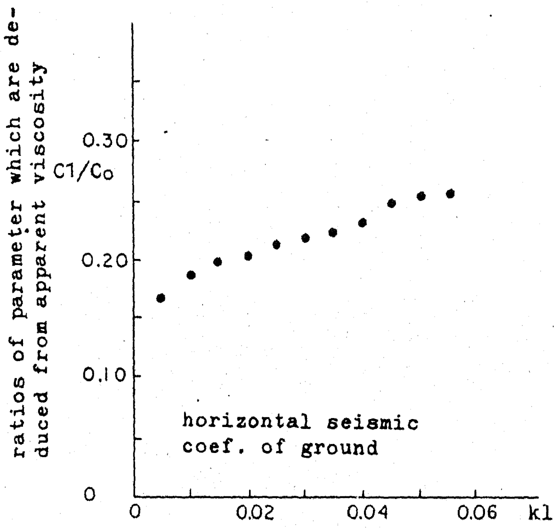

Fig.13 The optimum parameter of apparent viscosity (Cl/Co) and seismic coefficient on the base of Togo earth dam

Table 1 Observation Apparatus for Makio Rock Fill Dam

NO	Elevation meters	Measurement	Directions
1	880.0	displacement	para.
2	795.0	displacement	para.
3	880.0	displacement	perp.
4	880.0	acceleration	para.
5	880.0	"	perp.
6	850.0	"	perp.
7	850.0	"	para.
8	850.0	"	perp.
9	810.0	"	perp.
10	810.0	"	para.
11	830.0	"	perp.
12	830.0	"	perp.
13	830.0	"	para.
14	800.0	"	perp.

Table 2 Observation Apparatus for Togo Earth Fill Dam

NO	Elevation meters	Measurement	Directions
1	45.0	displacement	perp.
2	45.4	"	para.
3	60.0	"	perp.
4	72.0	"	para.
5	45.4	acceleration	para.
6	45.4	"	perp.
7	60.0	"	perp.
8	45.4	"	perp.
9	60.0	"	perp.
10	72.0	"	para.
11	72.0	"	perp.
12	60.0	"	perp.
13	60.0	"	para.

perp. = perpendicular to dam axis
para. = parallel to dam axis

Table 3 Recorded accelerations of Makio Rock Fill Dam

Date	Accelerations		Ratios
	crest	ground	
1962 10 11 day	75.0	33.0	2.3
62 11 12	13.0	4.0	3.3
63 11 15	6.0	1.5	4.0
63 2 4	6.5	2.0	3.8
64 2 4	8.5	2.4	3.5
64 5 7	7.5	1.5	3.3
65 4 20	50	9.0	5.5

Table 4 Recorded accelerations of Togo Earth Dam

Date	Accelerations		Ratios
	crest	ground	
1963 4 21 day	88.0	44.0	2.0
63 6 3	28.0	10	2.8
63 7 12	70.0	44.0	1.6
63 7 24	40.0	16.0	2.5
63 9 4	132.0	44.0	3.0
64 1 7	34.0	12.0	2.8
64 9 17	132.0	52.0	2.5
65 4 20	53.0	18.0	2.9

$$\bullet\ \text{Ratio} = \frac{\text{maximum acceleration at the top of dam}}{\text{maximum acceleration on the base of dam}}$$