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CHARACTERISTICS OF ELEMENTARY DYNAMIC BEHAVIOR FOR THREE DIMENSIONAL SEISMIC RESPONSE OF A FILL DAM

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ABSTRACT

The topographical features of dam sites are in general, so complex that two dimensional finite element models might not be applicable in the aseismic designs of these fill dams because of limited knowledge of how the seismic responses of dams are affected by them. Three dimensional vibration modes are not even well known. In this paper, elementary dynamic response behaviors for fill dams obtained from vibration tests on a three dimensional elastic model are discussed. These tests are simulated with a computer code for three dimensional seismic response analysis developed by the authors in order to both confirm the validity of the code and distinguish the fundamental modes. Finally, regarding the topographical features influencing the seismic responses of fill dams, the valley wall slopes in abutments and the width of a riverbed are taken into consideration in order to examine how every eigenfrequency up to the 4th order should fluctuate according to the change of each factor with a number of numerical analyses using the code. The results are presented in general diagrams representing the relationships between dimensionless eigenfrequencies and dimensionless topographical features.

Key words: aseismic design of fill dam, dimensionless diagrams for eigenfrequencies and topographical factors, model vibration test, three dimensional seismic response analysis, three dimensional vibration mode, topographical feature **(IGC:** E8/E13/E14**)**

INTRODUCTION

Two dimensional seismic response analyses are usually applied to confirm the earthquake resisting capability of fill dams, because they can be expected to obtain more accurate calculation results than a three dimensional one. Elements of finer sizes are available in a two dimensional finite element model of a structure which enhances the computer capability and economizes the calculation.

The topographic features of dam sites, however, are generally so complex that a two dimensional numerical model might not be able to correctly simulate the seismic response movements of a fill dams. Therefore, it is important to investigate the influence of topographic conditions at a dam site on the seismic response of the dam. There have been very few to date, papers in the technical literature concerned with these problems. The earliest papers dealing with these problems are those reported by Hatanaka (1955) and Ambraseys (1966). They studied the dynamic response of earth dams in rectangular canyons based on the assumption that the oscillations in stream direction can be treated in simple shear and also showed the effect of crest length to height ratios on these natural frequencies. With respect to more general dynamic response of earth dams, Makdisi (1976) performed seismic response analyses on both 2-*D* and 3-*D* finite element models of dams in triangular canyons with linear material properties and presented comparisons between the computed natural frequencies for different crest length to height ratios. Due to the coarse degree of discretization of the finite element models, however, no significant conclusions could be drawn. Majia and Seed (1983) also studied the difference in dynamic response of earth dams according to the difference in canyon geometry with numerical analyses. They used two dams located in triangular canyons both with moderate valley wall slope and with steep canyon wall in the studies. The former corresponded to Oroville Dam in California, U.S.A. and the latter to a hypothetical dam with the same main cross section as Oroville. Two dimensional analyses were also performed on the same main cross section model. The major conclusions drawn from the study were the following: 1) Comparison of the plane strain, τ_{xy2D}, stresses with the corresponding, τ_{xy3D}, stresses obtained from 3-*D* analysis of Oroville Dam, which was the typical dam in the canyon with moderate valley wall slope, was shown by

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computing the ratio τ_{xy2D}/τ_{xy3D}. The distribution of the ratio throughout the maximum cross section was quite erratic and exhibited values lower than 1.0, and yet in the upper section the stresses from plane strain analysis were within 20% of those computed from 3-D analysis of the dam, while for the dam in a steeper canyon with a crest length to height ratio of 2, the above stress ratio increased from 0.5 near the crest, to a value of about 1.0 at midheight and to a value of 4.0 near the base. 2) Accelerations were less accurate than stresses. For the dam in steeper canyon than that of Oroville Dam, plane strain analyses seemed unable to simulate correctly the behavior of the embankment. 3) The relationship between the ratio of the fundamental natural frequency computed from 3-D analysis to the one from 2-D and the crest length to height ratio of dam in the rectangular and triangular canyons was also computed and the stiffening effect of canyon geometry was clarified for the first time although it was only for the fundamental natural frequency.

For the dams in steeper canyons it may be necessary to perform 3-D analysis to obtain satisfactory results for design purposes as mentioned above, however, related computer capability and economy in calculation, 3-D analysis is not always available for design. In such cases, the information on natural frequencies and the modes dependent on canyon geometry will be a great help for carrying out aseismic embankment design. Above all, natural frequencies up to at least the 4th order will be desirable. From the earthquake observations on several embankment dams, it has been determined that there are three vibration modes of lower orders from the 1st to 3rd for which responses predominate in the same phase in some of stream, vertical and longitudinal directions, however, further higher order modes are not clearly found due to their smaller intensities.

Not many studies have been performed on three dimensional movements of embankment dams such as the seismic response of a rock fill dam against travelling seismic wave (Komada et al., 1977), the seismic stability of earth dams (Ohne et al., 1983; Wang et al., 1987) and so on. There is however few paper discussing the elementary dynamic movements of embankment dams including natural frequencies and these modes include higher order ones in various types of canyon geometry except for some which discuss the fundamental period only (Majia et al., 1983; Oner et al., 1984).

In this paper, elemental dynamic response behavior of a fill dam obtained from vibration tests on an elastic model is discussed. These tests are simulated with the computer program for three dimensional seismic response analysis developed by the authors in order to both confirm the validity of the code and distinguish the fundamental response modes. Finally, regarding the topographic factors influencing the seismic response of fill dams, the angle of inclination of a dam abutment and the width of a riverbed are adopted and the change of every eigenfrequency up to the 4th order according to the change of each feature is confirmed with a number of numerical analyses using the above mentioned computer program. These results are presented in general diagrams representing the relationships between dimensionless eigenfrequencies and topographic features.

VIBRATION TESTS ON A THREE DIMENSIONAL MODEL OF A FILL DAM

Method of Tests

Longitudinal and transverse cross sections of the model are shown in Fig. 1. The foundation of the model dam was made from plates of acrylic resin. The model dam body was made of silicone rubber which was in a liquid state when mixing silicone oil and a solidification agent and was set in a mold attached temporarily to the foundation after placing the liquid. The external appearance of the complete model is shown in Photo 1. Mechanical properties of the dam body such as shear modulus G, Young's modulus E and damping constant h were exam-

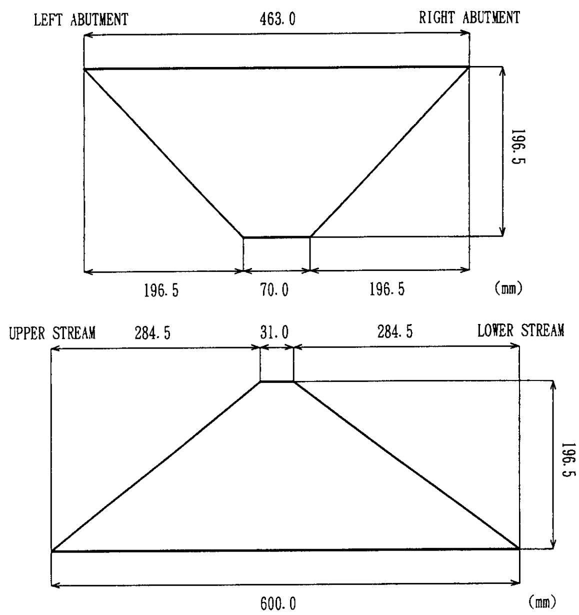

Fig. 1. Vertical cross sectional views at center on dam crest

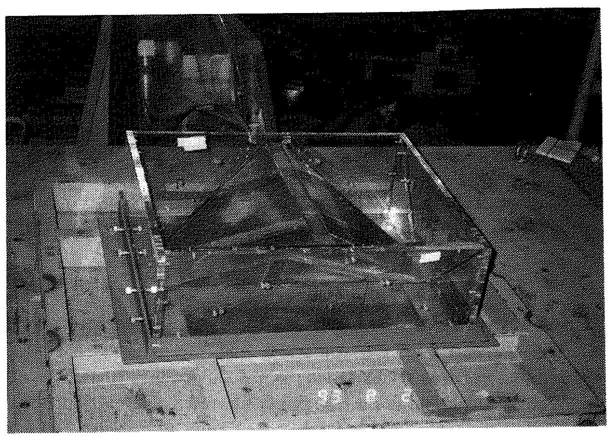

Photo. 1. Appearance of complete model

Table 1. Mechanical properties of model

G (Pa)	ν	h (%)	ρ (kg/m^3)
3.2634×10^4	0.345	3.94	982

ined by means of the vibration tests performed on a rectangular column specimen 12(cm^2) in cross sectional area and 12(cm) in length which was made of the silicone oil in liquid state selected from the same batch as the one for the dam body. Young's modulus E was estimated from the natural frequencies of a cantilever obtained from free flexural vibration tests which were performed on a cantilever supported in both hanging and upstanding states. Measured frequencies were 2.79(Hz) in the hanging state and 1.53(Hz) in the upstanding state due to the existence of an axial force due to gravity, the effect of which however was removed by making use of a method proposed by one of the authors (Watanabe, 1986). Shear modulus G was evaluated by means of application of the "1/4 wave length law" to the natural frequency obtained from a forced vibration test performed on the column placed on a rigid base firmly fastened at the bottom with a bonding agent. The damping constant h was determined from the resonance curve for the above stated test results by making use of $1/\sqrt{2}$ method. All of the mechanical properties thus obtained are shown in Table 1.

The vibration tests were carried out by exciting horizontally the three dimensional model fixed on a shaking table with a sinusoidal motion where amplitude was maintained constant at 100(gal) and frequency was gradually varied in the range from 8(Hz) to 45(Hz). These tests were performed with the excitations in both the stream and longitudinal directions. Accelerometers were used to measure the response of the model dam. Four piezoelectric type accelerometers were arranged at the positions shown in Fig. 2 and one strain gauge type accelerometer was set on the base. The excitation in each direction was repeated three times by resetting the accelerometers on the dam body in the stream, in both longitudinal and vertical directions. These accelerometers were calibrated together on the shaking table with a sinusoidal motion of constant intensity, before the test, in order to evaluate the frequency characteristics. The response of each piezoelectric type accelerometer was always kept constant in the frequency range from 8(Hz) to 50(Hz), however, for the strain gauge type, response was reduced in the range over 45(Hz). The properties of the sensor could be neglected because a frequency over 45(Hz) was out of the test range. The accelerometers were set on the dam surface with the aid of a small triangular column of balsa wood fixed on the surface of the model.

Results of Tests

The experimental results are shown in Figs. 3 to 10. Figures 3 to 6 show the resonance curves for excitation in the direction of stream flow at the measuring points shown in Fig. 2, namely the center on the dam crest, at

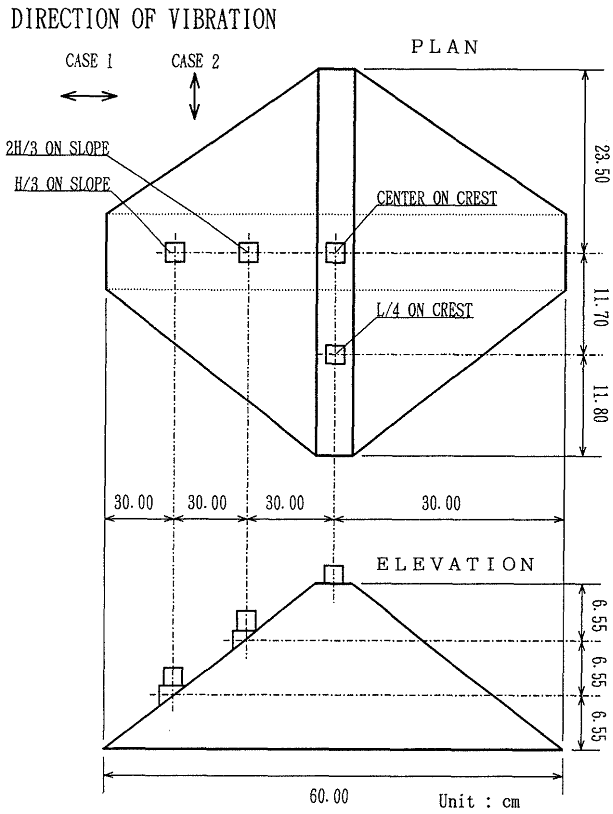

Fig. 2. Arrangement and positions of accelerometers

the point $L/4$ away from the abutment on the dam crest, at the points $2H/3$ and $H/3$ above the dam base on the slope respectively where L is the dam length and H is the dam height.

Figures 7 to 10 show the resonance curves of the tests for excitation in a longitudinal direction at the same

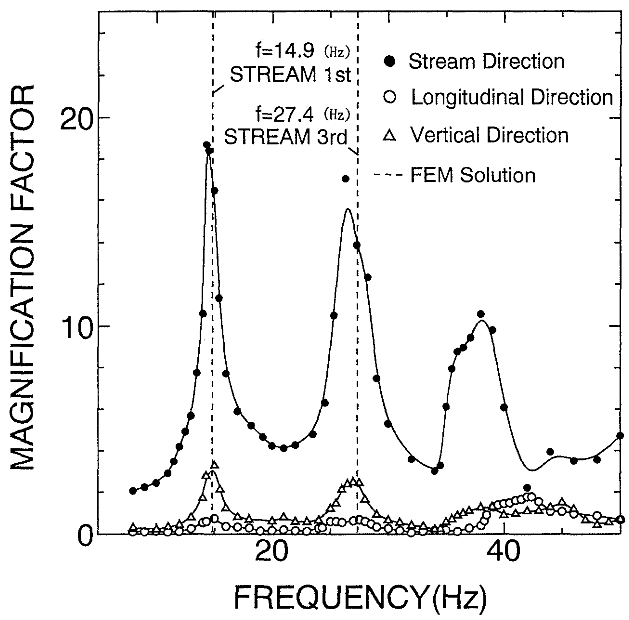

Fig. 3. Resonance curves at center on dam crest (for the case of excitation in stream direction)

points as the above. In each figure, the responses of three components in stream, longitudinal and vertical directions are plotted.

From Figs. 3 to 6, 14.4(Hz) and 26.6(Hz) were determined to be the natural frequencies of the 1st mode and the 2nd mode in stream direction respectively and from Figs. 7 to 10, 18.0(Hz) and 24.5(Hz) are shown to be the natural frequencies of the 1st mode and the 2nd mode in longitudinal direction respectively. Based on the well known facts obtained from earthquake observations on actual earth dams (Kawakami et al., 1967), there are three vibration modes of lower orders from the 1st to the 3rd as mentioned before (these modes are the 1st mode in stream direction, the 1st mode in vertical one and the 1st mode in longitudinal one respectively in the following discussion), and the frequency of the 1st mode in stream direction is always the lowest, and fundamentally the 1st mode in the vertical direction is higher. The 1st mode in longitudinal direction is close to either of those in stream and vertical directions, and it is assumed that there must

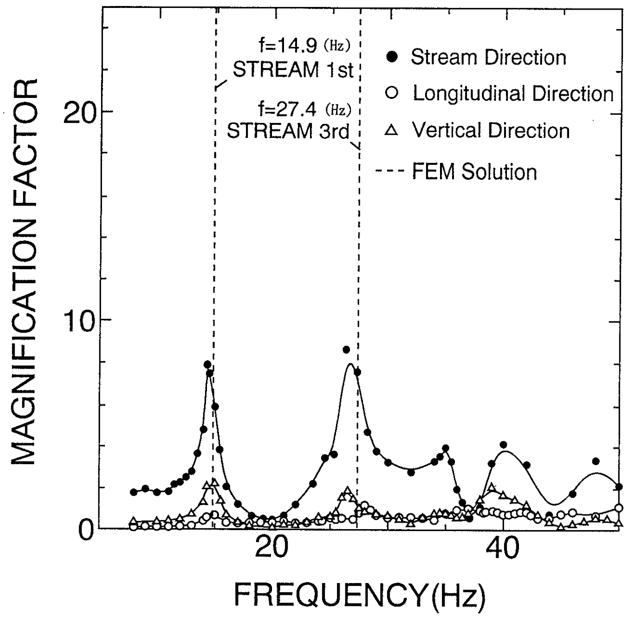

Fig. 4. Resonance curves at $L/4$ point on dam crest (for the case of excitation in stream direction)

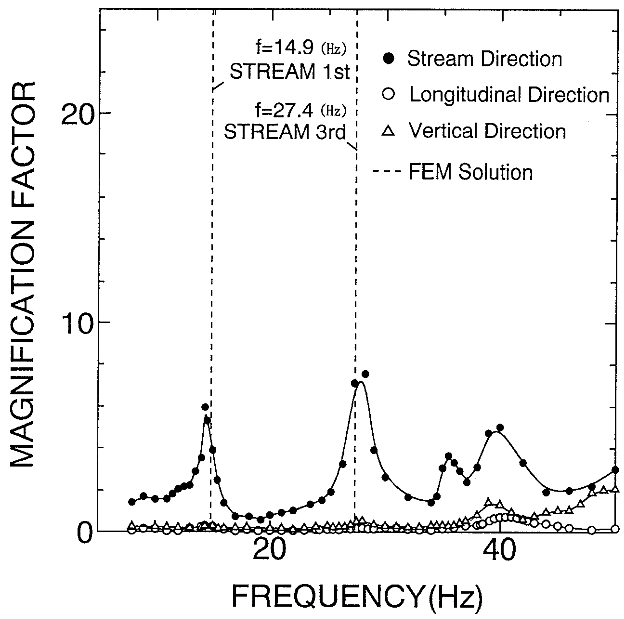

Fig. 6. Resonance curves at $H/3$ point on dam slope (for the case of excitation in stream direction)

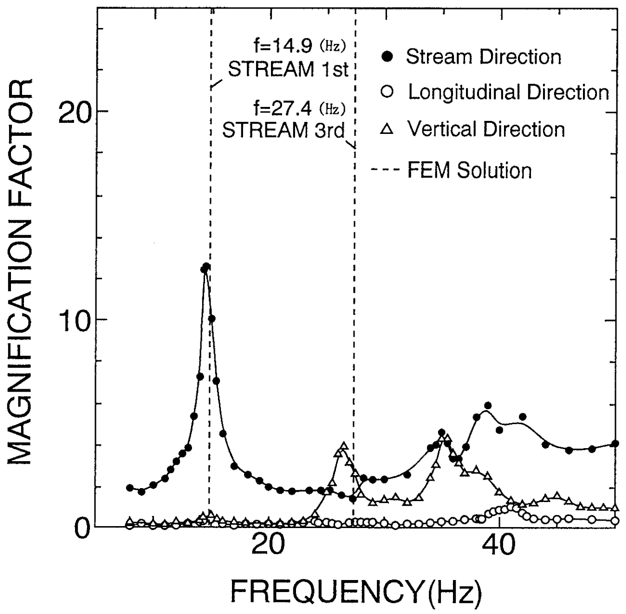

Fig. 5. Resonance curves at $2H/3$ point on dam slope (for the case of excitation in stream direction)

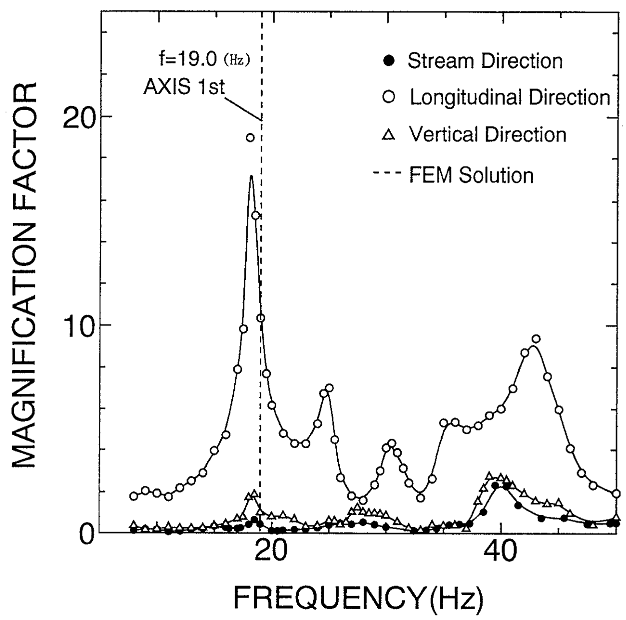

Fig. 7. Resonance curves at center of dam crest (for the case of excitation in longitudinal direction)

be an eigenfrequency corresponding to the 1st mode in vertical direction close to the frequency 18.0(Hz) corresponding to the 1st mode in longitudinal direction. For these resonance curves, however, any obvious and independent excellent response in the vertical direction can not be found near the above frequency, though a slightly excellent response can barely be noticed at near 20(Hz) in Figs. 3 and 7 for the resonance curves for excitations in both stream and longitudinal directions. This frequency may be regarded as the natural one for vertical response.

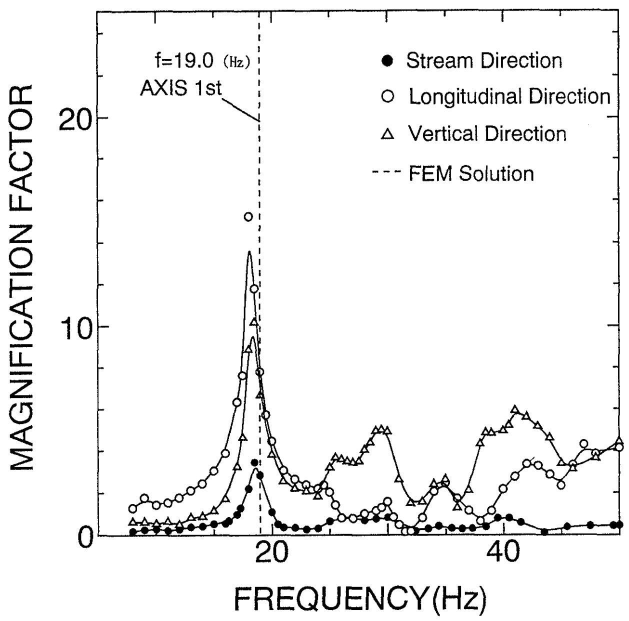

Fig. 8. Resonance curves at $L/4$ point on dam crest (for the case of excitation in longitudinal direction)

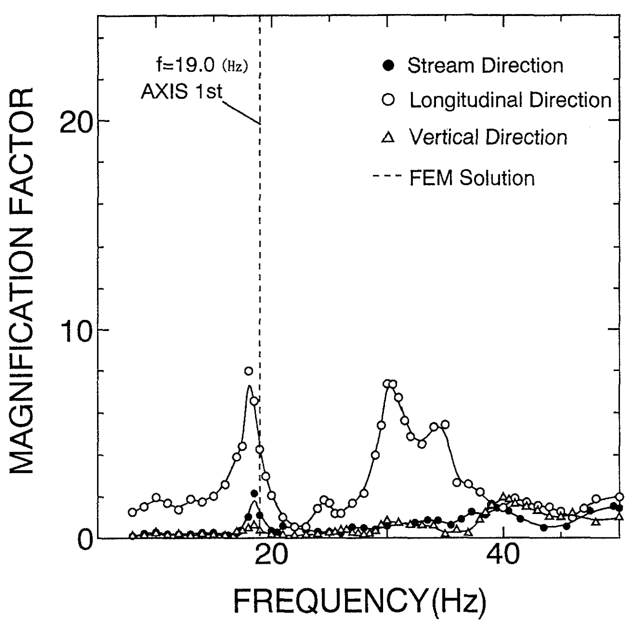

Fig. 9. Resonance curves at $2H/3$ point on dam slope (for the case of excitation in longitudinal direction)

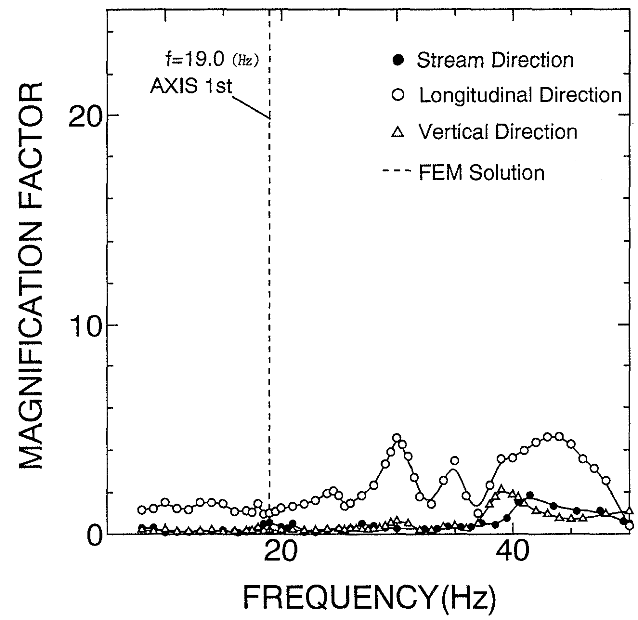

Fig. 10. Resonance curves at $H/3$ point on dam slope (for the case of excitation in longitudinal direction)

NUMERICAL SIMULATIONS ON THE VIBRATION TESTS

Numerical Model

Similar to the finite element model, three dimensional elements of Serendipity Family are used. One is a rectangular prism with 20 boundary nodes, another is triangular prism with 15 boundary nodes and the third is a tetrahedral element with 10 boundary nodes. The subdivision of the dam model is shown in Fig. 11 consisting of 60 rectangular prisms, 72 triangular prisms and 16 tetrahedral. The total number of nodes is 649 and the number of freedoms is 1332. With this numerical models modal analysis and step-by-step integration to the sinusoidal motions applied to the tests was carried out to simulate the vibration tests. In the latter, a linear acceleration method with the Rayleigh damping matrix of the form of $[c]=\{1.4\omega_1[m]+(0.6/\omega_1)[k]\}$ was utilized, where $[m]$ and $[k]$ are element mass and stiffness matrices respectively and ω_1 is

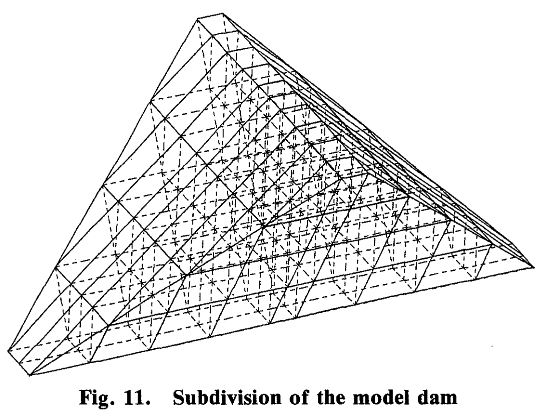

Fig. 11. Subdivision of the model dam

the first natural angular frequency.

Comparison of Experimental Results with Numerical Results for Vibration Modes and Eigenfrequencies

The eigenfrequencies up to the 10th order calculated with the mechanical properties of the dam body shown in Table 1 are tabulated together with the ones observed for the experiments in Table 2. As seen from this table, very good agreement can be observed between each pair of computed results and the experimental one such as the first eigenfrequency in calculation and the first one in the experiment for excitation in the stream direction, the second in calculation and the first for the excitation in longitudinal direction, the 6th in calculation and the second for the excitation in longitudinal direction and the 9th in calculation and the second for the excitation in stream direction respectively. We must examine further whether the phases of response acceleration for these frequencies in the experiments are consistent with the modes in calculation or not in order to identify the modes.

In Fig. 12 the vibration modes of the first, the second, the third, the 5th and the 9th obtained from the calculation are shown which are illustrated as the 1st mode in stream direction, the 1st mode in longitudinal (axial) direction, the 1st mode in vertical direction, the 2nd mode in stream direction and the 3rd mode in stream direction respectively. For the 1st mode in stream direction of the experiment, the response waves at all measured points have the same phase as seen in the 1st mode in the stream direction shown in Fig. 12 although time histories are abbreviated, so that we can confirm it to be the first mode in the stream direction. Concerning the 2nd mode in stream direction of the experiment, the response waves show 180 degrees in phase lag between the center and the point $L/4$ away from the abutment on the crest as well as a very small response at $2H/3$ on the slope as seen in the 3rd mode in stream direction in Fig. 12. Thus, it can be regarded as the third mode in stream direction. For the 1st mode of the experiment in longitudinal direction, the response waves at all measured points have the same phase as seen in the 1st mode in longitudinal direction in Fig. 12. Thus, it can be regarded as the first mode in the longitudinal direction. Although the

Table 2. Eigenfrequencies up to the 10th order (Comparison of calculation with experiment)

Order	Numerical results (Hz)		Experimental results (Hz)
1	14.9	Stream 1st	14.4
2	18.98	Axial 1st	18.1
3	19.79	Vertical 1st	
4	20.30		
5	22.5	Stream 2nd	
6	24.4		24.5
7	26.59		
8	26.88		
9	27.4	Stream 3rd	26.8
10	28.18		

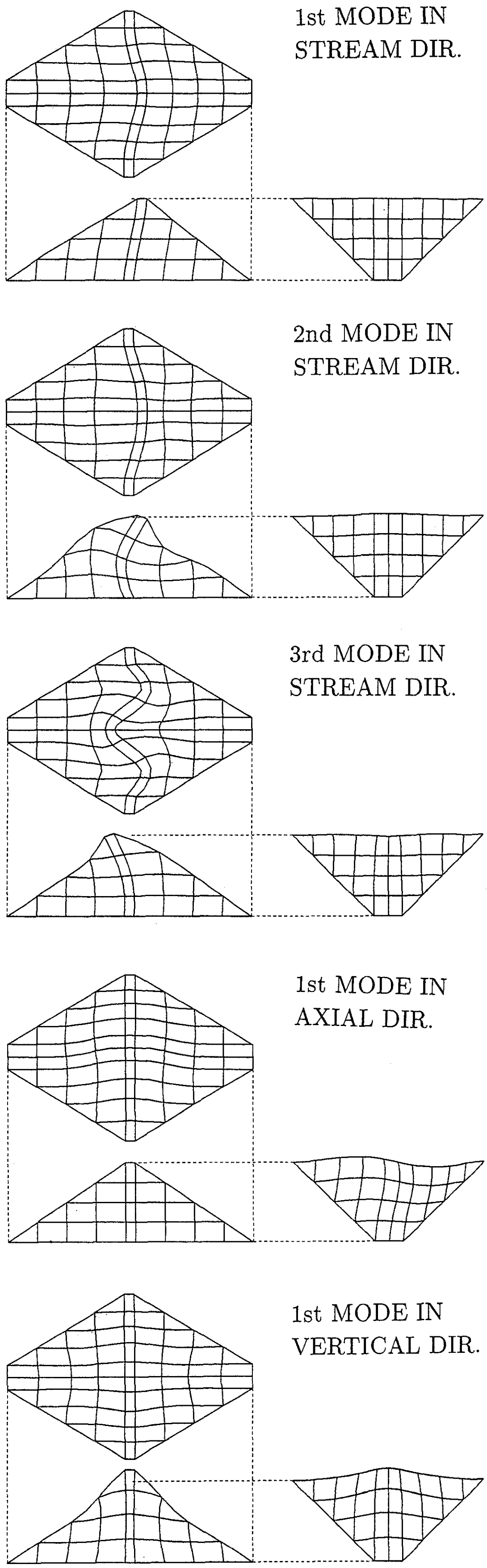

Fig. 12. Three dimensional vibration modes

2nd mode of the experiment in the same direction has a natural frequency very close to the one of the 2nd mode in the stream direction shown in Fig. 12, it is estimated to be the second mode in the longitudinal direction. The second mode in stream direction in the experiment could not be determined although a slight irregularity in the resonance curve is noted close to 22.5(Hz) as seen in Fig. 4. The response of this mode is so small that it is hidden in the response of the 3rd mode in the same direction. The 3rd mode in calculation corresponding to the 1st mode in vertical direction has a frequency of 19.79(Hz) which is very close to the one of the slightly excellent response barely noticed in the experiment mentioned before. We may therefore regard the above frequency in the experiment as the first mode in vertical direction which would be hard to determine from the excitation only in horizontal direction because of the symmetrical shape of the model dam.

Comparison of Experimental Results with Numerical Ones Related to Variation of Response Accelerations with Time

The steady state responses at the frequencies of the first modes both in stream and longitudinal directions in the experiment were calculated from the mechanical properties of the dam body given in Table 1 by means of a step-by-step integration and are determined with the experimental results in Fig. 13 and Fig. 14 for every natural frequency indicated in the figures. As seen from Figs. 13 and 14 the numerical results give comparatively good agreement with the experimental ones in amplitude. This, together with the coincidence of calculated eigenfrequencies with the experimental ones confirms the validity of the computer program prepared for the three dimensional seismic response analysis of fill dam.

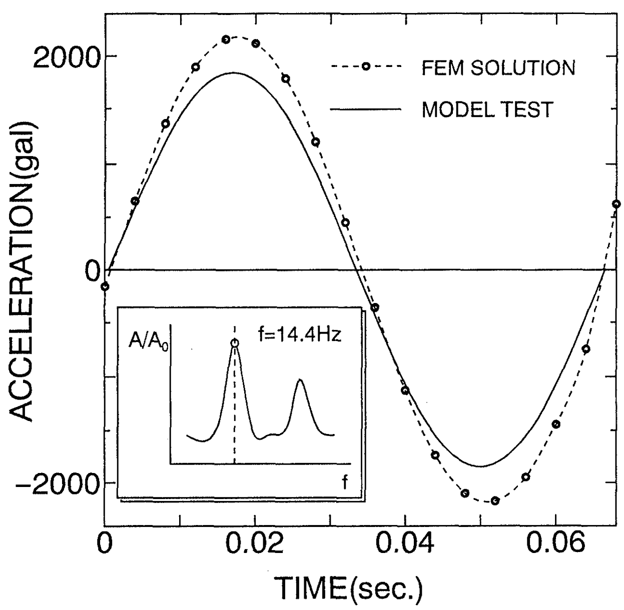

Fig. 13. Time history of acceleration in steady states for the 1st mode in stream direction (Experimental and numerical results)

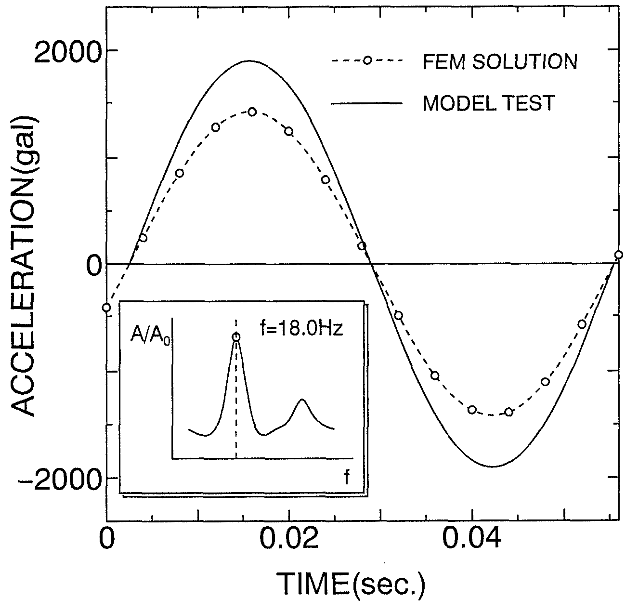

Fig. 14. Time history of acceleration in steady states for the 1st mode in longitudinal direction (Experimental and numerical results)

CHARACTERISTICS OF FLUCTUATION IN EVERY EIGENFREQUENCY FOR THE MAIN MODES OF FILL DAMS ACCORDING TO TOPOGRAPHICAL FEATURES OF DAM SITES

Making use of the above mentioned computer program for three dimensional seismic response analysis of fill dams, we examined how every eigenfrequency for the major modes up to the 4th order of a fill dam fluctuated in accordance with the variation of the topographical features at the dam sites.

For this purpose a standard hypothetical dam based on an actual dam was assumed. The actual dam is $H=175$ (m) high, 2.1(gr/cm^3) in average design dry density, 1:2.67 and 1:2.09 for upstream and downstream slopes and located in a canyon which has $W_B=H/4.375$ in riverbed width with $C_R/H=1.6$ and $C_L/H=0.8$ in the average valley wall slopes of both right and left banks respectively although C_L/H reaches 0.457 in the steepest part. The standard hypothetical dam is assumed to have 470(m/s) in average shear wave velocity and have the same geometry as the actual dam, so that $L_U=2.67H$ and $L_L=2.09H$ in the parameters with respect to dam slopes as shown in Fig. 15 where L_U is denoted by L_{UO} and W_B denoted by W_{BO}, and is assumed to be located in the canyon of which geometry is different from the actual dam site only in the valley wall slopes, which are assumed to be the same as the steepest part at the actual dam site for both abutments in common with $C_R/H=C_L/H=C/H$.

All valley wall slopes for both abutments and the width of the riverbed as well as the dam slopes are chosen based on the topographical features at the dam site. Based on changed L_U, C, C_R and W_B separately from the standard hypothetical dam, eigenfrequencies up to the 4th order have been calculated.

Denoting every eigenfrequency by f and dividing it by V_S/H to make it dimensionless, the relationships between $f/(V_S/H)$ up to the 4th order and dimensionless parameters such as L_U/L_{UO}, C/H, C_R/C_L and W_B/W_{BO} were obtained as shown in Table 3. Taking $f/(V_S/H)$ as the ordinate and taking L_U/L_{UO}, C/H, C_R/C_L and W/W_{BO} as abscissa, these results were plotted in Fig. 15 to Fig. 18 respectively. The geometry for both dam and canyon except for the one taken as a variable parameter is shown in the explanatory notes for each figure. These results have been obtained from the calculations for hypothetical dams of the same height and material properties, and we must check therefore whether or not these results are confirmed for other dams of different heights and material properties. The calculations on two hypothetical dams of different heights and different material properties have been added as shown in the explanatory notes of Fig. 18 assuming that they are located in two canyons of different valley wall slopes. Each of the material properties is estimated from both distributions of shear wave velocity and P wave velocity in the actual dam of the same geometry measured after completion of construction (Sawada et al., 1975). In Fig. 18, the eigenfrequencies of these two dams is plotted. The results for different material properties can not be distinguished because they coincide almost perfectly and are superimposed upon each other.

Table 3. Variation of each eigenfrequency according to the change of topography in dam site (Calculation)

C/H	$f/(V_S/H)$			
	Stream 1st	Vertical 1st	Longitudinal 1st	Stream 2nd
0.1	1.427	1.476	—	1.567
0.475	0.743	0.854	1.059	0.952
1.0	0.539	0.681	0.676	0.737
2.0	0.445	0.599	0.501	0.684
5.0	0.389	0.571	0.402	—

C_R/C_L	$f/(V_S/H)$			
	Stream 1st	Vertical 1st	Longitudinal 1st	Stream 2nd
0.1	0.989	1.073	1.512	1.173
0.5	0.851	0.948	1.260	1.048
1.0	0.743	0.854	1.059	0.952
2.0	0.625	0.752	0.839	0.848
5.0	0.503	0.665	0.593	0.789
10.0	0.445	0.615	0.492	0.717

L_U/L_{LO}	$f/(V_S/H)$			
	Stream 1st	Vertical 1st	Longitudinal 1st	Stream 2nd
0.1	0.682	0.873	1.052	0.961
0.5	0.739	0.874	1.072	0.982
1.0	0.743	0.854	1.059	0.952
2.0	0.735	0.845	1.054	0.931
5.0	0.715	0.818	1.050	0.906
10.0	0.700	0.834	1.051	1.022

W_B/W_{BO}	$f/(V_S/H)$			
	Stream 1st	Vertical 1st	Longitudinal 1st	Stream 2nd
0.2	0.927	1.059	1.337	1.182
1.0	0.743	0.854	1.059	0.952
3.0	0.539	0.653	0.744	0.738
5.0	0.451	0.580	0.589	0.668
10.0	0.377	0.528	0.434	0.619
25.0	0.344	0.496	0.343	—

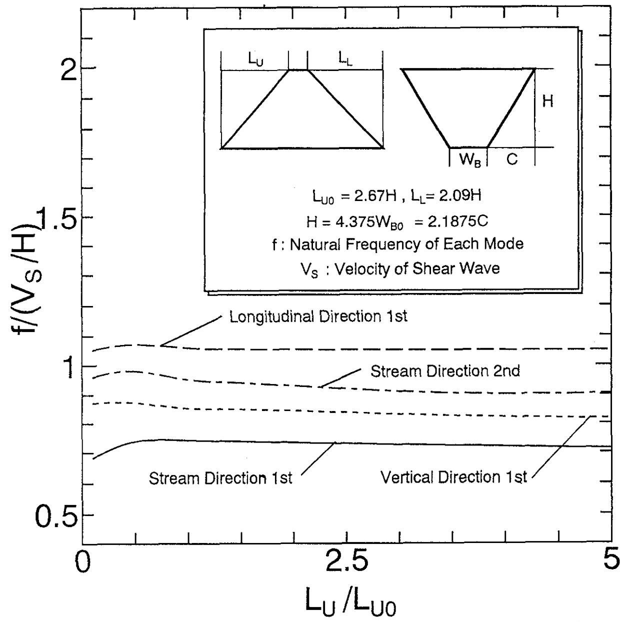

Fig. 15. Variation of dimensionless eigenfrequencies up to lower 4th order modes according to the change in dam slope of up stream side

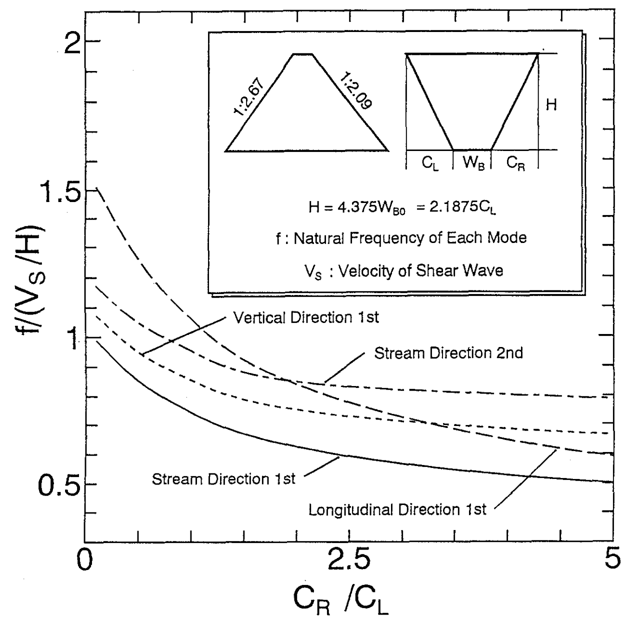

Fig. 16. Variation of dimensionless eigenfrequencies up to lower 4th order modes according to the change in dam slope of right abutment only

Based on the above mentioned examination it was determined that's.

(1) All eigenfrequencies are negligebly affected by the change of dam slope on the upstream side in the range larger than the one in downstream slope (Fig. 15). This may result from the steepness of the valley wall slopes for both abutments.

(2) All eigenfrequencies decrease uniformly as the slope of abutment becomes more level (Figs. 16 and 18) and as the width of riverbed becomes larger (Fig. 17).

(3) The rate with which every eigenfrequency decreases as the slope of the abutment becomes less steep is higher in the case when the slopes of both abutments are changed rather than when that of one bank only is changed (Figs. 16 and 18).

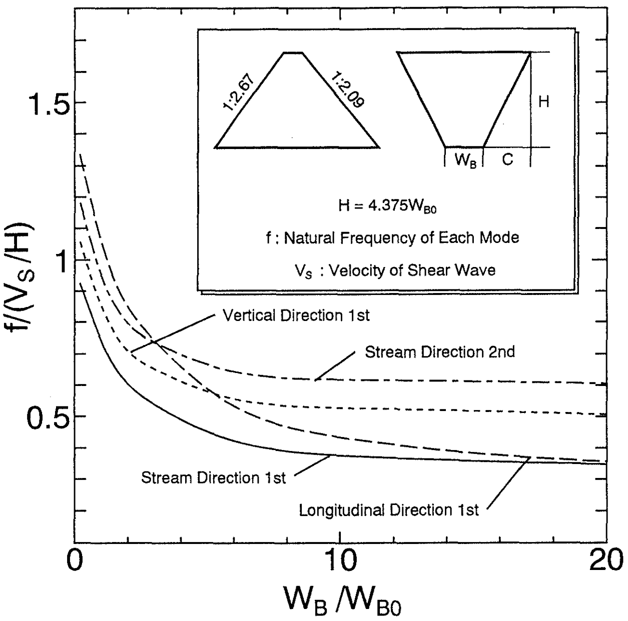

Fig. 17. Variation of dimensionless eigenfrequencies up to lower 4th order modes according to the change in width of riverbed

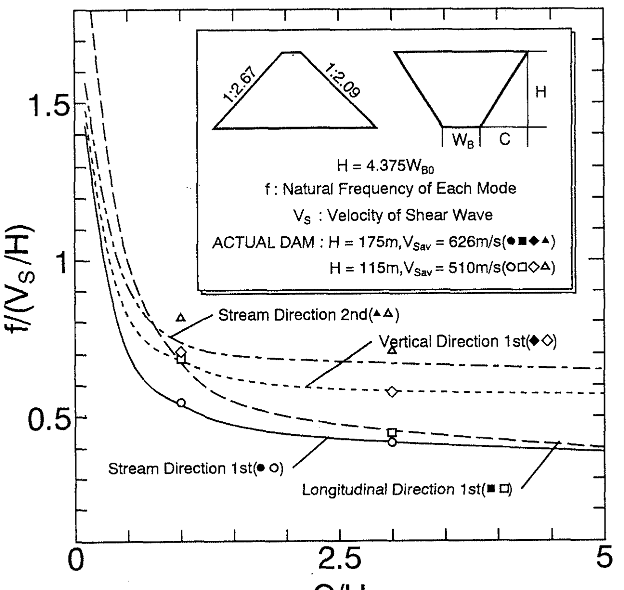

Fig. 18. Variation of dimensionless eigenfrequencies up to lower 4th order modes according to the change in both slopes of symmetry abutments

(4) The mode of the lowest eigenfrequency (fundamental mode) is always the first mode in the stream direction. The eigenfrequency of the first mode in vertical direction is always larger than the fundamental one and always smaller than the eigenfrequency of the second mode in stream direction.

(5) The rate of variation of eigenfrequency of the first mode in longitudinal direction (dam axial direction) is substantially higher than all others, in every case. Thus, the order of this mode can become the 4th or the 3rd or the 2nd one among major modes up to the 4th order in 3 dimensional responses of fill dams for every variation in both the slope of the abutment and the width of the riverbed.

(6) As seen in Fig. 18 the eigenfrequencies calculated for two additional hypothetical dams of different heights and material properties located in two canyons of different valley wall slopes agree fairly well with the curves for the relationships between $f/(V_S/H)$ and C/H plotted from Table 3. Consequently, it may be said that we can estimate approximate eigenfrequencies up to the 4th order for the fill dams of arbitrary height located in any canyon of which geometry can be simplified to such parameters as used in this paper by utilizing the diagrams in Figs. 17 and 18.

CONCLUSIONS

To summarize the discussions, the following conclusions can be made:

(1) In the resonance curves obtained from the vibration tests performed on a three dimensional fill dam model of silicone rubber, two clearly excellent responses for the excitation in stream direction and two clearly excellent responses for the excitation in longitudinal direction (dam axial direction) were observed, however, no obvious and independent excellent response in the vertical direction corresponding to the 1st mode in same direction was found. This mode may be hard to observe for excitation only in the horizontal direction because of the symmetrical shape of the model dam body.

(2) Eigenfrequencies up to the 10th order have been calculated for the model dam with its mechanical properties. Based on a comparison with observations in the experiments, very good agreement was found between every pair of computed results and the experimental one such as the first eigenfrequency calculated and the first experimental one for the excitation in stream direction, the second calculated and the first for excitation in longitudinal direction, the 6th calculated and the second for excitation in the longitudinal direction and the 9th calculated and the second for excitation in the stream direction respectively.

(3) Comparing the phases of response acceleration for all measurement points for each eigenfrequency in

the experiment with those in the vibration modes obtained from the calculations we have identified the first mode and the second mode in the experiment for the excitation in stream direction with the first mode and the third mode in stream direction respectively and have also identified the first mode and the second mode in the experiment for the excitation in longitudinal direction with the first mode and the second mode in the longitudinal direction respectively. The third mode calculated corresponding to the first mode in vertical direction has a frequency very close to the one for the slightly excellent response in the resonance curves based on experiments, and so this response in the experiment seems to correspond to the first mode in the vertical direction.

(4) Every time history of the steady state response acceleration at the center of dam crest calculated at frequency of every first mode in both stream and dam axial directions agree comparatively well with each of the experimental results in both amplitude and phase. Therefore, together with the coincidence of calculated eigenfrequencies with the experimental ones as mentioned above, the validity of the computer program developed in this paper for three dimensional seismic response analysis of fill dams, is confirmed.

Making use of this computer program, the follwing facts concerning the effect of topographical feature of dam sites on every eigenfrequency in the main modes can be stated: With regard to the examination of the effect of dam slopes considered in this paper as mentioned before, only the upstream slope was changed keeping the downstream constant. In Japan, the upstream slope in every fill dam is always flatter (less steep) than the downstream because saturated density is considered for seismic force and buoyancy for material strength on the upstream side. The upstream slope is flatter than the downstream as the design seismic coefficient is increased, and therefore only the change in upstream slope must be accounted for:

(5) All eigenfrequencies are scarcely affected by the change of dam slope on the upstream side in the range larger than the one for the downstream slope. This may be due to the steepness in the valley wall slopes in the numerical models.

(6) All eigenfrequencies decrease uniformly as the slope of the abutment becomes flatter and the width of the riverbed increases. The rate with which every eigenfrequency decreases as the slope of the abutment flattens is higher in the case when the slopes of both abutments are changed than when only one bank is changed.

(7) The mode of the lowest eigenfrequency (fundamental mode) is always the first mode in stream direction. The eigenfrequency for the first mode in the vertical direction is always larger than the fundamental one and is always smaller than the eigenfrequency for the second mode in the stream direction. The variation rate of eigenfrequency for the first mode in the dam axial direction is substantially higher than all others, in every case. Thus,the order of the first mode in the dam axial direction could change from the 2nd to the 4th among the major modes up to the 4th order in the three dimensional response for the fill dam based on every variation in both the slope of abutment and the width of the riverbed.

(8) The eigenfrequencies calculated on two additional hypothetical dams of different heights and material properties located in two canyons of different valley wall slopes agree fairly well with the curves for relationships between $f(V_S/H)$ and C/H plotted from Table 3. Consequently, it may be said that we can estimate approximate eigenfrequencies up to the 4th order of the fill dams of arbitrary height located in any canyon for which the geometry can be simplified to such parameters as presented in this paper by utilizing the diagrams in Figs. 17 and 18 together with Table 3.

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