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ELEMENTAL THREE DIMENSIONAL DYNAMIC BEHAVIOR OF FILL DAM

HIROYUKI WATANABE[1), ZENGYAN CAO[2) and KENJI KIKUCHI[3)

1) Professor, Dept. of Civil and Environmental Engg., Saitama University
Shimo-Ohkubo 255, Urawa-Shi, Saitama 338, JAPAN.
2) Research Engineer, Kaihatsu Keisan Center Co. Ltd.
Fukagawa 2-2-18, Kohto-Ku, Tokyo 136, JAPAN.
3) Engineer, Civil and Architecture Engg. Dept., Chubu Electric Power Co. Ltd.
Higashi-Shinmachi 1, Higashi-Ku, Nagoya 461, JAPAM.

ABSTRACT

On a prototype rockfill dam , the seismic prospecting tests are carried out before reservoir impoundment to estimate the material properties of the dam and then the microtremors tests are carried out before and after the reservoir impoundment to find out its natural frequencies up to the fifth mode from the fundamental one. With the material properties 3 dimensional modal analyses are carried out by means of the FEM computer program made by the authors and the five natural frequencies in every of both reservoir conditions are estimated. Comparing the numerical results with the observed ones, considerably good agreement between them are obtained. Besides, the reason why the natural frequencies in full reservoir reduce from those before reservoir impoundment is clarified.

KEYWORDS

Prototype Rockfill Dam; Seismic Prospecting Tests; Microtremors Tests; 3-Dimensional Vibration Modes; FEM Modal Analysis; Full Reservoir; Before Impoundment.

INTRODUCTION

Two dimensional seismic response analyses are usually applied to aseismic design of fill dams because finer sized elements are more available in 2-D FEM than 3-D one. The seismic response of fill dams, however, strongly influenced by the topographical feature of each dam site as pointed out so far (Ambraseys, 1966, Majia and Seed, 1983). Instead of the above we scarecely take the effect into consideration on aseismic design of fill dams because of the shortage of the knowledge concerned. Aside from the above we have scarecely knowledge how the natural frequencies of fill dams change according to the reservoir condition. This paper aims to reveal the elemental three dimensional dynamic behavior of fill dam such as natural frequencies of main modes, which must be influenced by the topographical feature of dam site and reservoir conditions.

FIELD TESTS AND THE RESULTS

METHOD OF FIELD TESTS

Field tests were carried out on KAMI-OHSU dam of CHUBU Electric Power Co. Ltd. which is located at the village of NEO in GIFU Prefecture. KAMI-OHSU dam is a rockfill dam of the center core type which is 98(m) high, 294(m) in the crest length, 3.19(Mm^3) in the volume, 11(m) in the top width and 458(m) in the base width. Two seismometers are installed at the grouting gallery of left abutment and on the toe of down stream slope and four ones are installed in the dam body for the sake of earthquake observation. Every seismometer has three components in the directions orthogonal to each other. Fig.1 shows plan and cross section of the dam and arrangement of all sensors.

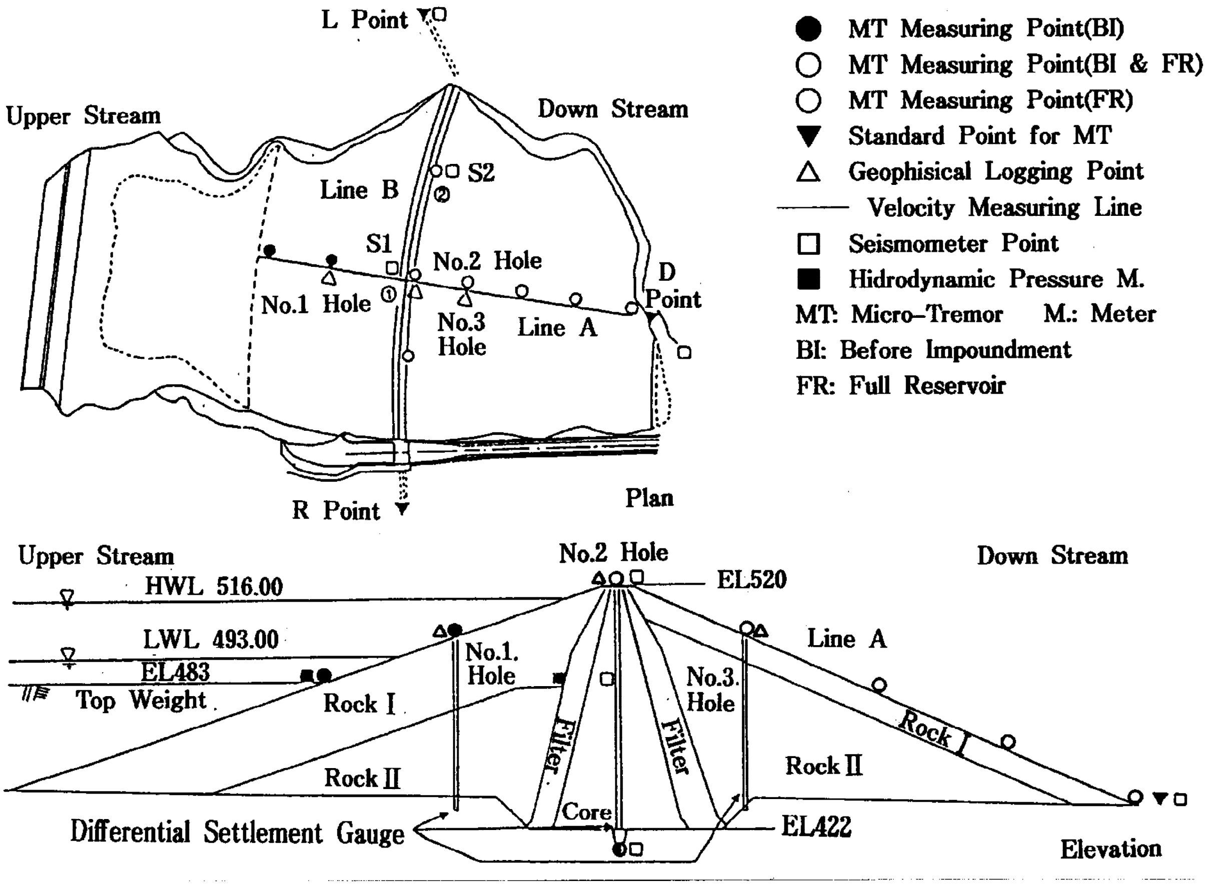


Fig. 1. Plan and cross section of dam, velocity measuring lines, and arrangement and positions of sensors

The seismic prospecting tests consist of the measurement of elastic wave velocities (P & S waves) on the dam surface and the geophysical logging by making use of holes No.1~No.3 provided for differential settlement gauges. The elastic wave velocities were measured along both line A in stream direction and line B in crestline one. P wave along line B was generated by means of falling a weight and P wave along line A was generated by means of hammering with a large mallet. S wave along every line was generated by plank hammering method. The exciting points were set up at intervals of

20~30(m) along every measuring line. The receivers were put at intervals of 2.5 (m). All signals were taken in by a personal computer and recorded in the hard disc under monitoring them by oscillograph. Geophisical logging was carried out with specially made detector composed of seismometers of three components installed at intervals of 1 (m) which could be fixed on the inner surface of the holes by air pressure. Both ways how to excite waves and record the signals were same ones as in elastic waves.

The measurement of microtremors was carried out three times, namely, before impoundment, in both conditions of H.W.L. and L.W.L. after impoundment. The observed points were put on both measuring lines for elastic wave velocities and on the points where seismometers were installed. The details under every condition are shown in Fig.1. Three components in stream, crestline and vertical directions were observed at every point. We used seismometers of velocity detection type, every of which had a natural frequency of 1 (Hz) and flat frequency characteristics in the range from 1~20 (Hz). Observed microtremors at six points with the combination of every three observed points and three standard points shown in Fig.1 were taken in and recorded simultaneously by a personal computer. Sampling frequency and duration were 200 (Hz) and 25 (sec) respectively. Observation of every combination was repeated five times.

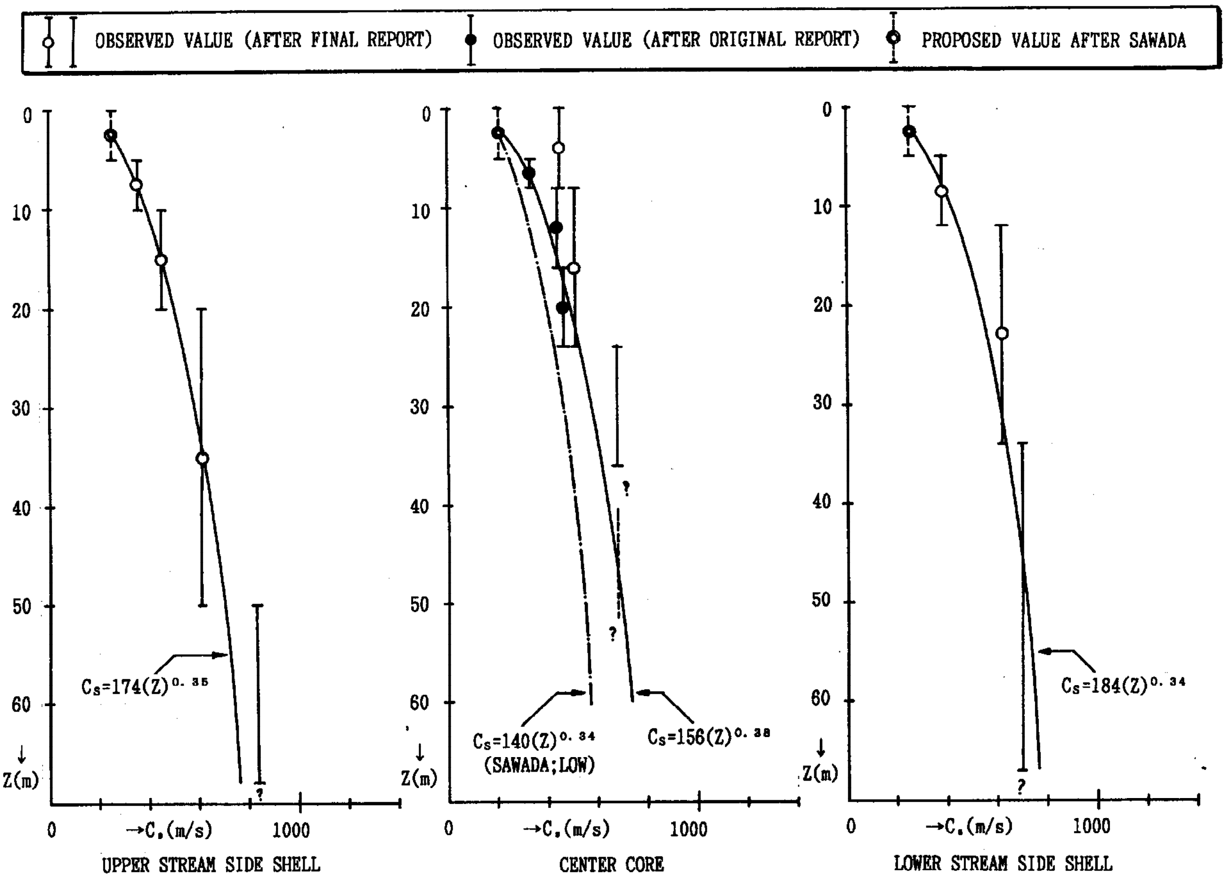
RESULTS OF FIELD TESTS

With the measurement of elastic wave velocities we could survey the velocity distributions only up to 10~15 (m) deep in the rockfill dam since vibration energy used to decay rapidly in the rockfill dams and we were prohibited from using higher exciting force such as exploisive. On the other hand, from the geophysical logging by making use of holes No.1~No.3 we could obtain very good results up to the deepest zones in the holes of No.1 and No.3 which were set up in the rockfill zones of both upper and down stream sides, however, we could not survey well in the part deeper than 38 (m) of No.2 hole set up in the core zone. Besides, at the part of core zone near surface observed velocities varied widely, so we repeated the measurement. From the observed velocities of P and S waves we can find that both velocities increase as the depth Z from dam surface increases and that every velocity may be expressed by m-th power of non-dimensional depth Z. For an example, Fig.2 shows the distribution of shear wave velocity expressed by C_s or V_s (m/s) in every zone and its curve fitting to $C_s=A(Z)^m$ as well as other material properties such as density ρ and Poisson's ratio μ which has been estimated together with observed P wave velocity to apply to FEM analyses.

Applying the material properties obtained from the above seimic prospecting tests and inserted in the table in Fig.2 to the initial stress analysis just after completion of the dam with FEM model mentioning later, we have obtained the mean effective principal stress σ_m' at the centroid of every FEM element. Plotting σ_m' vs. non-dimensional depth Z of the centroid for all elements following equation is obtained.

$$\sigma_m' = 0.14 \cdot Z. \qquad (1)$$

Substituting Eq.(1) into the equations for V_s~Z in Fig.1 and taking account of the average void ratio of every zone as well as the relationship between shear modulus G_0 in micro strain amplitude and void ratio e , we obtain the formuli of G_0 in all zones of the dam as shown in Table 1 where the reference strain amplitude γ_r and the maximum damping constant h_{max} obtained from dynamic triaxial tests are inserted too.



Material Properties Used in Analysis

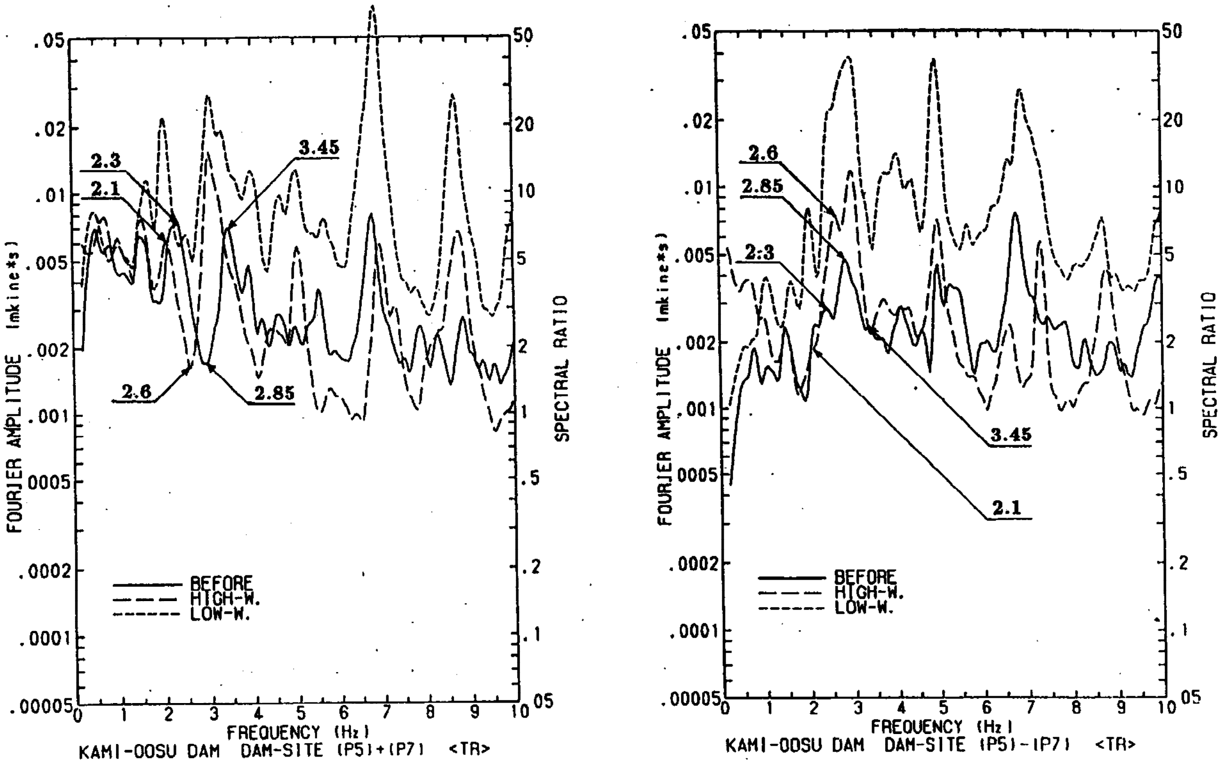
Zone	Z	ρ	V_s	μ
	(m)	(t/m^3)	(m/s)	$-$
Upstream Shell	$z \leq 34$	2.09	$174 \cdot z^{0.35}$	$0.4 - 0.0034 \cdot z$
	$z > 34$	2.14		
Core	$0 \leq z \leq H$	2.33	$140 \cdot z^{0.34}$	0.37
Downstream Shell	$z \leq 12$	2.09	$184 \cdot z^{0.34}$	$0.33 - 0.002 \cdot z$
	$z > 12$	2.14		

Fig. 2. Distribution of shear wave velocity and material properties of the dam

Table 1. Material properties of the dam expressed in the hyperbolic model

Zone	e	Z	ρ	G_0	γ_r	h_{max}
		(m)	(g/cm^3)	(kgf/cm^2)		
U.S. Shell	0.279	$z \leq 34$	2.22	$914\frac{(2.17-e)^2}{1+e}(\sigma'_m)^{0.70}$	$3.05 \times 10^{-4}(\sigma'_m)^{0.377}$	$0.274(\sigma')^{-0.223}$
		$z > 34$	2.27	$936\frac{(2.17-e)^2}{1+e}(\sigma'_m)^{0.70}$	$3.05 \times 10^{-4}(\sigma'_m)^{0.377}$	$0.274(\sigma')^{-0.223}$
Core	0.264	*all*	2.33	$617\frac{(2.17-e)^2}{1+e}(\sigma'_m)^{0.68}$	$3.73 \times 10^{-4}(\sigma'_m)^{0.238}$	0.173
L.S. Shell	0.279	$z \leq 12$	2.09	$983\frac{(2.17-e)^2}{1+e}(\sigma'_m)^{0.68}$	$3.05 \times 10^{-4}(\sigma'_m)^{0.377}$	$0.274(\sigma')^{-0.223}$
		$z > 12$	2.14	$1006\frac{(2.17-e)^2}{1+e}(\sigma'_m)^{0.68}$	$3.05 \times 10^{-4}(\sigma'_m)^{0.377}$	$0.274(\sigma')^{-0.223}$
Piled Zone	0.460	*all*	2.05	$640\frac{(2.17-e)^2}{1+e}(\sigma'_m)^{0.70}$	$3.05 \times 10^{-4}(\sigma'_m)^{0.337}$	$0.274(\sigma'_m)^{-0.223}$

$$G = G_0 \frac{1}{1+\gamma/\gamma_r} \qquad h = h_{max}\frac{\gamma/\gamma_r}{1+\gamma/\gamma_r} + 0.10$$



(a) Sum of Points ① & ② (b) Difference of Points ① & ②

Fig. 3. Fourier amplitudes of microtremors at Points ① and ② (transverse or stream direction)

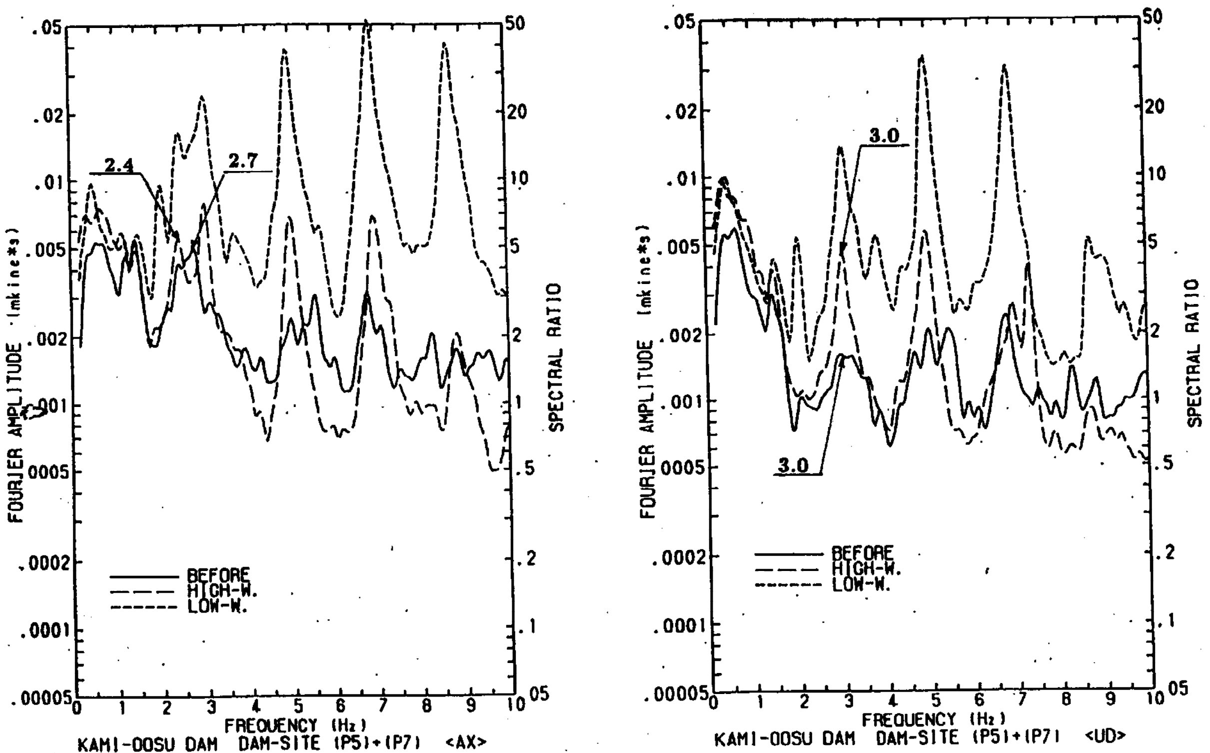


Fig. 4. Fourier amplitudes of microtremors at Points ① and ② (axis or crestline direction and UD or vertical direction)

Fig. 3 shows the fourier spectra obtained from the observation of microtremors at the points along axis of dam crestline. In the figure three fourier spectra obatained under the conditions of before impoundment, H.W.L. and L.W.L. after impoundment are superimposed. As seen from the figure there are so many peaks in every spectrum that it is a bit difficult for us to find out which peak corresponds to every vibration mode. Therefore, we make a half of the sum and the difference from observed records of microtremors at both points ① and ② as shown in Fig. 1 and then calculate the fourier spectra of them. Because the vibration modes have same or inverse phases at these two points, so that the sum emphasizes the response of same phase and the difference does the one of inverse phase as shown in Fig. 3 (a) and (b) respectively. Thus, we have found out five three dimensional natural frequencies from fundamental one up to the fifth one as shown in Figs. 3 and 4 although the fourier spectra of the sum only are shown for the responses in both axis and vertical directions in Fig. 4.

FEM MODAL ANALYSIS

In order to confirm the vibration mode for every natural frequency and to investigate how reservoir condition influences on the natural frequency we carried out modal analyses by FEM with three dimensional elements of Serendipity Family such as 170 hexahedra of 20 boundary nodes, 123 triangular prisms of 15 nodes and 13 tetrahedra of 10 nodes. In Fig. 5 is shown a bird's eye view of the mesh of numerical dam model. In advance of modal analyses, we carried out three cases of initial stress analyses under the conditions of full reservoir(case-1), full reservoir with natural moistured densities for submerged zones(case-2) and low water level(case-3) where we call the case of before impoundment case-0. With mean effective principal stresses obtained from the above stress analyses material properties shown in Table 1 are applied to the modal analyses in which saturated densities only are shown in the column of upper stream shell, however, the natural moistured densities as shown in the corresponding column in the table in Fig. 2 are applied to all emersed zones except for case 2 and the case of before impoundment.

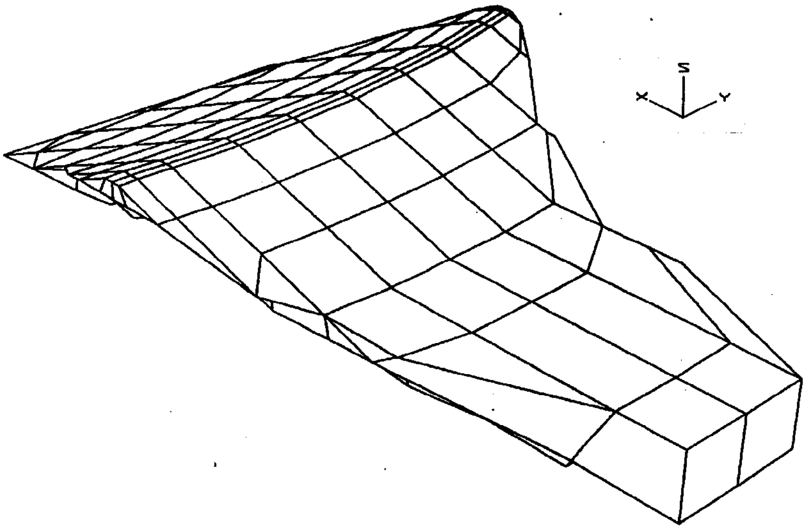


Fig. 5. Bird's eye view of the mesh of FEM model

Figs. 6 and 7 show the 1st and 2nd modes in stream direction calculated in case-1 for examples. Table 2 shows the natural frequencies up to the 10th order in all cases. With the mode shapes like the figures other main modes, such as the 1st in the crest line (axis 1), the 1st in the vertical and the 3rd in the stream, are selected. In this connection the 1st mode in every of case 1~3 is the mode in which piled soil in the reservoir only predominates. Table 3 shows the main five natural frequencies of both calculation and observation for case-0 and case-1.

From Table 2 we may say that natutal frequencies in full reservoir are considerably reduced from those before reservoir impoundment, however, the condition whether submerged materials are saturated or not affects only a bit the change of natural frequencies and that the reduction of water level up to a quarter of full height also

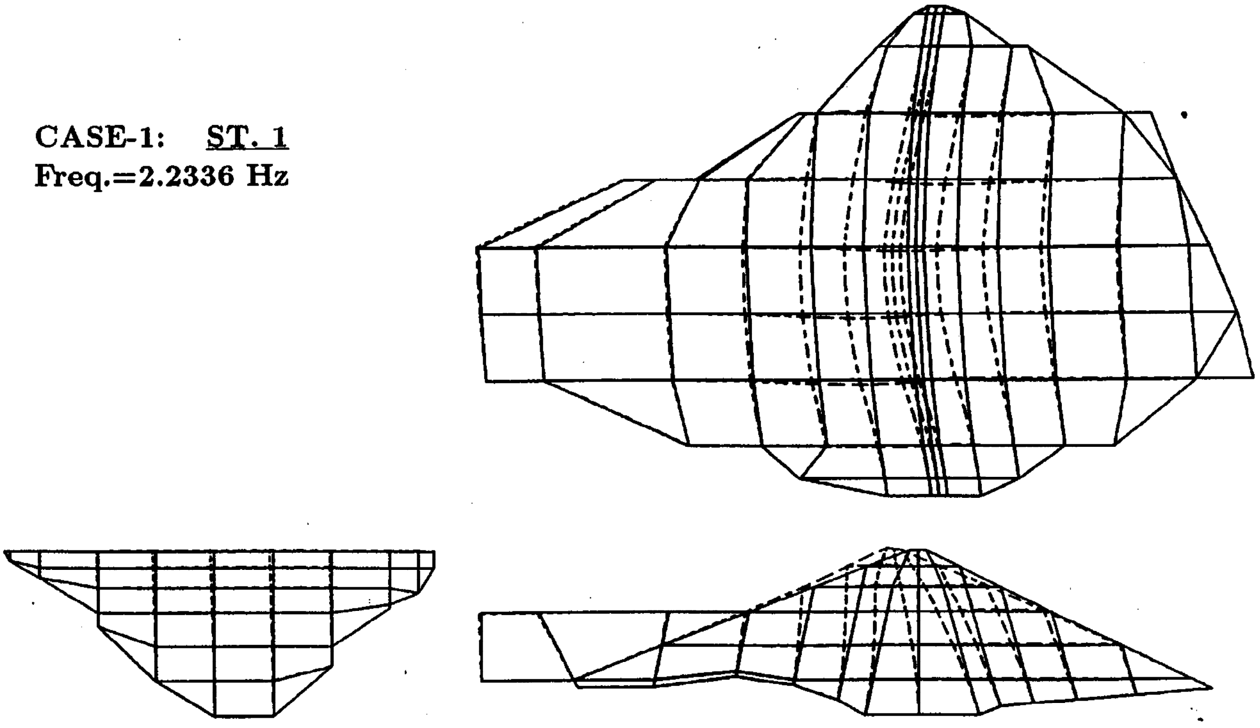


Fig. 6. The first mode in stream direction (case of full reservoir)

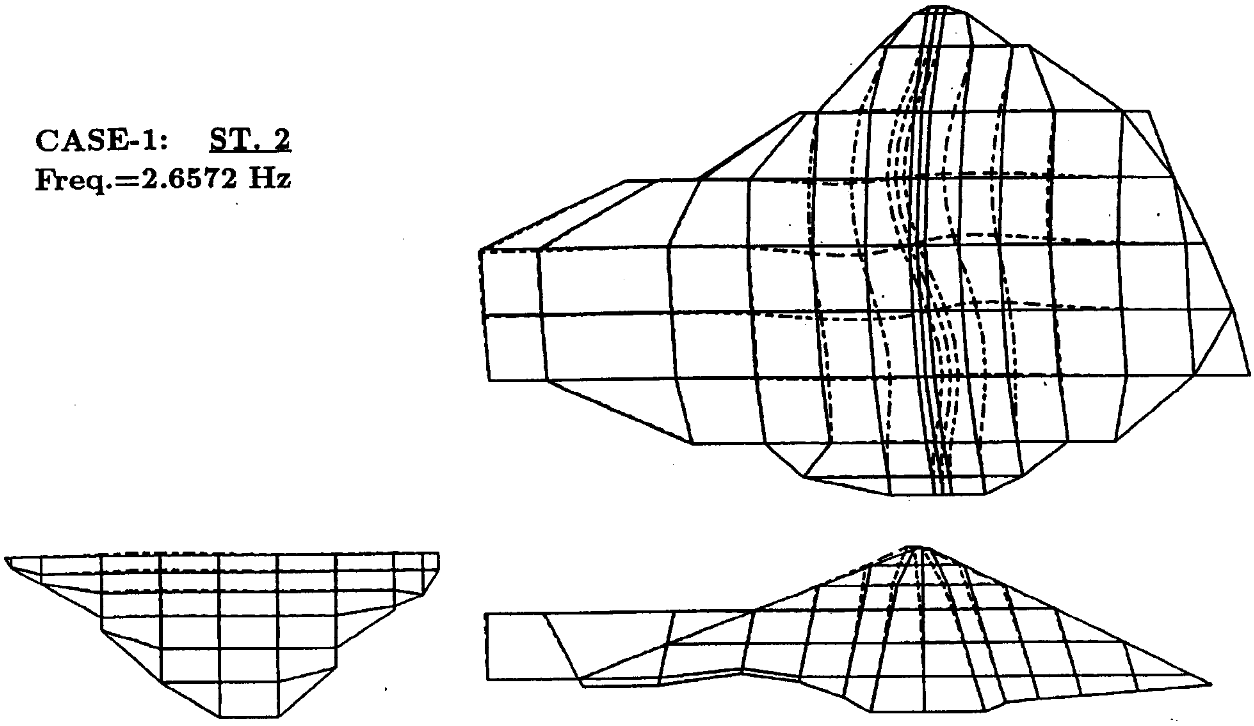


Fig. 7. The second mode in stream direction (case of full reservoir)

Table 2. Calculated natural frequencies and main modes

Mode	Case-0		Case-1		Case-2		Case-3	
1	2.3946	str. 1	2.1427		2.2216		2.1451	
2	2.6346	axis 1	2.2336	str. 1	2.2774	str. 1	2.3200	
3	2.6586		2.3199		2.4059		2.3517	str. 1
4	2.8550	str. 2	2.4666	axis 1	2.5104	axis 1	2.6190	axis 1
5	2.8815		2.6572	str. 2	2.7086	str. 2	2.7389	
6	3.1962	ver. 1	2.7376		2.8395		2.8299	str. 2
7	3.3301	str. 3	2.9109	ver. 1	3.0014	ver. 1	2.9807	
8	3.3901		3.0667		3.1432	str. 3	3.1788	ver. 1
9	3.5088	axis 2	3.0908	str. 3	3.1590		3.2595	
10	3.5899		3.2148		3.3219	axis 2	3.3055	str. 3

Table 3. Comparison of calculated natural frequencies with observed ones

Case	Empty Reservoir		Full Reservoir		—
Mode	Calculation	Observation	Calculation	Observation	Type
1	2.39	2.3	2.23	$2.1_{(2.0)}$	Str. 1
2	2.63	2.7	2.47	2.4	Axis 1
3	2.86	2.9	2.66	2.6	Str. 2
4	3.19	3.0	2.91	3.0	Ver. 1
5	3.33	3.5	3.09	3.3	Str. 3

affects only a bit. Thus we may say that only remaining cause of the above reduction of natural frequencies is the reduction of rigidity in submerged materials due to buoyancy. From Table 3 we may say that calculated natural frequencies agree fairly well with observed ones in both cases before and after reservoir impoundment.

CONCLUSION

From the microtremors tests carried out on a prototype rockfill dam before and after reservoir impoundment, main five natural frequencies and these modes are clarified which show that the natural frequencies in full reservoir reduces considerably from those before reservoir impoundment. The natural frequencies calculated from three dimensional FEM modal analyses with material properties observed from seismic prospecting tests agree fairly well with the observed ones and these calculated results clarify that the above reduction of natural frequencies in full reservoir is caused by the reduction of the rigidity of submerged materials due to buoyancy.

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