# COMPARATIVE ANALYSIS OF A ROCK-FILL DAM

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## ABSTRACT

Investigations of the dynamic behaviour of a rock-fill dam were aimed at definition of the dynamic characteristics and the dynamic response of the dam under empty and full reservoir conditions, and by comparison of the obtained results to evaluate water effect. The investigations comprise full-scale forced vibration tests, as well as geophysical and analytical measurements performed using a relatively simple plane mathematicah shear model. Out of the numerous obtained results, presented herewith are mainly those which are closely related to the explanation of the basic point of the water effect.

## DESCRIPTION OF THE DAM

The Rama rock-fill dam was constructed in 1969. The profile of the canyon, where the dam is constructed, consists of limestone. The site topography and the conditions for minimizing the dam body volume and the upstream reinforced concrete facing membrane conditioned unsymmetrical "S" shaped curviture of the dam base. Its hight varies up to 96 m above the ground, and its crest is 229,7 m long following the curviture. The average slopes of the upstream and the downstream face are 1:1,2 and 1:1,5, respectively. The average bulk density of the material built in the dam body is $\gamma = 2{,}1$ t/m$^3$. The dam is graphically presented in Fig. 1.

## GEOPHYSICAL MEASUREMENTS

Refrectory seismic method has been applied for definition of the elastic shear wave propagation velocity $V_s^e$ over the dam body, as one of the basic parametres for dam analysis. Microseismic tremor measurements have also been carried out.

Measurements were conducted under empty reservoir conditions. Refractory profiles were placed along the crest as well as the slope. Measurements were carried out for zones 40 - 50 m deep, which made possible that velocities over the major part of the dam body be defined. The measured velocities refer to elastic shear deformations of a rate smaller than $10^{-4}\%$ and are presented in Fig. 2.

The mean value of the velocity $V_s^e = 950$ m/sec corresponds to the presented velocities $V_s^e$ of 800 m/sec in the upper zone, 1000-1100 m/sec in the middle zone and 1200 m/sec in the lower zone within a 30 m deep zone in the central part of the dam body, as measured by the microseismic tremor method. Expressed in terms of functions of normal vertical stresses in the dam body $\sigma_1$, by the equation

$$V_s = 340(\sigma_1)^{1/4} \qquad \ldots (1)$$

$$\sigma_1 = \gamma Z$$

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[III] Senior Research Engineer, IZIIS, University "Kiril and Metodij", Skopje they show good correlation. The term Z is the depth as measured from the surface of the dam body.

## EXPERIMENTAL INVESTIGATIONS

Experimental investigations include full-scale forced vibration tests and recording the response at the characteristic points on the dam surface. The dam was excited by two vibration generators, placed on the dam crest, which were generating horizontal harmonic vibrations in radial direction with respect to the central curviture of the crest, i.e. in a direction parallel to the canyon. Horizontal accelerations mostly in radial direction to the dam curvitures were recorded at the measurement points over the crest and downstream slope of the dam. The places of the vibration generators and the measurement points are shown in Fig. 1.

To define the effect of the water within the reservoir, tests for both empty and full reservoir conditions were carried out.

As a result, the resonance frequencies for the three lowest modes of vibration were defined and from them several horizontal and vertical mode shapes and equivalent viscous damping values were determined.

Some characteristic resonance frequencies are presented in Figs. 3 and 4, and some characteristic results obtained for empty and full reservoir conditions are presented in Tables T1 and T2, respectively.

Comparison of the results obtained for empty and full reservoir conditions shows that they are considerably silimar or even identical. They refer to shear deformation level smaller than $10^{-4}\%$ which is identical to the deformation level in refractory measurements of the velocities $V^e_s$ over the dam body.

## MATHEMATICAL MODEL DEFINITION AND DYNAMIC ANALYSIS OF THE DAM

The equivalent mathematical model for dynamic analysis of the dam is defined by a plane shear wedge model which makes possible discretization of the dam over its vertical surface. The elements in the direction perpendicular to that surface are of the size which follows the thickness of the dam. Due to the unconformity of the dam body shape and the limited possibilities of the plane model for proper presentation, approximation have been applied by the closest possible proper form, as illustrated in Fig. 5. In that, a mean value of the velocity $V^e_s$ has been adopted for the whole dam, i.e. each element.

Presented in Fig. 6 are the resonance frequencies for the three lowest modes, selected out of the results obtained by dynamic analysis of the described model of the dam in empty reservoir conditions. The frequencies are given in terms of functions dependent on the average velocity $V^a_s$ over the dam body. Resonance frequencies $f^a_1 = 4{,}4$, $f^a_2 = 6{,}2$ and $f^a_3 = 7{,}7$, which are in good correlation with the experimental values of $f^e_1 = 4{,}3$, $f^e_2 = 6{,}3$ and $f^e_3 = 7{,}7$ c/sec, correspond to the average velocity $V^e_s = 950$ m/sec, as determined by geophysical measurements. Discrepency is 2,3%, -1,6% and 0,0%, respectively. Taking this correlation as good enough, it has been concluded that the adopted equivalent surface model might be considered as satisfactory.

Dynamic analysis for full reservoir conditions was also performed for the same model. The water effect has been taken into account by the equivalent added mass of the water corresponding to the hydrostatical pressure on the membrane surface. Due to the low dynamic excitation level achieved by the experiment the dynamic effect is also small and can be neglected. The obtained resonance frequencies for these reservoir conditions, for the three lowest modes are also given in terms of functions of the equivalent average velocity $V^a_{s,w}$, which has been varied by several characteristic values in the analysis (see Fig. 7). Related to the experimental frequency values of $f^e_{1,w} = 4,2$, $f^e_{2,w}$ ) 6,3 and $f^e_{3,w} = 7,6$, which are practically equal to the frequencies for empty reservoir conditions, the presented diagrams show good correlation for $V^a_{s,w} = 1020$ m/sec. The corresponding values of $f^a_{1,w} = 4,3$, $f^a_{2,w} = 6,1$ and $f^a_{3,w} = 7,6$ show discrepancy from the experimental results only for 2,1%, -3,3% and 0,0%, respectively.

## COMPARISON OF THE RESULTS OBTAINED FOR EMPTY AND FULL RESERVOIR CONDITIONS AND WATER EFFECT

The investigations have shown that the resonance frequencies of the dam for the lowest three modes, for the tested empty and full reservoir conditions, are practically identical having values $f_1=4,2 - 4,3$, $f_2=6,3$ and $f_3=7,6 - 7,7$. Such a result was rather unexpectable, as lower frequencies were expected for the full reservoir conditions due to the additional water mass acting together with the system. Based on the analytical investigation results, in the case of the same conditions as those for an empty reservoir, i.e. for equivalent velocity $V^e_s = 950$ m/sec over the dam body the frequencies for full reservoir conditions should be $f^a_{1,w} = 4$, $f^a_{2,w} = 5,5$ and $f^a_{3,w} = 7,0$ c/sec, that is equal to a decrease rate of 7,5%, 10,9% and 8,6%, respectively.

The fact that resonance frequencies remain practically unchanged results from the additional stress effect in the dam body due to water pressures. As the dam is constructed of cohesionless material, the velocity $V_s$, i.e. the dynamic shear moduli G are also in function of the effective stresses within the dam. In this case, due to the effect of the upstream concrete face membrane, the dam body remains dry even under full reservoir conditions, so that the effective stresses increase in direct proportion with the water pressure.

According to the analyrical study the experimentally obtained resonance frequencies correspond to the equivalent average velocity $V^a_{s,w} = 1020$. Compared with $V^e_s = V^a_s = 950$ m/sec it is 7% larger, i.e.

$$\overline{V}_{s,w} = 1,07\ \overline{V}_s \qquad \ldots(2)$$

If the water effect upon stresses within the dam body are presented by the equivalent supposed bulk density of the built-in material it is obtained

$$\gamma_w = 2,52\ t/m^3 \qquad \ldots(3)$$

$$\gamma_w = 1,20\gamma$$

Taking the bulk density of the material directly proportional to the stresses in the dam body and expressing velocities $V_s$ in terms of it, it is obtained good correlation for

$$\bar{V}_s = 800\gamma^{1/4} \qquad \ldots(4)$$

For empty reservoir conditions it is

$$\bar{V}_s = 800 \times 2{,}1^{1/4} = 963 \text{ m/sec} \qquad \ldots(5)$$

while for full reservoir conditions it is

$$\bar{V}_{s,w} = 800 \times 2{,}52^{1/4} = 1008 \text{ m/sec.} \qquad \ldots(6)$$

## CONCLUSIONS

The investigations have shown that in dynamic analysis of the considered dam under full reservoir conditions the dam and the water should be treated as a unique dynamic system. The water effect consists of the effect upon the mass of the system and the effect upon the strength criteria of the system expressed in terms of velocity $V_s$.

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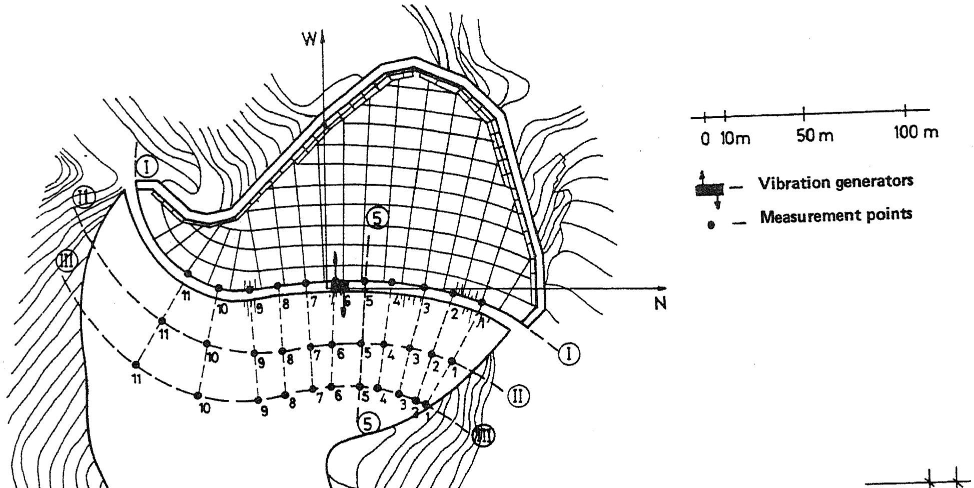

**Fig. 1** Location of Vibration Generators on the Dam Crest

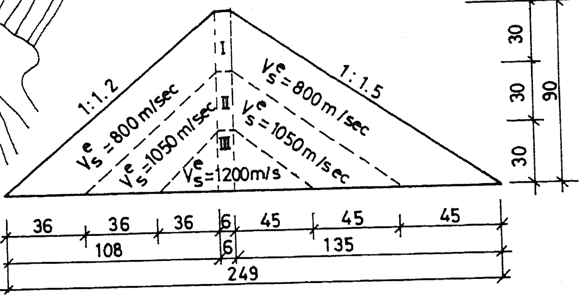

**Fig. 2** Experimental values of Velocity $V^e_s$ as correlated with $\sigma_1$

$V^e_s$ = Velocity $V_s$ as defined by experimental testing (m/sec)

$\overline{V}^e_s$ = average, equivalent velocity $V^e_s$ referring to the whole dam (m/sec)

$\sigma_1$ = vertical perpendicular stresses in the dam body (t/m$^2$)

Z = depth, as measured from the surface of the dam body (m)

$\gamma$ = bulk density of the built-in material = 2,1 t/m$^3$

$$V_s = 340(\sigma_1)^{1/4}$$

Zone I : $\overline{\sigma}_1 = 31{,}5$ t/m$^2$ $\quad V_s = 340 \times (31{,}5)^{1/4} = 805$ m/sec

Zone II : $\sigma_2 = 94{,}5$ t/m$^2$ $\quad V_s = 340 \times (94{,}5)^{1/4} = 1060$ m/sec

Zone III : $\sigma_3 = 157{,}5$ t/m$^2$ $\quad V_s = 340 \times (157{,}5)^{1/4} = 1204$ m/sec

$$\overline{V}^e_s = \Sigma(V^e_i)^2 \times li/\Sigma li \quad ^{1/2} = 950 \text{ m/sec}$$

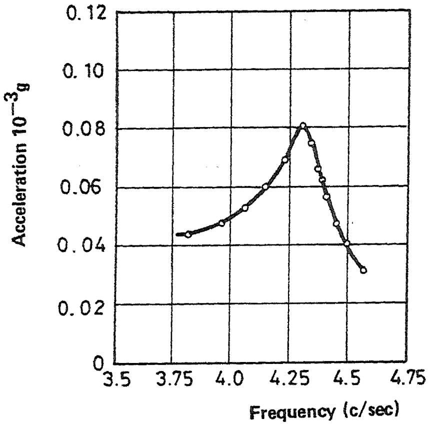

Fig. 3 Characteristic Resonance curve for the First Mode of Vibration for empty Reservoir Conditions

| EMPTY RESERVOIR | Resonance frequencies (c/sec) | | |
|---|---|---|---|
|  | I mode | II mode | III mode |
| | 4,3 | 6,3 | |
| | Equivalent damping (%) | | |
| | I mode | II mode | III mode |
| | 2,3-2,8 | 1,6-2,4 | 1,4-2,3 |

Table 1 Experimental Values of Resonance Frequencies and Equivalent Viscous Damping for empty Reservoir Conditions

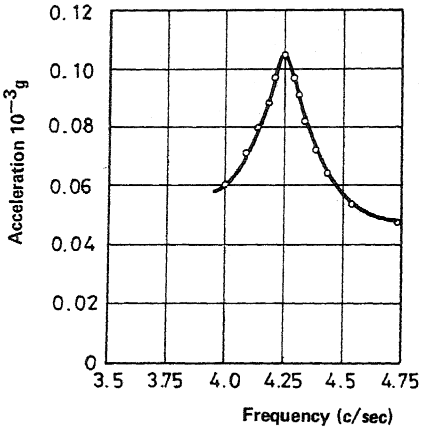

Fig. 4 Characteristic Resonance curve for the First Mode of Vibration for full Reservoir Conditions

| FULL RESERVOIR | Resonance frequencies (c/sec) | | |
|---|---|---|---|
|  | I mode | II mode | III mode |
| | 4,25 | 6,3 | 7,6 |
| | Equivalent damping (%) | | |
| | I mode | II mode | III mode |
| | 2,3-2,8 | 1,6-2,4 | 1,4-2,3 |

Table 2 Experimental Values of Resonance Frequencies and Equivalent Viscous Damping for full Reservoir Conditions

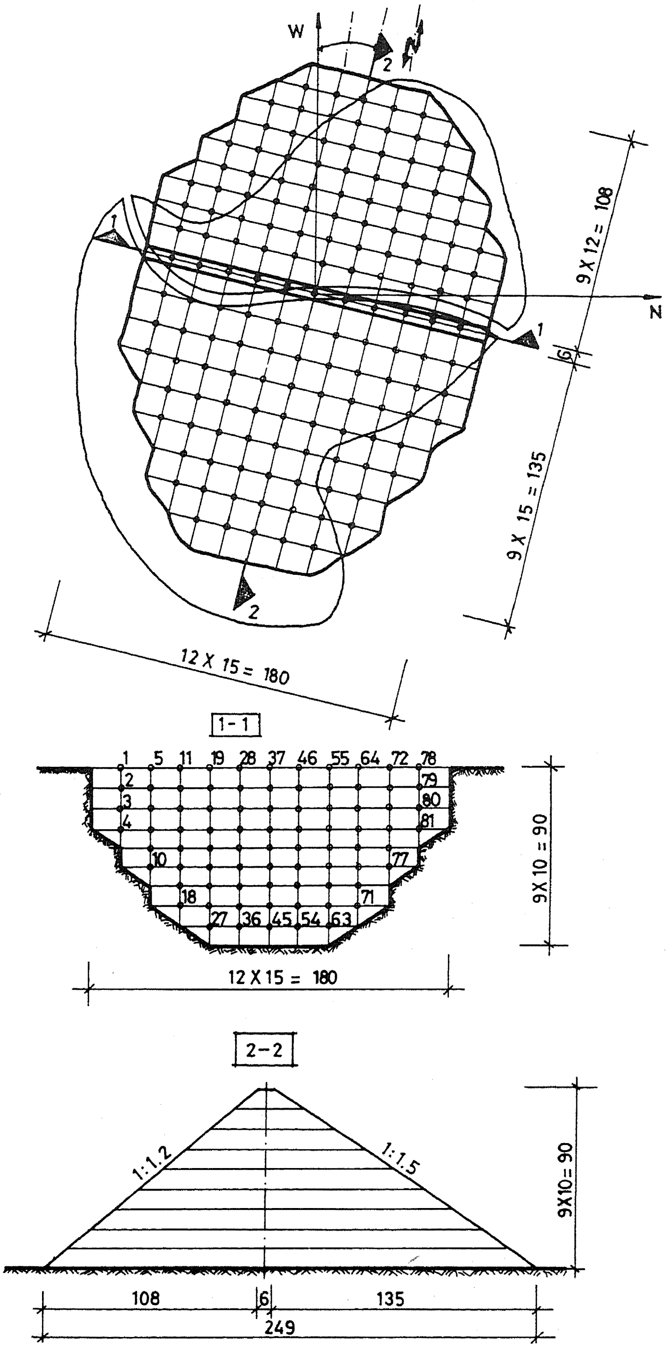

Fig. 5 Adopted Mathematical Model of the Dam

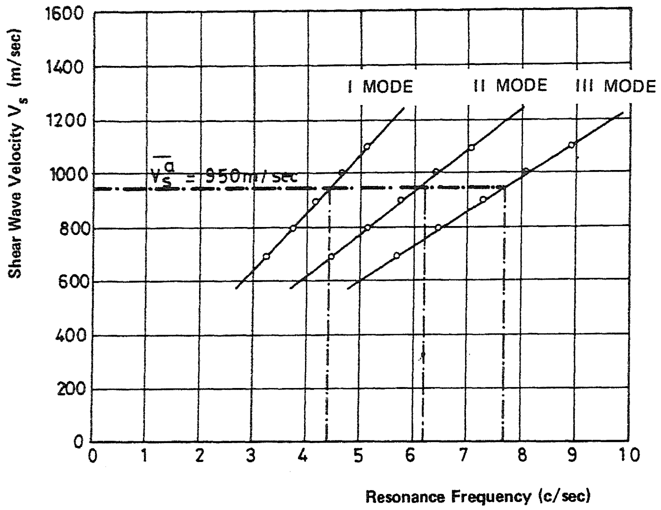

Fig. 6 Resonance Frequency Dependance upon Equivalent Velocity $V_s$ under Empty Reservoir Conditions

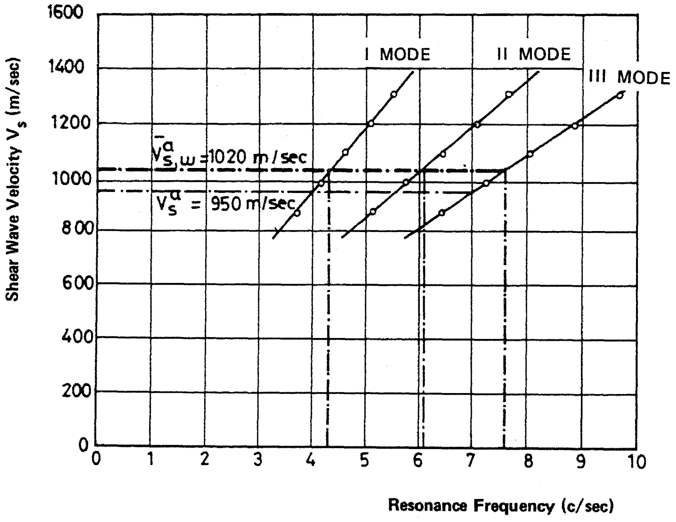

Fig. 7 Resonance Frequency Dependence upon Equivalent Velocity $V_s$ under Full Reservoir Conditions