SOME ASPECTS OF ASEISMIC DESIGN OF ROCKFILL DAMS

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SYNOPSIS

The current trend in the seismic stability analysis of rockfill dams is to assess the earthquake induced deformations in the maximum cross-section of the dam assuming rigid plastic behaviour of the materials. In the present paper two probable sections of a 99m high rockfill dam, one with a central core and the other with an inclined core have been analysed for obtaining earthquake induced deformations. The effect of confinement on dynamic elastic properties of the dam material has also been considered. The results of analysis have been compared with those observed in simulated model studies of the two sections which show fairly good agreement.

INTRODUCTION

In the past psuedo-static approach had been in use for ascertaining the stability of rockfill dams during earthquakes. Recently the trend has been to assess the deformations in the slope of the dam from the response of dam as a whole by suitable mathematical modelling and using the yield acceleration concept (2,3,4). Model testing based upon laws of simlitude (1) also offers a very useful tool for studying the qualitative behaviour and for comparison of different designs.

In the present study two probable sections of a 99.0m high rockfill dam, one with a central core, Fig 1, and the other with an inclined core, Fig 2, have been studied for determining their behaviour under the action of design earthquake, the response spectra of which is shown in Fig 3. The deformations of the dam have been worked out by computing its acceleration response by shear beam analysis and applying the yield acceleration concept. The effect of variation in elastic properties of the materials due to confinement has also been studied. The results of the analysis have been compared with those obtained in simulated model studies. The dynamic elastic properties used in the analysis were determined from in-situ vibration and wave propagation tests and the values at strain levels associated with the earthquake were adopted.

MATHEMATICAL MODEL OF THE DAM

The dam section has been treated as a shear beam and the continuous system idealised as a discrete spring-mass system consisting of 33 elements. Shear stiffness K_i of any horizontal slice of the dam cross-section has been obtained by assuming that the continuity of various materials within a slice is maintained at all stages of deformation.

$$K_i = \frac{1}{h_i} \sum_{j=1}^{m} \frac{A_{ij}\, G_{ij}}{C_s} \quad \ldots (1)$$

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where K_i = shear spring stiffness of a horizontal slice i, h_i = height interval between the two consecutive mass points i and i + 1, C_s = shape factor for shear stress distribution across each material in the slice, A_{ij}= horizontal cross-sectional area of the slice, G_{ij} = average shear modulus of the material, and m = number of materials constituting the slice.

The shear modulus has been assumed in two ways: (i) to be independent of confining pressure and (ii) to be varying in proportion to the square root of the confining pressures (1). For determining the effective shear modulus values at any elevation the variation (in confinement pressure over the width of each material) was worked out depending on the overburden of the material and averaged over the whole width of the particular material.

RESPONSE TO EARTHQUAKE MOTION

Contribution of the first ten shear modes of vibration has been considered in the analysis in each case. The time periods and participation factors are given in Table 1. Damping in the first, second and remaining modes of vibration has been taken as 10%, 20% and 30% of the critical viscous damping respectively. Total response to earthquake motion has been obtained from the modal responses by two methods (i)the quadratic super-position that is the square root of the sum of the squares, the results are shown in Table 2 for comparison and (ii) timewise super-position of the modal responses for the displacement analysis.

DISPLACEMENT ANALYSIS

Sliding of material near the slopes would occur if the accelerations exceed the 'yield' or 'threshold' limit. For purely frictional materials the surface slope is itself the most critical surface of least resistance, hence a conservative value of deformation will be obtained by considering the sliding of a rigid solid down the surface slope and restrained only by friction. The upstream slope being submerged becomes less stable because the horizontal inertia force acts on the saturated soil mass whereas the effective weight of the material providing frictional resistance is reduced due to buoyancy.. Under horizontal motion, the expression for yield acceleration, K_y, for a slope with material having effective angle of internal friction ϕ_e is given by

$$K_y = (\gamma_b / \gamma_s) \tan (\phi_e - \theta) \qquad \ldots (2)$$

where θ the slope of the inclined surface of dam, γ_b and γ_s are the buoyant and saturated unit weights of the upstream shell material. For $\phi_e = 36^\circ$, $\phi_e = \tan^{-1} (0.4)$, γ_b = 1.08 gm/cm^3 and γ_s = 2.08 gm/cm^3 yield acceleration is obtained as 125 cm/sec^2.

To obtain the deformation along the slope the values in Fig 5, determined for a solid resting an a horizontal surface ($\theta = 0$), are multiplied byaa factor $F(\theta) = \tan \phi_e \sin \theta + \cos \theta = 1.20$.

Variation of the maximum absolute acceleration along the height of the dam is shown in Fig 4. (It remains almost constant in the major portion of the height varying from 0.246g at the top to 0.16g in the middle portion). It is seen that the top portion near the crest is most critical for sliding of material which is also observed in the model tests. Larger accelerations near the base are associated with much higher frequency components approaching that of the ground motion thus giving smaller displacements. The average 'slip' of the material near the critical top portion was obtained by considering the absolute acceleration response at One-eight height of the dam below the crest. For the central core dam assuming shear moduli to be unaffected by confining pressures, the plot in Fig 5 show the time-wise acceleration response and also velocity response. The yield acceleration and the procedure of computing displacements are also shown in the same Fig. Two slopes as shown, when multiplied by F (θ) give a total downhill displacement of 25 cm. Corresponding values for the inclined core dam with constant and varying shear moduli are 17 cm and 205 cm respectively. Maximum crest acceleration in the three cases are 0.246g, 0.273g, 2.10g respectively.

MODEL STUDIES

Models of the central and inclined core dam sections made to scale ratio 1:150 were tested to compare their relative performance under reservoir full and reservoir dry conditions. The materials for the shell and core of the model were selected after extensive tests so that the simlitude requirements with respect to strength could be satisfied as far as possible. Table 3 shows a comparison of the required and actual properties of the model material. Figure 6 shows a typical view of the model before testing and also a typical record of table motion. The tests were performed by subjecting the model to simulated ground motion by horizontal impact of a falling pendulum on the platform of the shake table. The total weight of the falling pendulum and height of fall were adjusted such that, in both the elastic and inelastic ranges, the effect was more severe than that of ground motion. Observations were made of (i) time history of table acceleration (ii), time history of model response at different elevations and (ii) profile measurement before and after the shock.

Elastic Response Characteristics. The best way of comparing the forces developed in the model and prototype is by means of acceleration response spectra. The fundamental period of the prototype from shear beam analysis for the central core section is 2.587 seconds. The maximum modal acceleration corresponding to 10% damping from Fig. 3 is 150 cm/sec^2. The response spectra for the table motion is shown in Fig. 7 for reservoir full case. The fundamental period for the model with central core is 0.0552 sec and corresponding modal acceleration for 10% damping is 1100 cm/sec^2. To compare the total response directly in all modes, the prototype response is plotted with time axis converted to model scale in Fig. 7. It is seen that corresponding to any period the acceleration developed through table motion is much more severe than earthquake effect on prototype. Similar observations are made in case of inclined core model.

Inelastic Response. The damage potential of table motion was obtained by integrating the area of recorded accelerogram of simulated earthquake above the yield acceleration level of the model slopes (3, 4). The damage potential of the design earthquake with respect to the prototype was also obtained similarly. For similitude, the damage potentials should be in the ratio

$$\frac{(\text{Damage Potential})_{\text{Model}}}{(\text{Damage Potential})_{\text{Proto.}}} = \frac{(\text{Unit weight})_{\text{Proto.}}\ (\text{Shear modulus})_{\text{Model}}}{(\text{Unit weight})_{\text{Model}}\ (\text{Shear Modulus})_{\text{Proto.}}}$$

The damage potential of the table motion converted to prototype scale for the central core section are shown in Table 4, along with the values for the prototype. It is observed that damage potential of table motion is much higher than that of ground motion. Similar observation are made for the inclined core model.

The observed deformations of the model shown in Fig 8 and may be extrapolated to prototype scale. The maximum vertical displacement in the model for one simulated earthquake, in case of central core, is 0.2 cm and corresponding prototype deformation 0.30m. In case of inclined core model the deformation is 0.36cm and corresponding prototype deformation 0.54m.

DISCUSSION

The values of displacements as obtained in these studies by the constant and varying values of shear modulus are given in Table 5. It is seen that for the inclined core dam, the analytical as well as experimental results agree fairly well if the variation of shear modulus is included in the analysis. Since the spectra of an actually recorded earthquake (modified though) has been used, it is difficult to guess what results would have been obtained for the central core dam with varying shear modulus as the periods get modified. However it is evident that as the response of the dam would be larger due to the higher effective stiffnesses, larger deformation would have been shown.

It is however interesting to note that though pseudo-static analysis of the top portion of the dam with seismic coefficients corresponding to the computed response at that elevation would have indicated unsafe design, the deformations as calculated and also as observed fro model tests are as small as 76cm which is less than 1% height of the dam.

CONCLUSIONS

The results reported here above indicate the following: (1) The consideration of the effect of confining pressures on the value of shear modulus increases the effective stiffness of the dam section compared to the case where a uniform shear modulus obtained on the basis of surface tests (as in the common practice) is used. This leads to larger forces and larger permanant displacements. The actual variation of the values of shear modulus in the dam section is therefore very important and needs careful investigation. (2) The results of the analytical studies agree better with the results from model tests variation in shear modulus with confinement is considered. (3) The model tests also show that slumping of the crest is larger when the dam has an inclined core. Although the tendency of separation of the shell from the core is more with central core section.

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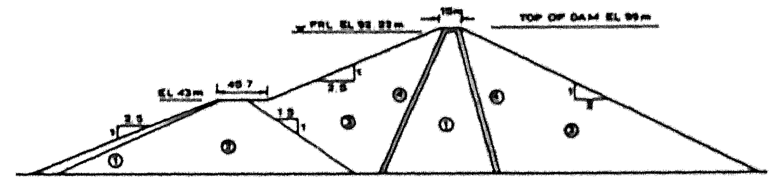

FIG. 1 _DAM SECTION WITH CENTRAL CORE

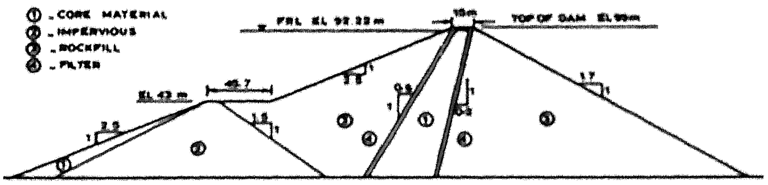

FIG. 2 _DAM SECTION WITH INCLINED CORE

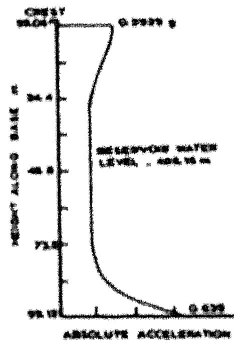

FIG. 4 _ENVELOPE OF MAX ABSOLUTE ACCELERATION ALONG THE HEIGHT OF THE DAM

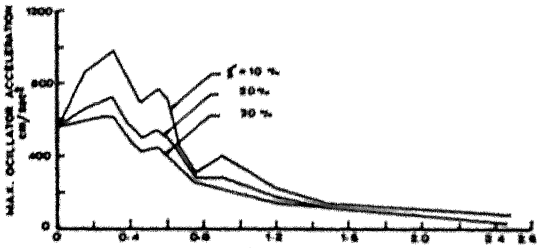

FIG. 3 _ RESPONSE SPECTRA FOR DESIGN EARTHQUAKE

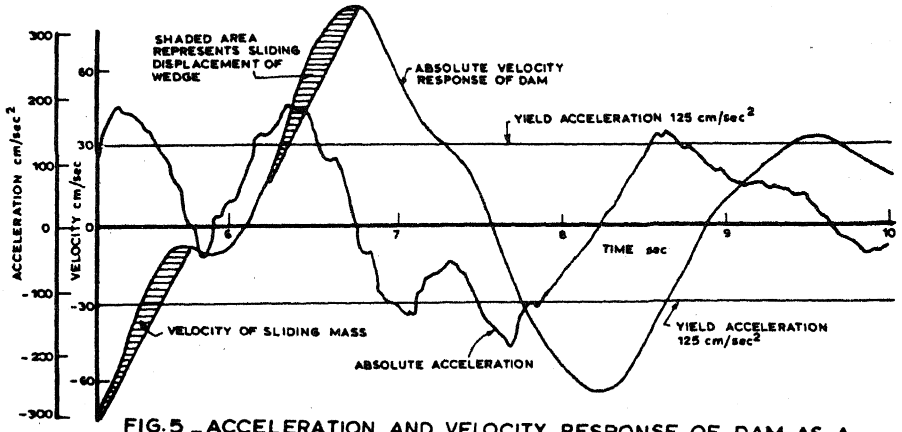

FIG. 5 _ ACCELERATION AND VELOCITY RESPONSE OF DAM AS A FUNCTION OF TIME FOR A POINT 13.34 m BELOW CREST

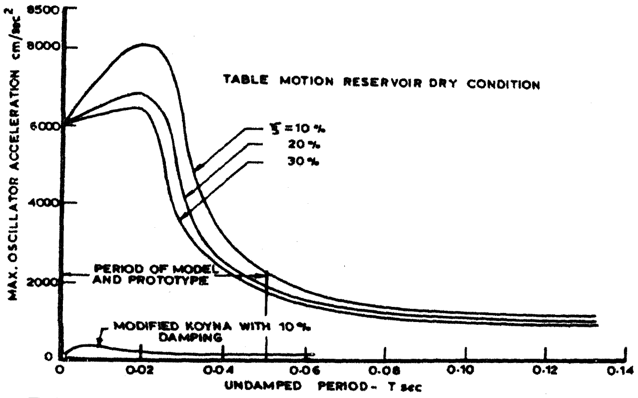

FIG. 7 _ ACCELERATION SPECTRA FOR SIMULATED EARTHQUAKE AND MODIFIED KOYNA EARTHQUAKE

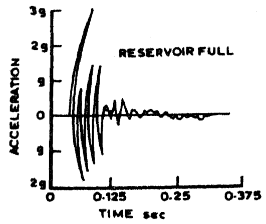

FIG. 6 _ TYPICAL VIBRATION RECORD OF THE SHAKE TABLE

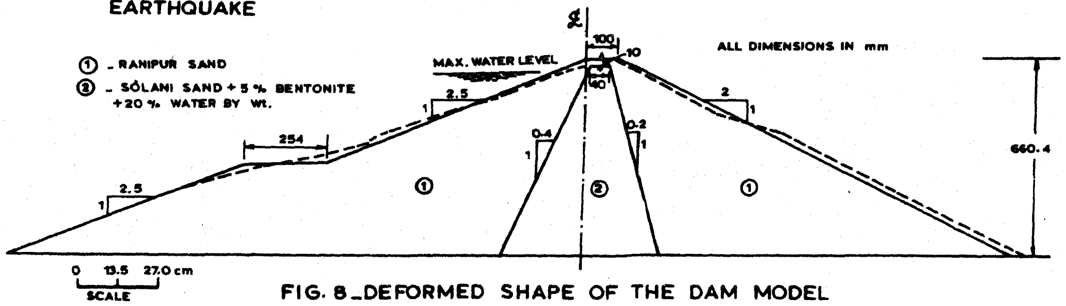

FIG. 8_DEFORMED SHAPE OF THE DAM MODEL

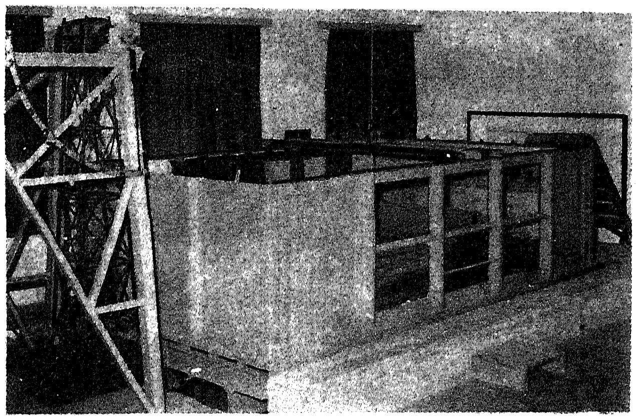

FIG. 9_ A VIEW SHOWING SHAKE TABLE AND DAM MODEL

TABLE 1 - COMPARISON OF PERIODS AND FACTORS

		MODE									
		1	2	3	4	5	6	7	8	9	10
TIME PERIOD (SEC)	CENTRAL CORE CONSTANT G	2.59	1.13	0.70	0.52	0.40	0.34	0.29	0.25	0.23	0.21
	INCLINED CORE CONSTANT G	2.45	1.11	0.69	0.52	0.40	0.34	0.29	0.25	0.22	0.20
	INCLINED CORE VARYING G	1.16	0.58	0.38	0.28	0.23	0.19	0.16	0.14	0.13	0.12
MODE PARTICIPATION FACTOR	CENTRAL CORE CONSTANT G	1.58	0.99	0.76	0.65	0.58	0.53	0.41	0.41	0.34	0.29
	INCLINED CORE CONSTANT G	1.65	1.09	0.84	0.70	0.60	0.53	0.46	0.42	0.37	0.34
	INCLINED CORE VARYING G	1.95	1.71	1.51	1.39	1.21	1.11	1.05	0.93	0.86	0.74

TABLE 2 - MAXIMUM RESPONSE OF INCLINED CORE DAM

Sec No.	x/h	Y_{max}(cm) Const G	Y_{max}(cm) Vary G	V_{max}(t) Const G	V_{max}(t) Vary G	α_h/g Const G	α_h/g Vary G	Average α_h/g Const G	Average α_h/g Vary G
1	0	24.8	64.5	5	28	0.27	1.63	0.27	1.63
								0.21	0.84
2	1/8	24.7	52.4	78	311	0.19	0.59		
								0.18	0.52
3	1/4	22.4	41.7	195	582	0.15	0.28		
								0.15	0.35
4	3/8	19.5	33.4	337	792	0.12	0.16		
								0.13	0.27
5	1/2	16.1	26.7	487	1023	0.09	0.16		
								0.11	0.25
6	5/8	12.7	20.7	680	1487	0.08	0.22		
								0.10	0.24
7	3/4	8.9	14.3	869	2062	0.07	0.22		
								0.09	0.23
8	7/8	4.8	7.7	1037	2669	0.05	0.18		
								0.08	0.20
9	1	0	0	1443	2980	0.01	0.01		

$\frac{x}{h}$ = Ratio of depth of section below top to the height of dam

Y_{max} = Maximum horizontal displacement

V_{max} = Maximum shear force

α_h = Equivalent horizontal acceleration at the section

Average α_h = Effective uniform seismic coefficient acting on the mass above the section

TABLE 3 - REQUIRED AND USED PROPERTIES OF MODEL MATERIALS

PROPERTY	VALUE IN PROTOTYPE	SCALE RATIO	VALUE IN MODEL REQUIRED	VALUE IN MODEL USED
Height(m)	99.0	1/150	0.66m	0.66m
ϕ(shell) (°)	40	1	40	40
(shell) gm/cu^3	2.0	0.957	1.99	1.99
ϕ (core)	25	1.0	25	25
C (core) kg/cm^2	0.0975	0.957/150	.000624	.0027
(core) gm/cc	2.03	0.957	1.940	1.960
(shell) kg/cm^2	.260	0.957/150	1.658	23.2

TABLE 4 - DAMAGE POTENTIAL OF DESIGN EARTHQUAKE AND TABLE MOTION

Motion on Prototype scale	Damage Potential for Yield acceleration of			
Design earthquake	0.1g	0.15g	0.2g	0.25g
Table motion	97.0	61.0	34.4	-
1) Reservoir dry	137.0	130.0	123.0	117.8
2) Reservoir full	148.0	174.0	172.0	168.0

ϕ = angle of internal friction;

γ = dry density; C = cohesion;

G = shear modulus.

TABLE 5 - ESTIMATED DISPLACEMENT OF U/S SLOPE

DAM SECTION	ANALYTICAL STUDIES SLIP FOR CONSTANT G Along slope (cm)	ANALYTICAL STUDIES SLIP FOR CONSTANT G Vertical (cm)	ANALYTICAL STUDIES SLIP FOR VARYING G Along slope (cm)	ANALYTICAL STUDIES SLIP FOR VARYING G Vertical (cm)	MODEL TESTS VERTICAL SETTLEMENT (cm)
CENTRAL CORE	25.0	9.25	-	-	30.0
INCLINED CORE	17.0	6.3	205.0	76.2	54.0