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AN OVERVIEW OF APPROXIMATE METHODS FOR SEISMIC ANALYSIS OF GRAVITY DAMS

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ABSTRACT

The purpose of approximate method of seismic analysis is to make a reasonable estimate of dynamic forces in a gravity dam without resorting to elaborate calculations. The approximate method is considered adequate at the stage of preliminary design when the cross section and geometry of the dam is being established Several simplified procedures are in use for such studies and the designer often finds difficult to choose the best of these methods. This paper presents an overview of four different analysis methods in use with the assumptions involved and their limitations. Using the different methods, the seismic analysis of eight gravity dams ranging from 60m to 225m is carried out. The comparison of the bending moments and shear forces obtained by different methods is presented treating the bending shear method as a reference. It has been observed that the time periods obtained by the IS code method is on the lower side as compared to the values obtained by bending-shear analysis. The period coefficients for considering the reservoir effect as an added mass of water is also presented.

Key Words : Seismic Analysis, Gravity Dam, Approximate Methods, Dynamic Shear, Dynamic Moments, Period Coefficient.

INTRODUCTION

The gravity dams are the structures of great importance that must be protected from catastrophic failure during the earthquakes. Methods of analysis and design of gravity dams for earthquake motion is in the continuous process of development. Much sophisticated methods considering reservoir-dam-foundation interaction during earthquakes have been developed. These methods based on the finite element methods are time taking and expensive procedures. The detailed methods are indeed necessary while checking the final designs It is essential that for structures like dams, the design organisations are conversant with approximate methods of aseismic design, its assumptions and limitations, so that the finally adopted section of the dam may not later be found inadequate against dynamic forces due to strong ground excitation. The simplified procedures should be such that it could be easily adopted and provide results with a reasonable accuracy compared with the values obtained by more sophisticated methods. Each of the simplified methods have certain assumptions and limitations. The paper describes four different methods, its assumptions and limitations. These four methods are (i) Saini–Vishwanath method (ii) IS Code method, (iii) Bending-Shear analysis and (iv) Chopra's method.

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Using the different approximate methods, the seismic analysis of eight gravity dams ranging from 60 m to 225 m is carried out. The comparison of the fundamental period and responses obtained by different methods is presented treating the bending-shear method as a reference It has been observed that the time periods obtained by IS Code method is on the lower side as compared to the values obtained by bending-shear analysis. The period coefficient in the fundamental time period formula of the dam considering the reservoir effect as an added mass of water is also presented.

SIMPLIFIED METHODS OF DYNAMIC ANALYSIS

The four simplified procedures for preliminary design of gravity dams under earthquake motion are presented here in brief for completeness of discussion. The details of these methods are available in references 1 to 4.

Saini-Vishwanath method (1)

The procedure is based on the Rayleigh method in which an approximation is made of the dynamic deflection configuration. The method is based on the following assumptions,

(i) The static deflected shape is considered as the dynamic deflection configuration of the dam.

(ii) The deformation due to both bending and shear are considered.

(iii) The dynamic analysis is based on beam model.

(iv) Water effect is considered as an added mass of water.

The steps involved in the method are described below :

(i) The dam is discretized by lumping the masses at a convenient number of points.

(ii) Determine the static deflections at each node point under gravity turned on position.

(iii) Determine the fundamental period by Rayleigh method.

(iv) Using the response spectrum determine the dynamic response.

The following are the limitations of the method :

(i) Limitation of beam methods and added mass of water to include hydrodynamic effect are present.

(ii) The dam is considered fixed at the base of the foundation.

IS Code method (2)

There are two methods suggested in IS: 1893-1975 for preliminary design of dams, (a) seismic coefficient method, and (b) response spectrum method. The seismic coefficient method is recommended for dams below 100m in height and response spectrum method for dams above 100m in height. In the study presented here the response spectrum method is employed both for dams above and below 100m in height. The assumptions in the method are stated below :

(i) The method is based on bending-shear analysis of different sections of gravity dams.

(ii) The influence of higher modes is considered in moment and shear curves presented in the code.

(iii) The effect of water is not considered in the response spectrum method, but it is considered separately as hydrodynamic pressure.

(iv) The dam is considered fixed at the base of dam section, foundation-structure interaction affects are not included.

The following steps are involved in the response spectrum method.

(i) Determine the fundamental period of vibration of dam by the following formula,

$$T = C_T \, H^2/B \sqrt{w_m/g \, E_s} \quad (1)$$

where H and B are the height and base width of dam in meters, w = unit weight of material in kg/m³, g=acceleration due to gravity in m/s², and E_s=modulus of elasticity of the material in kg/m², C_T = 5.55 (period coefficient in IS Code)

(ii) Using the time period and a damping factor of 5% for concrete, the design seismic coefficient α_h shall be obtained as follows,

$$\alpha_h = \beta I F_o \frac{S_a}{g} \quad (2)$$

where β, I, F are soil-foundation factor, importance factor and zone factor respectively. The spectral acceleration ratio Sa/g is directly obtained from the response spectrum curve.

(iii) The base shear V_B and base moment M_B are obtained from the following formula,

$$V_B = 0.6 \, W\alpha_h$$

$$M_B = 0.9 \, W\bar{h}\alpha_h \quad (3)$$

where W=total weight of concrete in the dam in kg and $\bar{h}$ = height of the centre of gravity of the dam above the base in meter.

(iv) For any horizontal section at a depth y below top of the dam, the shear force, V_y and bending moment M_y are obtained as follows,

$$V_y = C'_v V_B$$

$$M_y = C'_m M_B \quad (4)$$

where C'_v and C'_m are given in Figure 1. These curves are based on average values obtained from the analysis of dams of different height and base width.

The following limitations of IS Code method must be observed :

(i) The effect of water on time period is not considered.

(ii) The limitations of beem method are present.

(iii) The factors and coefficients are average figures and may not be representative for dams of all heights, base widths, slope etc.

Bending Shear Analysis (3)

The dynamic analysis in this method is based on lumped mass beam model in which both bending and shear deformations are considered. Since the IS Code method is also based on bending-shear analysis, the assumptions in this method are the same as mentioned in IS code method. However the bending-shear analysis of a dam has following merits over the method presented in IS Code,

(i) Actual dam profile can be considered in the analysis.

(ii) Elastic properties could vary along the height.

(iii) Effect of water can be considered as an added mass of water or separately as hydrodynamic pressure.

(iv) The effect of any number of modes could be considered.

The following st ps are involved in this method.

(i) Determine the first-three or four natural frequencies by the method of transfer functions or stiffness matrix method.

(ii) Using the reponse spectrum, determine the reponse in different modes of vibration.

(iii) Determine the total response by square root of sum of squares method.

The following limitations of bending-shear analysis must be observed.

(i) The limitation of beam method are present.

(ii) The dam is considered fixed at the base.

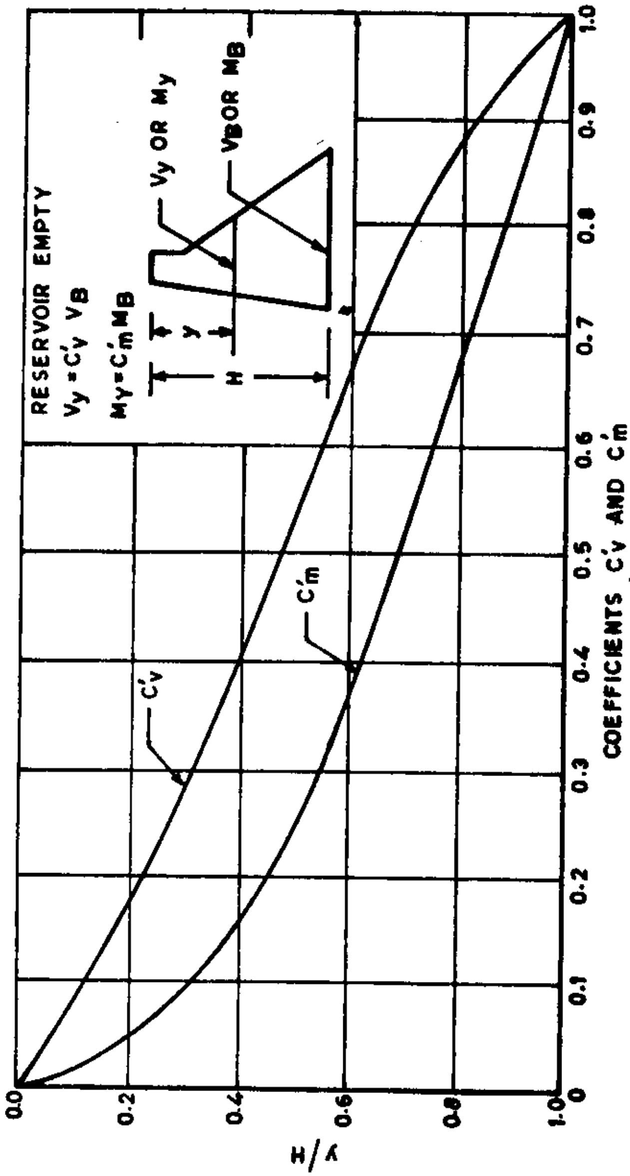


Fig. 1—Values of C'_v and C'_m Along the Height of Dam

Chopra's method (4)

The earthquake forces are approximately obtained for the preliminary design of concrete gravity dams having short fundamental time period. The following are the assumptions in this method,

(i) This procedure considers only fundamental mode of vibration.

(ii) The effect of only horizontal component of vibration is considered.

(iii) Cross-sectional shapes of gravity dams do not vary too widely.

(iv) The effect of compressibility of water due to reservoir dam interaction is taken into account.

The following steps are involved in this method of dynamic analysis,

(i) The fundamental period of vibration of the dam, T_s, is computed without considering the influence of water,

$$T_s = 12H_s/\sqrt{E} \qquad (5)$$

where, H_s = height of dam in meter, E = modulus of elasticity of material of dam in Kpa (1 Kpa = 1000N/m²).

(ii) The fundamental period of vibration of the dam, $\bar{T}_s$ is then computed considering the influence of stored water,

$$\bar{T}_s = R_1 \bar{T}_s$$

where R_1 = period ratio determined from the curves (ref. 4) for the design values of H_1 and E, H = depth of stored water.

(iii) Compute R_2, the ratio of the fundamental period of the impulsive hydrodynamic pressure and $\bar{T}_s$,

$$R_2 = 1/\bar{T}_s.\ (4H/C) \qquad (7)$$

where C = velocity of sound in water = 1438 m/sec.

(iv) Compute f_s (y), the lateral earthquake forces over the height of the dam including the hydrodynamic effects, from,

$$f_s(y) = \alpha_1\ Sa\ (\bar{T}_s)/g\ [w_s(y)\Psi(y) + g\ \bar{p}_1\ (y)] \qquad (8)$$

$\alpha_1 = 4$, $Sa(\bar{T}_s)$ = ordinate of the design response spectrum, g = acceleration due to gravity, $w_s(y)$ = weight per unit height of the dam, Ψ (y) = fundamental mode shape of the dam given in curve (ref. 4). Corresponding to the computed values of R_2 and for $H/H_s = 1$, the quantity $gp_1(y)$ is determined from the given curves; the result is multiplied by the design value of $(H/H_s)^2$ and substituted in equation (8).

(v) The lateral earthquake forces without the hydrodynamic effects may be computed from,

$$f_s(y) = \alpha_2\ Sa(T_s)/g.[w_s\ (y)\ \Psi(y)] \qquad (9)$$

where $\alpha_2 = 3$.

The following limitations of the method must be observed.

(i) The effect of higher modes is not considered. The method is suitable for concrete dams of low height.

DAM SECTIONS CONSIDERED FOR STUDY

Eight dam sections have been considered in this study. The characteristics of these dams is presented in Table 1. The dam profiles are given in Figure 2. The heights of these dams range from 60 m to 225 m which cover the range of most gravity dams in the country. The analysis of all the dams has been carried out for modulus of elasticity, $E = 2.1 \times 10^6$ t/m^2, unit weight of the material of dam = 2.4 t/m^3, Poisson's ratio = 0.2 and shear deflection factor = 1.2

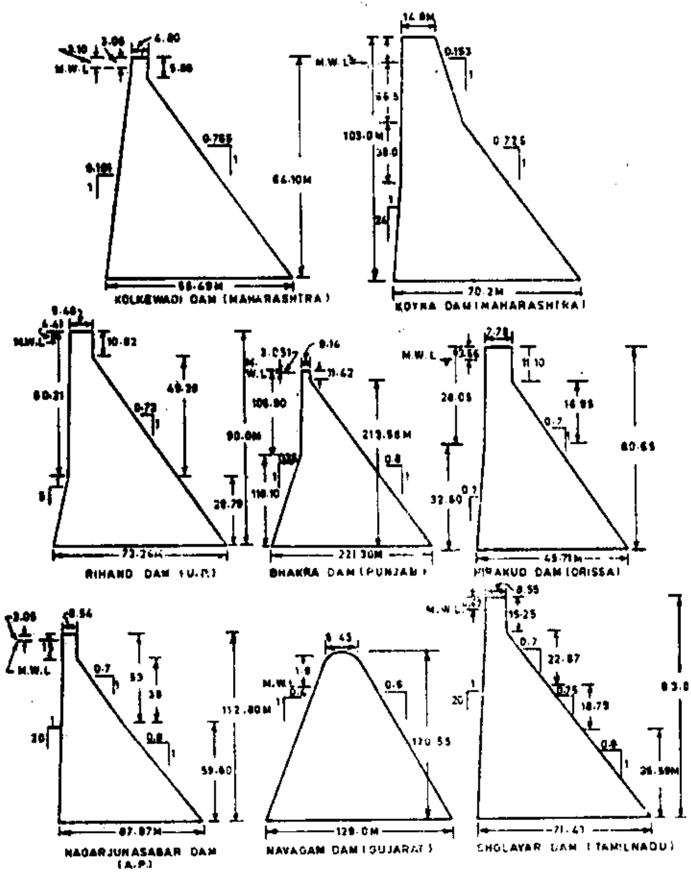


Fig. 2—Dam Considered for Seismic Study by Approximate Methods

TABLE—1

CHARACTERISTICS OF DAM SECTIONS

Sl. No.	Name of Dam	State to which it belongs	Height m	U/S slope	D/S slope	Top width in m	Free board in m	Base width in m	Ratio of base width to height of dam	Material of construction
1.	Kolkewadi	Maharashtra	64.10	.101	.765	4.80	3.10	55.49	0.865	Masonry
2.	Koyna	Maharashtra	103.00	.04	.153 and .725	14.80	11.00	70.20	0.763	Rubble. Concrete
3.	Rihand	U.P.	90.00	.20	.73	9.48	4.41	73.24	0.815	Concrete
4.	Bhakra	Punjab	225.00	.35	.80	9.14	3.05	221.30	0.982	Masonry
5.	Nagarjunasagar	A.P.	112.80	.05	.75	8.54	3.05	87.87	0.776	Masonry
6.	Hirakud	Orissa	60.65	.10	.70	7.78	3.66	45 71	0.750	Masonry
7.	Navagam	Gujarat	120.55	.40	.60	8.45	18.00	129.00	1.07	Concrete
8.	Sholayar	Tamilnadu	93.00	.05	0.7,0.75 and 0.8	8.55	4.57	71.43	0.768	Masonry

EARTHQUAKE DATA AND DAMPING

The response of the dams considered have been evaluated for Zone IV in India and the average acceleration spectra (Fig. 3, IS: 1893) for 5% damping is used. The effect of horizontal component of ground motion has only been considered in the analysis.

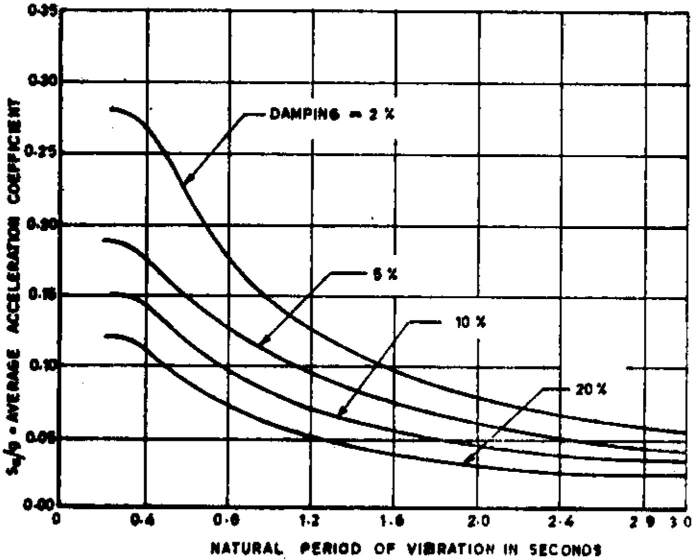


Fig. 3—Average Acceleration Response Spectrum

RESULTS OF ANALYSIS

As a result of seismic analysis, the fundamental time periods are obtained for eight dams using four methods. The seismic response is obtained in terms of base bending moment, base shear, and distribution of moment and shear along the height.

Fundamental Period :

The fundamental time periods and period coefficient, C_T obtained by four methods for eight dams is presented in Tables 2 and 3 for reservoir empty and full condition respectively. It is observed that the average value of C_T given in IS Code is on the lower side for all dams with respect to the values obtained by the other methods.

TABLE—2

FUNDAMENTAL TIME PERIOD IN SECOND AND COEFFICIENT C_T FOR RESERVOIR EMPTY CONDITION

Sl. No.	Dam Sections	IS : Code Method		Saini's Method		Bending-Shear Analysis		Chopra's Method	
		T	C_T	T	C_T	T	C_T	T	C_T
	Above 100m height								
1.	Bhakra Dam	0.433	5.55	0.440	5.639	0 469	6.004	0 594	7.607
2.	Koyna Dam	0.286	—	0.342	6.625	0.351	6 805	0 272	6 272
3.	Nagarjuna sagar Dam	0.274	—	0.267	5.403	0.281	5.687	0.298	6 028
4.	Navagam Dam	0 213	—	0.245	6.365	0 263	6 844	0.318	8 269
Average C_T for dams above 100m			5.55		6 008		6.335		6.794
	Below 100m height								
6.	Hirakud Dam	0.153	5.55	0.164	5.960	0.171	6.225	0.160	5 828
6.	Kolkewadi Dam	0.140	—	0.140	5.527	0.147	5 815	0.169	6.694
7.	Rihand Dam	0.210	—	0.222	5.880	0.228	6.036	0.226	5.978
8.	Sholayar Dam	0.229	—	0.233	6.059	0.251	6.072	0.246	5.951
Average C_T for dams below 100m.			5.55		5.857		6.037		6.113

TABLE—3

FUNDAMENTAL TIME PERIOD IN SECOND AND COEFFICIENT C_T FOR RESERVOIR FULL CONDITION

Sl. No.	Dam Sections	Saini,s Method		Bending-Shear Analysis		Chopra's Method	
		T	C_T	T	C_T	T	C_T
	Above 100m height						
1.	Bhakra Dam	0.451	5.775	0.478	6.121	0 787	10.076
2.	Koyna Dam	0 347	6.726	0.360	6 978	0.787	6.183
3.	Nagarjuna sagar Dam	0.277	5.604	0.298	6.028	0 386	7.809
4.	Navagam Dam	0.247	6.423	0.266	6.917	0.359	9 335
Average C_T for dam above 100m.			6.132		6.511		8.351
	Below 100 m height						
5.	Hirakud Dam	0.167	6.079	0.182	6.625	0.198	7.207
6.	Kolkewadi Dam	0.143	5.657	0.150	5.934	0.213	8.426
7.	Rihand Dam	0.228	6.039	0.240	6 357	0.284	7.522
8.	Sholayar Dam	0.239	5.782	0.258	6.242	0.306	7.403
Average C_T for dams below 100m.			5.890		6.290		7.640

The fundamental time period of dam obtained by IS : 1893-75 for reservoir empty condition is about 12% less than that obtained by bending shear analysis for dams above 100 m height and 8% less for dams below 100 m height.

The fundamental time period obtained by Saini-Vishwanth method is about 5% less for reservoir empty condtion and is about 6% less for reservoir full condition than the value obtained by bending-shear analysis.

The fundamental time period obtained by Chopra's method for reservoir empty condition is about 7% more for dams above 100 m in height and is about 2% more for dams below 100 m in height.

The fundamental time period by Chopra's method for reservoir full condition is about 28% more for dams above 100 m and about 22% more foɹ dams below 100 height. The considerable increase in fundamental period is possibly due to the effect of compressibility of water considered in this method.

Average Period Coefficient :

The average period coefficient C_T in bending shear-analysis for reservoir full condition on the basis of added mass of water is observed to be 6.511 for dams above 100 m height and 6.290 for dams below 100 m height.

Dynamic Shears and Moments :

The dynamic shear and moment distribution along the height of dam for eight dams, obtained by four different approaches are shown in Figures 4-11. It is observed from the Figures (4-11) that base shear and base moment values obtained by Chopra's method in reservoir full condition are higher in all the dams except in Bhakra. The lower values obtained in Chopra's method in this case is possibly due to omission of higher modes in this method. The effect of higher modes in 225 m Bhakra dam would be significant.

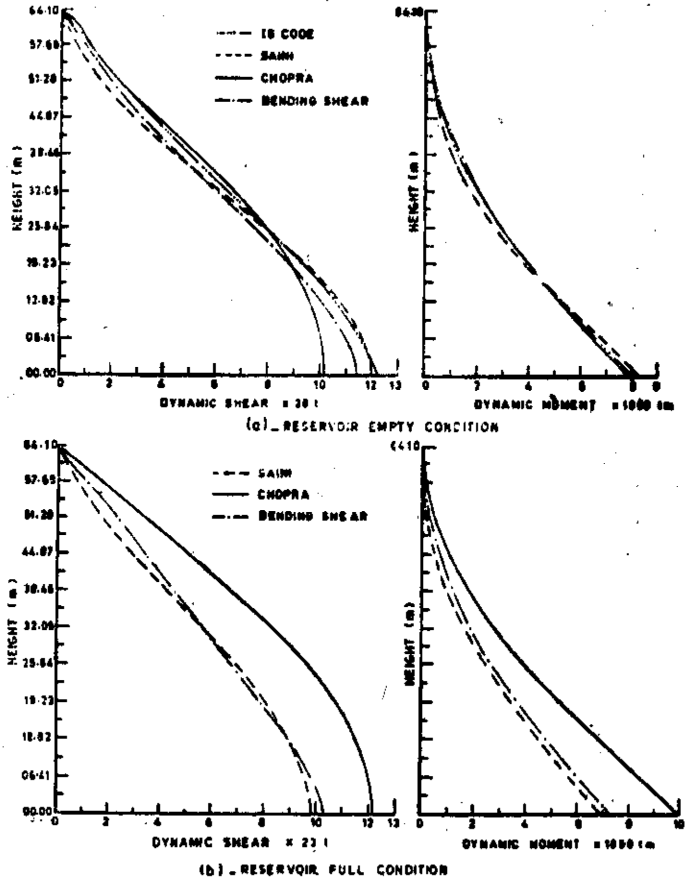


Fig. 4—Dynamic Shears and Moments for Kolkewadi Dam

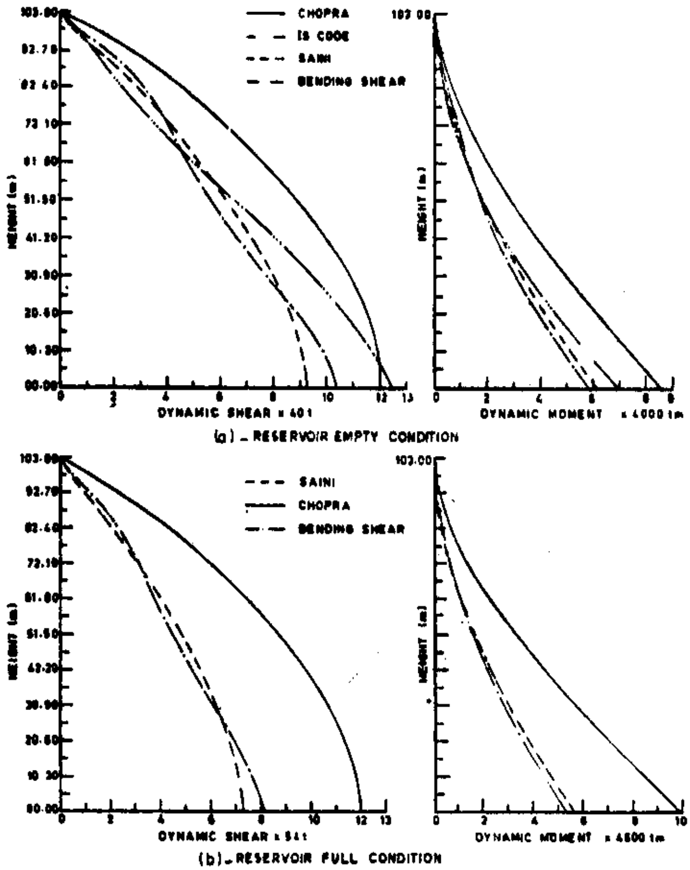


Fig. 5—Dynamic Shears and Moments for Koyna Dam

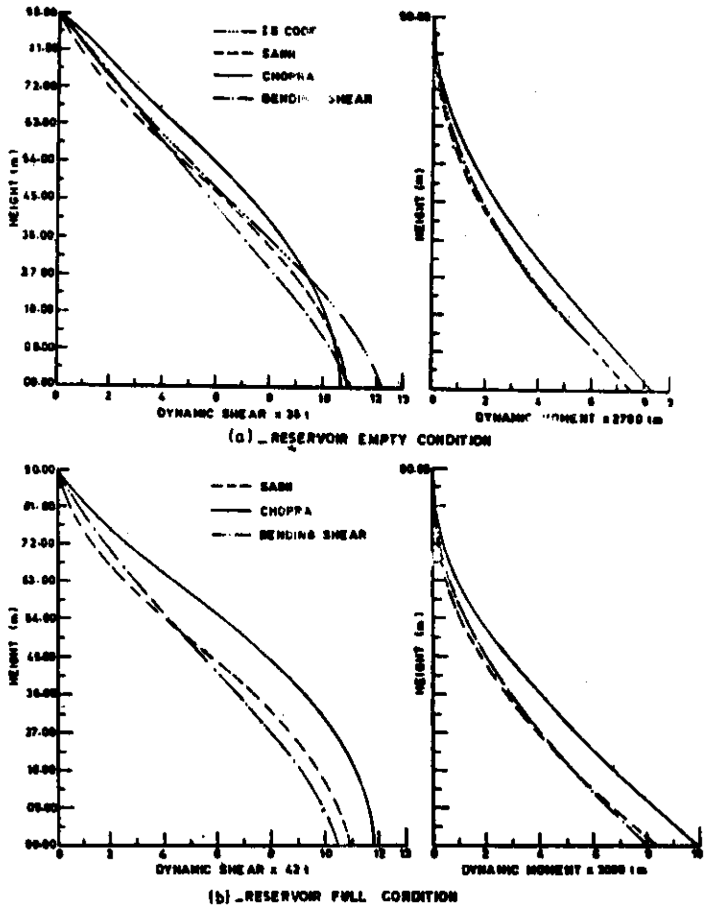


Fig. 6—Dynamic Shears and Moments for Rihand Dam

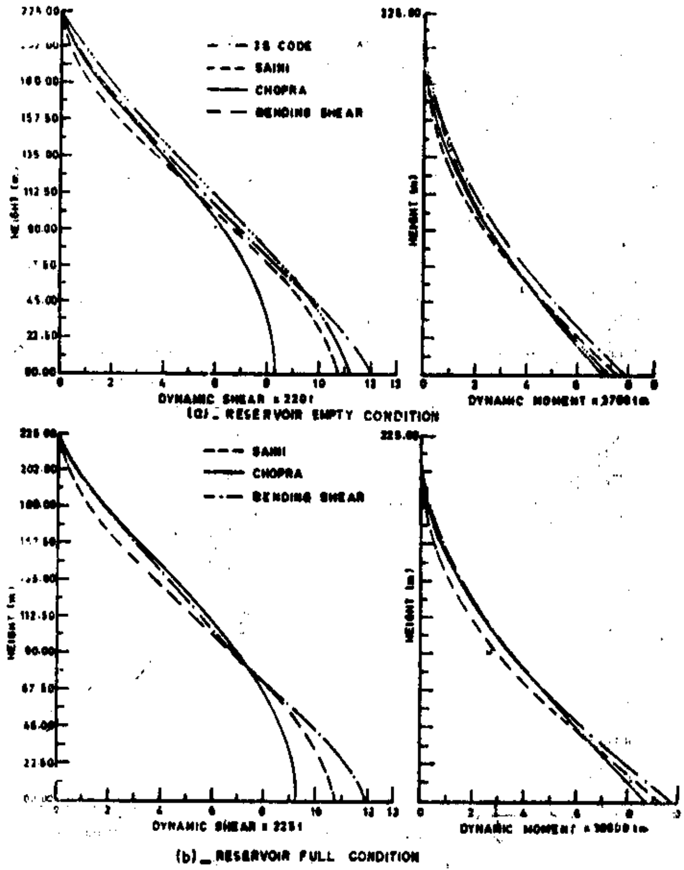
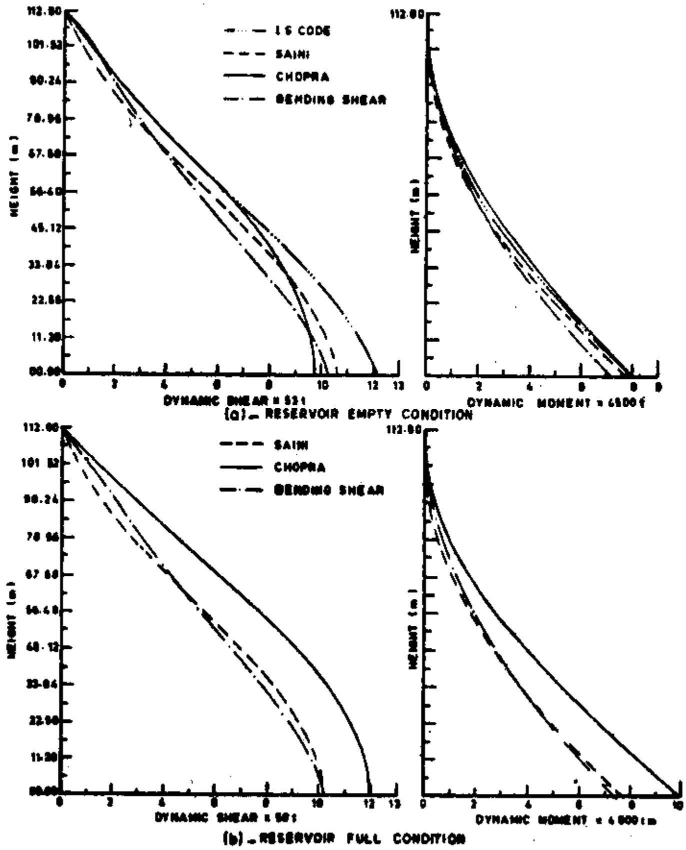


Fig. 7 — Dynamic Shears and Moments for Bhakra Dam



8—Dynamic Shears and Moments for Nagarjun Sagar Dam

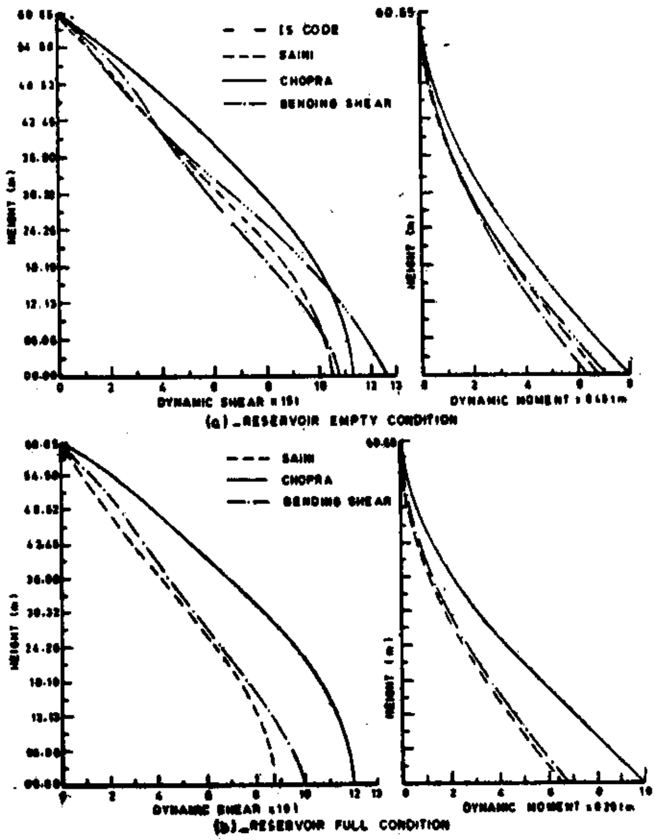


Fig. 9—Dynamic Shears and Moments for Hirakud Dam

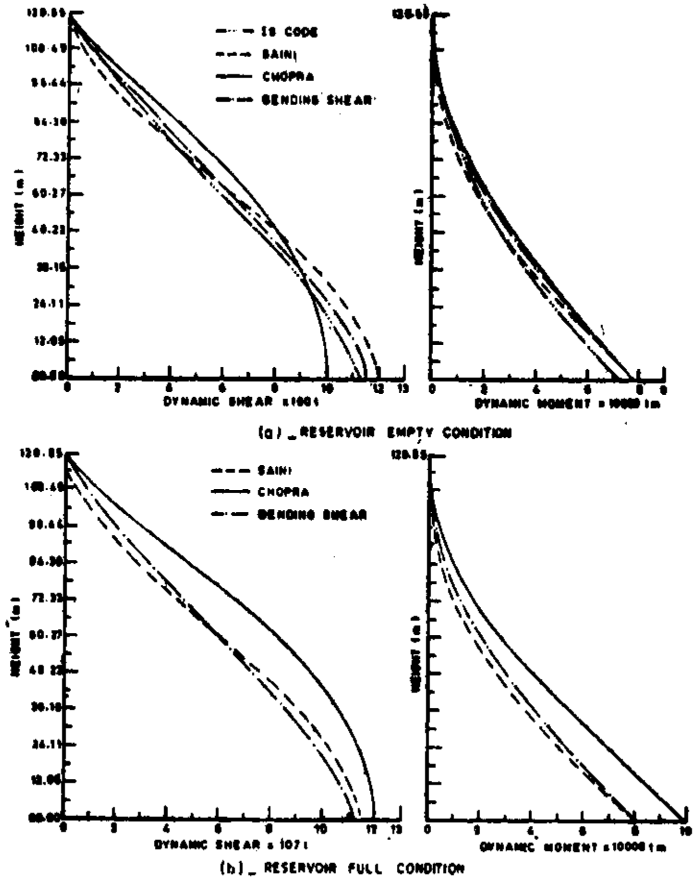


Fig. 10—Dynamic Shears and Moments for Navagam Dam

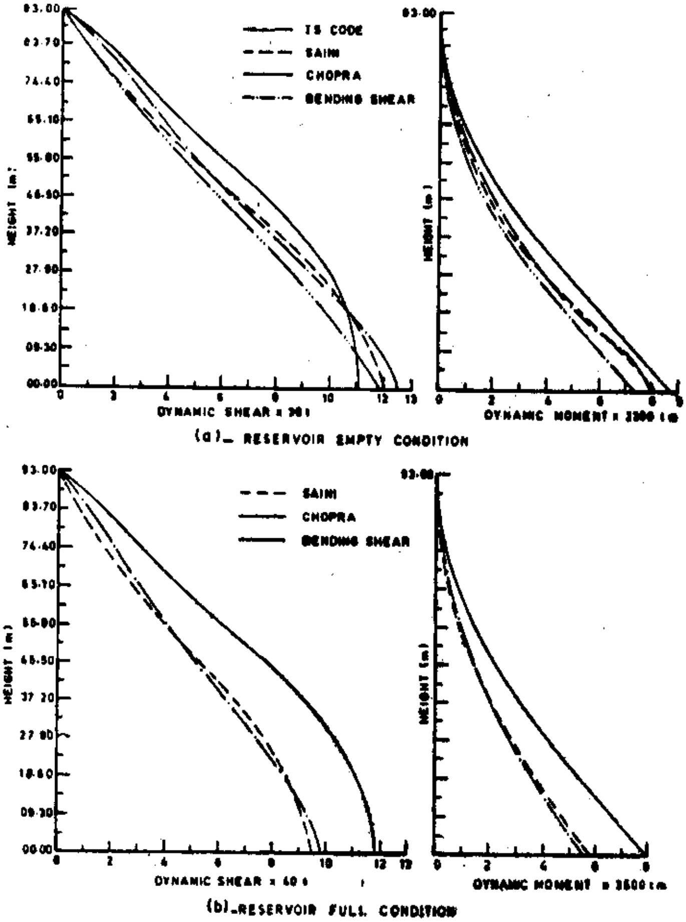


Fig. 11—Dynamic Shears and Moments for Sholayar Dam

TABLE—4

COMPARISON OF BASE SHEAR COEFFICIENT C_V AND BASE MOMENT COEFFICIENT C_M (RESERVOIR EMPTY)

Sl. No.	Dam Sections	IS : Code Method		Saini's Method		Bending-shear analysis		Chopra's Method	
		C_V	C_M	C_V	C_M	C_V	C_M	C_V	C_M
	Dams above 100m								
1.	Bhakra Dam	0.6	0.9	0.570	0.930	0.638	0.985	0.445*	0.848*
2.	Koyna Dam*	—	—	0.446	0.796	0.502	0.746	0.582	0.725
3.	Nagarjunasagar Dam	—	—	0.520	0.875	0.502*	0.806	0.479*	0.907
4.	Navagam Dam	—	—	0 637	0.974	0.614	0.976	0.532	0.966
Average value for dams above 100m		0 6	0.9	0.576	0.926	0.626	0.922	0.557	0.937
	Dams Below 100m								
5.	Hirakud Dam	0.6	0.9	0.498*	0.855*	0.515*	0.800*	0.538	1.024
6.	Kolkewadi Dam	—	—	0.584	0.932	0.562	0.905	0.498*	0.879
7.	Rihand Dam	—	—	0.532	0.890	0.533	0.883	0.522	0.982
8.	Sholayar Dam	—	—	0.629	1.017	0.661	0.987	0.585	1.085
Average value for dams below 100m		0.6	0 9	0.582	0.946	0.585	0.925	0.548	0.993

* Values are not included in averaging

TABLE – 7

COMPARISON OF BASE SHEAR COEFFICIENT C_V AND BASE MOMENT COEFFICIENT C_M (RESERVOIR FULL)

Sl. No.	Dam Sections	Saini's Method		Bending-Shear analysis		Chopra's Method	
		C_V	C_M	C_V	C_M	C_V	C_M
	Dams above 100m						
1.	Bhakra Dam	0.586	0.961	0.648	1.002	0.506*	0.937
2.	Koyna Dam	0.473*	0.838*	0.532*	0.794	0.777	1.483
3.	Nagarjunsagar Dam	0.548	0.929	0.550	0.893	0.640	1.210
4.	Navagam Dam	0.652	0.994	0.636	1.008	0.679	1.236
	Average Value for dams above 100m.	0.595	0.961	0.611	0 968	0.699	1.304
	Dams below 100m						
6.	Hirakund Dam	0.526*	0.902	0.598	0.938	0.720	1.376
6.	Kolkewadi Dam	0.610	0.976	0 587	0 946	0.666	1.163
7.	Rihand Dam	0.561	0.938	0.590	0.982	0.697	1.311
8.	Sholayar Dam	0.666	1.079	0.694	1.043	0.828	1.492
	Average value for dams below 100m.	0.612	0.974	0.617	0.977	0.728	1.336

* Values are not included in averaging

Base Shear and Base Moment Coefficient

The base shear coefficient C_v, and base moment coefficient C_m, are worked out by four methods for different dams. The average values of these coefficients for dams above and below 100 m height are tabulated in Tables 4 and 5. The average value of C_v and C_m for reservoir full condition are observed to be 0.611 and 0.968 respectively for dams above 100 m height For dams below 100 m height the average value of C_v and C_m are observed to be 0.617 and 0.977 respectively.

SUMMARY AND CONCLUSIONS

This paper presents an overview of four different simplified procedures for dynamic analysis of gravity dams. The assumptions and limitations of these methods are also presented. Eight gravity dams of different heights have been analysed using these methods. The comparison of fundamental time periods, base shears, base moments and distribution of moments and shears are presented treating the bending - shear-analysis as reference method. The period coefficients for considering the reservoir effect as an added mass of water is presented. The following conclusions can be made from this study.

1. The fundamental time period obtained by IS Code method are on the lower side. There is a variation of as much as 12% for dams above 100 m in height.
2. For tall dams above 100m in height the methods that include the effect of higher modes must be employed. For dams that are below 100 m in height, the methods that consider first mode response may be sufficient for preliminary analysis.
3. The Chopra's method generally estimates higher values af base shears and moments in dams compared to the other simplified methods.

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