DYNAMIC BEHAVIOUR OF GRAVITY DAM WITH LIGHT STRUCTURAL SYSTEMS AT TOP

S.K. Thakkar (I)
A.K. Dinkar (II)
R.P. Mathur (III)
Presenting Author : S.K. Thakkar

SUMMARY

The dynamic analysis of conventional concrete gravity dams during earthquakes have demonstrated that critical tensile stresses occur in the upper portions of the dam. A finite element study of concrete gravity dam with different types of light structural system replacing the crest is carried out in this paper with the view to determine its efficacy in reducing seismic effects on dams. A comparison of displacements, accelerations and stresses for different light structural systems with the conventional solid crest dam is presented. It is found that the critical tensile stresses under seismic condition in the upper as well as lower portion of the dam is substantially reduced with the use of light structural crest.

INTRODUCTION

The safety of gravity dams in earthquakes is of great importance because their failure may prove to be catastrophic. The current practice in the design of dams to be located in seismically active zones, is to analyse these structures based on the principles of dynamics. There are continuing research efforts made in the rational dynamic response determination of dams so as to closely understand the dynamic behaviour, while relatively much less studies are made on the methods of reducing seismic effects on dams by making some modifications in the structural system itself. Dynamic analysis of conventional concrete gravity dams subjected to earthquakes has shown that very high horizontal accelerations develop near the top of the dam. These high accelerations acting on the massive crest of conventional gravity dams generate large inertia forces and moments. Consequently it is found that critical tensile stresses occur in the upper portions of the dam. The cracking of Koyna dam near the neck in the upper portion of dam during the Koyna Earthquake of Dec. 11, 1967 is a practical example. With the view to reduce critical tensile stresses in the dam, some studies were made by Saini(Ref. 1) and Chopra and Chakrabarty (Ref. 2) by reducing the mass near the crest. These studies indicated the possibility of reducing the tensile stresses in the dam by reducing the crest weight but the crest sections adopted in these studies were not practical. A dynamic study of concrete gravity dam with different types of possible light structural system was carried out by Arya, Thakkar and Prajapati, (Ref. 3) employing beam type of idealization. This study also revealed the possibility of reduction in tensile stresses in the dam under seismic conditions. The beam analysis naturally has limitations of not predicting realistic distribution of stresses inside the body of the

---

(I) Professor of Earthquake Engineering, University of Roorkee, Roorkee,India
(II) Lecturer in Earthquake Engineering, University of Roorkee, Roorkee,India
(III)Lecturer in Civil Engineering, University of Roorkee, Roorkee, India.

dam. For accurate estimation of stresses in dams, the finite element technique is most appropriate.

This paper presents the finite element study of static and dynamic behaviour of a concrete gravity dam with (i) conventional solid crest, (ii) idealized theoretical triangular section and (iii) using different types of light structural system replacing the crest. In these light structural systems, the level of roadway is lowered by 1.0m and the crest weight is substantially reduced. The base of the dam is subjected to simultaneous action of horizontal and vertical ground motion of May 18, 1940 Elcentro Earthquake. The static analysis of the dam is carried out by standard finite element procedure. The elastic dynamic analysis, under earthquake excitation, is carried out using direct step-by-step implicit integration. A comparison of displacements and principal stresses in the dam for different crest structural systems are presented both under static and combined static and earthquake conditions.

DAM SECTIONS CONSIDERED FOR ANALYSIS

The basic section of 129 m high dam selected for study is shown in Fig. 1a. The portion above the level a a where the downstream face meets the vertical from the road will be referred to as the top portion or crest of the dam. It is only in this portion that modifications are made in the stiffness and mass. The different modifications in the crest are shown in Fig. 1e. Four different cases of crest are considered for comparison of response with the basic case.

Case 1: The basic case consists of conventional solid crest, Fig. 1b.

Case 2: The crest is made triangular. This is a theoretical section and ideal for comparison but not the practical one, Fig. 1c.

Case 3: The portion above the structural profile is made hollow by providing vertical walls of thickness 1m on upstream and downstream side,Fig.1d.

Case 4: The concrete above the maximum water level is removed and roadway lowered upto this level. Cantilever projections on upstream and down stream side are provided as shown in Fig. 1e.

The significant structural data of gravity dam is given below,

Fundamental period of dam (solid crest) = 0.256 sec; Damping factor in first mode = 0.05; Modulus of elasticity = 3.5175 x 10^6t/m^2; Poisson's ratio= 0.2; Weight density = 2.475 t/m^3.

STATIC AND DYNAMIC ANALYSIS OF DAM

Static analysis

The dam is considered as two dimensional plane strain idealization. Eight noded isoperametric elements are employed in making mathematical model of the dam as shown in Fig. 1a. The static analysis of the dam is made for self weight, hydrostatic pressure and uplift pressure. The uplift pressure is considered only at the base of the dam and is treated as initial stress. The static analysis of the dam is carried out using standard finite element procedure (Ref. 4). As a result of static analysis principal stresses are computed in the body of the dam.

Dynamic Analysis

The equations of motion of discretized linear system at any time 't' can be written as,

$$M\ddot{u}_t + C\,\dot{u}_t + K\,u_t = R_t \tag{1}$$

where dots denote differentiation with respect to time M,K and C are mass, stiffness and damping matrices, R_t is the externally applied dynamic forces. For the structure subjected to ground acceleration $\ddot{y}$ at its base,

$$R_t = -\,M\,\ddot{y} \tag{2}$$

The equations of motion (1) are solved by direct step-by-step Newmark implicit integration method (Ref. 5,6,7). The free parameters in Newmark method are taken as $\beta=0.25$ and $\gamma=0.50$. The damping is considered to be mass proportional with damping factor equal to 5% in the first mode of vibration. The hydrodynamic effect of water is considered as virtual mass of water based upon Zangar's method (Ref. 8). As a result of dynamic analysis the maximum values of displacements, accelerations and stresses are obtained during the history of ground motion.

The N-S component of Elcentro Earthquake of May 18, 1940 is used as input horizontal ground motion. The earthquake in the vertical direction is considered to be 0.5 of horizontal motion and having the same waveform.

COMBINATIONS OF STRESSES

The following combinations are considered for combining normal and shear stresses.

(i) Static load only: This includes stresses due to self weight of dam, hydrostatic pressure and uplift pressure. The reservoir full condition has been assumed.

(ii) Static + Earthquake Load: The stresses due to earthquake include those due to horizontal and vertical ground motion and hydrodynamic effect of water. The maximum dynamic stresses are combined with static stresses.

(iii) Static-Earthquake load: The maximum dynamic stresses are combined with negative sign also because of reversible nature of earthquake motion.

The principal stresses are determined for each of the above combination and principal stress variation along the height of the dam is drawn.

RESULTS OF ANALYSIS

Static analysis

The static analysis indicates that the principal stresses in the dam do not show much variation when using light structural system instead of conventional solid crest. There is slight increase in stresses by 2% in lower region and slight decrease in stresses in upper region of upstream face by about 2% by using light structural system. The nature of principal stresses is generally compressive in the body of the dam except in the heel corner of upstream face where tensile stresses of the order of 10 kg/cm^2 are developed.

Dynamic analysis

Dynamic deflections: Figure 2 shows the variation of displacements along the height in different cases. It is observed that the horizontal displacement is maximum in case 3 and minimum in case 2 while vertical displacement is maximum in case 1 and minimum in case 2 in the upper region of dam. In the lower region the variation in displacements in different cases is small.

Accelerations: Figure 3 shows the distribution of maximum horizontal and vertical acceleration along the height of the dam on the upstream face. It is observed that maximum horizontal acceleration on the crest occurs in case 3 and vertical acceleration occurs in case 1 and 4. The variation in horizontal acceleration along the height in the lower region is small while the variation of vertical acceleration in the lower region is significant (Fig. 3)

Principal stresses

Upstream face: Figure 4 shows the maximum tensile and maximum compressive principal stress plot on upstream face under static ± earthquake loading in reservoir full condition. It is observed from Fig. 4a that there is a clear reduction of tensile stresses in upper portion of dam when using light structural system, the reduction being as much as 36% in case 3. In the lower portion of dam there is also a reduction in tensile stresses in case 3 and 4, the reduction being as much as 16%. There is a reduction in compressive stresses in the upper portion of the dam by about 37% in case 3. In the lower portion of the dam there is an increase in compressive stress by about 18% in case 3. The case 3 shows the maximum reduction in tensile stresses amongst the practical cases considered (cases 3 and 4).

Downstream face: Figure 5 shows the maximum tensile and maximum compressive principal stresses plot on downstream face under static ± earthquake loading in reservoir full condition. It can be observed that there is a reduction in tensile stresses in upper portion of dam by 50% in case 3. In the lower region of dam there is a reduction in tensile stresses by 8% in case 3. It can be observed from Fig. 5b that there is reduction in compressive stress in upper portion by 43% and reduction in compressive stress in lower region by about 1% in case 3. The case 3 again shows the maximum reduction in stresses amongst the practical cases considered.

The reduction of stresses indicated by finite element study presented here are quite significant compared to the reduction of stresses observed by beam analysis (Ref. 3).

CONCLUSIONS

A finite element study of static and dynamic behaviour of a gravity dam is carried out with conventional solid crest and with different types of light structural system replacing the solid crest. The following important conclusions can be drawn from this study.

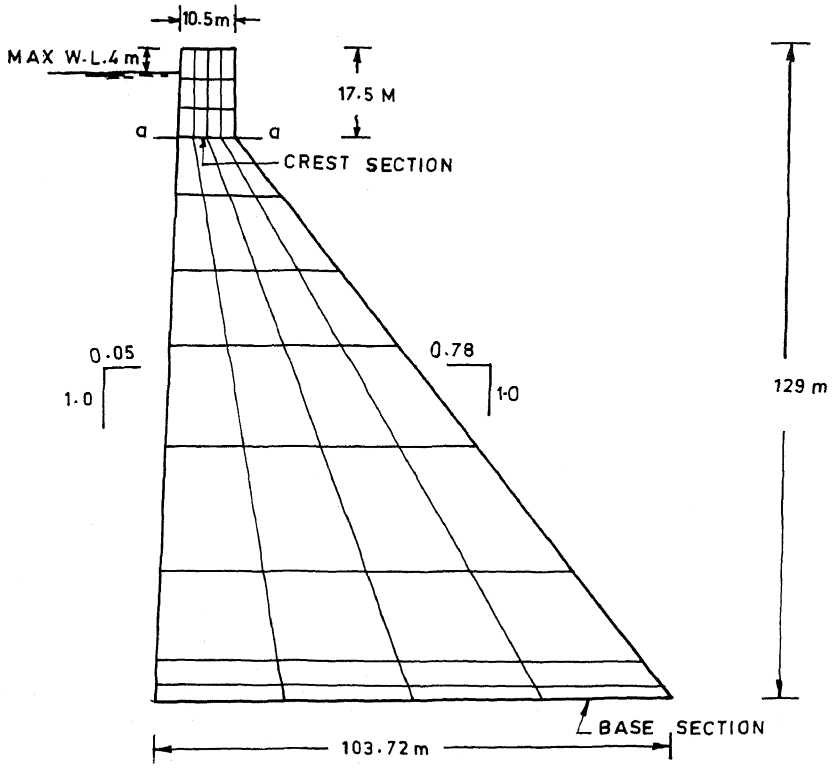
(i) The decrease of mass near the top with the use of light structural system does not cause appreciable reduction in stresses under static loading due to self weight, hydrostatic pressure and uplift pressure.

(ii) The tensile principal stresses are found to be significantly reduced in both upper portion as well as lower portion of dam with the light structural crest, under combined static and earthquake loading. The compressive principal stresses are also reduced under this loading combination but to lesser extent.

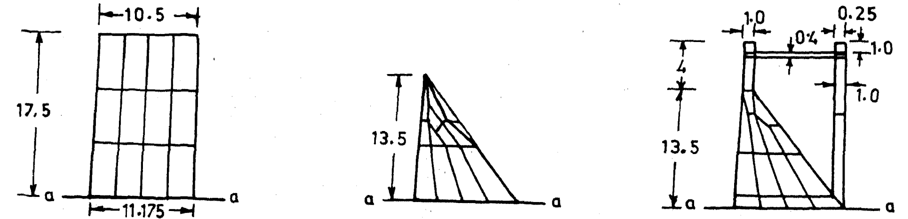
(iii) The use of light structural system at top instead of conventional solid crest is found to be beneficial for practical design of dams from seismic view point.

REFERENCES

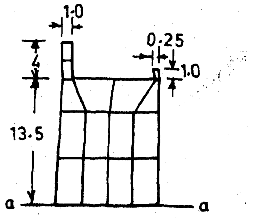
1. Saini, S.S., 'Vibration Analysis of Dams', Ph.D. Thesis, University of Roorkee, Roorkee, September 1968.
2. Chopra, A.K. and Charkrabarti, P., 'The Koyna Earthquake of December 11, 1967 and the Performance of Koyna dam', Report No. EERC-71-1, Earthquake Engineering Research Centre, University of California, April, 1971, pp. 12-45.
3. Arya, A.S. Thakkar, S.K. and Prajapati, G.I., 'Earthquake Stresses in Gravity Dams with Light Structural System at Top', Journal of Irrigation and Power, Oct. 1973.
4. Zienkiewicz, O.C., 'The Finite Element Method' McGraw-Hill Book Company (UK) Ltd., 1977.
5. Thakkar, S.K. and Sarma, G., 'Linear Seismic Response of Gravity Dam by Direct integration', Symposium on Earthquake Disaster Mitigation, University of Roorkee, Roorkee, March 4-6, 1981, Vol. I.
6. Bathe, K.J. and Wilson, E.L., 'Numerical Methods in Finite Element Analysis', Prentice - Hall, 1976.
7. Newmark, N.M., 'A method of computation for structural dynamics' Journal of Engineering Mechanics Division, Proc. ASCE, 85, pp. 67-94, (1959).
8. IS: 1893-1975, Indian Standard Criteria for Earthquake Resistant Design of Structures, Indian Standards Institution, New Delhi.



(a) BASIC SECTION OF GRAVITY DAM



(b) CASE 1 _ SOILD CREST (c) CASE 2 _ TRIANGULAR SECTION (d) CASE 3 _ LIGHT CREST



(e) CASE 4 _ LIGHT CREST

FIG. 1 _ FINITE ELEMENT MESH OF GRAVITY DAM AND DIFFERENT MODIFICATIONS OF CREST

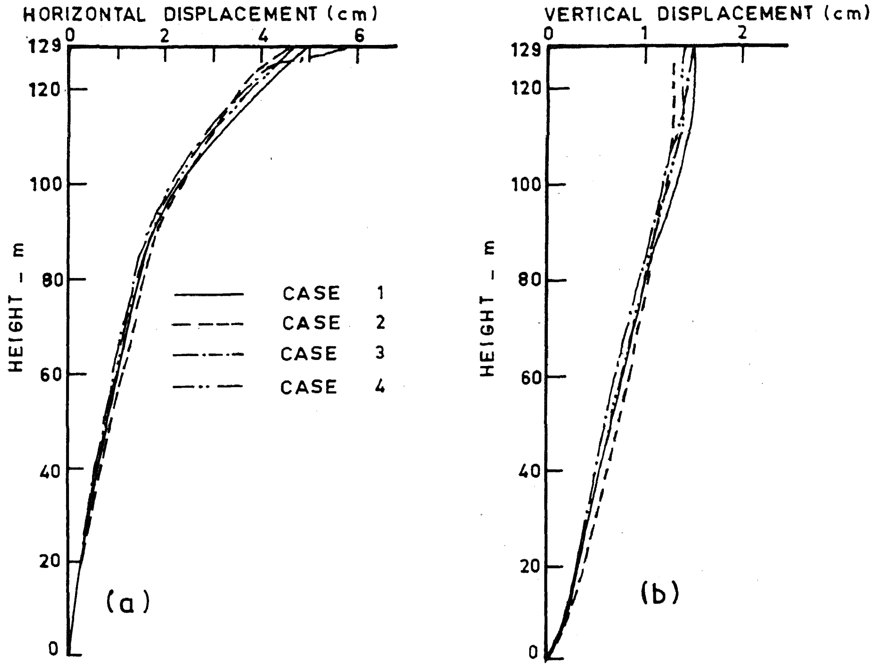


FIG. 2_ DYNAMIC DEFLECTIONS DUE TO EL CENTRO EARTHQUAKE

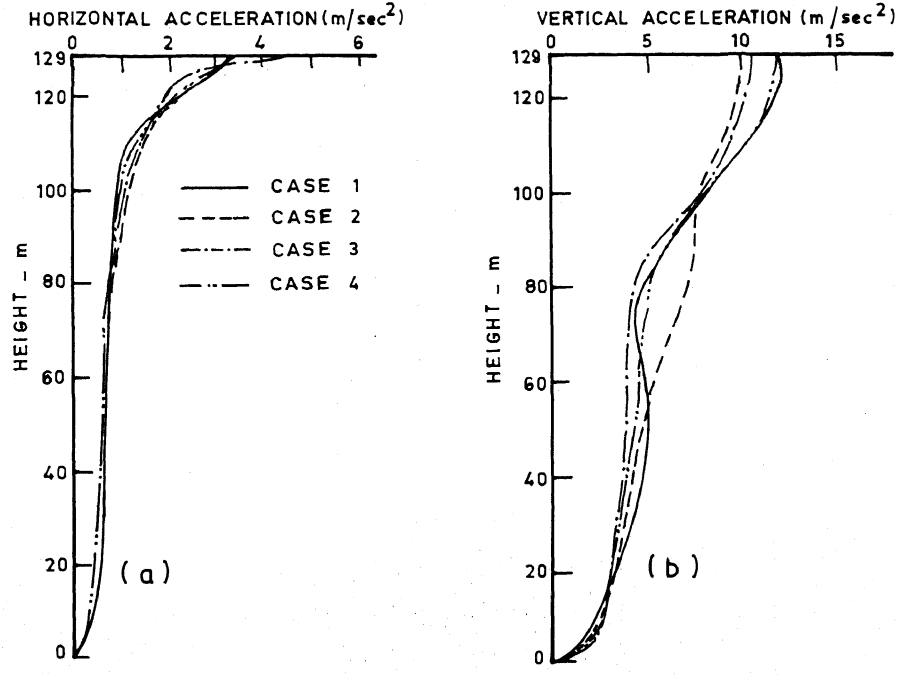


FIG. 3_ ACCELERATION VARIATION ALONG THE HEIGHT DUE TO EL CENTRO EARTHQUAKE

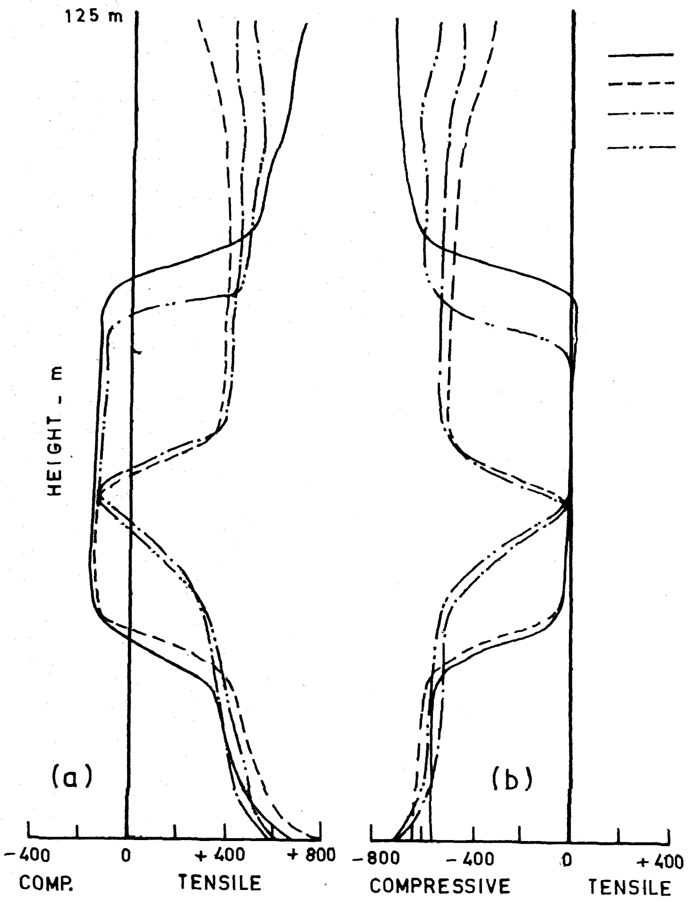


FIG. 4 – MAXIMUM PRINCIPAL STRESSES DUE TO STATIC ± EARTHQUAKE LOADING ON UPSTREAM FACE

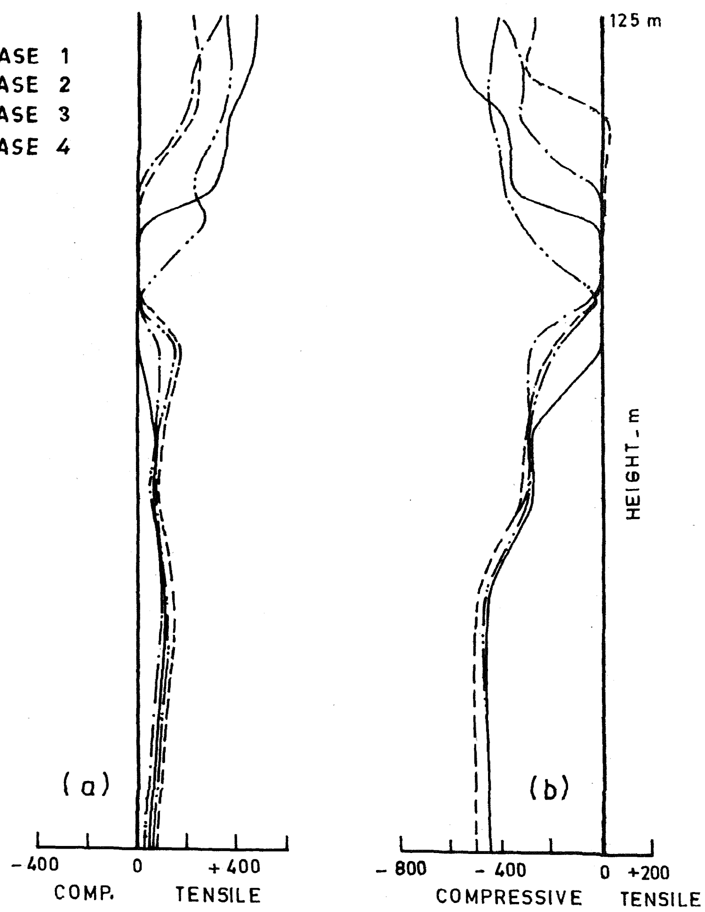


FIG. 5 – MAXIMUM PRINCIPAL STRESSES DUE TO STATIC ± EARTHQUAKE LOADING ON DOWNSTREAM FACE