Nonlinear Seismic Analysis of a High Concrete Gravity Dam

* *Manjunatha Lakkundi*
** *D. K. Paul*

Abstract

Nonlinear dynamic analysis of a high concrete gravity dam is a real complex problem. In this study the dynamical behavior of a high concrete gravity dam has been analyzed by finite element method. The case study is Bhakra concrete gravity dam with the height of 158.049 m. The response subjected to dynamic loading is a combined effect of the dam with foundation system. The concrete damaged plasticity model is used for nonlinear material properties of concrete to simulate the damage induced in the concrete dam under earthquake excitations. Mesh size effect on tensile damage detection of the dam is also carried out. Modeling and analysis work is done by ABAQUS software tool. According to dynamical analysis, results have been calculated, time history of normal stress, displacement of dam at crest level, and their peak responses at different excitations have been compared and investigated.

Keywords : **ABAQUS, Bhakra artificial earthquake, damage, earthquake, foundation**

I. INTRODUCTION

A dam is constructed across the river to create a reservoir. Dams are constructed for power generation, flood control, irrigation, shipping, fishing, and drinking water. Due to large scale urbanization, industrial revolution and increasing population, there is huge demand of water and electricity generation. This was possible by constructing large reservoirs, so safety of these reservoirs was increased against disasters. Concrete dams are very common and higher and higher concrete dams are being constructed all over the world. Although not many concrete dams have failed during earthquake, still seismic safety of high concrete dams is a civil engineering challenge.

For nonlinear time history analysis, principle stresses with and without foundation were nearly same [16] but displacement with the foundation is more than without the foundation effect.

The tensile stresses are more at heel when earthquake loads are considered [10]. Nonlinear analysis can predict large tensile stresses which develop in excess of strength of concrete as compared to linear analysis [5].

Burman, Reddy, and Maity [4] studied linear and nonlinear time history analysis of concrete gravity dam using finite element software SAP 2000. The material nonlinearity of foundation material was simulated with Bouc-Wen elasto-plastic model. They found that displacements and stresses increased with the flexibility of the foundation as compared to rigid foundation. Displacement and stresses were more when material nonlinearity was considered as compared to linear case.

Lee and Fenves [11] used concrete damaged plasticity model for nonlinear time history analysis of Koyna concrete gravity dam. They investigated consideration of vertical ground excitation with horizontal excitation that gives post cracking responses. More stress concentration was observed at the downstream slope change and at the heel point.

The stresses and crest displacements increased with decrease in foundation modulus. If reservoir level is more

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Manuscript Received: April 25, 2020, Revised : May 18, 2020, Accepted : May 21, 2020.

* *M. Lakkundi,* C/o Iranna K. Pattar, H. No. S64, Near Bharath Sevadal, Sector No. 63A, Navanagar, Bagalkot – 587 103, Karnataka (email : msliitr@gmail.com)

** *D. K. Paul* is with Earthquake Engineering Department, IIT- Roorkee, Roorkee – 247 667, Haridwar, Uttarakhand.

DOI : 10.17010/ijce/2020/v3i1/152718

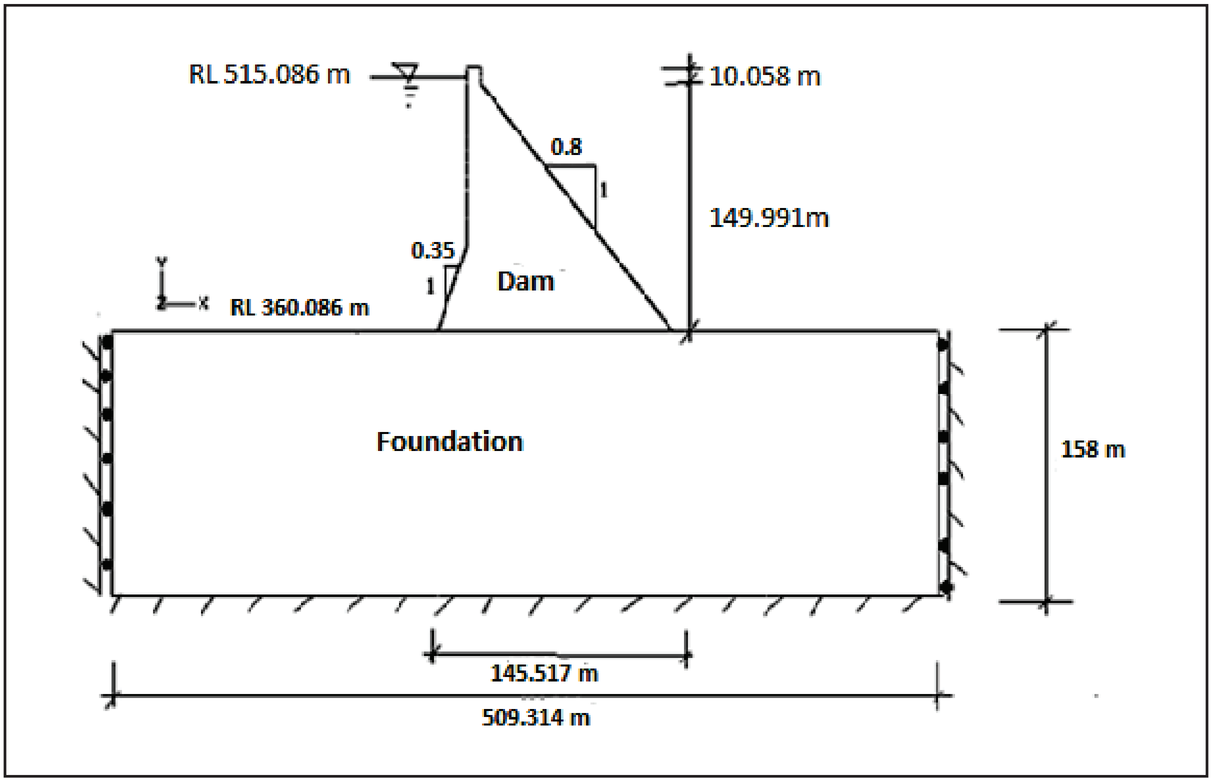

Fig. 1. Geometry of Non-overflow Section

than 0.7 times the full reservoir, then it only affects under earthquake excitations [15].

Ghrib and Tinawi [6] studied damage mechanics in concrete gravity dams under seismic loads. For non-linear analysis, stress concentration at the heel and the toe was observed. Mlakar [13] observed that cracks propagation takes place near the heel and downstream slope change portions. Maximum deflection at the crest level and maximum stress at the toe and the heel points were observed.

Saouma, Uchita, and Yagome [14] studied stress concentration and crack development in concrete gravity dams under nonlinear transient analysis. 3D modeling of dam was done using Merlin finite element software tool. Analytical results were compared with different types of practical tests on dam model. Both the results were compared and it was concluded that nonlinear analysis gives good results with practical tests.

This study is for the nonlinear seismic response of a high concrete gravity dam resting on rock foundation. A 2D finite element modeling of dam is used for analysis. Gravity load, uplift pressure, hydrostatic pressures are considered as initial static load. Throughout this study, analysis are performed by the software ABAQUS (Version6.7). The tensile damage in concrete under dynamic condition is simulated by the concrete damaged plasticity model proposed by Lubliner, Oliver, Oller, and Oñate [12], and Lee and Fenves [11], and is incorporated in ABAQUS.

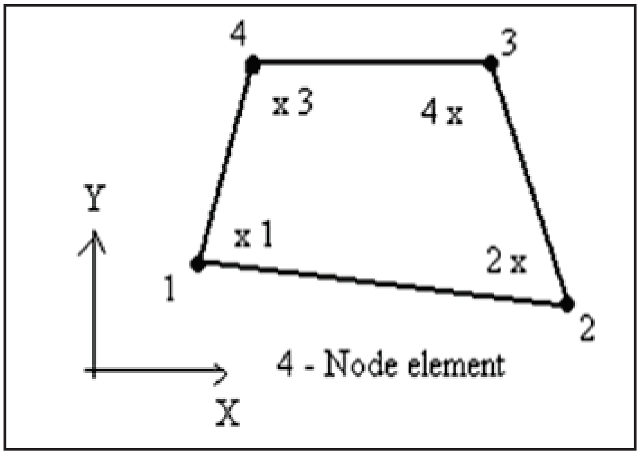

Fig. 2. CPS4R Geometry [1]

II. MODELING OF DAM BY ABAQUS SOFTWARE

The geometry used is as shown in Fig. 1. The monolith is 158.049 m high and 145.517 m wide at its base. The upstream wall of the monolith is straight up to reservoir water level (RWL) 411.46 m and the latter is inclined to 0.35 (H): 1 (V). The downstream face is inclined to 0.8 (H): 1 (V). The base of the monolith is idealized as straight base RL 360.086 m. The depth of the reservoir at the time of earthquake is assumed as full reservoir level with RL 515.086 m. Top width of the dam is 9.144 m. The non-over flow section of the dam is assumed to be in plane stress condition. It is modeled with plane stress elements (CPS4R). It employs reduced integration. The dam is assumed to rest on rocky foundation. Bottom of the foundation is assumed to be fixed and translation at vertical sides on both the sides of the foundation is considered as free but restrained in horizontal direction. The foundation is modeled with quadratic plane strain elements (CPE4R).

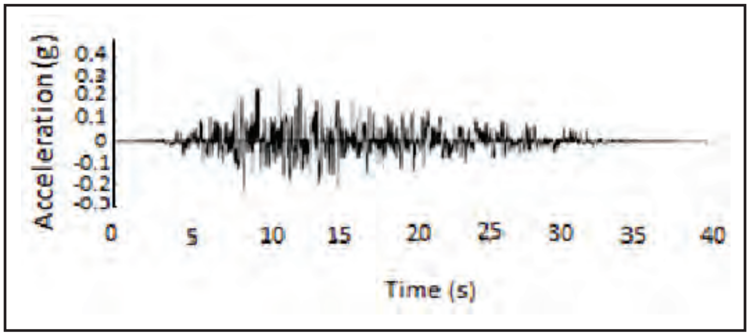

Fig. 3. Bhakra Artificial Earthquake Normalized to 0.3g [2]

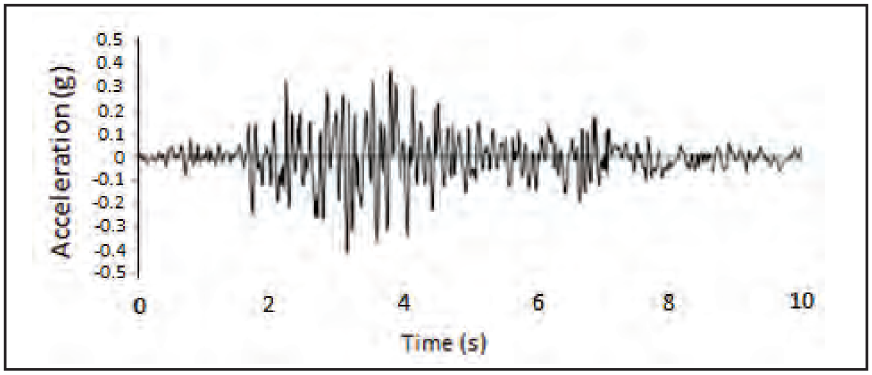

Fig. 4. Koyna Horizontal Earthquake Record

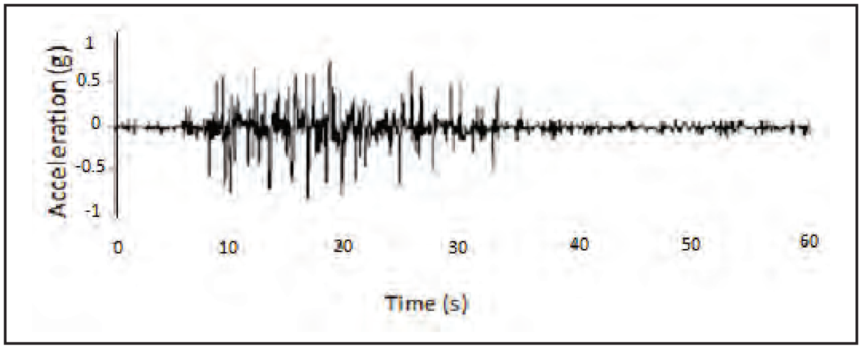

Fig. 5. Bhuj Earthquake Record

III. ELEMENT DESCRIPTION

CPS4R (Fig. 2) is a 4 - node bilinear plane stress quadrilateral element which is used for 2-D modeling of solid structures. The element is defined by four nodes having two degrees of freedom at each node, that is, translation in x and y directions. In CPS4R element, C: solid (continuum) stress/displacement, PS: plane stress (PE: plane strain), 4: number of nodes and R: reduced integration.

IV. EARTHQUAKE GROUND EXCITATIONS

Only the horizontal ground excitations were applied to the model. The Bhakra artificial, Koyna and Bhuj (Fig. 3, 4, and 5 respectively) earthquakes were used by normalizing to 0.3g for linear and nonlinear time history analysis.

V. FREE VIBRATION ANALYSIS

To investigate dynamical behavior of dam, the calculation of natural frequencies of the dam model is very important. Using these natural frequencies, we can calculate the damping coefficient of the dam with the foundation system.

The first mode fundamental time period = 0.53s. Dam without foundation is also analyzed and first mode time period = 0.378s is found. The fundamental time period calculated from IS: 1893 – 1984 [9] is 0.33s. Therefore, the first mode fundamental time for both analytical and IS: Code are nearly same, but when the foundation is considered, its time is increased. Flexibility of foundation increases the fundamental time of a mode.

TABLE I.

FUNDAMENTAL TIME PERIODS OF THE DAM WITH AND WITHOUT FOUNDATION SYSTEM

Mode	Without foundation		With foundation	
	Frequency (cycles/s)	Time	Frequency (cycles/s)	Time (s)
1	2.6481	0.378	1.8868	0.530
2	5.7319	0.174	3.1447	0.318
3	6.8199	0.147	3.4247	0.292
4	9.5916	0.104	4.4444	0.225
5	13.852	0.072	4.5045	0.222
6	14.498	0.069	4.5872	0.218

TABLE II.

MATERIAL PROPERTIES OF THE DAM [10]

S. No.	Material Properties	Concrete Dam	Foundation Material
1	Density (kg/m^3)	2467.25	2400
2	Young's modulus (N/m^2)	2.0691×10^{10}	1.7243×10^{10}
3	Poisson's ratio	0.17	0.14

Dams are generally having damping ratio of about 2 to 5%. In this study, the material critical damping of 5% is taken. Assuming Rayleigh stiffness, proportional damping β required to provide a fraction ξ of critical damping for the first mode, $\beta = {}^{2\xi 1}/_{\omega 1}$. From the natural frequency extraction analysis of the dam with foundation system, the first Eigen frequency is 11.85 rad sec-1, therefore, $\beta = 0.00843$.

VI. CONCRETE DAMAGED PLASTICITY MODEL

The concrete damaged plasticity model, which has been used to simulate the nonlinear properties of the concrete is described briefly in this section (Fig. 6). This model is primarily intended to provide a general capability for the analysis of concrete structures under cyclic and/or dynamic loading. Under low confining pressures concrete behaves in a brittle manner, the main failure mechanisms being (a) cracking in tension, and (b) crushing in compression. The brittle behavior of concrete disappears when the confining pressure is sufficiently large to prevent crack propagation ([12] and [11] and is incorporated in ABAQUS).

VII. MATERIAL PROPERTIES

The material properties of concrete dam and foundation rock are taken from reference [10] and are given in Table II. The density of water is assumed to be 1000 kg/m^3 to consider hydrostatic pressure on upstream. The cube compressive strength of concrete f_c is 20 N/mm^2 for the analysis (Ref. 7).

The mechanical behavior of the concrete material is modeled using the concrete damaged plasticity constitutive model described by Lubliner *et al.* [12] and Lee and Fenves [11] and is incorporated in

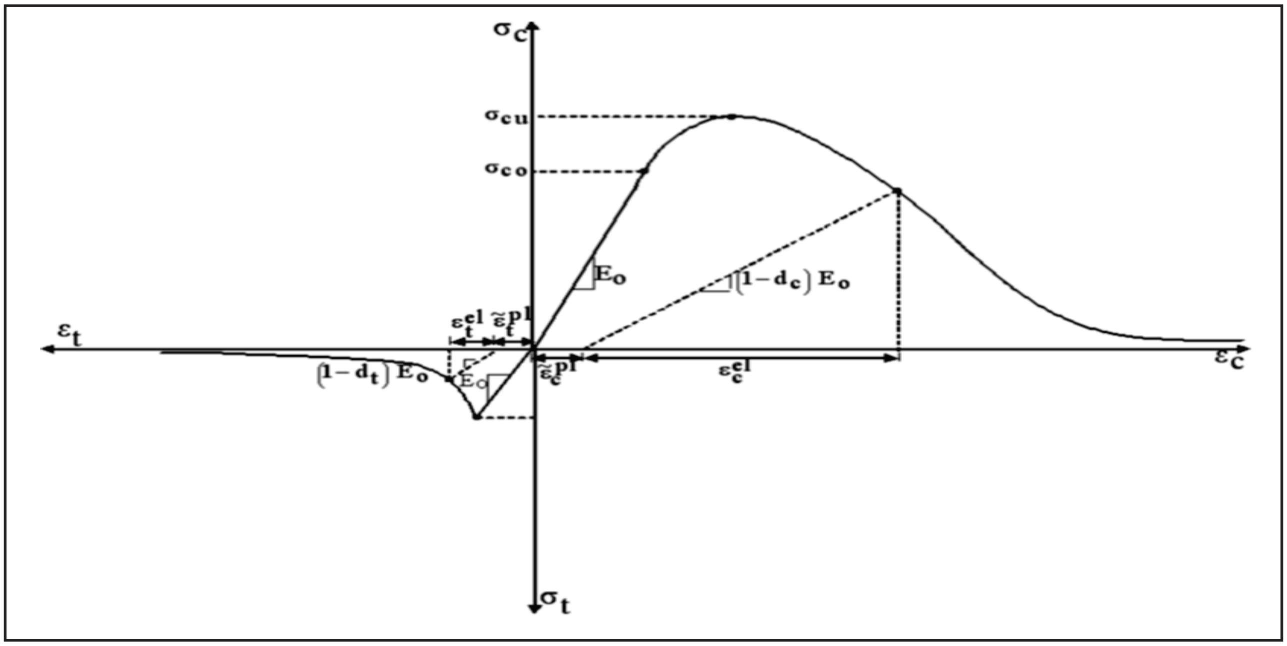

Fig. 6. Response of Concrete to Uniaxial Loading in Compression and Tension

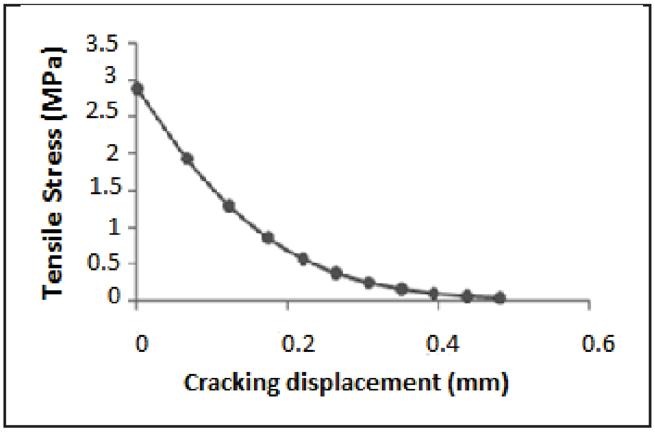

Fig. 7. Tension Stiffening

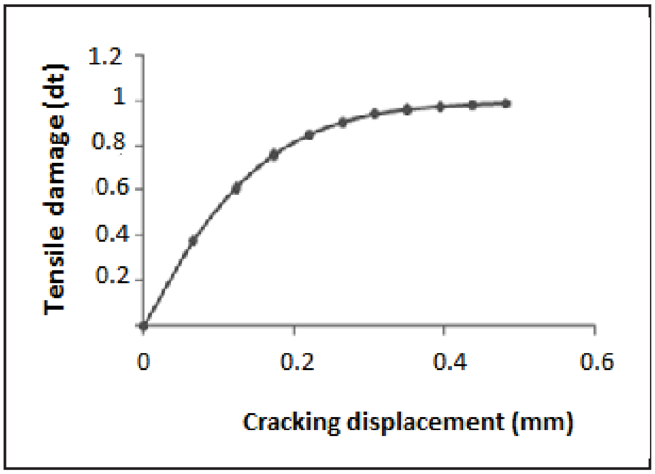

Fig. 8. Tension Damage

TABLE III.
PARAMETERS OF CONCRETE MATERIAL

Dilatation angle, ψ_c	36.31^o
Compressive initial yield stress, σ_{co}	13.0 MPa
Compressive ultimate stress, σ_{cu}	24.1 MPa
Tensile failure stress, σ_{to}	2.9 MPa

ABAQUS v6.7. The tensile strength of concrete is estimated to be 10% of the ultimate compressive strength (σ_{cu} = 24.1 MPa), multiplied by a dynamic amplification factor of 1.2 to account for rate effects, thus tensile failure stress is 2.9 MPa. The tensile post failure behavior is given by specifying a stress-displacement curve, as shown in Fig. 7. Similarly, tensile damage d_t is specified in Fig. 8. The stiffness degradation damage caused by compressive failure (crushing) of the concrete, d_c is assumed to be zero ([1], [3] and [6]). The parameters of concrete material are given in Table III [15].

VIII. DYNAMIC ANALYSIS AND DETERMINATION OF PEAK STRESS AND DISPLACEMENT IN STUDIED POINTS OF CONCRETE DAM WITH FOUNDATION

In this section, dam with foundation rock is modeled

TABLE IV.

PEAK VALUES OF RESPONSES DURING TIME HISTORY STUDY FOR LINEAR AND NONLINEAR ANALYSIS

Earthquake Cases in x-direction	Analysis	Heel (MPa)			Toe (Mpa)			Crest displacement (cm)
		SX	SXY	SY	SX	SXY	SY	
Bhakra	Linear	–6.2	–4.8	–10.1	–8.2	+7.1	–7.2	+14.0
artificial	Nonlinear	–5.2	–3.1	–7.5	–6.1	+5.1	–5.5	+14.2
Koyna	Linear	–3.85	–2.5	–6.1	–6.0	+4.5	–5.0	+14.8
	Nonlinear	–3.5	–2.0	–5.3	–5.1	+4.6	–4.5	+15.1
Bhuj	Linear	–8.3	–6.0	–12.2	–8	+6.1	–7.0	+54.1
	Nonlinear	–8.0	–5.2	–10.1	–7.0	+5.1	–6.3	+55.05

in ABAQUS. By using damping coefficient the system has been analyzed in time domain using the Bhakra artificial, Koyna and Bhuj earthquake acceleration records as the input motion. The following responses of the system have been compared :

- ➯ Peak values of responses during time history study for linear and nonlinear analysis (Table IV).
- ➯ Normal stress at heel and upstream slope change position for linear and nonlinear analysis.
- ➯ Crest displacement and normal stress at heel for linear and nonlinear analysis under different earthquake motions which are normalized to 0.3g.

Table IV consists of both positive (+ve) and negative (-ve) values. In stresses, +ve sign indicates tensile stress and –ve sign indicates compressive stress. In crest displacement, +ve sign indicates downstream direction and –ve indicates sign upstream direction. Maximum crest displacement is observed in nonlinear analysis compared to linear analysis. Normal stress (SY) for linear analysis is more as compared to nonlinear analysis at both heel and toe.

From the Fig. 9 to 15 it is observed that due to static loading before the dynamic loading, the initial displacement and normal stress response has occurred. It is also observed that after some time interval, normal stresses at the heel reduce suddenly. It is due to tensile damage at the heel for concrete nonlinearity. Concrete loses its strength at those damaged locations to take the tensile loads coming due to dynamic loading of the system.

IX. TENSILE DAMAGE IN THE DAM

The constitutive model used here simulates the tensile damage patterns based on the stress-strain curve of the concrete shown in Fig. 6. The tensile damage in the concrete dam can be traced using concrete damaged

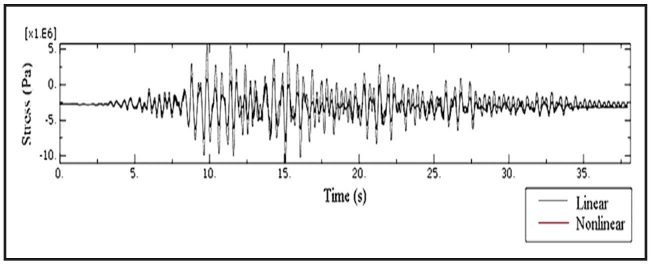

Fig. 9 (a). At the Heel

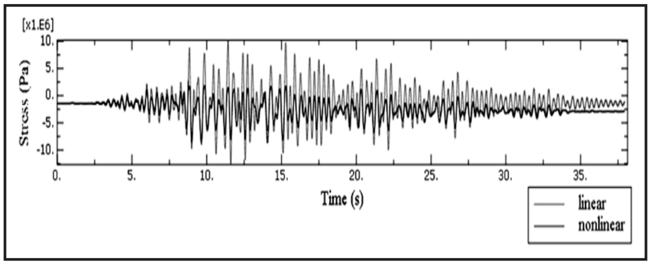

Fig. 9 (b). At the Upstream Slope Change

Fig. 9. Normal Stress Under Bhakra Artificial Earthquake Normalized to 0.3g

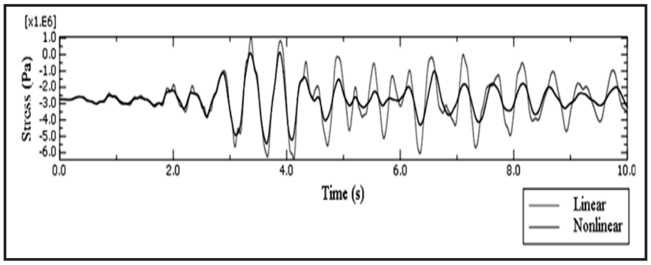

Fig. 10 (a). At the Heel

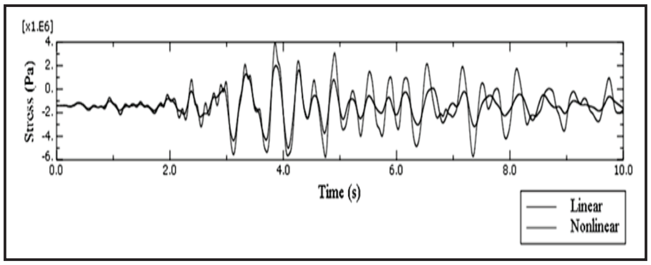

Fig. 10 (b). At the Upstream Slope Change

Fig. 10. Normal Stress Under Koyna Earthquake Normalized to 0.3g

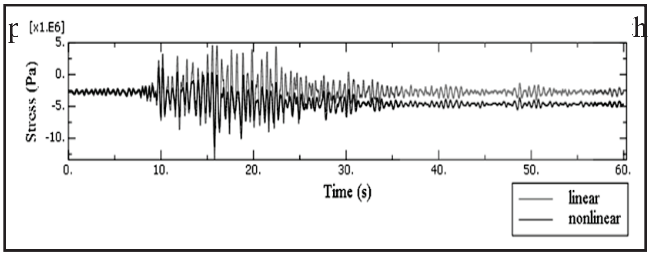

Fig. 11. Normal Stress at Heel Under Bhuj Earthquake Normalized to 0.3g

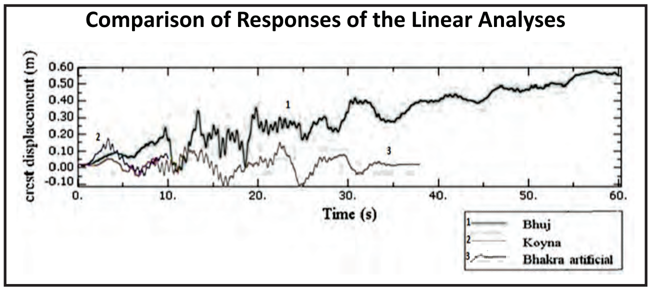
Comparison of Responses of the Linear Analyses

Fig. 12. Horizontal Crest Displacement for Linear Analysis

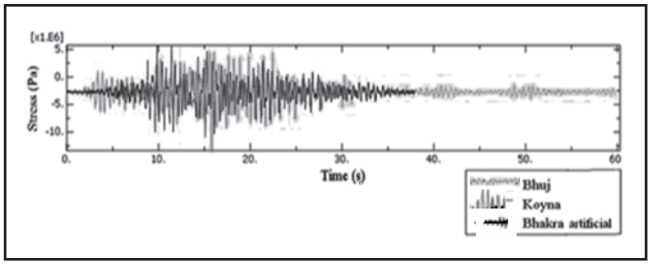

Fig. 13. Normal Stress at the Heel for Linear Analysis

Comparison of Responses of the Nonlinear Analyses

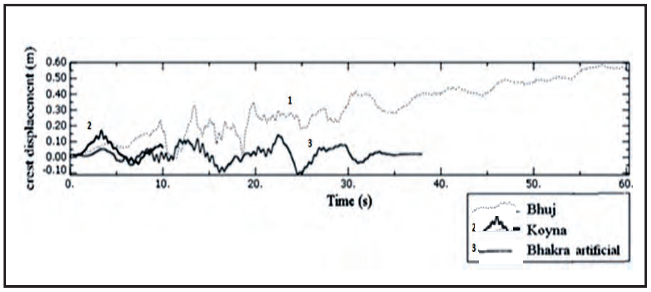

Fig. 14. Horizontal Crest Displacement for Nonlinear Analysis

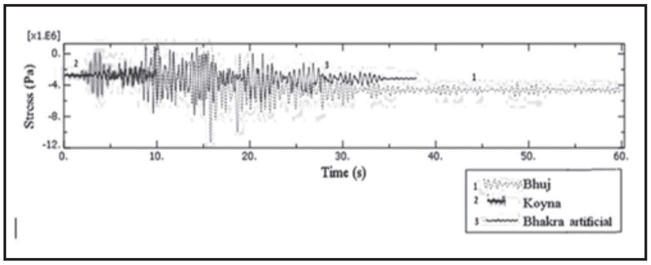

Fig. 15. Normal Stress at the Heel for Nonlinear Analysis

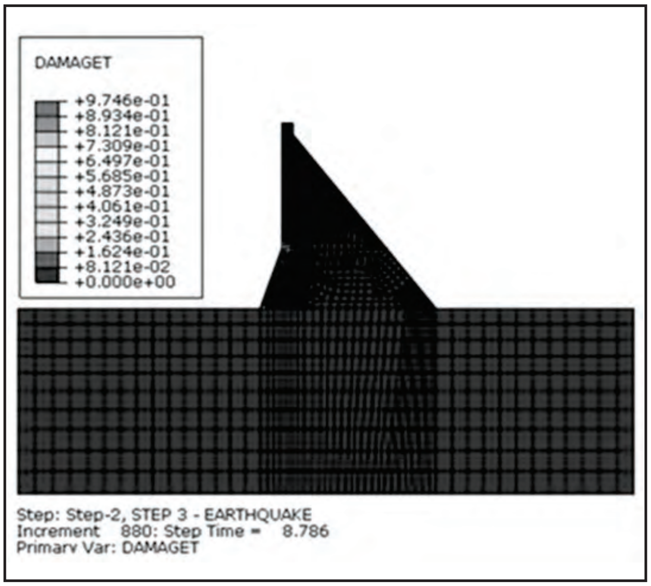

Fig. 16 (a). Time Step = 8.786

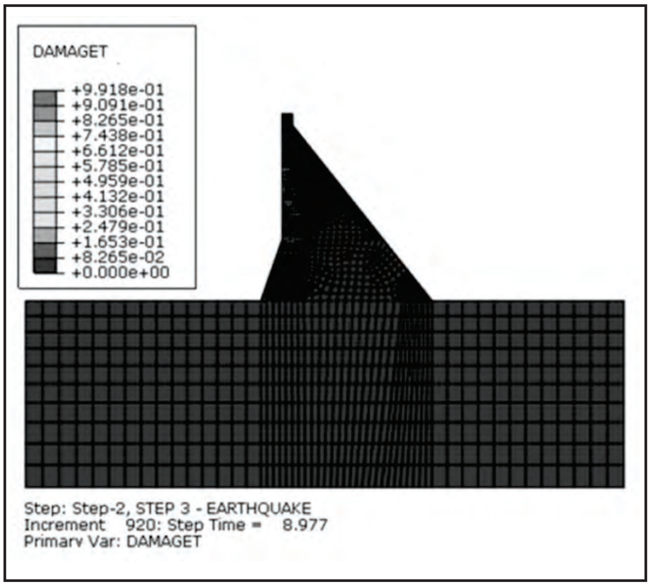

Fig. 16 (b). Time Step = 8.977

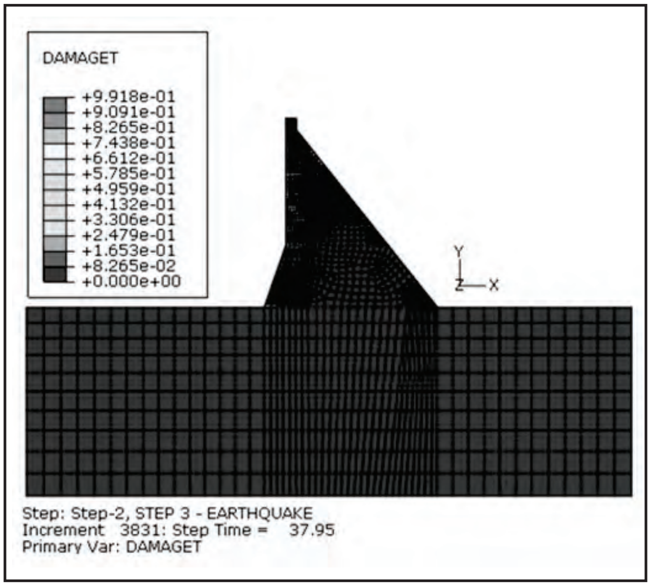

Fig. 16 (c). Time step = 37.95 sec

Fig. 16. Formation and Propagation of Tensile Damage in Dam-Foundation System Having Fine Mesh Size, Under Bhakra Artificial Earthquake

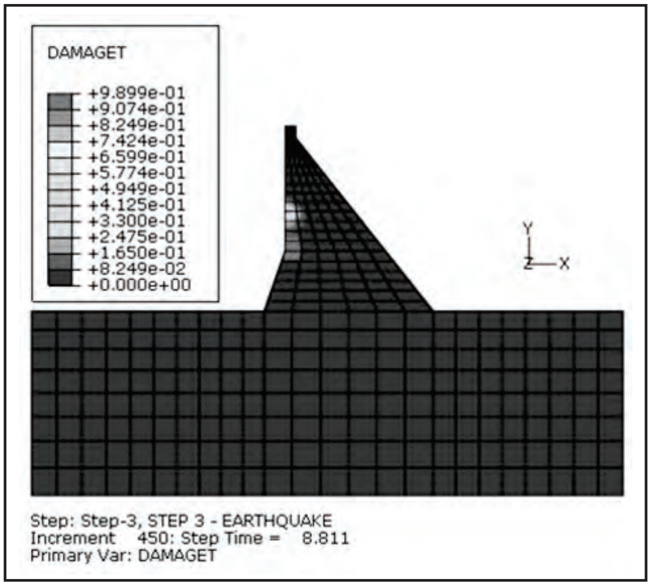

Fig. 17 (a). Time Step = 8.811 sec

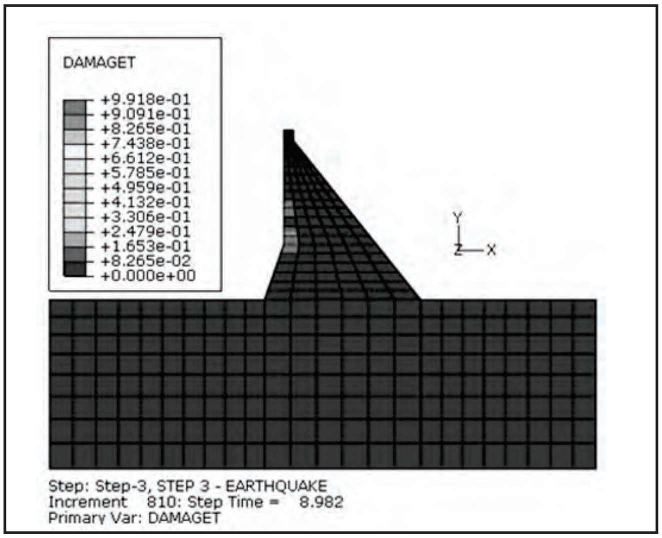

Fig. 17 (b). Time Step = 8.982

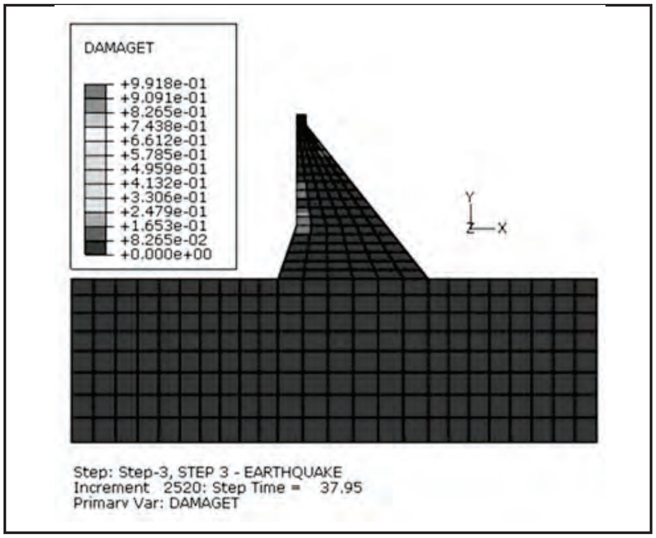

Fig. 17 (c). Step time = 37.95 sec

Fig. 17. Formation and Propagation of Tensile Damage in Dam Foundation System Having Coarse Mesh Size, Under Bhakra Artificial Earthquake

plasticity model. The initiation and the propagation of the region of tensile damage at different times are shown in Fig. 16 to 18. Tensile damage detection with foundation system is considered. The study of mesh size effect on tensile damage detection is also given in Fig. 16 to 18. For the time history analysis Bhakra artificial, Koyna and Bhuj earthquakes are normalized to 0.3g. It is observed that damage at the heel is found for Bhakra artificial earthquake but no damage occurs for Koyna earthquake. In Bhuj earthquake tensile damage at heel as well as in foundation rock near heel region is also observed. Most of the damages originate at upstream slope change point and later in the heel portion.

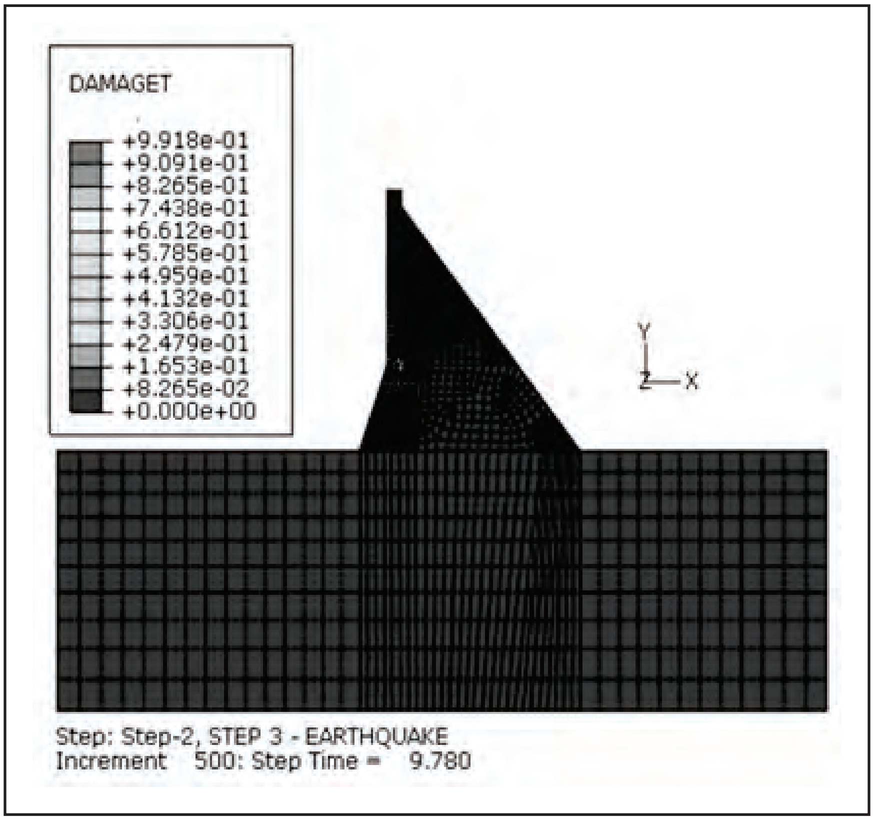

Fig. 18 (a). Step Time = 9.78 sec

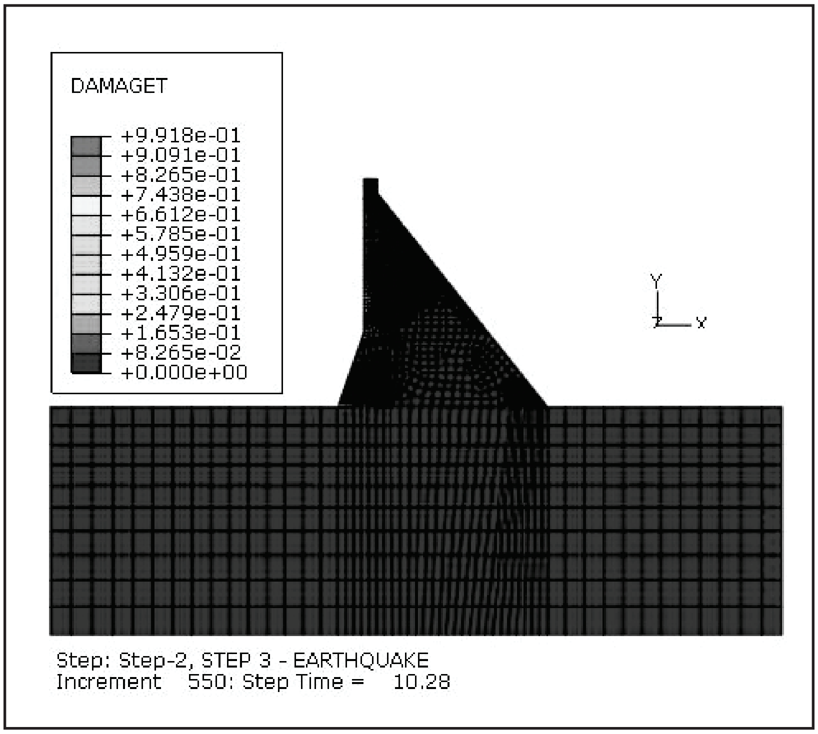

Fig. 18 (b). Step Time = 10.28 sec

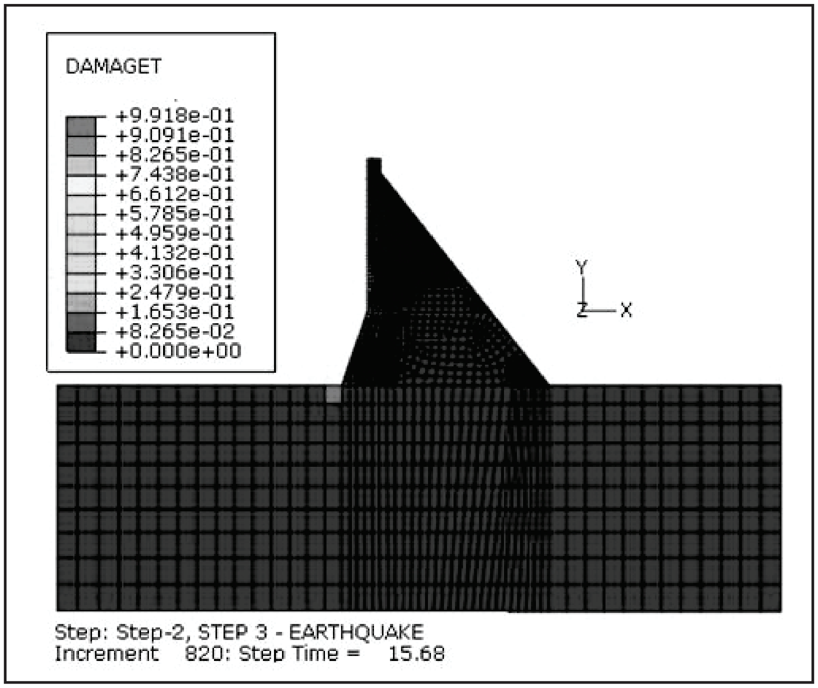

Fig. 18 (c). Step Time= 15.68 sec

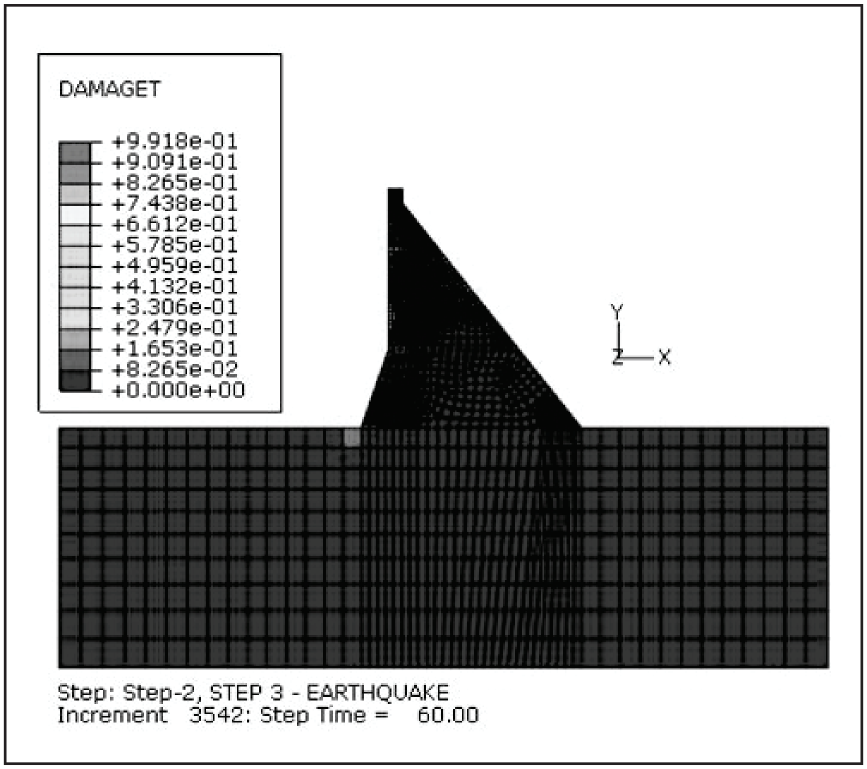

Fig. 18 (d). Step Time = 60 sec

Fig. 18. Formation and Propagation of Tensile Damage in Dam Foundation System Having Fine Mesh Size, Under Bhuj Earthquake

X. SUMMARY AND CONCLUSION

The earthquake response of concrete gravity dam-foundation system was investigated with emphasis on the non-linear behavior. For the sake of simplicity, the dam was idealized by considering plane stress conditions with foundation as plane strain. Viscous damping in the form of stiffness-proportional damping has been used. Uplift pressure and hydrostatic pressures have been considered in the model. Three time history records have been used for the linear and non linear dynamic analysis of the dam. Convergence study has been carried out for damage identification. Based on this study, the following main conclusions are drawn:

- Consideration of foundation in the finite element model imparted flexibility to the structure.
- Maximum crest displacement is observed in nonlinear analysis compared to linear analysis.
- Normal stresses are found to be more for linear analysis compared to nonlinear analysis at both the heel and the toe.
- Most of the damages are observed to originate at the upstream slope change point and later moved towards the heel point.
- Coarse meshing did not detect the damage at the heel portion while a finer mesh detected the damage under the same seismic condition.

REFERENCES

[1] ABAQUS v6.7 Documentation 2007, DassaultSystemes, France.

[2] *Bhakra Dam Rep.* 2010, Earthquake Eng. Dept., Indian Inst. of Technol., Roorkee, India.

[3] S. S. Bhattacharjee and P. Léger, “Seismic cracking and energy dissipation in concrete gravity dams,” *Earthquake Eng. Structural Dynamics*, vol. 22, no. 11, pp. 991–1007, 1993. Doi: https://doi.org/10.1002/eqe.4290221106

[4] A. Burman, B. V. Reddy, and D. Maity, “Seismic analysis of concrete gravity dams considering foundation flexibility and nonlinearity,” *The 12th Int. Conf. on Comput. Methods and Advances in Geomechanics* (IACMAG) 1-6 October, 2008, Goa, India, pp. 2882 – 2888.

[5] A. K. Chopra and P. Chakrabarti, “The earthquake experience at Koynadam and stresses in concrete gravity dams,” *Earthquake Eng. Structural Dynamics*, vol. 1, no. 2, pp. 151– 164, 1972. Doi: https://doi.org/10.1002/eqe.4290010204

[6] F. Ghrib and R. Tinawi, “An application of damage mechanics for seismic analysis of concrete gravity dams,” *Earthquake Eng. and Structural Dynamics*, vol. 24, no. 2, pp. 157-173, 1995. Doi: 10.1002/eqe.4290240203

[7] Indian Nat. Committee for Int. Commission on Large Dams, “Design and construction features of selected dams in India," *Central Board of Irrigation and Power*, Part 1, pp. 1-68, 1979. New Delhi.

[8] *Criteria for earthquake resistant design of structures*, IS: 1893 (Part 1).

[9] *Criteria for Earthquake Resistant Design of Structures*, IS: 1893 – 1984.

[10] P. Krishna and S. S. Saini, “Second report on stress analysis of the Bhakradam," Point 4, Structural Eng. Section, Dept. of Civil Eng., University of Roorkee, Roorkee, 1984.

[11] J. Lee and G. L. Fenves, “A plastic-damage concrete model for earthquake analysis of dams,” *Earthquake Eng. Structure Dynamics,* vol.27, no. 9, pp. 937– 956, 1998. [Online]. Available: https://www.deepdyve.com/lp/wiley/a-plastic-damage-concrete-model-for-earthquake-analysis-of-dams-7S9JpVsQR9

[12] J. Lubliner, J. Oliver, S. Oller, and E. Oñate, “A plastic-damage model for concrete,” *Int. J. of Solids and Structures*, vol. 25, no. 3, pp. 299–326, 1989. Doi: https://doi.org/10.1016/0020-7683(89)90050-4

[13] P. F. Mlakar, “Nonlinear response of concrete gravity dams to strong earthquake-induced ground motion,” *Comput. and Structures*, vol. 26, no. 1/2, pp. 165-173, 1987. Doi: https://doi.org/10.1016/0045-7949(87)90246-X

[14] V. E. Saouma, Y. Uchita, and Y. Yagome, “3D nonlinear transient analysis of concrete dams,” Inter. Assoc. of Engineers (IAENG), pp. 1022-1027, 2009.

[Online]. Available: https://www.pwri.go.jp/eng/ujnr/joint/39/paper/63saouma.pdf

[15] R. Sarkar, D. K. Paul, and L. Stempniewski, "Influence of reservoir and foundation on the nonlinear dynamic response of concrete gravity dams," *ISET J. of Earthquake Technol.*, paper no. 490, vol. 44, no. 2, pp. 377–389, 2007. [Online]. Available: http://home.iitk.ac.in/~vinaykg/Iset490.pdf

[16] L. Yaghin and M. A. Hesari, "Dynamic analysis of the arch concrete dam under earthquake force with Abaqus," *J. of Appl. Sciences*, vol. 8, no. 15, pp. 2648 – 2658, 2008. Doi: 10.3923/jas.2008.2648.2658

About the Authors

Manjunatha Lakkundi completed B.E. (Civil Engineering) from Basaveshwara Engineering College, Bagalkot. He completed M. Tech with specialisation in Structural Dynamic from Earthquake Engineering Department, Indian Institute of Technology, Roorkee. He completed research work on Non-linear seismic analysis of a high concrete gravity dam using finite element software Abacus v6.7 under the guidance of Prof. D. K. Paul, Earthquake Department, IIT Roorkee. He is a life member of Indian Society of Earthquake Technology (ISET).

Professor Paul is the Chairman of Earthquake Engineering Sectional Committee, CED 39, Bureau of Indian Standards. He is a Fellow of Indian National Academy of Engineers, (FNAE) ; Fellow of Indian Institute of Engineers (FIE) ; and Fellow of Indian Society of Earthquake Technology (FISET).

Dr. Paul has an outstanding academic record, obtained his B.E. in Civil Engineering (1969) and ME in Earthquake Engineering (1971) from University of Roorkee, and Ph.D. from UK under a Commonwealth Scholarship in 1981.

He joined as a faculty in the Department of Earthquake Engineering, IIT Roorkee in 1972. He served in many capacities such as Professor & Head, Department of Earthquake Engineering, Dean of Faculty Affairs and Deputy Director. After serving for 40 years he retired as Professor/ Deputy Director, IIT Roorkee. He continued to serve as Emeritus Fellow. He also served as President, Indian Society of Earthquake Technology (ISET).

Dr. Paul is consulted for Seismic Safety of many Special Structures in the country involving Earthquake Resistant Analysis and Design. He is a leading authority in the field of Earthquake Engineering and Earthquake Disaster Mitigation.