IDENTIFICATION OF SYSTEM PARAMETERS OF THE KOYNA DAM FROM ACCELEROGRAMS RECORDED ON THE DAM

D.K. PAUL and A.R. CHANDRASEKARAN
Dept. of Earthquake Engg., Univ. of Roorkee, Roorkee, 247 667, India

S.L. BHINGARE
Superintendent Eng., Koyna Hydro Electric Project, Pune 411 011, India

Paper No. 1710. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

ABSTRACT

Identification of dam-foundation-reservoir system is made based on the matching of the predominant period of vibration obtained from the Fourier analysis of recorded accelerograms with the time periods of vibration obtained by eigen value analysis using 2D plane stress finite element analysis of the dam section where the motions were recorded.

The study indicates that the apparent modulus of elasticity of concrete under dynamic condition is much higher than those under static condition. Analyses of strong motion data recorded over the last twenty years have shown that there are no apparent sign of deterioration of concrete as adjudged from consistency in the natural frequencies.

KEYWORDS

Koyna dam, Identification of system parameters, Safety assessment, Strengthening of dam, Natural frequencies of vibration, Modulus of elasticity of dam, Dynamic stiffness, Accelerogram recorded on dam.

INTRODUCTION

After the December 11, 1967 Koyna earthquake, various aspects concerning the safety of Koyna dam were reviewed and the dam was strengthened. However the review of safety analysis is not a one time process for a structure that is supposed to have a life longer than 100 years and the one that supports a major power station as well caters to irrigation and water supply needs of large population downstream. Instead safety analysis is carried out at regular intervals particularly for a major dam in active seismic zone using updated data base.

The review of safety analysis involves review of earthquake environment, aging effect on dam, modification in the control levels etc. Reference to updated data base is an important aspect of the review. The data base consists of strong motion records of ground motion and the response of the dam due to it. Information obtained from these records can be used to understand the behaviour of the dam subjected to an earthquake. This in tern may throw light upon the understanding or identifying the various parameters affecting the dynamic behaviour of the dam.

In analyzing response of a structure, a analyst has many sets of models to choose from. In case of a major structure like a large dam a wide database, built from preconstruction investigations, statistical quality control analysis done during the construction period and instrumentation before, during and after implementation is generally available. The representative (basic) system parameters are chosen from this database for the safety analysis. Stress analysis of Koyna dam has been carried out before the December 1967 earthquake and after its strengthening as an exercise for review of safety. While doing this various analysts have chosen different models befitting the techniques adopted and parameters found appropriate. To predict the response of a dam for the prescribed design earthquake certain parameters reflecting the physical properties of the structure and behavior of the system as a whole must be understood. This, in many cases may be very important since the response may be very sensitive to material properties of the system.

Analysis of recorded accelerogram is used to evaluate the dam model. By systematically adjusting the parameters to provide a close correlation between the computed and measured response the form of mathematical model can be refined. The success of the exercise will lead to refinement in safety review. In this context an attempt has been made to carry out the system identification studies for the Koyna dam system using accelerograms recorded on the dam top.

BACKGROUND

Extensive database and the geology of the area are available in respect of the Koyna dam through the completion report of Koyna project. The dam is basically a rubble concrete dam though there is an upstream concrete septum 1.8 m wide and the buttresses added subsequently are in concrete. Earthquake forces considered were of uniform seismic coefficient of 0.05g throughout the height. It may be mentioned that as per the prevalent practice at that time the basic seismic coefficient was zero.

The dam cross section would appear somewhat non-standard. It was originally intended to build a dam of thinner section with a lower FRL to store less water, to meet the requirements of stage-I of the project and later thickened the same to the final section corresponding to the stage-II FRL. Such thickening was done by putting additional concrete on the downstream face only.

The shooting-up of the power demand earlier than anticipated, however, made it necessary to build up the storage in one go. A review of the design of the already constructed section indicated that by making the remaining portion of the dam towards top thicker and raising top of the dam by 3.05m the resulting modified section would be as safe as the conventional section. The dam construction was done accordingly. In the overflow section the same curves have been maintained by suitably cantilevering the top of the dam on upstream side [Mane *et al.* (1962)].

<u>The Seismic Disturbance and damage to the dam:</u> After partial impounding up to Koyna Reduced Level 632.60m small earth tremors were frequently reported in the vicinity of the dam, the frequency of which increased considerably from 1963 onwards. On December 11, 1967 the dam experienced an earthquake of magnitude 6.5 on Richter scale with epicenter 12 km away. The earthquake caused distress to the dam and appurtenant structures along with structures in the construction colony and in the nearby settlements. The most important damages to the dam were (i) horizontal cracks on the up-stream and down-stream sides of deeper NOF monoliths, (ii) increase in leakage through monolith joints (this continued there after), (iii) spalling of concrete in both piers and girders at the fixed ends of spillway bridge, (iv) cracking

of masonry and concrete of auxiliary structures on the top of the dam, mainly the elevator tower. (v) The peak accelerations recorded by the AR 240 instrument in the gallery of monolith 1B were as (i) longitudinal component 620.34 cm/s^2., vertical component 333.20 cm/s^2, transverse component 480.20 cm/s^2.

Strengthening of the Dam: An experts committee was appointed by Government of India which suggested a number of strengthening measures. [Report of UNESCO Committee of Experts]. The temporary strengthening of the dam was taken up accordingly. This included grouting of cracks by epoxy and polyester, prestressing of 7 deep monoliths, drilling internal drainage holes. These works were completed by August 1968. The committee suggested concrete backing as the permanent strengthening measure. The suggested design criterion were: 100% uplift water pressure at the base on the upstream side and reduced to 50% at the gallery and to the tail water level at the toe. For the intermediate sections in the dam body the uplift force reduced to zero at the drainage shafts. The dynamic seismic coefficients taken were, α_h = 0.5 and α_v = 0.3. For this condition the tensile strength was assumed as 300t/m^2 whereas the SFF requirement was reduced to 3.0. For the rest of the monoliths less severe conditions were recommended. The concrete backing work was completed in 1973. As against the dam this work was in concrete and elaborately designed and detailed shear keys were provided between the original face of the dam and the buttresses. The concrete backing work of the deep monoliths consists of a full backed section up to 600.6m and buttresses of varying widths above this up to 653.96m.

Analytical studies: Chandrasekaran, Arya and Saini (1969) carried out one dimensional cantilever model studies to find out the stresses in the NOF monolith no 17 when subjected to the December 1967 earthquake. The periods of vibration for the first two modes of vibrations have been computed as 0.340s and 0.132s. Influence of reservoir water on natural periods was not considered. Based on the exercise the suggested design seismic coefficients α_h and α_v were 0.375 and 0.20 respectively. Hydro dynamic pressure was computed using Zanger's approach. The peak ground acceleration for this was chosen as 0.40g. The stress concentration region was identified. Addition of mass on the downstream side has been recommended.

Table-1 Model parameters and computed natural frequencies of vibration

		Chandrasekaran, Arya, Saini	Jai Krishna, Chandrasekaran, Saini	Chopra and Chakrabarti	Saini Kulkarni
Model Idealization		one dimensional cantiliver 115 mass pts. fixed base without vm	2 D fem 83 nodes 94 elem fixed base with vm	2 D fem 136 nodes 162 elem fixed base without vm	2 D fem 403 nodes 116 elem flexible with vm
E Conc. 10^7 t/m^2		N.A.	0.317	0.317	0.31
Freq. of Vib	before strengthening	2.94, 7.56	2.82, 7.41 (2.49, 6.17)	3.06, 8.19	
	after strengthening		3.79, 9.09 (3.26, 7.69)	4.17, 10.0	(2.89, 6.75)

Unit weight and Poisson's ratio of concrete are taken as 2.65 t/m^3 and 0.2. vm is the virtual mass of water.

Jai Krishna, Chandrasekaran and Saini (1970) carried out 2D static and dynamic fem analysis of the Koyna dam. The section at the time of December '67 earthquake as well as the section after the proposed strengthening were analyzed. Influence of reservoir has been considered as added mass.

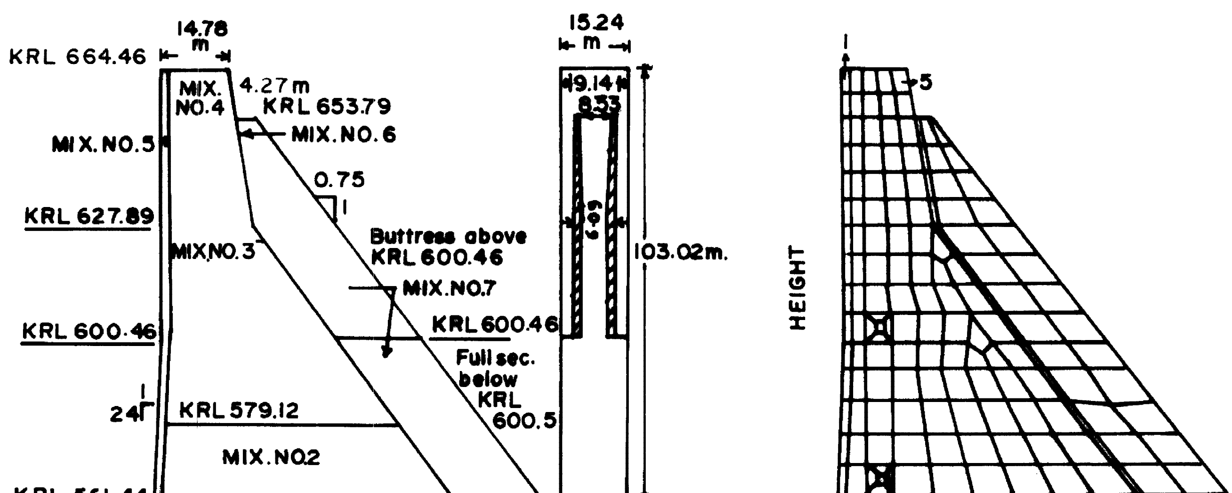
Chopra and Chakrabarti(1973) have analyzed the Koyna dam (monolith 17) for the section before strengthening. Natural periods for first four modes were computed treating the base as fixed and without considering the influence of the reservoir. The natural periods and principal stresses were also computed for the proposed strengthened section.

Vibration tests on gelatine model were carried out by Okamoto *et al.* (1969). Natural periods for first two modes for monolith 1A and for monolith 18 have been computed from free vibration testing. Influence of the reservoir was also simulated by adding mass. The computed frequencies for the prototype in modes 1 and 2 were 3.83 Hz and 9.61 Hz respectively. With the reservoir influence the computed frequencies were 3.3 Hz and 7.52 Hz. Table 1 shows the frequencies obtained by various investigators. The figures in bracket shows frequencies considering the virtual mass of water

MATHEMATICAL MODELLING

Figure 1 shows the dam section and the finite element model for the NOF section of the dam only. The dam is represented by 160 elements defined by 539 nodes. The foundation is represented by 216 elements defined by 653 nodes. The varying width of the buttresses is considered by specifying appropriate element width. The hydrodynamic effect and the foundation compliance has been considered.

Hydrodynamic Pressure: For incompressible water, if a dam is having the upstream face vertical upto or more than half of the total height then the hydrodynamic pressure will practically be the same for a dams with the up-stream face vertical upto its full height. In case of Koyna the up-stream face of the dam is vertical for top 64 m out of the total height of 103 m and below that the slope is only nominal-1:24. The dam, therefore is assumed as having vertical upstream face as far as the hydrodynamic pressure computation is concerned. The reservoir in the present case is vary large and has a long fetch and the errors on account of the limited reservoir length will be very small. The reservoir effect is considered using Zanger's approach and virtual masses are lumped at the upstream nodes.



(a) Strengthened section of monolith 17 of koyna dam

(b) Finite Element mesh

Fig.1 Nonover flow section of strengthened koyna dam

The foundation compliance: Koyna dam is founded on basaltic rock. The rock is sound and has a vary high modulus of elasticity. In most previous analysis the dam is assumed fixed at the foundation level. The dynamic response of stiff, heavy structures, like dams to earthquake loading is influenced by the interaction between the structure and foundation. Neglecting the interaction effect would not give the true behaviour of the structure and therefore while carrying the dynamic analyis, it is important to consider the foundation structure interaction.

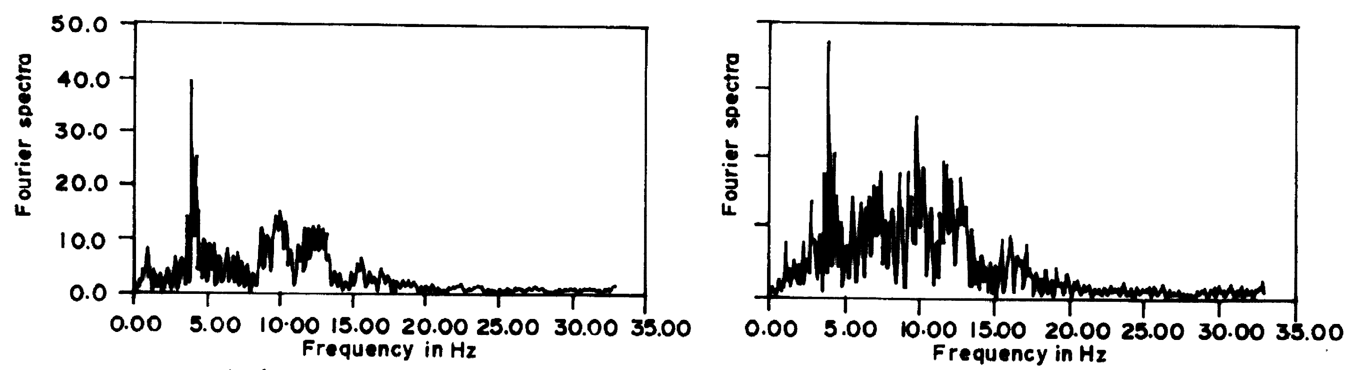
The substructure method is used to treat the structure-foundation system. The foundation is analysed first independently of the dam to the influence coefficient matrix corresponding to dam-foundation contact nodes. The corresponding stiffness matrix obtained by inversion of influence matrix is appropriately added to the stiffness matrix of the dam structure while analysing the dam. The material properties assigned to various element groups are conforming to project completion report and published literature. [Completion Report of Koyna Project, Murti *et al.* (1964)]. Table 1 shows the adopted basic material properties conforming the specifics of the database.

Table 1 - Basic Material Properties

	E value(t/m^2)	ν	unit weight(t/m^3)
Concrete	$0.250*10^7$	0.2	2.48
Rubble concrete	$0.315*10^7$	0.2	2.64
Buttress concrete	$0.250*10^7$	0.2	2.59
Foundation rock	$0.705*10^7$	0.2	2.90

RESULTS AND DISCUSSIONS

Analysis of strong motion accelerograph records: Up to March 94, in all 147 accelerograms were recorded by various strong motion accelerographs on the dam. For a few simultaneous records at the foundation and at the dam top are available. The accelerograms selected were installed at the dam top between 1975 and 1994.



(a) Transverse trace (b) Vertical trace

Fig.2 Fourier spectra of acceleration recorded at the top of dam

Processing of the strong motion records obtained from the strong motion instruments installed at the dam top was carried out. The Fourier spectra for 12 transverse traces and 6 vertical traces were obtained. Figure 2 shows a typical Fourier spectra for transverse and vertical record at the dam top. The Fourier spectra and the response give the information about the amplitudes at various frequencies of the input motion. In the present case the input motion is the response of the dam. The amplitude contents of the input motion therefore would highlight the natural frequencies of the dam. The peak amplitude corresponds to the natural frequencies of the system. With this hypothesis the frequencies corresponding to high distinct peaks in the desired range are obtained from the Fourier and response spectra.

Recorded frequencies of the dam will be different for different reservoir levels due to variation in the virtual mass. This aspect has been taken care of by normalising the frequencies recorded at different reservoir levels to the frequencies at FRL condition for modes 1 and 2. The results of analysis of the Fourier spectra are given in Table-2. It is seen that the first natural frequency obtained from the transverse traces is between 3.64 Hz and 4.23 Hz and the average value is 3.84 Hz.

Table-2 Natural frequencies of vibration from Fourier analysis of transverse records at the dam top

				natural frequencies (Hz)			
Record	Reservoir	Normalising factor		mode 1		mode 2	
No.	level (m)	mode 1	mode 2	Rec	Norm	Rec	Norm
KT 15T	76.14	0.887	0.916	4.10	3.64	10.20	9.04
KT 17T	70.42	0.872	0.900	4.50	3.74	10.30	9.27
KT 21T	96.34	1.000	1.000	4.13	4.13	8.90	8.90
KT 22T	95.04	0.987	0.995	3.82	3.82	9.60	9.47
KT 25T	85.52	0.926	0.946	3.98	3.68	9.60	9.08
KT 26T	74.26	0.882	0.910	4.80	4.23	9.30	8.46
KT 31T	91.23	0.951	0.961	3.91	3.71	9.00	8.56
KT 32T	96.12	1.000	1.000	3.82	3.82	9.50	9.50
KT 34T	96.40	1.000	1.000	3.95	3.95	9.85	9.85
KT 35T	96.12	1.000	1.000	3.90	3.90	9.25	9.25
KT 36T	96.49	1.000	1.000	3.80	3.80	8.75	8.75
KT 40T	87.71	0.916	0.960	4.05	3.71	9.90	9.50
average value					3.84		9.14

* normalising factor extrapolates the recorded frequency to the frequency at FRL.
Rec - recordec ; Norm - Normalised

The third mode is the vertical mode and the correction on account of the vertical motion is not required. Results of Fourier analysis of the vertical records were used for this study.

Table- 3 Natural frequencies of vibration from Fourier analysis of vertical records at the dam top

Record No.	Reservoir level m	Recorded Natural Frequencies Hz (Mode 3)
KT 32V	96.12	11.10
KT 34V	96.40	11.60
KT 35V	96.12	11.30
KT.36V	96.49	10.65
KT.37V	93.97	10.40
KT.40V	87.71	10.30
Average recorded frequency in mode 3,		10.99Hz

The computed first three frequencies for the basic material properties for the reservoir full condition are 3.252, 7.655, 9.636 Hz. The comparison between the results obtained for the basic material properties and the observed frequencies shows that the computed frequencies of the dam-foundation system are on the lower side . This indicates that the apparent stiffness is much higher than the static stiffness. The frequencies are therefore computed for the increased modulus of elasticity of the dam and foundation materials i.e. 25% and 40% and the results are shown in the Table 4.

Natural frequencies of the system, for the first four modes of vibrations have been computed with the basic system parameters. These frequencies are compared with the results of the Fourier analysis of the accelerograms recorded by the strong motion recording instruments installed on the dam top.

Table-4 Computed frequencies in Hz for different cases

Sl. No.	Ec/Eco	Erc/Erco	Ef/Efo	Mode 1	Mode 2	Mode 3	Mode 4
1	1.00	1.00	1.00	3.252	7.655	9.363	13.413
2	1.00	1.00	1.25	3.284	7.746	9.576	13.552
3	1.00	1.00	1.40	3.298	7.787	9.673	13.614
4	1.25	1.25	1.00	3.608	8.470	10.224	14.869
5	1.25	1.25	1.25	3.651	8.592	10.505	15.057
6	1.25	1.25	1.40	3.670	8.647	10.632	15.140
7	1.40	1.40	1.00	3.790	8.891	10.660	15.623
8	1.40	1.40	1.25	3.839	9.030	10.980	15.840
9	1.40	1.40	1.40	3.861	9.093	11.126	16.937

Eco, Erco and Efo are the modulus of elasticity of concrete, rubble concrete, and the foundation rock for the basic material.

The results corresponding to sl. no. 9 leads to a fair match between the computed frequencies and the frequencies obtained from the strong motion records. This is considered as a reasonable identification of the Koyna dam system. The average vertical predominant frequency obtained from the Fourier spectra is 10.99 Hz, which very closely matches with the computed natural frequency in the third mode i.e. 11.13 Hz.

CONCLUSIONS

The analysis of the accelerograms recorded on the dam show that the recorded fundamental frequencies of vibrations of the dam are consistent over a period of about 20 years. This indicates that there has been almost no deterioration of the dam material.

Comparison between the natural frequencies of vibrations of Koyna Dam obtained from the strong motion records and the computed values for different mathematical model shows that the system's dynamic stiffness is 40% more than the static stiffness.

REFERENCES

Chandrasekaran A. R., Arya A. S., Saini S. S.(1969), Stresses in Koyna Dam due to Earthquake of December 11, 1967, Earthquake Engineering Research Studies, University of Roorkee, Roorkee.

Chopra A.K., Chakarbarti P.(1971), The Koyna Earthquake of December 11, 1967 and performance of Koyna Dam, Earthquake Engineering Research Centre, University of California, Berkeley.

Guha S.K., Gosavi P.D., Krishnand, PadaleJ. G., Marwadi S.C. (1974), Koyna Earthquakes upto December 1973, Report published by CWPRS, Pune.

Gupta I.D., Joshi R.G., Rambabu V.(1993), Accelerograms of Koyna Dam Earthquakes", Technical Memorandum Published by CWPRS, Pune.

Jai Krishna, Chandrasekaran A.R., Saini S.S.(1970), Static and Dynamic Stress Analysis of Koyna Dam, Earthquake Engineering Research Studies. University of Roorkee, Roorkee.

Mane P. M. and Gupte V. S.(1962), Koyna Dam, Indian Journal of Power and River Valley Development, Koyna Project Special Number.

Murti N.G.K., Mane P.M., and Vinayak M.R.(1964), Evaluation of Rubble Concrete for the Koyna Dam and performance of the structure, Transactions- Eighth Congress on Large Dams.

Okamoto S. *et al.*(1969),Study on Dynamic Behavior of Koyna Dam During Earthquake on 11th Dec., 1967, A report by the Institute of Industrial Science. University of Tokyo.

--(1992), Analysis of Structural Stability of Koyna Dam for Maximum Credible Earthquake, A Report prepared for the Dam Review Panel appointed by Govt.of Maharastra.

--Extracts from Reports of Consultants, Technical Subjects (B),Geology, Completion Report, Koyna Hydro-Electric Project, Govt.of Maharashtra.