Bull. Ind. Soc. Earth. Tech., Paper No.360, Vol.33 No.4, Dec.1996, pp 241-257

RECENT DEVELOPMENTS IN SEISMICITY ASSOCIATED WITH RESERVOIRS

H.N. Srivastava,
Emeritus Scientist
India Meteorological Department
New Delhi

ABSTRACT

Developments in the understanding about earthquakes associated with reservoirs have been reviewed, in particular based on Deterministic Chaos and Principal components analysis. Our analysis has shown that the earthquake system around Koyna reservoir is predictable with a minimum of 5 parameters in comparison to a large number of parameters around Nurek Dam in complex tectonic setting. Principal component analysis based on global data had brought out a better physical insight into reservoir associated parameters about earthquake hazard assessment. The continued seismic activity around Koyna reservoir in relation to earthquakes of magnitude 5 could be analysed in greater depth than attempted so far using the same method.

Key Words : Reservoirs, Earthquakes, Chaos, Principal Components Analysis.

INTRODUCTION

Reservoir associated earthquakes have necessitated the attention of geoscientists to evolve new approches. Inspite of differences among the scientists about the causes of earthquakes near the reservoirs after impounding, a basic question arises whether earthquakes are predictable around reservoirs using dynamic approach based on deterministic chaos. Also application of principal component analysis to the global and site specific cases would enable us to estimate earthquake hazard assessment in greater depth. The object of this paper is to examine these aspects which have been attempted by scientists for the first time. Also the continuing nature of seismic activity near Koyna reservoir requires developments of models for quantification of earthquake risk. It may be mentioned that a state of art on the subject available till 1990 was given by Gupta (1992).

METHOD OF ANALYSIS

Application of deterministic chaos

(a) Grassberger and Procaccia (1983) method :

A phase space is defined by the variable :

$$x(t),\ x\ (t+\tau)\ldots\ldots\ldots x\ (t+n-1)\tau)$$

The dimension d of the attractor is related to C_m by the relation.

$$C_m(r) = r^d$$

Log C_m is plotted aganist log r. The slope of the scaling region is obtained for various embedding dimensions. As we increase the embedding dimensions (m), the sloipe saturates to a limiting value which is considered as fractal dimension of the strange attractor. The delay time is slowly increased till same fractal dimension is obtained for two consecutive delay times, τ.

(b) Lyapunov Exponent (Woef et al, 1985)

We consider a system described by N ordinary differential equations.

$$\frac{dx_i}{dt} = F_i\left(x_i \ldots\ldots x_n\right)\ ;\ i = 1 \ldots N$$

The solution space for this problem conceptually follows solutions that start within a hypershere of radius r. As the solution evolves, the hypersphere is deformed into a hyperellipsoid with principal axes. The Lyapunov Exponent is

$$\lambda_i = \left\{ \lim(t \to \infty) \lim(r \to 0) \right\} \times \left\{ \frac{1}{t} \left(\frac{e_i(t)}{r} \right) \right\}$$

If $\lambda_i \leq 0$ all solutions that start with initial conditions close to each other will converge i.e. there is no sensitivity to initial conditions. But if just one l is positive, the nearby solutions will diverge i.e. there will be extreme sensitivity to initial conditions.

The growth of uncertainity in time t is given by

$$N = N_0 e^{\lambda t}$$

where N is initial condition related to the concept of entropy in information theory and also related to the concept i.e. the Lyapunov Exponent, which measures the rate at which nearby trajectories of a system in phase space diverge.

PRINCIPAL COMPONENT ANALYSIS OF PARAMETERS AROUND RESERVOIRS

The principal component analysis provides a simple means of transforming linear functions of p original variables e.g. x_m, m=1,2 ...,p to another set of variables, e.g., X_m. The function x_i may be written as :

$$X_i = a_{i1}x_1 + a_{i2}x_2 \ldots\ldots a_{ip}x_p$$

where a_{im} values are constants.

As a_{im} varies, one gets different linear functions and one can calculate the variance of any such linear function. The first Principal Component (PC) is that linear function which has the maximum possible variance ; the second PC is the linear function with maximum possible variance subject to being uncorrelated with the first PC and so on. Thus, it is easy to construct 'p' principal components providing optimal m - dimensional representation of the data for each m = 1,2,..,p for various different definitions of optimality. In particular at each stage, the sum of the variance of the PCs is as large as possible. In other words, with Principal Component Analysis we get for each m = 1,2, ...,p the 'm' linear functions of $X_1, X_2, \ldots\ldots, X_p$ which account for the maximum possible proportion of the original variations. Here a_{im} (m = 1,....,p) are vectors consisting of the weights of different variables in the ith PC. We compute eigen vectors of the (pxp) co-variance (Covar) matrix between all X_m. The orthogonality condition on X_i implies that covar matrix of X_m has off diagonal terms as zero while that of x_m has the diagonal and off diagonal terms also. The transformation from x to X therefore can be achieved by only diagonalising the covariance matrix.

Thus the first eigen vector is the set of coefficient a_{im} ,m = 1,....,p appearing in the first PC. Similarly, subsequent eigen vectors consist of coefficients of $X_2, X_3, \ldots\ldots, X_p$ in each successive PC. The first eigen value is the variance of the first PC and so on. To define the principal components uniquely, the normalisation condition is imposed. Method of normalisation used in this paper is given by :

$$\sum_{i=1} \alpha^2 = \frac{1}{\lambda_i}$$

where Var (X_i) = 1 for m = 1,....,p being the corresponding eigen value.

As an example, we may consider subscripts 'i' to define the time and 'm' to define space domains. The primary advantage of the principal component solution is its ability to compress almost the total variability of the original data set into a relatively few temporally uncorrelated components. However, the spatial othogonality of the eigen vectors is a strong and often undersirable constraint imposed on the principal component solution. While the first principal component and its eigen vectors are not influenced by this constraint, the remaining eigen vectors often bear predictable geometric relationships to the first eigen vector.

RESULTS AND DISCUSSIONS

Chaotic Dynamics

We have considered three periods for Koyna region as follows :

(i) Period I covers data for the period from February 1967 to December 1981. It includes the largest foreshock of magnitude 5.0 during September 1967, main shock of December 1967 and its immediate aftershocks of the same month besides earthquakes of magnitude 5.0 during October 1973 and September 1980.

(ii) Period II includes data from January 1968 to September 1973 and is a part of the period I. This period begins a few days after occurrence of main earthquake and ends a few days prior to the earthquake of 1973.

(iii) Period III covers the data from January 1968 to August 1980. It is a part of the period I but also includes period II. This period begins a few days after occurrence of main earthquake and ends a few days prior to the earthquake of September 20, 1980. The period contains the earthquake of October 17, 1973.

The result for period I is shown in Figs. 1a and 1b. It may be noted that the slopes for $\tau = 4$ and 6 are converging to 4.2 as the embedding dimension is increased. We get fractal dimension of the attractor as 4.4 for period II. The result for period III gives fractal dimension of the attractor as 4.4. It may be mentioned that care has been taken to avoid spurious result being obtained by keeping the number of earthquakes N for each period such that the criterion 2log N D is satisfied. Here D is the fractal dimension (7). In view of consistency in the fractal dimension in the Koyna region, Srivastava et al. (1994) suggested it as a new measure of seismotectonics. Srivastava et al. (1995) have extended similar studies pertaining to Aswan and Nurek reservoirs and found a strange attractor dimension of 3.8 and 7.2 respectively. Since Koyna and Aswan reservoirs are located in shield regions as compared to Nurek reservoirs in a complex tectonic zone, it was surmised that strange attractor dimensions could be a measure of seismotectonics around such reservoirs. Further studies on strange attractor dimensions in tectonic regions in India like Hindukush (Bhattacharya and Srivastava,

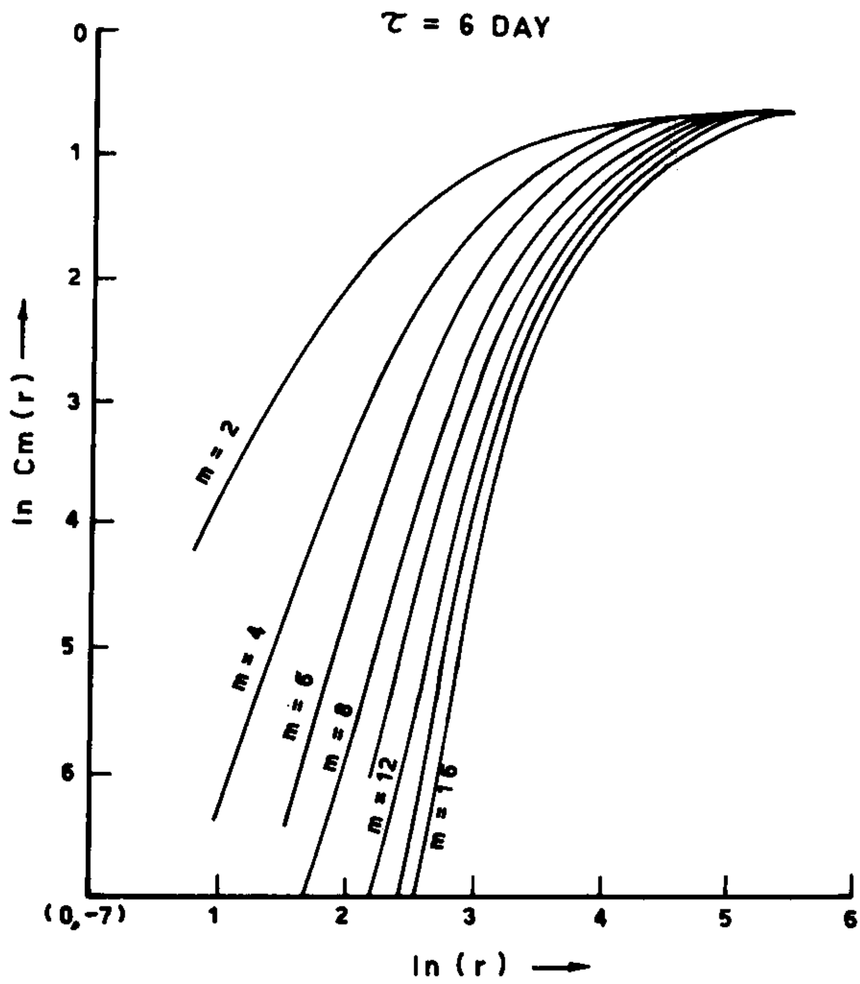

FIG. 1(a) KOYNA EARTHQUAKE (FEB. 1967 - DEC. 1981) DISTANCE DEPENDENCE OF THE CORRELATION FUNCTION FOR A SEQUENCE OF EMBEDDING DIMENSIONS (m = 2,4,6,8,10,12,14 AND 16)

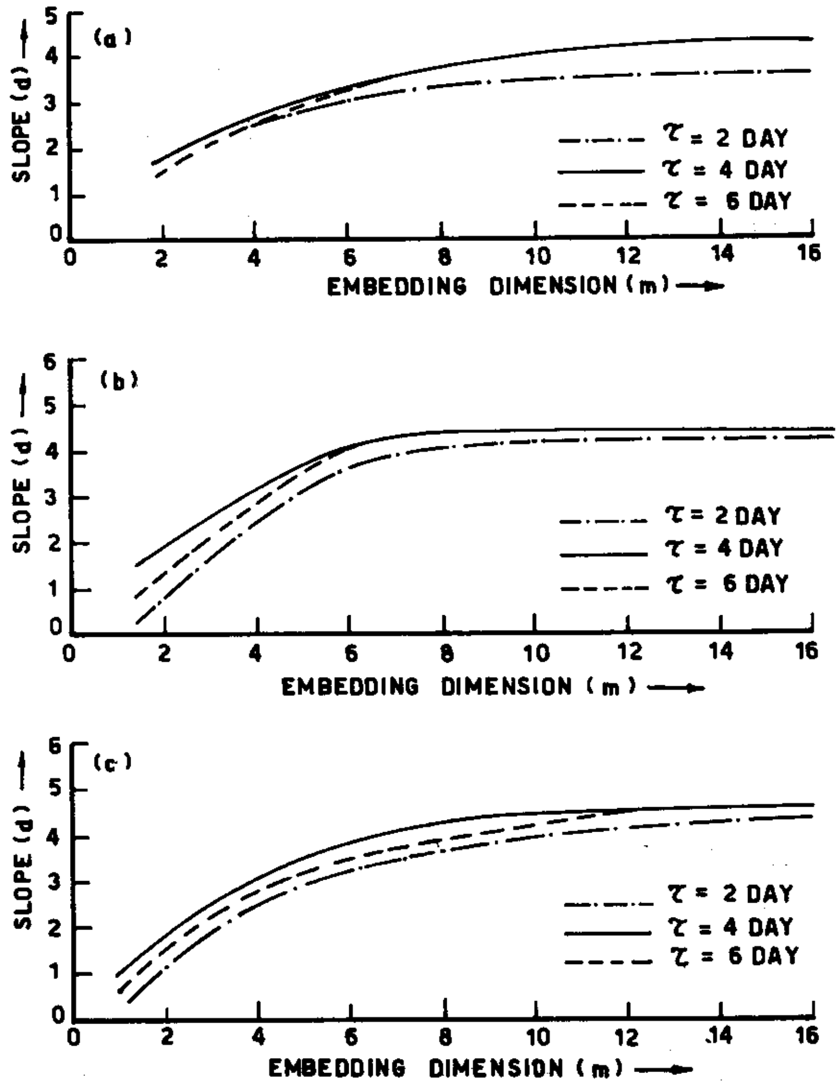

FIG. 1(b) _ DIMENSIONALITY d OF THE ATTRACTOR AS A FUNCTION OF EMBEDDING DIMENSIONS
(a) February 1967 - December 1981
(b) January 1968 - September 1973
(c) January 1968 - August 1980

(1992) north west Himalayas (Bhattacharya, 1990) and north east India suggest a new method of distinguishing interplate and intraplate earthquakes (Srivastava et al.,1996)

It is interesting to note that no evidence of deterministic chaos could be found near Oroville reservoir, USA.

PCA Analysis Results

1. Global Data

Empirical orthogonal functions (EOF) associated with the parameters conducive to reservoir induced seismicity were computed based on 37 cases throughout the world. It was found that the first EOF explained 54% variance. It showed a correlation of 0.36 with the maximum magnitude of earthquakes and had larger loadings for reservoir volume and the time lag of the occurrence of the largest earthquake since the filling of the reservoir. The second EOF which explained about 34% variance showed largest loading for the height of the reservoir but had a correlation of only 0.1 with this parameter. Srivastava and Dube (1996) inferred that the combined influence of the reservoir volume and the time lag appears to be more important than the height of the reservoir from the view of hazard assessment.

2. Koyna Region

The methodology was extended to site specific case of the Koyna reservoir for earthquakes of magnitude 5.0 occurring in September, 1967, October, 1973 and September, 1980. The seismicity pattern proceeding these earthquakes were remarkably different. Keeping in view that all these earthquakes occurred after the reservoir was filled to the largest level and the events occurred towards the end of monsoon season, an attempt was made to examine the role of the following parameters (Srivastava and Bhattacharya, 1996) :

(i) Number of microearthquakes recorded by Koyna observatory close to focal region.
(ii) Number of epicentres detected by local network.
(iii) Number of earthquakes of magnitude 2.0
(iv) Number of earthquakes of magnitude 3.0.
(v) Sense of first motion, compression, C.
(vi) Sense of first motion, dilatation, D.
(vii) Percentage ratio of compression/dilatation at Koyna observatory.
(viii) Sense of first motion at Pune observatory.
(ix) Seismic energy released.
(x) Largest magnitude recorded.
(xi) Height of reservoir level.
(xii) Change of reservoir level.

The PCA analysis brought out the following interesting results

(i) The first principal component (PC) which explained 57% variance had the largest loading due to microearthquakes at Koyna observatory followed by number of dilatations. The influence of height of reservoir and seismic energy release had almost similar loading but of lesser extent.

(ii) The first PC in the case of the 1973 earthquake explained a variance of 56% with the largest loading due to the height of the reservoir followed by the percentage ratio of C/D and the reservoir level change.

(iii) The first PC in the case of the 1980 earthquake explained a variance of 73% with the largest loading on microearthquakes at Koyna followed by number of dilatations at Pune observatory. Thus the influence of the reservoir height or the change in its level became ess marked.

In view of non availability of data for Koyna earthquakes occurring in 1993 when the largest magnitude again reached 5.0, PCA analysis could not be undertaken. In contrast to detailed seismological bulletins prepared by CWPRS, Pune for Koyna earthquakes, upto 1981, epicentral information is now given in the monthly bulletins thus making it difficult to extend the new methodology for 1993 earthquakes. As discussed earlier, since the minimum number of parameters for earthquake predictability in the Koyna region is 5, we may choose appropriate parameters using PCA analysis to develop a predictive model.

STRESS VARIATIONS NEAR RESERVOIRS

(A) Laboratory Studies

Masuda et al., (1993) reported laboratory study of effects of insitu stress state and strength on fluid induced seismicity. No induced micro-fractures were observed during the injection into a dry granite rock under hydrostatic pressure. However, thousands of induced micro fractures were detected during the injection into a saturated granitic rock subjected to the differential stress state. The locations of detected hypocentres and distribution of surface volumetric strains showed that induced micro-fractures occurred in the region where local fracture strength was weak. The triggering of seismicity by fluid flow or water pressure changes underground is controlled by the pre-existing insitu differential stress state and the strength distribution in a host rock.

Savich et. al. (1992, Personal communication) of Hydro Meteorological Institute, Moscow have carried out geophysical monitoring to record deformation processes at different scales at the Rogun Dam area. It was found that dissipation of tectonic stress in the form of microearthquakes is accompanied by considerable deformations at small scale level monitored in seismic and ultrasonic frequency range.

Three elements in this case based on hydroseismicity hypothesis are

(i) Large ground water basin with relatively high surface topographic gradients.
(ii) A hydraulically permeable upper crust.
(iii) A strong insitu stress field.

(B) Case Studies

Chaudhury and Srivastava (1978) presented analysis of seismological observations for Pong and Bhatsa Dams and did not find any increase in seismicity. It may be noted that seismological data for Pong Dam is available since 1965 while the filling of this dam started in May 1975. This result was further corroborated by Srivastava and Dube (1982) and Srivastava (1990) for these two as well as for Pandoh Dam. While noting the temporary decrease of seismicity around Tarbela reservoir in Pakistan after impounding and keeping in view the thrust type of environment where these dams are located, Gupta and Rajendran (1986) suggested that the apparent lack of RIS at Himalayan reservoir sites may be attributed to predominantly thrust fault environment. Chander and Sarkar (1993) attributed deficiences in the model proposed by Snow (1972) which explained lack of seismicity in thrust type of environment. Zhu (1992) has reported results of continuous monitoring at two reservoirs in Canadian shield at Quebeck. Focal mechanism computed for 16 induced events (maximum magnitude 4.1) showed a combination of thrust/strike slip or pure thrust faulting. The largest events at either sites showed pure thrust faulting with a NNE direction of P axis suggesting that the two regions are under compressive stress. Also Chung and Lin (1992) have reported thrust faulting for Srinagarind, Thailand earthquake of April 1983 (magnitude, $m_b = 5.8$) where the time interval between impounding and the largest induced earthquake was about 68 months. The stress drop for this intraplate event was 180 bars. Nurek reservoir is also a well known example of thrust type environment. It is of interest to note that in the Koyna region Gupta and Rambabu (1993) reported large variations in stress drops based on strong motion data which were broadly in agreement with those derived from digital seismographs (B.K. Rastogi- Personal Communication).

Grasso et al. (1992) have considered triggered earthquakes as stress gauge based on a reservoir in Grenoble area, France. They have found that shallow events within 10 km of the reservoir resulted from first filling effects. Later more distant events at greater depths in 1979-1984 resulted from gradual diffusion of water from the reservoir to hypocentral depths.

A question arises whether Tehri Dam located in seismically active region of the Himalayas is more vulnerable from earthquakes as compared to Mangla, Pong, Pandoh and Bhakra dams. Since no increase on seismicity close to reservoir could be detected so far it could be inferred that the threat from reservoir induced seismicity may not be appreciable. The other question is the possibility of a great earthquake. (magnitude 8) near the dam. Studies by Tandon and Chatterjee (1968) have shown that an earthquake of magnitude 8.0 may occur once in 40 years. Srivastava and Dattatreyam (1986) have reported a return period of about 500 years for an earthquake of magnitude of 8.5 by Gumbels' methods and 300 years by Gutenberg Richter's method for India Nepal border region. The probability of occurrence of an earthquake decreases further for smaller areas and thus there is remote possibility of an earthquake very close to the site. However, suitable design of the dam may ensure adequate safety for such structures against earthquake forces.

Chander and Sarkar (1993) have suggested that a moratorium should be placed on the use of seismological data for drawing conclusions about the possibility or lack of RIS in the Himalaya. It may be mentioned that the seismic monitoring around Pong and Pandoh Dams is one of the few cases in the world where seismological observations were started through a network of 10 seismological stations using Hagiwara electomagnetic seismographs. The epicentral parameters in this region were accurate ±1 km and focal depth to about 5 km. Thus our results about lack of increase in seismicity around Pong and Pandoh dams cannot be questioned. Similarly, there is no significant change in seismic activity around Bhakra and Salal dams which are monitored through the same network after addition of three more seismological observatories with Kinemetrics analog instruments.

Of late however, lack of financial support from the Bhakra and Beas Management Board has resulted in the closure of some of these run by the Indian Meteorological Department. Also the seismological equipment needs to be replaced due to its continuous use for more than 25 years or so. Keeping in view the necessity of the local seismological stations to assess earthquake hazards around a reservoir, it is felt that establishment of a network should be made mandatory through the Central Water Commission which is the apex body to sanction the design seismic coefficient well before the start of any river valley project.

EARTHQUAKE SWARMS NEAR RESERVOIR

Earthquake swarms have been reported near Usmansagar, Sriramsagar (Rastogi et al.,1986, I,II) Bhatsa and Koyna regions in India. Although larger earthquakes with continued seismic activity were followed near Bhatsa and Koyna reservoirs, the seismic activity dissipated rapidly near Usmansagar and Sriramsagar reservoirs. Singh et al.,(1992) examined the occurrence of earthquake swarms in 1988 near Idduki and attributed them to Periyar and Kamban lineaments. The occurrence of swarms for several years near Kelia reservoir, Valsad district raised a question whether they can be induced with a lake of only 18 meter depth (Rao et al, 1991). It is of interest to note that earthquake swarms near Norris lake in 1993 has several characteristics of reservoir induced earthquakes. The lake is small (96 acres), of 2-5 meter depth where the largest earthquake of magnitude 2.7 occurred on September 23, 1993. Over 10,000 earthquakes were detected with average focal depth of 1 km. The elevation of the lake was nearly constant since 1950. Long et al., (1994) summarised that reservoir induced earthquakes may have the same mechanism as for natural seismicity. The case of small area reservoir in Gujarat also brings to light similar inference where an earthquake of magnitude 4.6 occurred in 1991 after water was totally withdrawn from the lake.

The occurrence of two types of swarms namely non-precursory and precursory swarms in the peninsular India is important from the point of view of risk assessment since damage may occur with the main earthquakes following precursory swarms. Srivastava and Dube (1996) worked out distinctive criteria between precursory and non-precursory swarms keeping in view that Killari earthquake of 1993 in the peninsular India was preceded by swarms about one year before the main event. It may however be noted that earthquakes with precursory type of swarms are characterised by four phases of seismic activity namely swarms, foreshock, main shock and aftershocks. Thus asperity model (Kanamori, 1981) appears to hold good in these regions.

Reliable estimates of the thickness of Deccan traps and sedimentary layers of peninsular India have been obtained through deep seismic sounding explosion experiments conducted by National Geophysical Research Institute. The average thickness of Deccan traps has been considered as 1.2 km increasing towards the Western Ghats, The focal depths of non-precursory swarms as monitored through a close network of seismological stations extended upto 2km. Thus their foci lay close to the boundary of the Deccan traps/sediments and the crystalline basement granitic layer. Their occurrence is attributed to crustal adjustments along the shear zones. On the other hand, the focal depth of the largest foreshock of September 13, 1967 earthquake in Koyna region was reported as 5 km based on source inversion of seismic wave forms (Langston, 1981). The focal depths of Koyna aftershocks generally extended from about 5 to 20 km with their foci in the granitic layer. Also, the focal depths of the largest foreshock (1992) of the main Killari earthquake of 1993 was about 7 km (US Geol. Surv.). Synthesis of these observations in conjunction with the earthquake depth frequency distribution shows that precursory earthquake swarms are associated with greater focal depth.

It has been observed that with the exception of the Killari earthquake of 1993 three precursory swarms have occurred near the reservoirs. By plotting the logarithm of the time interval, t between the earliest felt swarm and the main earthquake versus its magnitude, M, we find that the data for reservoir associated swarms lie on a straight line with a very small root mean square error (RMSE) of 0.0574. Maximising the data set by including Killari swarms we get the following relationship between the magnitude M of the main earthquake and the time, t (RMSE=0.214).

$$M = 1.88 + 1.5 \log t$$

Thus the duration of precursory swarm increases with the magnitude of impending shock. It may be surmised that the distinctive criteria for two types of swarms, whether associated with the reservoir or not, could be refined when additional data become available.

ANOMALOUS SEISMIC WAVE VELOCITIES IN THE KOYNA REGION

Accurate determination of seismic wave velocities and crustal structure is obtained with explosions of exact origin time and location. Making use of DSS explosion experiments by National Geophysical Research Institute, a network of high gain microearthquake stations around Koyna region (phase I and phase II) enabled us to obtain the results given in Table I (Srivastava, 1988).

Table 1 : Crustal Velocities in Koyna region from Explosion data (Srivastava et al, 1984)

H.1. (km)	P (km/Sec)	S (km/Sec)
0.0	4.60	-
1.20	5.82	3.41
17.30	6.61	4.09
36.30	8.23	4.60

The following interesting observations may be noted (Srivastava et al.,1984) :

(i) Velocities of Pg and Sg waves are lower in the Koyna region as compared to other regions of peninsular India.

(ii) Marked heterogeneity in the crust on either side of Karad and strong attenuation of waves west of Karad suggest a fault.

It is of interest to note that the above model in the Koyna region gave least errors in the hypocentral parameters. An independent study by P.Talwani (personal communication) for redetermination of epicentral parameters of earthquakes of magnitude $\leq$ 3.0 of this region also corroborates our results. The model was again validated through the aftershocks of Killari earthquake of 1993 (S.N. Bhattacharya,-personal communication). Under the seismicity project of the Department of Science and Technology, the establishment of a few more digital seismographs in the Koyna region would improve the epicentral determination of earthquakes to provide better understanding the mechanism of earthquakes of the region.

Lower values of P and S waves within the Koyna region as compared to other regions of peninsular India has given a V /V ratio as 1.706 in Koyna region as against 1.65 in the other parts of peninsular India. Lower values of P and S could be attributed to :

(i) Highly fractured region saturated with less rigid material like water.

(ii) Closing of pre-existing cracks.

EARTHQUAKE RECURRENCE IN THE KOYNA REGION

Earthquakes of magnitude 5.0 are occurring in the Koyna region at a longer interval of time. We compare the occurrence of earthquakes, particularly aftershocks, of the Koyna region with other earthquakes of similar magnitude. We note the following differences :

(i) Aftershocks of earthquakes in the peninsular India subside over a very short interval of time (as for Killari earthquake of peninsular India) as compared to almost similar magnitude earthquakes of Koyna.

(ii) Aftershock activity of earthquakes in tectonically active regions of Himalayas like the Uttarkashi earthquake of 1991 also decreased repidly.

On the basis of residual seismicity and the largest aftershocks, a schematic model can be worked out from the trend of micro earthquakes near the Koyna reservoir. The largest aftershock had a magnitude of 5.0 and during the last 20 years, three earthquakes of similar magnitudes have occurred in 1973, 1980 and 1993. Thus earthquakes of magnitude 5.0 are occurring with an increased interval of time. Keeping in view the occurrence of an earthquake in 1764 of magnitude 6.5 in the same region (Kelkar, 1968) it may be noted that it took about 200 years for an earthquake of similar earthquake to recur during December, 1967. The continuing active phase of the seismic activity in the Koyna region does not allow the energy to accumulate. Recurrence of earthquake of magnitude 6.5 in the region is, therefore, ruled out in the near future. Since energy accumulates at a slower rate than that released through smaller events, earthquakes with magnitude upto 5.0 continue to take place. The trend pattern in seismic activity near Koyna can be shown by a schematic model (Fig.2). This model suggests that the largest impending earthquake magnitude may not exceed that of the largest aftershock. Extending this model to the Bhatsa tremors, Srivastava et al. (1991) predicted the magnitude of the earthquake of June, 1990. The model was further validated when earthquakes of magnitude about 5.0 occurred again in 1993 in Koyna region. Srivastava (1990) fitted this model with that proposed by Kanamori (1981). Mahmoud et al.,(1995) have extended the model to Aswan reservoir.

CONCLUSIONS

1. The most important finding which is based on deterministic chaos suggests that for modelling of earthquakes near Koyna reservoirs, we need at least 5 parameters which could be specified using the principal component analysis. Also greater physical insight into earthquake risk due to reservoir could be obtained using the same methodology (PCA).

2. Detailed analysis of seismograms for all the project observatories in the country in the form of monthly bulletins should be undertaken similar to that done by IMD,NGRI and BARC so that data is readily available for research for applying new techniques.

3. Seismological observations around reservoirs should be made mandatory through the committee set up by the Central Water Commission at the time of deciding the design seismic coefficient to understand the complexities of reservoir associated seismicity.

ACKNOWLEDGEMENT

I am grateful to Dr. K.G. Bhatia and the Indian Society of Earthquake Technology for inviting me for ISET Annual Lecture. Thanks are also due to the Council of Scientific and Industrial Research for financial support.

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