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ORIGINAL PAPER

Complexity in hydro-seismicity of the Koyna–Warna region, India

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Abstract Koyna–Warna region in western India is known to be the largest case of the reservoir-triggered seismicity in the world with M6.3 earthquake in 1967. This region continues to be seismically active even after 45 years with occurrences of earthquakes up to M5.0. The porous crustal rocks of Koyna–Warna region respond to changes in the prevailing stress/strain regime. This crustal section is highly fractured and is being fed by rivers and reservoirs. It is also subjected to fluctuating plate boundary forces and significant gravity-induced stresses due to crustal inhomogeneities. These changes induce variations in the water level in bore wells before, during and after an earthquake, and their study can help in understanding the earthquake genesis in the region. The ongoing seismicity thus requires understanding of coupled hydrological and tectonic processes in the region. Water table fluctuations are a reflection of the ongoing hydro-tectonics of the region. The fractal dimension of water levels in the bore wells of the region can be used as measure of the nonlinear characteristics of porous rock, revealing the underlying complexity. In this paper, we present values of correlation dimensions of the water level data in the bore wells using the nonlinear time series methodology. The spatiotemporal changes in the fractal

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dimensions have also been determined. The results show that hydro-seismically the region behaves as a low-dimensional nonlinear dynamical system.

Keywords Seismicity · Nonlinear · Hydro-tectonics · Porous rock

1 Introduction

The seismicity in the Koyna–Warna region in western India within the interior of the Indian continental plate started in 1962 after the impoundment of the Koyna reservoir. Since then, the earthquakes continue to occur in this region, even after more than 45 years with moderate earthquakes of $M > 4$ occurring frequently. The seismicity in this region is believed to be reservoir triggered. The region has been extensively studied (Rastogi et al. 1997, Gupta 2002; Chadha et al. 1997 and Talwani 1997), and it is seen that the region between the Koyna and Warna reservoirs consists of several tectonic blocks with earthquakes occurring on the edges of the blocks. Several workers have provided qualitative interpretation for the triggered earthquakes in the Koyna region during the last four decades, but the mechanism of triggering seismicity has still not been understood satisfactorily. Rajendran and Harish (2000) put forward a conceptual model based on percolation of reservoir water through vertically permeable fault zone present in the area, to explain the earthquakes in the Koyna–Warna region.

The occurrence of intraplate earthquakes can be modeled by using the hydro-seismicity hypothesis, which requires the existence of connected deep permeable fractures from the surface to hypocentral depths of the region. Most fractured porous rocks show a strong dependence of their fluid transport properties on the pore pressure. This process of pore pressure diffusion is governed by the nonlinear diffusion equation.

Earthquakes are associated with changes in the bore well water levels. The water level fluctuations in deep bore wells within the region have been analyzed to study anomalous changes in well water level vis-a-vis earthquakes to understand the stress transfer in the crust. Anomalous changes in the well water level fluctuations related to earthquakes have been reported by several workers (Wakita 1975; Igarashi et al. 1992; Reoloffs 1996, 1998). These changes could be pre-seismic or co-seismic (Koizumi et al. 1996, 1999; King et al. 2000; Chadha et al. 2003). Water level fluctuations in deep bore wells of seismically active Koyna region in western India thus can provide an opportunity to understand the causative mechanism underlying reservoir-triggered earthquakes. The water levels in the wells in porous crustal rocks of Koyna region respond to changes in the prevailing stress/strain regime. As the crustal porous rocks behave nonlinearly, their characteristics can be obtained by analyzing time series of water level fluctuations, which reflect an integrated response of the medium. The correlation dimension of the water level time series describes the complexity of the system by providing the information related to the minimum number of variables needed to describe the nonlinear dynamical system. The correlation dimension of the water level time series for a particular well in the Koyna–Warna region has been presented recently by Ramana et al. (2009). In the present work, we study the spatiotemporal variation of the correlation dimension in the Koyna–Warna region using available bore well water level time series data at different locations within the region.

2 Methodology

The Grassberger–Procaccia (GP) algorithm is used to estimate the correlation dimension of some measure μ from a given set of points randomly distributed according to μ. The algorithm is based on the phase space reconstruction of the time series. According to the Taken's embedding theorem (Takens 1981), an n-dimensional phase space can be reconstructed from the single available time series x_i of water table variations as

$$X_i = \left(x_i, x_{i+\tau}, x_{i+2\tau}, \ldots, x_{i+(m-1)\tau}\right) \tag{1}$$

Here, τ and m are the time delay and embedding dimension, respectively. Let the N points be denoted by X_1, X_2, …,X_N in some metric space with distances $|X_i - X_j|$ between any pair of points. For any positive number r, the correlation sum $C(r)$ is then defined as the fraction of pairs whose distance is smaller than r,

$$\hat{C}(r) = \frac{2}{N(N-1)} \sum_{i<j} \theta\left(r - \left|x_i - x_j\right|\right), \tag{2}$$

Here, $\theta(x)$ is the Heaviside step function. It is an unbiased estimator of the correlation integral

$$C(r) = \int \mathrm{d}\mu(X) \int \mathrm{d}\mu(Y) \theta(r - |X - Y|). \tag{3}$$

Both '$C(r)$' and '$\hat{C}(r)$' are monotonically decreasing to zero as $r \to 0$. If $C(r)$ decreases like a power law, ($C(r) \sim \boldsymbol{r}^{D}$), then D is called the correlation dimension. Formally, the dimension is defined by

$$D = \lim_{r \to 0} \frac{\log C(r)}{\log r} \tag{4}$$

The GP algorithm is used generically for any algorithm that attempts to estimate $\boldsymbol{D}$ [and more generally $C(r)$] from the small 'r' behavior of $C(r)$, in particular when the input data are in the form of a time series. Because this involves an extrapolation to a limit where the statistics is severely undersampled for any finite N, this is an inherently ill-posed problem. The simplest and most naive way to estimate D is to plot $C(r)$ against r on a log–log plot and to fit a straight line to the small r tail of the curve. D is then the slope of this line. The complexities of the system are described by the correlation dimension. The plot between the correlation D and m saturates at some finite value. This finite value is called the correlation dimension of the time series and describes the dynamic system. The details of the calculation for the time series are given in Ramana et al. (2009).

3 Results and discussions

Koyna–Warna region have been investigated by the integrated geophysical studies to understand the mechanism of the earthquakes. Twenty-two bore wells have been drilled in the vicinity of the Koyna–Warna region during 1996–1998 to monitor the water table variations in the region. The Koyna–Warna region along with the location of the bore wells as well as location of March 14, 2005, earthquakes is shown in Fig. 1.

We selected the water level fluctuations around the March 14, 2005, Koyna–Warna earthquake. Figure 2 shows the bore well water level fluctuations in twelve bore wells.

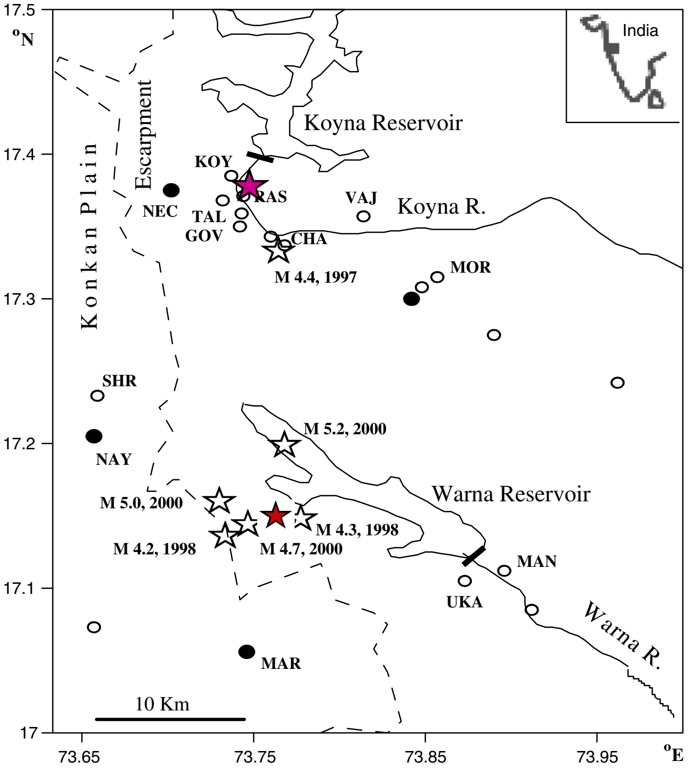

Fig. 1 Location of the Koyna–Warna reservoirs; *Circles* (*open* as well as *closed*) indicate the locations of bore wells. The three letters like UKA show the name of the bore well. *Small star* (in *red*) indicates the main shock and March 14, 2005, event, and other stars indicated some more significant events; *big red star* indicates the main shock of Koyna–Warna

Only four bore wells, viz., in Ukalu, Nayari, Marleswar and Nechal show the co-seismic water level changes during the origin time of March 14, 2005. From the Fig. 2, it is seen that the maximum and minimum variations in the water levels is shown at Ukalu and Marleswar wells respectively.

The correlation dimension is computed for water level fluctuations observed in the bore wells. We have taken two wells (Ukalu and Nechal) in which the co-seismic variation is seen and one well (Taloshi) where there is no co-seismic change. The statistical analysis is carried out on standardized time series by subtracting the mean from the original data and dividing it with standard deviation. Mutual information function is used to determine the optimum c. It is observed that the first minimum mutual information function occurs at lag 60, 44 and 36 for three wells Ukalu, Nechal and Taloshi, respectively.

We used the TISEAN software to compute the correlation dimension. In the software, the r and correlation integral $C(r)$ and the correlation dimension for different r's are computed. The MATLAB GUI is developed to get the automatic graphs. If the time series originates from a system with low-dimensional attractor, D approaches a constant value as the embedding dimension m increases. This limiting value provides a lower bound of the dimension of the considered dynamics. If the dynamics of the system is complex, the correlation dimension does not remain stable with changes in the embedding dimension

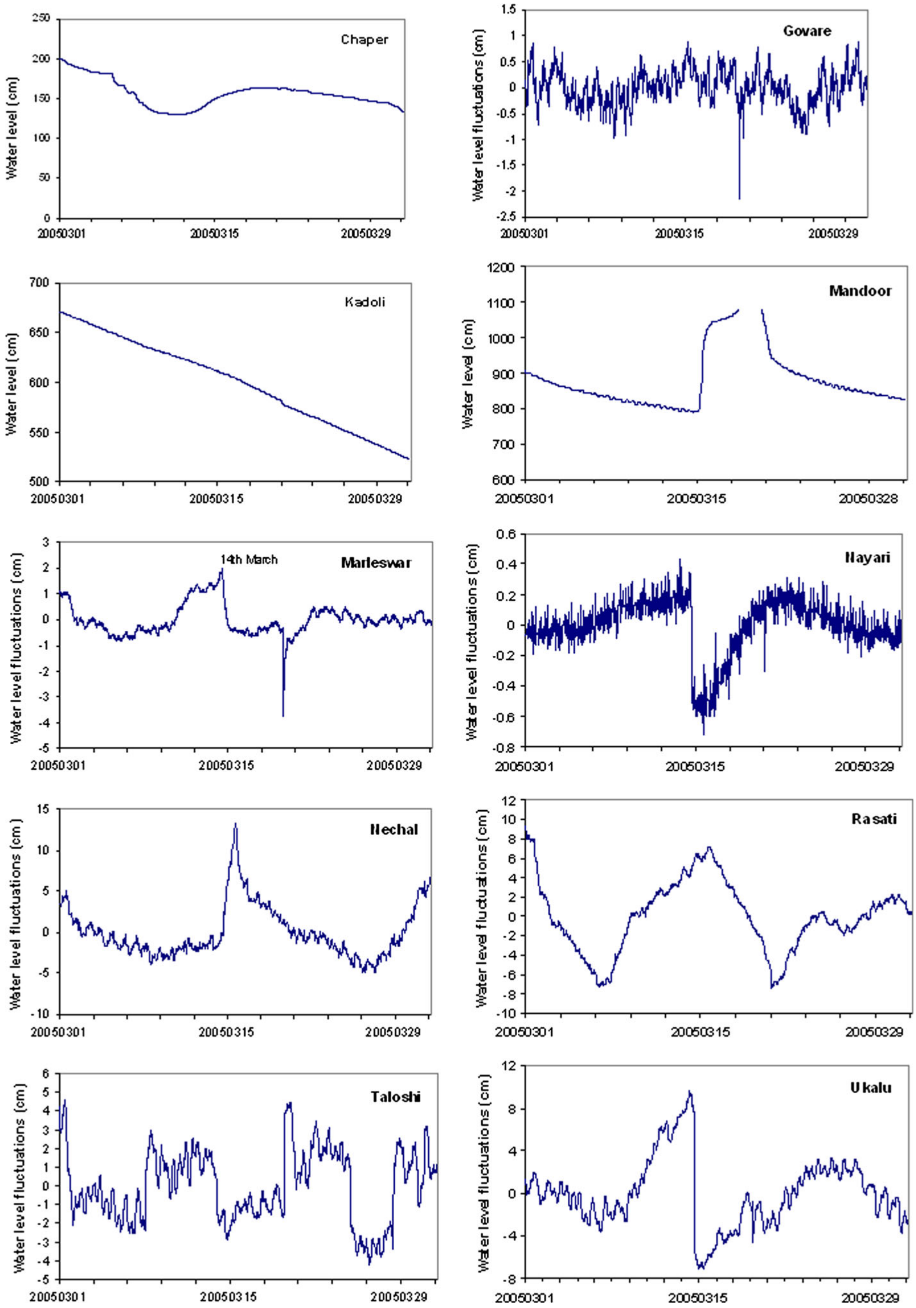

Fig. 2 The water level variations of various bore wells in the Koyna–Warna region

and does not converge to a limiting value. With the appropriate choice of scaling region of r, correlation integral is computed and based on that the correlation dimension is determined over different m. Fig. 3 shows the correlation integral for different scaling region

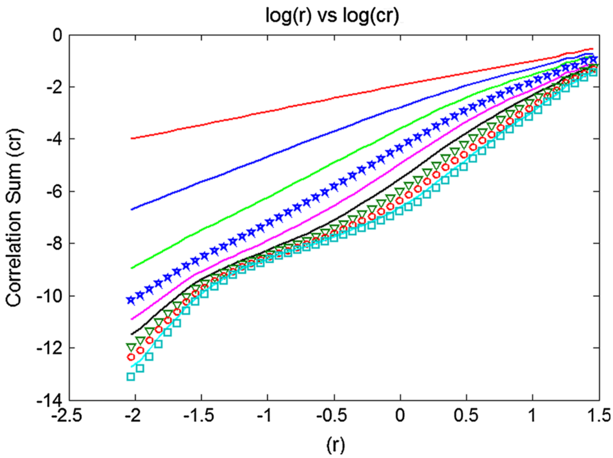

Fig. 3 Log (*r*) versus log (*cr*) plot for the year 2005 of Ukalu bore well

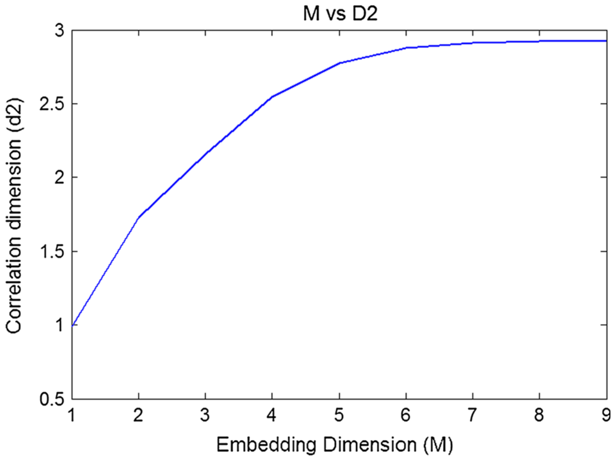

Fig. 4 Correlation dimension for the year 2005 of Ukalu bore well

r. Fig. 4 shows the graphical representation of the computed correlation dimension (*D*2) values for different radius, and the corner of the graph shows the numerical values of the correlation dimension at different *m*'s. In TISEAN, the values of the correlation dimension are obtained from the local slopes of the logarithm of the correlation sum. Table 1 shows the values of correlation dimension at different bore wells and are 2.1, 2.2 and 2.8 for water level fluctuations in Ukalu, Nechal and Taloshi wells, respectively. Nechal and Taloshi wells are far from Ukalu and nearer to each other. The correlation dimension is varied spatially, for example at Govare and Taloshil which are close to the Koyna reservoir has the *D* value 2.2 and 2.8 respectively. This shows spational changes in the correlation dimension are significantly near the Koyna reservoir. The correlation dimension at the bore wells near to Warna reservoir, i.e., at Mondoor and at Ukalu shows same value 2.1 and not significantly varies. From all these results, it may be concluded that there is a significant

Table 1 The correlation dimension at different bore wells for March 2005

Bore well stations	*D*2 values
Chaper	1.9
Govare	2.2
Kadoli	2.7
Mandoor	2.1
Marleswar	2.2
Nayeri	1.9
Nechal	2.2
Taloshi	2.8
Ukalu	2.1

Table 2 The correlation dimension at Ukalu well for the year 2005 at different time

Year 2005	*D*2 value
January	2.3
February	2.5
March	2.1
April	2.3
May	2.3

variation in the correlation dimension in Koyna–Warna region. It shows a variation in the correlation dimension, but still the minimum number of parameters to describe the nonlinear dimensional system remains three.

In order to study the variability in correlation dimension over time, the Ukalu well is selected. To understand the variation in the correlation before and after the occurrence of an earthquake, the correlation dimension has been computed for Ukalu well data in 2005 at each month separately. An increase (or decrease) in effective stress acting on a fault system results in a corresponding decrease (or increase) in the *b* value. The values of correlation dimension are tabulated and shown in Table 2 for January, February, March, April and May 2005. The results reveal that the correlation dimension starts decaying before the occurrence of earthquake. During the period of an earthquake, it is minimal and then again starts increasing. The correlation dimension is computed for the earthquake occurred on March 14, 2005; data are observed to be 2.1. This indicates that earthquake occurrence suddenly results in the decreased correlation dimension of the time series. If analyzed for January to March and then April to May, i.e., before and after earthquake, the correlation dimension observed is 2.3 and 2.3, respectively.

4 Conclusions

Water levels in the wells in porous crustal rocks of Koyna region respond to changes in the prevailing stress/strain regime. Analysis of water level data in some of the bore wells within the Koyna–Warna region has shown co-seismic anomalous variation due to March 14, 2005, Koyna earthquake. The present analysis of the water level data showed that the correlation dimension of the underlying nonlinear system is between 2 and 3. Thus, a three-component nonlinear dynamical system is needed to model the phenomena. Spatiotemporal variation of seismicity cannot be understood by the linear poro-elastic model, and we need nonlinear diffusion models. The study of the time variation in the fractal dimension for pre, co and post at the time of an earthquake occurrence is important in forecasting the moderate earthquakes at the region.

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