ARE RESERVOIR-INDUCED EARTHQUAKES OF MAGNITUDE $\geq 5.0$ AT KOYNA, INDIA, PRECEDED BY PAIRS OF EARTHQUAKES OF MAGNITUDE $\geq 4.0$?

BY HARSH K. GUPTA* AND H. M. IYER

ABSTRACT

Foreshocks of Koyna, India, earthquakes of magnitude $\geq 5.0$ are investigated using data from the Poona WWSSN Seismic Station situated at a distance of 120 km from Koyna. Schemes for estimating earthquake magnitude on the SPZ component seismogram at Poona have been developed. These schemes are applicable to earthquakes of magnitude $\geq 2.0$ occurring in the Koyna region.

Earthquakes of magnitude $\geq 5$ on 13 September 1967, 10 December 1967, and 17 October 1973 in the Koyna region were each preceded by two earthquakes of magnitude $\geq 4.0$ occurring within the preceding 15 days. In comparison, the activity of September 1980 was different. An earthquake of magnitude $\geq 5.0$ occurred on 2 September and two more $\geq 5.0$ earthquakes occurred on 20 September. These earthquakes were not preceded by pairs of $\geq 4.0$ events. All events of magnitude $\geq 4.0$ during 1974 through 1976 were singular (no two such events occurred within 15 days of one another). There appears to be a 50 per cent probability of occurrence of a magnitude $\geq 5.0$ earthquake if two earthquakes of magnitude $\geq 4.0$ are closely spaced in time (within 15 days) in the Koyna region.

INTRODUCTION

The continued occurrence of earthquakes in the vicinity of the Koyna Dam, situated 230 km south-southeast of Bombay in the Peninsular Shield of India, is a classical example of reservoir-induced seismicity (Guha et al., 1974; Gupta and Rastogi, 1976). Reports of earth tremors began soon after the impounding of the Koyna reservoir in 1962. On 10 December, 1967, a damaging 6.3 magnitude earthquake which claimed over 200 human lives, injured over 1500, and rendered thousands homeless, occurred in this region. This earthquake was followed by an unusually long sequence of aftershocks, which included several earthquakes of magnitude 5 and 4. The latest significant activity occurred in September 1980 when three earthquakes of magnitude $\geq 5.0$ and several earthquakes of smaller magnitudes occurred.

Gupta et al. (1972a, b) have identified certain common characteristics of reservoir-induced earthquake sequences. One among these is that the reservoir-induced earthquake sequences belong to type 2 of Mogi's (1963) classification of foreshock-aftershock patterns: i.e., the main shock is preceded by foreshock activity and followed by aftershocks. In the Koyna region, earthquakes of magnitude nearly 4 occur frequently and cause anxiety as to whether they are foreshocks to a future larger event to follow. Earthquakes of magnitude $\geq 5$ are locally damaging, and several such earthquakes have occurred in the Koyna region, one in September 1967, one in October 1973, and three in September 1980, in addition to the main shock of December 1967 and the earthquakes in the aftershock sequence following it. Reservoir-induced earthquakes seem to have long aftershock sequences. The

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aftershock activity in the Koyna region following the 10 December 1967 earthquake continued for a long time and returned to the pre-December 1967 level only in 1971.

Foreshocks are recognized only after the main event has occurred. Identification of foreshocks soon after they occur is an extremely important problem in earthquake prediction studies. Yamashina (1981), using the ISC catalog of world-wide earthquakes, has developed some empirical rules on foreshock magnitude and time history and their relation to the magnitude and time of occurrence of the main shock. Kodama and Bufe (1979) have examined foreshock occurrences in central California. Other approaches to identify foreshocks include investigation of changes in stress.

Table 1

<table>
<thead>
<tr>
<th>Sl No.</th>
<th>Date (m/d/yr)</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Depth (km)</th>
<th>Magnitude t</th>
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<td>6.2</td>
<td>Rastogi and Talwani (1980)</td>
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<td>73°42.75'</td>
<td>5.9</td>
<td>5.4</td>
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<td>4.9</td>
<td>Gupta et al. (1980)</td>
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<td>33.0</td>
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* The source of hypocenter data is given in the remarks column.
† Magnitudes as estimated in the present paper.
‡ This event is not shown in Figure 1.

The continued seismic activity in the Koyna region provides an excellent opportunity to examine the relationship between the foreshock activity and the main shock. The present seismic activity in the Koyna region is confined to a fairly small area of about 25 km x 25 km size (Gupta et al., 1980). Moreover, there is no other seismic activity within 100 km of the Koyna region (Mohan et al., 1981) to complicate the situation.

Here, we have examined the foreshocks of all the Koyna earthquakes of magnitude...
≥ 5.0 using the WWSSN station at Poona, India. As shown in Table 1, six earthquakes of magnitude ≥ 5.0 (including the main shock of 10 December 1967 and excluding its aftershocks) have occurred in Koyna. Even though a network of seismic stations has been in operation in the Koyna region since 1963 (Guha et al., 1974), we have chosen not to use the data from this network because inadequate time keeping and lack of proper calibration have degraded the quality of the data. We show that 3 of the 6 earthquakes of magnitude ≥ 5.0 seem to be preceded within

15 days by a pair of magnitude ≥ 4.0 earthquakes. We also show that, in general, earthquakes of magnitude ≥ 4.0, which are not foreshocks, occur singularly, i.e., no two such events occur within 15 days.

ESTIMATIONS OF EARTHQUAKE MAGNITUDES

Seismograms of the Poona WWSSN station, situated at a distance of 120 km north of the Koyna Dam (Figure 1), are used for estimating the magnitudes of Koyna earthquakes. This station has been continually in operation since 1964. The

![Figure 1](image-url)
short-period system has a magnification of 50,000. We used signal duration to estimate earthquake magnitudes. Signal duration has been defined as the time interval from the first phase arrival to the point where earthquake signal falls to the background noise level. A number of relations between earthquake magnitude and signal duration (Gupta et al., 1980) were tried. The following relation, developed by Gupta et al. (1980) for Koyna earthquakes was found to be most satisfactory

\[ M_T = -2.44 + 2.61 \log T \]

where \( M_T \) is the surface-wave magnitude, and \( T \) is the signal duration in seconds on SPZ component at Poona. This relation gives magnitudes comparable with the surface-wave magnitudes estimated by international agencies for the Koyna earthquakes and is found to be quite suitable in the magnitude range of interest, i.e., 2 to 6. The \( Sg-Pg \) time interval at Poona for Koyna shocks is about 16 sec. There is no other seismic source at an equivalent distance from Poona. We believe that all earthquakes of magnitude \( \geq 2.0 \) are clearly recorded at Poona. A distinct advantage in using Poona seismograms is that the small magnitude (less than 2.0) shocks from

![Diagram](image-url)
the Koyna region, which are not required in the present study, are automatically filtered out. Earthquakes of magnitude \( \geq 4.0 \) can be seen on long-period seismograms at Poona. Magnitudes estimated from the signal duration on SPZ seismograms are found to be consistent with their amplitudes measured on long-period seismograms at Poona. Three possible sources of errors can cause changes in signal duration, and hence affect the magnitude estimates. These are: changes in fault-plane orientations, variations in focal depths, and multiple events. With our single-station study, we could not examine the effect of fault-plane orientation on magnitude estimates. The errors in magnitudes due to changes in event depth are considered negligible as the Koyna earthquakes are very shallow, and they all fall within a depth range of a few kilometers. Occasionally, another shock may occur before the signal from the previous shock has returned to the background level. To overcome this problem, time durations were also measured between the first phase arrival and the time when the peak to trough amplitude reduces to 2, 6, and 10 mm on the Poona SPZ component seismogram. Figure 2 shows the relationships between the total signal duration and the duration amplitudes of 2, 6, and 10 mm. The observations are quite consistent. We have no suitable explanation for the “elbow” seen around 650 sec for 6 and 10 mm durations. These relations have been found to be quite useful in estimating the total signal duration for the events which were contaminated by other events. We believe that the above-mentioned procedure provides a fairly good estimate of the relative sizes of the Koyna earthquakes used in this study.

In the following sections, we analyze the \( M \geq 4 \) seismicity preceding all Koyna

![Figure 3](image-url)

**Fig. 3.** The Koyna earthquake of 13 September 1967 and its foreshocks. The aftershocks are not shown. For details, see text.
earthquakes of $M \geq 5$ which occurred during 1967 to 1980 and perform a special study of all $M \geq 4$ events which occurred during October 1973 to December 1976. The events used are listed in Table 1. Although the magnitudes in the Guha et al. (1974) catalog (also used by Rastogi and Talwani, 1980) show additional events of $M \geq 5$, their magnitude estimates are not reliable and our reanalysis of the data, based on the procedure described above, shows that all events of $M \geq 5$ are included in Table 1.

**EARTHQUAKES OF MAGNITUDE $\geq 5.0$**

We now examine the foreshock sequences of the earthquakes of magnitude $\geq 5.0$ in detail (Figure 1, Table 1). The 13 September 1967 earthquake of magnitude 5.2 was preceded by two shocks of magnitudes 4.8 and 4.1 on 12 September (Figure 3). There were other smaller magnitude foreshocks as indicated in Figure 3. The main shock was followed by numerous aftershocks, which are not shown in Figure 3. The 10 December 1967 earthquake of magnitude 6.2 was preceded by two foreshocks, one of magnitude 4.6 on 1 December and another magnitude 4.2 on 10 December besides several other foreshocks of smaller magnitude (Figure 4). Similarly, the 17 October 1973 earthquake of magnitude 5.4 was preceded by two foreshocks of magnitudes 4.0 and 4.6 on 17 October (Figure 5). In these three earthquake sequences, the main shocks were preceded by two foreshocks of magnitude 4.0 within the preceding 15 days time.
The September 1980 activity is different from the previous sequences, in that three earthquakes of magnitudes between 5.0 and 5.5 occurred within 18 days of one another (Figure 6). The 2 September 1980 earthquake of magnitude 5.2 was preceded by a 4.5 magnitude foreshock on 19 August 1980. Unlike the previous three foreshock sequences associated with magnitude \( \geq 5.0 \) earthquakes, the 2 September 1980 earthquake had only one foreshock of magnitude \( \geq 4.0 \). However, it had fewer aftershocks than other magnitude \( \geq 5.0 \) earthquakes. Two other earthquakes of magnitudes 5.3 and 5.4 occurred on 20 September 1980, i.e., 18 days after the 2 September earthquake (Figure 6). The 20 September earthquake of magnitude 5.4 was followed by a number of aftershocks, which is usual for earth-

![Fig. 5. The Koyna earthquake of 17 October 1973 and its foreshocks. The aftershocks are not shown. For details, see text.](image)

quakes of magnitude \( \geq 5.0 \) in the Koyna region and other sites of reservoir-induced seismicity in the world.

From the above data, we conclude that three earthquakes of magnitude \( \geq 5.0 \), of a total population of six such events, in the Koyna region during the period 1967 to 1979 were preceded within a fortnight by two foreshocks of magnitude \( \geq 4.0 \). The activity of September 1980 seems to be an exception when three earthquakes of magnitude \( \geq 5.0 \) occurred within 18 days of one another.

**Earthquakes of Magnitude \( \geq 4.0 \)**

Having inferred that the earthquakes of magnitude \( \geq 5 \) in the Koyna region have a 50 per cent probability of being preceded by two earthquakes of magnitude \( \geq 4.0 \) in the preceding 15 days time, it was thought necessary to examine whether the
converse is true or not. That is, we investigate whether two earthquakes of magnitude 4 to 5 occurred within 10 days of one another and were not followed by an earthquake of magnitude \( \geq 5.0 \).

Gupta et al. (1980) have investigated all earthquakes of \( M_s \geq 4.0 \), their foreshocks, and their aftershocks in the Koyna region for the period October 1973 through December 1976. This restricted data set was used instead of the whole data set of Guha et al. (1974) because Gupta et al. (1980) have calculated reliable hypocentral parameters for all earthquakes of magnitude \( \geq 4.0 \), their foreshocks and aftershocks for this period October 1973 through December 1976. The seismic activity in October 1973 was associated with a magnitude 5.4 main event, as discussed earlier. There was no other magnitude \( \geq 4.0 \) event during the remaining part of 1973. During 1974 through 1976, 11 earthquakes of magnitude \( \geq 4.0 \) occurred in the Koyna region. These were located by Gupta et al. (1980) and are included in Figure 1. We analyzed Poona seismograms for a period of 15 days preceding and 15 days following each of these events. No two earthquakes of magnitude \( \geq 4.0 \) were found to occur within 15 days of one another. In December 1975, two earthquakes of magnitude \( \geq 4.0 \) occurred at an interval of 22 days (Table 1). These were the closest two earthquakes of magnitude 4.0 to have occurred during the period 1974 through 1976 and were not followed by an earthquake of magnitude \( \geq 5.0 \). Representative examples of earthquake sequences associated with earthquakes of magnitude \( \geq 4 \) in the months
of August and November 1974 and March 1976 are shown in Figure 7. In this study, we have not examined the pattern of activity of magnitude 4 earthquakes prior to 1973 or after 1976 because reliable hypocentral parameters are not available.

![Graphs showing earthquake sequences in the Koyna region](image)

**FIG. 7.** Typical earthquake sequences in the Koyna region associated with earthquakes of magnitude between 4.0 and 4.9.

**DISCUSSIONS AND CONCLUDING REMARKS**

The reservoir-induced seismic activity in the Koyna region is unique: it has continued over the last 18 yr, and medium-size earthquakes occur frequently. The fact that these earthquakes occur in a fairly small volume, that there are no other seismically active regions in their vicinity, and that the epicentral region is easily
accessible, make the Koyna region most suitable for undertaking detailed earthquake prediction and related studies.

Magnitude estimates for the Koyna earthquakes in the past have been very questionable. For example, the 10 December 1967 earthquake was assigned a body-wave magnitude of 7.0 by the Government of India, Central Water and Power Research Station (Guha et al., 1974), 7.5 by the India Meteorological Department (Tandon and Chaudhury, 1968), and 6.3 by the NEIS of the U.S. Geological Survey. The scheme of estimating relative magnitudes of Koyna earthquakes presented in this paper, using data of the Poona WWSSN seismic station, appears to be most appropriate for any study needing relative magnitudes.

Earthquakes of magnitude $\geq 5$ tend to be locally damaging. When an earthquake of magnitude $\geq 4$ occurs in the Koyna region, there is concern whether a magnitude $\geq 5$ earthquake would follow. On the basis of the analyses presented in this paper, it may be concluded that if two earthquakes of magnitude $\geq 4.0$ occur within a 10- to 15-day interval, there is a 50 per cent probability that a magnitude $\geq 5$ earthquake will follow.

Due to lack of proper instrumentation, reliable estimates of earthquake magnitudes are not available at most sites of reservoir-induced seismicity. However, at Kremasta, Greece, on 5 February 1966, the main earthquake of magnitude 6.2 was preceded by earthquakes of 4.2 magnitude on 26 January 1966 and magnitude 4.0 on 31 January 1966, as seen from the catalog published by Comninakis et al. (1968). Similarly at Oroville, California, on 1 August 1975, an earthquake of magnitude 5.7 was preceded by two earthquakes of magnitude 4.7 and 4.5 on the same day. In later years, earthquakes of magnitude $\geq 4.0$ have occurred singularly in the Oroville region, i.e., no two such events have occurred within 15 days of one another, and no earthquakes of magnitude $\geq 5.0$ occurred. At Nurek, USSR, two earthquakes of magnitude 4.6 and 4.3 occurred in November 1972. However, no earthquake of magnitude $\geq 5.0$ occurred. It may be noted that the Nurek reservoir is situated on a thrust-fault environment, and earthquakes are associated with the emptying of the reservoir (Simpson and Negmatulleav, 1981), unlike the strike-slip or normal fault environment where reservoir impoundment causes instability. Filling of a reservoir in the thrust-fault environment tends to bring stability (Gupta and Rastogi, 1976).

It would be interesting to examine whether reservoir-associated earthquakes of magnitude $\geq 5.0$ are preceded by pairs of earthquakes of magnitude between 4 and 4.9 at other sites of reservoir-induced seismicity.

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The research reported in the present paper was carried out during the visit of one of the authors (H. K. G.) to the U.S. Geological Survey in Menlo Park, California. The author thanks the U.S. Geological Survey for providing the opportunity. Discussions with Willie Lee, Jerry Eaton, Allan Lindh, and Bill Bakun were very useful. The WWSSN Seismogram Library at the Office of Earthquake Studies, Menlo Park, California, was extensively used. Will Rinehart helped in using the NOAA Seismogram Library at Boulder, Colorado, for some data. Tim Hitchcock and K. Ramana Rao assisted in the preparation of the manuscript. An anonymous referee made some useful suggestions.

**REFERENCES**


