A statistical study of Koyna aftershocks for the period January 1968-October 1973

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ABSTRACT. A statistical study of the aftershocks originating from Koyna region recorded at Gauribidanur seismic array is made to find the time dependence of energy release. A total number of 210 aftershocks, most of whose magnitudes on Richter scale vary from 3.8 to 5.8, which occurred during the period January 1968 to October 1973 were analysed. It is found that the cumulative energy release in this period shows, in general, a tendency to vary as the square root of time that elapsed after January 1968 apart from some fluctuations.

1. Introduction

The major earthquake that occurred at Koyna on 10 December 1967 was followed by a number of aftershocks. These were studied by Guha et al. (1971) and by Avadh Ram and Singh (1971) with a view to understand among other things the manner in which the energy is released as a function of time after the major earthquake. The data for both these studies is obtained from observations close to the region of seismic activity. It covers a period starting from 1964 to 1969. In the present study we have excluded the earthquakes which are immediately coming after the 10 December 1967 event, but have chosen only those events coming from Koyna from January 1968. This choice of time is no doubt arbitrary, but is preferred because we feel that the relaxation of the strained system is studied better by excluding the period immediately following the rupture than by including the period of rupture also in the energy estimates.

The details of all the events included in this study are given in Table 1. Most of the events listed in Table 1 are identified in the visual seismograms reproduced in 8-channel play-outs from the original magnetic tapes recorded at Gauribidanur array as coming from Koyna from an estimate of azimuth, Z, of the direction of arrival (mean value 320.4°, s.d. = 2.8°) of signal at the Gauribidanur array centre and the difference (D) in the arrival times of P-phase (longitudinal wave) and S-phase (transverse wave) from the source which lies in the range 56.3 sec; s.d. = 0.8 sec. In some of the events a second phase is also seen which is interpreted as most probably the surface reflected P-phase (Murty 1969, 1970). Where it is possible, the direction of first motion of the P-signal is identified from these playouts. The data is used to derive (a) the frequency-magnitude relation, (b) the energy release-time relation and (c) the focal depth of the events.

All the events are treated as belonging to one population and no notice is taken of the variations in the epicentral distance and the azimuth of the source with respect to Gauribidanur.

2. Frequency-Magnitude relation of aftershocks

One of the oft-used empirical relations in the statistical study of foreshocks and aftershocks of earthquakes is the Gutenberg-Richter formula:

\[ \log N(M) = a - bM \]  

where \( N(M) \) is the cumulative number of earthquakes defined as the total number of shocks whose magnitude is \( M \) or larger than \( M \), and \( a \) and \( b \) are numerical constants (Richter 1968). There exists extensive literature regarding the use and interpretation of this formula (Ohtake 1970, Drakopoulos 1971). The value \( b \) is of great significance because it reflects the pattern of energy distribution in a given number of events. The parameter \( b \) is determined in the laboratory study of fracturing of rocks and is found to vary between 0.3 and 2.5 depending on the ambient stress and the nature of the material subjected to deformation until cracking (Scholz 1968). The general conclusion is that the values of \( b \) are larger for heterogeneous medium than for homogeneous medium.
Owing to these various factors if log \( N(M) \) versus \( M \) curve does not fit a single straight line, one may conclude that the population of the events is a mixture of several types of populations with different characteristic values of \( b \). The data under study is shown in Fig. 1 where we see that log \( N(M) \) versus \( M \) curve is not a straight line. This probably reflects also the fact that the low magnitude events are underestimated due to ambient noise, and that the magnitudes are estimated from single point observations without regard to azimuthal variation of radiation pattern.

3. Release of energy versus time

A knowledge of the rate of energy release from a seismically active region is of great interest in the study of earthquakes. Such studies have been made both for global and for local seismicity by several people (Benioff 1951, Kisslinger 1968). The aftershock energy release from Koyana region was studied by Avadh Ram and Singh (1971) and Guha et al. (1971). Both these authors conclude that the cumulative energy release varies at \( t^\alpha \) where \( \alpha \) is a constant of the order of unity. For all the events listed in Table 1, the cumulative energy is calculated by estimating the energy of each event by the formula (Richter 1968, Scholz 1968)

\[
\log E = 11.4 + 1.5 M
\]

(2)

where the magnitude is calculated on the basis of the observed amplitude of the \( P \)-wave seismic signal at the central sensor (short period 1 c/s seismometer) of the Gauribidanur Seismic Array (Singh et al. 1969), and \( E \) is expressed in ergs.

In estimating the magnitude, the small correction due to frequency-response of the seismometer which has a maximum response at about 1 cps is ignored through the Koyana aftershocks recorded at Gauribidanur have a spectral peak at 4 cps (Murty 1969). Since the frequency response is nearly flat between 1 cps to 5 cps, this approximation does not affect the magnitude estimates drastically. Further, we are primarily interested in the overall variation of earthquake energy release with time, and not in the absolute values of the energy released in the aftershocks.

The cumulative energy is calculated for all events listed in Table 1 by means of the Eq. (2) for the periods from January 1968 to October 1973, and the results are shown in Fig. 2. We see from this figure that the average variation of cumulative energy \( E_t \), defined as the sum of energy of all the aftershocks up to time \( t \) from January 1968 can be approximated by the formula

\[
E_t = 10 \times \left( \frac{t}{32} \right)^{1/2} \times 10^{20} \text{ ergs}
\]

(3)

where \( t \) is the time measured in months from January 1968.

In the Eq. (3) the numerical values should not be taken as an estimate of actual energy release, but only as an indication of the order of magnitude.
| S. No. | Date   | Onset time (GMT) at Georhiota-nur | Body wave magnitude | First motion phase signal (Richter scale) | Probable depth arrival (sec) | S. No. | Date   | Onset time (GMT) at Georhiota-nur | Body wave magnitude | First motion phase signal (Richter scale) | Probable depth arrival (sec) |
|-------|--------|----------------------------------|--------------------|-------------------------------------------|-----------------------------|-------|--------|----------------------------------|--------------------|-------------------------------------------|-----------------------------|
| 1     | 3 Jan 68 | 04:36:21.5 | 4.4 Down | 9 Mar 68 | 10:25:52.0 | 4.5 Down |
| 2     | 3 Jan 68 | 11:35:32.5 | 4.8 Up    | 10 Mar 68 | 08:21:09.2 | 5.1 Up    |
| 3     | 4 Jan 68 | 06:20:11.2 | 4.8 Down | 11 Mar 68 | 04:54:31.8 | 3.8        |
| 4     | 4 Jan 68 | 07:25:16.7 | 4.7 Down | 11 Mar 68 | 13:23:23.1 | 4.1        |
| 5     | 5 Jan 68 | 08:42:11.5 | 4.5 Up    | 11 Mar 68 | 20:07:37.7 | Weak signal |
| 6     | 5 Jan 68 | 09:33:18.1 | 4.4        | 16 Mar 68 | 00:52:14  | 4.6 Up    |
| 7     | 7 Jan 68 | 02:25:06.9 | 5.5 Down  | 18 Mar 68 | 15:49:47  | 4.1        |
| 8     | 9 Jan 68 | 20:11:42.4 | 4.3        | 19 Mar 68 | 17:22:59.6 | 4.1 Down  |
| 9     | 16 Jan 68 | 03:34:27.5 | 4.4 Down  | 20 Mar 68 | 04:05:04.5 | 4.5 Up | 1.5 |
| 10    | 16 Jan 68 | 06:18:18.8 | 5.3 Down  | 20 Mar 68 | 17:16:22.5 | 4.1        |
| 11    | 17 Jan 68 | 21:10:14.8 | 4.4 Up    | 22 Mar 68 | 06:34:76.1 | Very weak signal |
| 12    | 25 Jan 68 | 02:16:32.2 | 5.2 Up    | 23 Mar 68 | 16:18:25.5 | 4.4 Down | 2.2 |
| 13    | 25 Jan 68 | 22:21:16.4 | Very weak signal | 25 Mar 68 | 16:50:09.4 | 4.5 Up    | 3       |
| 14    | 27 Jan 68 | 16:53:24.9 | 4.7 Up    | 26 Mar 68 | 02:45:28.6 | 4.4 Down  |
| 15    | 27 Jan 68 | 23:45:04.7 | 4.4 Up    | 26 Mar 68 | 11:21:39.8 | 4.3        |
| 16    | 30 Jan 68 | 12:09:25.4 | Very weak signal | 28 Mar 68 | 09:59:25.5 | 5.1 Up    | 2       |
| 17    | 7 Feb 68 | 23:50:42   | 3.8        | 29 Mar 68 | 07:54:39.8 | 4.1        |
| 18    | 8 Feb 68 | 19:38:54.2 | 4.1 Down | 30 Mar 68 | 17:23:26.9 | 4.8 Down  |
| 19    | 9 Feb 68 | 22:53:16.9 | 5.4 Up    | 31 Mar 68 | 07:02:21.4 | 4.4        |
| 20    | 10 Feb 68 | 12:11:40  | Very weak signal | 31 Mar 68 | 22:56:30  | Very weak signal |
| 21    | 11 Feb 68 | 07:48:40  | 4.1        | 2 Apr 68  | 09:19:07.6 | 3.8        |
| 22    | 11 Feb 68 | 17:30:36.7 | Very weak signal | 8 Apr 68  | 04:10:10.5 | 4.4        |
| 23    | 12 Feb 68 | 09:14:41.4 | 3.7 Down  | 6 Apr 68  | 07:05:10.0 | 4.9 Down | 1       |
| 24    | 13 Feb 68 | 21:43:22.4 | 4.4        | 7 Apr 68  | 04:23:38.8 | 4.3 Down | 1       |
| 25    | 14 Feb 68 | 03:11:40.8 | 4.6 Up    | 8 Apr 68  | 05:42:33.5 | 4.3        |
| 26    | 14 Feb 68 | 06:17:54.4 | 4.1        | 9 Apr 68  | 23:25:05.0 | 4.7 Up    |
| 27    | 14 Feb 68 | 20:34:30.2 | 5.5 Up    | 25 Apr 68 | 04:16:33  |
| 28    | 15 Feb 68 | 18:23:20  | Very weak signal | 28 Apr 68 | 12:53:54.6 | 4.5 Up    |
| 29    | 20 Feb 68 | 17:50:24.4 | 5.1 Up    | 30 Apr 68 | 03:23:28.0 | 4.3 Down | 1       |
| 30    | 20 Feb 68 | 20:39:36  | 4.1        | 1 May 68  | 07:47:34.8 | 4.7 Down | 1       |
| 31    | 21 Feb 68 | 10:45:40  | Very weak signal | 1 May 68  | 15:46:04.3 | 4.3 Up    |
| 32    | 21 Feb 68 | 16:28:11.8 | 4.4        | 3 May 68  | 02:38:18.3 | 4.4        |
| 33    | 22 Feb 68 | 08:18:43.1 | 4.4 Down  | 6 May 68  | 10:42:02.9 | 4.1        |
| 34    | 22 Feb 68 | 19:28:34  | Very weak signal | 9 May 68  | 13:04:32.5 | 4.3 Down | 1       |
| 35    | 25 Feb 68 | 01:00:16.5 | 4.1        | 10 May 68 | 04:58:24.4 | 4.1 Down | 1       |
| 36    | 25 Feb 68 | 21:43:32.6 | 3.8        | 11 May 68 | 11:29:07.9 | 4.1        |
| 37    | 26 Feb 68 | 04:10:34.8 | 3.8        | 22 May 68 | 15:23:57.2 | 4.9 Up    |
| 38    | 26 Feb 68 | 06:49:15.0 |           | 24 May 68 | 20:46:19.5 | 4.4        |
| 39    | 26 Feb 68 | 07:55:40.0 |           | 24 May 68 | 20:58:16.5 | 4.1        |
| 40    | 26 Feb 68 | 14:01:25.0 |           | 28 May 68 | 16:11:20.8 | Very weak signal |
| 41    | 26 Feb 68 | 22:16:51.0 |           | 30 Jun 68 | 14:32:13.4 | 4.1        |
| 42    | 29 Feb 68 | 18:22:49.0 | 4.6 Up    | 21 Jun 68 | 04:18:32  | 4.6 Up | 1.5 |
| 43    | 3 Mar 68 | 21:47:27.5 | 5.1 Up    | 21 Jun 68 | 06:52:27.7 | 4.5 Up    |
| 44    | 4 Mar 68 | 21:37:51.0 | 5.3 Down  | 22 Jun 68 | 09:24:30.0 | 5.1 Down | 1       |
| 45    | 4 Mar 68 | 23:32:49.2 | 4.1        | 26 Jul 68 | 08:06:54  | 3.8        |
| 46    | 7 Mar 68 | 22:16:59.5 | 4.1        | 28 Jul 68 | 04:12:25.4 | 4.6 Down  |
| 47    | 9 Mar 68 | 07:48:54.5 | 5.0 Up    | 26 Aug 68 | 20:12:46.5 | 4.3 Up    | 1       |
| S. No. | Date       | Onset time (GMT) at Gauribidanur | Body wave magnitude of P signal (Richter scale) | First motion phase arrival w.r.t. 1st arrival (sec) | S. No. | Date       | Onset time (GMT) at Gauribidanur | Body wave magnitude of P signal (Richter scale) | First motion phase arrival w.r.t. 1st arrival (sec) |
|-------|------------|----------------------------------|-----------------------------------------------|-----------------------------------------------|-------|------------|----------------------------------|-----------------------------------------------|-----------------------------------------------|
| 95    | 30 Aug 68  | 08:16:00                         | Very weak signal                              |                                               |       |            |                                  |                                               |                                               |
| 96    | 31 Aug 68  | 02:54:54                          | 5-6 Down                                       |                                               |       |            |                                  |                                               |                                               |
| 97    | 2 Sep 68   | 02:50:43                          | 4-7 Up                                         | 2                                             |       |            |                                  |                                               |                                               |
| 98    | 20 Sep 68  | 10:12:47                          | 5-3 Up                                         | 2-5                                           |       |            |                                  |                                               |                                               |
| 99    | 7 Oct 68   | 00:03:55                          | Very weak signal                              |                                               |       |            |                                  |                                               |                                               |
| 100   | 29 Oct 68  | 10:91:19                          | 5-5 Up                                         | 1                                             |       |            |                                  |                                               |                                               |
| 101   | 30 Oct/68  | 11:31:10                          | 3-8                                           |                                               |       |            |                                  |                                               |                                               |
| 102   | 23 Nov 68  | 11:32:56                          | 5-2 Up                                         |                                               |       |            |                                  |                                               |                                               |
| 103   | 25 Nov 68  | 23:55:49                          | 4-6 Up                                         |                                               |       |            |                                  |                                               |                                               |
| 104   | 5 Dec 68   | 22:58:45                          | 5-7 Down                                       | 2                                             |       |            |                                  |                                               |                                               |
| 105   | 22 Dec 68  | 22:14:57                          | 6-5 Down                                       | 2-5                                           |       |            |                                  |                                               |                                               |
| 106   | 21 Jan 69  | 22:33:28                          | 4-4 Down                                       | 1-8                                           |       |            |                                  |                                               |                                               |
| 107   | 13 Feb 69  | 22:17:10                          | 6-1 Down                                       | 1-8                                           |       |            |                                  |                                               |                                               |
| 108   | 7 Mar 69   | 18:29:49                          | 4-6 Down                                       | 2-5                                           |       |            |                                  |                                               |                                               |
| 109   | 15 Mar 69  | 04:05:28                          | 4-7 Up                                         | 2                                             |       |            |                                  |                                               |                                               |
| 110   | 26 Mar 69  | 00:48:40                          | 4-3                                           | 2-5                                           |       |            |                                  |                                               |                                               |
| 111   | 1 Apr 69   | 21:34:39                          | 4-4                                           |                                               |       |            |                                  |                                               |                                               |
| 112   | 3 Apr 69   | 16:19:37                          | 4-3                                           | 2-5                                           |       |            |                                  |                                               |                                               |
| 113   | 3 Apr 69   | 17:17:58                          | Very weak signal                              |                                               |       |            |                                  |                                               |                                               |
| 114   | 27 Jun 69  | 20:06:25                          | 5-3 Down                                       | 2                                             |       |            |                                  |                                               |                                               |
| 115   | 18 Jul 69  | 01:31:23                          | 4-7 Up                                         | 1-5                                           |       |            |                                  |                                               |                                               |
| 116   | 22 Jul 69  | 21:50:42                          | 5-2 Up                                         | 1-8                                           |       |            |                                  |                                               |                                               |
| 117   | 13 Aug 69  | 01:05:27                          | 4-4                                           |                                               |       |            |                                  |                                               |                                               |
| 118   | 19 Aug 69  | 00:36:44                          | 4-6                                           |                                               |       |            |                                  |                                               |                                               |
| 119   | 16 Sep 69  | 18:20:59                          | 4-1                                           |                                               |       |            |                                  |                                               |                                               |
| 120   | 16 Sep 69  | 21:44:45                          | 4-5                                           |                                               |       |            |                                  |                                               |                                               |
| 121   | 23 Sep 69  | 21:14:16                          | 4-1                                           |                                               |       |            |                                  |                                               |                                               |
| 122   | 3 Nov 69   | 22:23:28                          | 5-2 Up                                         | 1-8                                           |       |            |                                  |                                               |                                               |
| 123   | 4 Nov 69   | 05:13:05                          | 4-4 Up                                         | 1-8                                           |       |            |                                  |                                               |                                               |
| 124   | 29 Dec 69  | 04:48:57                          | Very weak signal                              |                                               |       |            |                                  |                                               |                                               |
| 125   | 1 Jan 70   | 22:32:07                          | 5-4 Up                                         | 2-2                                           |       |            |                                  |                                               |                                               |
| 126   | 9 Jan 70   | 22:35:57                          | 4-9 Up                                         | 1-5                                           |       |            |                                  |                                               |                                               |
| 127   | 12 Jan 70  | 07:37:42                          | 4-1                                           |                                               |       |            |                                  |                                               |                                               |
| 128   | 12 Jan 70  | 09:06:32                          | 4-5                                           |                                               |       |            |                                  |                                               |                                               |
| 129   | 12 Jan 70  | 15:24:42                          | 4-5                                           |                                               |       |            |                                  |                                               |                                               |
| 130   | 12 Jan 70  | 16:38:55                          | 4-5                                           | 2                                             |       |            |                                  |                                               |                                               |
| 131   | 24 Jan 70  | 09:47:32                          | 4-4 Up                                         |                                               |       |            |                                  |                                               |                                               |
| 132   | 5 Mar 70   | 01:48:43                          | 4-6                                           | 2-2                                           |       |            |                                  |                                               |                                               |
| 133   | 16 Apr 70  | 14:48:10                          | 5-4 Up                                         | 2-2                                           |       |            |                                  |                                               |                                               |
| 134   | 27 May 70  | 12:46:55                          | 5-6 Up                                         | 2                                             |       |            |                                  |                                               |                                               |
| 135   | 29 May 70  | 05:42:09                          | 4-3                                           |                                               |       |            |                                  |                                               |                                               |
| 136   | 8 Jun 70   | 05:31:30                          | 5-3                                           |                                               |       |            |                                  |                                               |                                               |
| 137   | 17 Jun 70  | 06:50:11                          | 5-0                                           |                                               |       |            |                                  |                                               |                                               |
| 138   | 19 Aug 70  | 00:36:44                          | 4-7 Down                                       | 1-8                                           |       |            |                                  |                                               |                                               |
| 139   | 21 Sep 70  | 03:03:35                          | 4-8 Up                                         | 1-8                                           |       |            |                                  |                                               |                                               |
| 140   | 21 Sep 70  | 08:52:08                          | 4-7 Up                                         | 1                                             |       |            |                                  |                                               |                                               |
| 141   | 25 Sep 70  | 04:14:15                          | 5-3 Down                                       |                                               |       |            |                                  |                                               |                                               |
| 142   | 26 Sep 70  | 16:37:57                          | 5-8                                           |                                               |       |            |                                  |                                               |                                               |
TABLE 1 (contd)

| S. No. | Date     | Onset time (GMT) at Gauribidanur | Body wave magnitude (Richter scale) | First motion phase arrival w.r.t. 1st arrival (sec) | Probable magnitude of P phase arrival (sec) |
|--------|----------|----------------------------------|-------------------------------------|---------------------------------------------------|--------------------------------------------|
| 191    | 4 Oct 72 | 14:26:46                          | 4.3                                 |                                                   |                                            |
| 192    | 11 Nov 72| 04:03:07                          | 4.8                                 | Up                                                |                                            |
| 193    | 29 Jan 73| 17:14:36                          | 4.5                                 |                                                   |                                            |
| 194    | 28 Jan 73| 18:54:49                          | 4.3                                 |                                                   |                                            |
| 195    | 6 Mar 73 | 07:14:38                          | 4.8                                 |                                                   |                                            |
| 196*   | 31 Mar 73| 02:10:10                          | Very weak event                     |                                                   |                                            |
| 197    | 1 Apr 73 | 13:32:24                          | 4.5                                 | Up                                                |                                            |
| 198    | 2 Apr 73 | 20:22:41                          | 5.1                                 |                                                   |                                            |
| 199    | 2 Apr 73 | 20:46:07                          | 4.7                                 |                                                   |                                            |
| 200    | 19 Apr 73| 19:01:46                          | 201*                                | 5 Jun 73                                          | 10:28:39                                   |
|        |          |                                   | 202†                                | 3 Oct 73                                          | 14:38:47                                   |
|        |          |                                   | 203‡                                | 6 Oct 73                                          | 09:22:23                                   |
|        |          |                                   | 204‡                                | 13 Oct 73                                         | 07:46:38                                   |
|        |          |                                   | 205‡                                | 13 Oct 73                                         | 07:58:40 Very feeble                       |
|        |          |                                   | 206‡                                | 17 Oct 73                                         | 08:04:28                                   |
|        |          |                                   | 207‡                                | 17 Oct 73                                         | 14:41:33                                   |
|        |          |                                   | 208‡                                | 17 Oct 73                                         | 15:26:05                                   |
|        |          |                                   | 209‡                                | 24 Oct 73                                         | 05:02:55                                   |
|        |          |                                   | 210‡                                | 24 Oct 73                                         | 18:07:00                                   |

The table gives list of Koyna aftershocks recorded at Gauribidanur seismic array. Most of the events are read on the 3-channel visual seismograms obtained from the magnetic tapes. Some events marked with asterisk are read on the three channel helicorders, and confirmed by a comparison with the data from Poona. The events marked with dagger are read on the helicopter only. For 161 events, both the azimuth $Z$ and the time difference, $D$, of arrival of $P$-Phase and $S$-Phase could be determined. It is found that the mean value of $Z$ (s.d. = 0.8) sec. The magnitude of the events is determined from the amplitude of $P$-wave as seen in the 8-channel playback or the helicorder as the case may be.

The half yearly release of energy from Koyna as observed at GBA has not drastically changed during the past six years though the seismic activity has not come to a halt.

The histogram of half yearly release of energy during the period under study in Fig. 3, where we see a general decrease in the energy release with time with a tendency to fluctuate with a period of about two years. Since the energy release in an earthquake is a non-linear phenomenon, it is difficult to establish a direct correlation with external factors like water level in Koyna dam, etc. However one fact emerges from the present study that whatever be the factors that caused the Koyna earthquake, the strain release pattern has not changed drastically till now since January 1968 and the average rate of energy release seems to be varying inversely as the square root of time that elapsed since January 1968.

4. Focal depths of the aftershocks

In Table 1, some of the aftershocks are observed to contain a phase following the first arrival with a lag of 1 to 3 sec. In a previous study of Koyna aftershocks, it was suggested that the second signal in Koyna aftershocks is most probably a surface reflected $P$-phase (Murty 1969, 1970). Following this suggestion, the 'depth' of source of these events showing a 'second phase' is estimated to vary between 4 to 12 km with a mean value of 6·8 km and a standard deviation of 2·3 km.
The cross-correlation coefficient between the estimated magnitude and estimated depth is 0.3, which indicates that there is a very weak correlation between these variables.

5. Conclusions

The aftershocks observed at Gauribidanur from Koyna region during January 1968-October 1973 show that the seismic activity is decreasing and the rate of energy release is varying inversely as the square root of time that elapsed after January 1968. There seems to be a tendency for the energy release to fluctuate around the general trend with a period of about 2 years. There is a little correlation between the estimated depths and the estimated magnitudes of the events under study.

We wish to emphasise that our conclusions are based exclusively on the data obtained along only one azimuthal direction with respect to the source. It would be worthwhile to compare our results with those obtained from data along other azimuthal directions.

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