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Recurrence relations of Koyna and Bhadrachalam aftershock activity

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ABSTRACT. Estimates of seismic risk require a recurrence relation between the expected number of earthquakes per year and a measure of earthquake size. The recurrence relations of Koyna and Bhadrachalam aftershocks are discussed in the light of low seismicity and poor geographic distribution of seismographic stations in south India. As the definition of an 'active fault' may vary according to the type of land use contemplated, it is emphasized that multi instrument micro-earthquake investigations should be carried out in order to take into account even the smallest earthquakes and know not only which faults may move but how they may move.

1. Introduction

The Peninsular shield of India is supposed to have remained largely stable except for minor folding, block faulting and regional epirogenic movements. Historical records show that, except for a few moderate events, no major earthquake had its origin in south India. Mention must however be made of the notable earthquakes located at Bellary (1 April 1843), Coimbatore (8 February 1900), Koyna (11 December 1967) and Bhadrachalam (13 April 1969).

Seismicity of south India was never a topic of serious discussion until a decade ago when a calamitous earthquake occurred near Koyna on 11 December 1967. This event and two other earthquakes that followed, one in the Godavari valley near Bhadrachalam and the other at Broach forced a revision of the old ideas of the Peninsula being free from earthquakes. After commissioning a seismic array station by BARC at Gauribidanur, Arora *et al.* (1970) observed that there is frequent and sporadic seismic activity in south India. This activity is probably due to recent movements derived from quaternary tectonic activity taking place since the tertiary period. It has been observed by the author that seismic activity within and south of the Cuddapah basin, as monitored by GBA station, is associated with fracture lineaments to a large extent. Visakhapatnam observatory has been recording one to two events on the average every day for the last two months. In fact, there were 15 shocks on 7 February 1978. Most of the shocks are found to originate at about 2° and 9° epicentral distance. Azimuthal determination of local events has become a problem at VIS observatory, for want of suitable equipment. Similar problems besides poor geographical distribution of seismographic stations in south India need consideration. In this paper, the aftershock activity of the two significant earthquakes that occurred in south India are discussed in the light of poor geographic distribution of seismographic stations.

2. Koyna and Godavari valley earthquakes

Banghar (1972) observed from focal mechanism solutions of these two main events that they are characterised by strike-slip faulting on nearly vertical planes and that the major movements are nearly horizontal. Magnitude ratio between the largest aftershock and the main shock for both the events was 0.9. The number of tremors in the Koyna region increased sharply since 1963 and aftershocks are innumerable. The Godavari valley earthquake and its immediate aftershocks, on the other hand, appeared to be followed by queiscence.

Guha *et al.* (1974) observed that detailed studies on the development of the source region around the focus of Koyna earthquake of 11 December 1967 which was possible with the help of a very powerful seismological net, afforded unique data regarding progressive changes with time in the active focal region along with energy, active volume and energy density during the foreshock, main shock and aftershock sequence. Data derived from the seismological net lead Guha *et al.* (1974) to confirm that during the post-earthquake period the foci of aftershocks migrated to deeper and south-western region of the dam site. Two strain meters have been giving detailed results of strain in the foundation level of the dam. Deflection observations of the dam monoliths in three components indicated changes during the earthquakes of magnitude 4 and above.

Geometry of the Godavari valley and disposition of the NGRI and GBA stations, which are supposed to be the best among the seismograph stations situated in south India, are such that not much of azimuthal control could be expected. For the NGRI observatory, even 70 to 80 km of epicentral variations of the aftershocks along the valley would not very much change the epicentral distance (Gupta *et al.* 1970). Arora *et al.* (1970) observed that the Moho refracted phase from the direction of Bhadrachalam emerged at smaller angles compared with the angles of emergence in other azimuths for GBA. This has been explained as due to non-uniform intermediate layers or to a Moho which dips by atleast 4° in the direction of GBA. It is thus evident that azimuthal variations are not unusual when there are changes in mean velocity in the upper layers of the earth. Study of the spatial distribution of aftershocks in the Godavari valley using data from the existing seismograph stations need not be attempted in view of the said limitations. Although precise locations could not be made, about 40 aftershocks were well recorded at the NGRI observatory during the first 24 hours after the main shock according to Gupta *et al*. (1970). GBA recorded about 65 aftershocks over a period of 15 days following the main shock.

3. Recurrence relations

The seismic risk analysis models require cumulative frequency function of the type

$$\log N = a' - b'M$$

Constants a' and b' can be determined by least square methods. a' is the number of earthquakes and b' is normally taken to depend on the nature of earthquake generation. Mogi (1962) showed experimentally that b' depends on the heterogeneity of the material in the seismic zone and also on the distribution of applied stress. Scholz (1968) observed that the state of stress rather than the heterogeneity of the material plays the most important role in determining the value of b'. According to Scholz (1968) the regional variation in the values of b' may reflect on the changes in the state of stresses.

Availability of very detailed seismic data over a long period in the Koyna region made it possible to study the significance of b' in recurrence relations. The yearwise values of b' as reported by Guha *et al.* (1974), changed significantly immediately after the earthquake of 11 December 1967. The post-earthquake values of b' are found to be greater than the pre-earthquake values. The continued fall of b' values prior to the main event may signify strain building process.

The main Koyna event and 46 aftershocks having magnitudes above 4.0 recorded during the first three days by GBA station have been utilised by Gupta *et al.* (1969) to determine the frequency-magnitude relation and the corresponding value of b' was found to be 0.8. The main earthquake of Godavari valley and all its aftershocks from 13 April 1969 to 2 May 1969, having magnitude 2.1 and above gave 0.51 for b' (Gupta *et al.* 1970). The b' value of Godavari valley aftershock activity is quite low. This may be due to incompleteness of the data and to probable error in the magnitude values. From detailed studies, Miyamura found that b' values are related to the geotectonic structures and his observations were summarised by Mogi (1962) thus:

> The b' value is very small (0.4 to 0.6) for old shield zones. Small (0.6 to 0.7) in the continental rift zones and platform block zones. Moderate (0·7 to 1.0) in the orogenic zones including island arcs of big islands and peninsulas. Large (1.0 to 1.8) in the oceanic region including mid-ocean ridges and islets.

The epicentre of the Bhadrachalam earthquake is situated in the Godavari rift valley. The geology of the area, affected by the event, is complex with a number of fold and fault systems. From geoseismological studies, Raju and Krishnaswami (1977) related the earthquake to build-up of regional strains in the rift valley and the sudden release of the strains with renewed movement at depth along the post-Pakhal fault mapped by W.King. The fault enters the river section at Parnasala, displaces the Gondwana sequence and is only 15 km to the east of the epicentre. Thus association of Bhadrachalam earthquake with the Godavari rift valley requires a range of 0.6 to 0.7 for b' while the computed value is small. It appears, therefore, that even the best seismograph stations situated in south India proved inadequate in providing precise estimates of epicentre and magnitude of smaller shocks in the Godavari valley region. In contrast the Koyna region has a good seismological net and the computed value of b' for the December 1967 aftershock sequence is in agreement with the expected value.

4. Identification of capable faults

Commonly, faults are regarded as 'active' and of concern to land-use planning when there is evidence that they will move during historic time or, there is a significant likelihood that they will move during the projected use of a particular structure or piece of land. Knowing that a particular fault is active is only part of the problem. The other part is predicting the likely location of fault ruptures during the next significant earthquake.

Active faults can be recognised remarkably well in reconnaissance fashion by their geomorphic expression as observed in aerial photographs Micro-earthquake studies based on dense array.

of short-period seismographs permit three-dimensional mapping of seismogenic sections of active faults as well as identification of 'locked' sections of major known active faults.

Utility of seismological net in micro-earthquake investigations and three-dimensional projection of hypocentres has been amply demonstrated by the Koyna Seismological Net. Landsat Imagery data proved very valuable for field geologists. Since seismographic distribution in south India is very poor and since the best seismograph stations of NGRI & BARC proved inadequate on account of azimuthal errors in the location of Godavari valley events, multi-instrument micro-earthquake surveys coupled with other geophysical investigations are highly essential for studying the capability of faults and weak planes in the region.

It is generally observed that spatial distribution of very small earthquakes correlates with historical seismicity. Micro-earthquake activity may be treated as a measure of activity or capability of the geological formations. Micro-earthquake data may also be utilised in recurrence relations. It may thus be concluded that systematic micro-earthquake investigations in different parts of south India are highly essential in view of the observed mild seismic activity so as to know not only which faults may move but how they may move.

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DISCUSSION

N.D. Mitra (G.S.I.) : Do you feel the boundary faults of Godavari are still active ? If so which one the eastern or western boundary fault is more active ?

2. What is the magnitude and frequency of earthquakes in Godavari valley?

Author : Because the geology of the area affected by the Godavari valley earthquake is complex and since the existing seismological stations situated in south India are inadequate in providing precise estimates of epicentres of smaller shocks in the region, it is difficult to explain as to which part or fault is active. From geoseismological studies, Raju and Krishnaswami (1977) attributed the activity to renewed movement at depth along the post-Pakhal fault mapped by King. Multi-instrument micro-earthquake investigations in the area are likely to throw light on the question.

2. The instrumentally assessed magnitude of the earthquake on the Richter scale was 5.7. Mukherjee (1971) calculated the most probable value using Karnik formula as 6.5. About 40 aftershocks were recorded at the NGRI observatory during the first 24 hours and about 65 were recorded by GBA over a period of 15 days following the main shock. It may be noted that the very low value of b for the sequence may be indicative of incompleteness of data and of probable error in the magnitude values for the aftershocks.