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Some quantitative seismicity studies in north India including Kutch

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ABSTRACT. Strain release characteristics of various regions of India have been studied by dividing the northern India from Assam to Kashmir into three regions and taking Kutch as the fourth region. Strain accumulation and relaxation curves have been prepared showing the maximum and minimum strain levels except for the Bihar-Nepal region. From these curves store of strain available to be released in future earthquakes have been estimated.

1. Introduction

Benioff (1951) and Ritsema (1954) reported that the rate of strain released by shallow earthquakes over the whole world appears to have been approximately constant since 1907. This may mean either that the source of strain for these earthquakes involves a global stress pattern or that in every region individually there are processes acting at constant rate. Further Benioff (1955) has suggested that under the oceans, deep and intermediate layers are part of one system and over the continents shallow and intermediate earthquake zones are related.

Regional strain release characteristics of the Indian shallow earthquakes have been studied by Chouhan (1966) who observed two segments, first nonlinear followed by a linear one. Chouhan *et al.* (1966) studied in detail the strain characteristics of Assam.

2. Theory and method

Benioff (1949) has shown that the potential energy E_p of a volume of rock W is given by

$$E_p = 0.5\,\mu.W.S^2 \qquad (1)$$

where μ is the coefficient of shear and S is the average strain just before the earthquake. Then the energy of released seismic waves is given by

$$E_T = 0.5.f.\mu.W.S^2 \qquad (2)$$

where f is the fraction of energy released as seismic waves.

If the strain is reduced to zero during the earthquake by movement along a fault, then S is proportional to the fault displacement.

$$\text{or} \quad S = C.\,x_f \qquad (3)$$

where C is a constant.

$$\text{Hence, } E_T = 0.5 f.\mu.W.C^2.x_f^2 = C_1^2 x_f^2 \qquad (4)$$

where $C_1 = (0.5 f.\mu.W.C^2)^{1/2}$

Thus the displacement on a fault is seen to be proportional to the square root of the energy released as seismic waves, all factors on which C_1 depends being equal. Hence using magnitude energy relation of Gutenberg and Richter (1956) and relation (4) we get:

$$\log E_T^{1/2} = \log C_1 x_f = 5.9 + 0.75\ M_s$$
$$\text{or} \quad x_f = 1/C_1 .\ 10^{5.9+0.75 M_s} \qquad (5)$$

where M_s is the surface wave magnitude of an earthquake.

This gives the relation between the fault displacement and magnitude M_s. Thus if we know the magnitudes of all earthquakes occurring on any one fault system over a period of years we can plot fault displacement (strain) occurring during that time.

From such studies it appears that the large regions seem to be locked in some manner whereby the average rate of release of strain or fault displacement (Eqn. 3) throughout the regions is constant over long period of time. It is as though displacements were slowly taking place on a single fault.

Furthermore the structures are limited in depth to which they extend although occasionally earthquakes at two depth ranges belong to the same system. Hence it can be assumed that the structures along which earthquakes occur have greater horizontal extent than vertical continuity.

Strain rebound characteristics described above represent spurts of seismic activity separated by relatively quiescent periods. The resulting figure is thus a sawtooth curve the upper peaks of which represents the end of an event (activity), a near

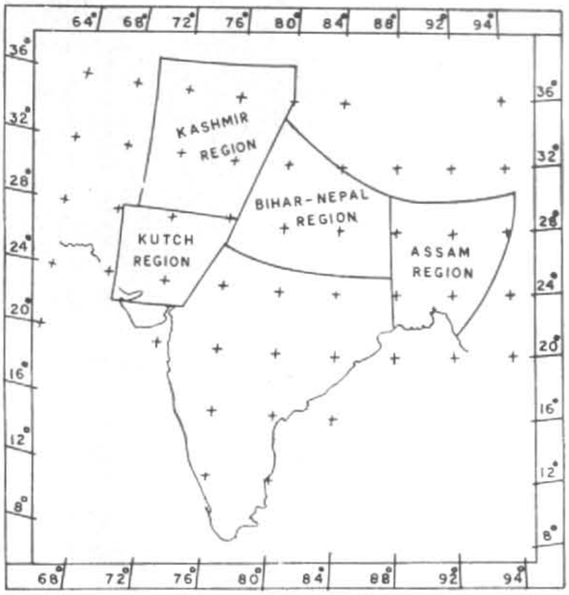

Fig. 1. Various seismic regions of northern India including Kutch, used in the present study

exhaustion of the accumulated strain. A line drawn through these points (peaks), therefore, represents the rate of secular strain generation in a given region. Considering a mean rate of strain generation in that region it is then possible to illustrate the relative strain levels obtained at different times by means of a strain accumulation and relaxation curve. In the beginning of the period under study, the strain accumulation and relaxation curve starts from an arbitrary level which represents the store of strain at that time. It is then made to follow a slope equal to the mean rate of strain generation, as obtained from the strain rebound characteristics, until an earthquake representing a release of strain takes place. At this point on the time axis, the curve drops vertically by an amount equivalent to the strain of that earthquake and follows the slope of mean rate of strain accumulation until the occurrence of the next earthquake.

A remarkable point illustrated by these curves is that although the strain level following an earthquake or a series of earthquakes may fluctuate from one active period to another, but every region is characterised by a certain minimum level of strain which is seldom crossed. This minimum level of strain which may or may not be zero, perhaps represents the remnant or residual strain that may persist even after the entire accumulated strain had an opportunity to be released by a large earthquake and, therefore, suggests itself as a suitable reference from which to estimate the amount of strain available at a given time in the near future to be released as seismic waves, which in turn may give an estimate of possible maximum magnitude if the strain is released instantaneously.

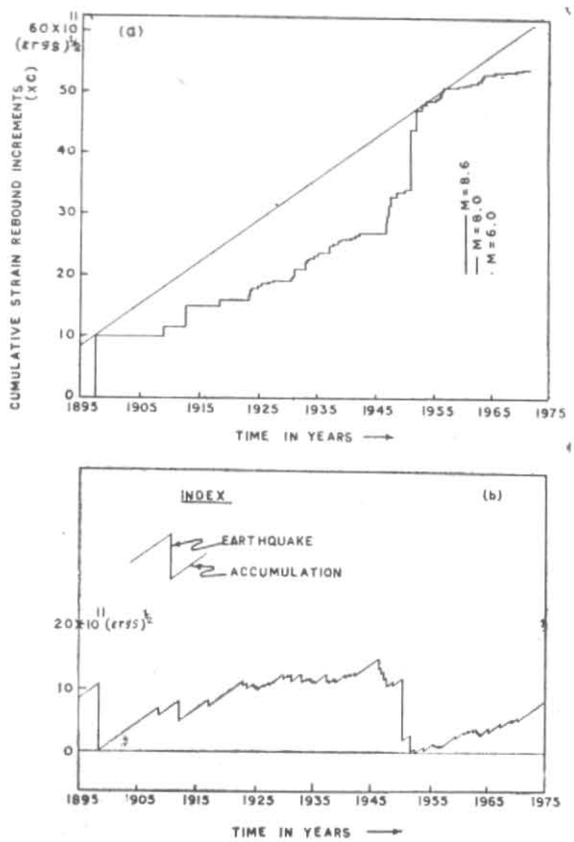

Fig. 2. Strain release characteristics of the Assam region using all earthquakes of $M \geqslant 6$ from 1897 to 1970. Each vertical line represents an earthquake and the relation of this line with earthquake mangitude is also shown in Fig. 2(a). A line drawn slightly to the left of these vertical lines is the line of strain generation. Using the slope of this line strain accumulation and relaxation curve, Fig. 2(b), has been drawn where the inclined lines represent strain accumulation and vertical strain release. A horizontal line drawn through the lowest points of the strain accumulation and relaxation curve is the reference strain level.

3. Observational data

The data used in the present study has been extracted from the records of India Meteorological Department (I.M.D.), International Seismological Summary, Seismicity of the Earth and Associated Phenomena by Gutenberg and Richter (1954) and U.S. Coast and Geodetic Survey. For the sake of consistency all the data of I.M.D. has been used but where this is not available data from other sources mentioned above have been used. Time periods and lower limit of magnitudes for different regions (as shown in Fig. 1) are as follows:

S. No.	Region	Magnitude (M_S) Lower limit	Time (year)
1	Assam	6·0	1897 to 1970
2	Kashmir	5·0	1925 to 1970
3	Kutch	4·8	1928 to 1970
4	Bihar-Nepal	5·3	1913 to 1970

The lower limit of magnitudes varies from region to region owing to non-uniform record of seismic activity. As an example in the Kutch region the lower limit of magnitude is 4.8 and it is likely that a few minor shocks might have been missed. However, the error involved would be very small by such omission of a few events partly because of poor activity of the region and because of small contributions made by the shocks of lower magnitudes. This implies equally well to other regions also. The aim of the present paper is to study in detail the strain release characteristics of the four regions cited above and estimate the earthquake of maximum possible size (magnitude) that may occur in these regions in the near future.

4. Application of the method to various regions

(a) *The Assam region*

Fig. 2(a) is a plot of the cumulative strain factor ΣS in (ergs)$^{\frac{1}{2}}$ as given by Eqn.(3) against time for all shallow earthquakes of Assam from 1897 to 1970. Each vertical line represents one earthquake and the relation between the height and magnitude is shown in Fig. 2(a). The continuous line in this figure represents the secular strain generation curve showing strain accumulation in this case is linear which may be represented by an equation of the form:

$$\Sigma S = A + Bt \qquad (7)$$

where A and B are constants and t is time in years.

From this figure it appears that the tectonic activity was sporadic in the beginning because of the fact that the aftershocks of the Assam earthquake of 12 June 1897 have been excluded in this study as aftershock sequences can be studied in detail independently. After 1924 the tectonic activity is almost continuous though the strain release is small except a gap of about five years. In the year 1950, a major earthquake with $M=$ 8·6 occurred in northeast Assam which is being followed by a minor tectonic activity (producing shocks of small magnitudes) in this area till 1970.

Following the method described above and using the rate of strain generation from Fig. 2(a), a zigzag pattern of relative strain accumulation and relaxation curve is obtained as shown in Fig. 2(b). The pattern of relative strain accumulation curve shows that the lowest strain level was reached in 1897. Thereafter the relative strain level gradually increased till it reached the highest level in 1947. Then the strain was released in instalments and in the year 1950 a major earthquake occurred which brought down the strain level and in the year 1951 to 1952 the strain level was same (minimum) as obtained in the year 1897. Thus the method gives an insight into the minimum strain level which may be used as a reference level to determine the accumulated strain available at any time. Again, 1952 onwards the strain accumulation continues with minor release of strain though the activity was almost continuous till 1970. Accumulated strain stored by the year 1971 if released instantaneously may result in an earthquake of magnitude 8.3 but if the strain is released in instalments it may give rise to a number of earthquakes of small magnitude.

However, it is observed that in this region the strain was released intermittently producing earthquakes of magnitudes 6.2 and 6.3 in 1971 and many earthquakes of magnitudes between 5 and 6 till 1973 indicating that the strain build up is fairly high in Assam which may result in a major earthquake in the near future.

(b) *The Kashmir region*

The cumulative strain release map shown in Fig. 3(a) for this region also shows a linear rate of strain generation as in the Assam region. The tectonic activity was fairly high from 1925 to 1955. In the first two years after 1955 the activity was rather intense which was followed by a lull of about 5 years. Thereafter the activity was almost continuous till 1970.

The relative strain accumulation and relaxation curve shown in Fig. 3(b) shows that the highest levels of stored strain were recorded in the years 1931, 1949 and 1955. All these stored strain resulted in earthquakes of large magnitude of the order of 7.5. It is important to note that the lowest levels of strain were recorded in the years 1934 and 1957. In the year 1971 the strain build up was fairly high and it could have produced an earthquake of magnitude 7·5 had the entire accumulated strain was released at a stretch. But, actually the stored strain was released in instalments producing earthquakes of magnitudes 5.1 and 5.0 in 1971: 5.6, 5.3, 5.5, 6.6, 5.4, 6.1, 5.6 in 1972 and 5.5 and 5.6 in 1973 respectively.

(c) *The Kutch region*

Strain release map of the Kutch region is shown in Fig. 4(a) which again shows a linear segment of strain generation. In this case the tectonic activity is sporadic. The strain accumulation and relaxation curves (Fig. 4b), clearly depicts that the high levels of strain in the years 1928 and 1957 resulted in earthquakes of large magnitude bringing the strain level practically to the reference strain level. In the year 1971 the stored strain was enough to produce an earthquake of magnitude 6.4 if the entire accumulated strain was released at a time. However the only notable earthquake recorded here till 1973 has a magnitude of 4.9 indicating that the stored strain in this region is also fairly high.

(d) *The Bihar-Nepal region*

The strain release map of this region shown in Fig. 5 is different from the maps discussed earlier as in this case the time span is short to permit the preparation of strain accumulation and relaxation

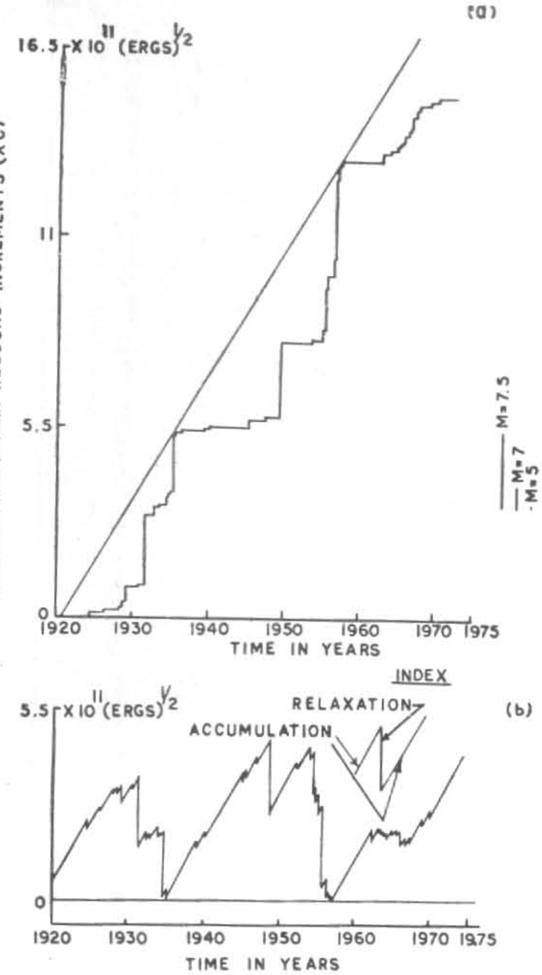

Fig. 3. Similar to Fig. 2 for the Kashmir region using earthquakes from 1925 to 1970 and $M \geqslant 5$

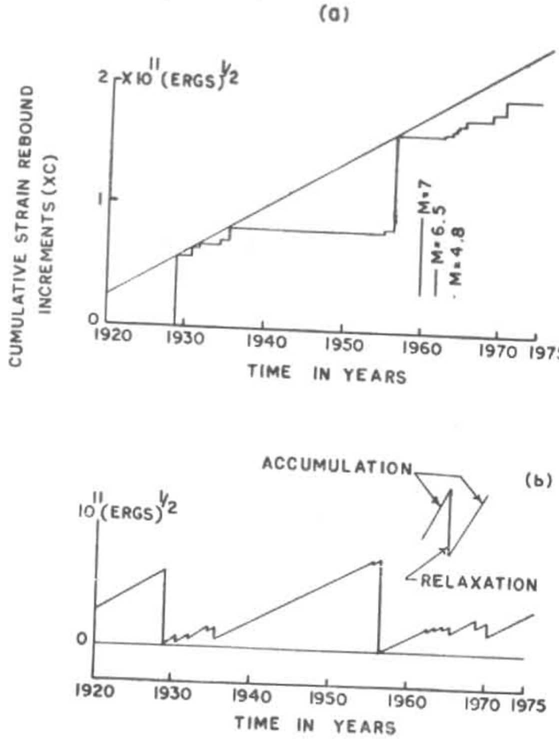

Fig. 4. Similar to Fig. 2 for the Kutch region using earthquakes from 1928 to 1970 and $M \geqslant 4.8$

curve. In this region the tectonic activity was sporadic till 1953 with the occurrence of moderate to major earthquakes and thereafter the activity was almost continuous till 1970 with the occurrence of moderate earthquakes.

5. Discussions

There are enough evidences that the seat of the strain producing forces is in the upper mantle. It is also evident that the strain producing forces cannot change in the time interval of some hundreds of years (Galanopoulos 1972 b). Thus it may be assumed that in a geological unit the rate of strain generation and possibilities of strain storage per unit volume are everywhere the same. Consequently, the total amount of strain that may be accumulated in a given region remain constant for many years as reported by Benioff (1951 b), Ritsema (1954), Galanopoulos (1972 b).

The uniform pattern of strain accumulation does not imply a uniform pattern of strain release as shown by Bath and Benioff (1958), Hedervari (1963) and Chouhan (1968). The pattern of strain release depends on the block structure of geological unit. Thus an area of block faulting is characterised by sporadic seismic activity as south India and an area of complex faulting is characterised by continuous activity as the Assam region.

In general, the strain generation in a particular tectonic unit is linear as in the Kutch region. However, if a large area is taken as a region then the complication introduced by the combination of various tectonic units results in making the strain release pattern erratic such as the Bihar-Nepal region, as a consequence of which it becomes essential to take a large span of time in order to derive the rate of strain accumulation. This is a limitation

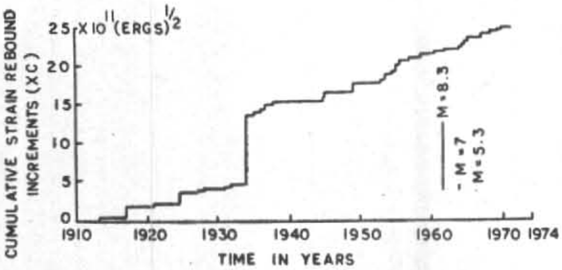

Fig. 5. Similar to Fig. 2(a) for the Bihar Nepal region using earthquakes from 1913 to 1970 and $M \geqslant 5.3$.

of the method. However when a small area is chosen, the time needed to determine the rate of strain generation may be about 15 years as shown by Chouhan (1968) and Galanopoulos (1972 a).

The method of estimating the maxiumm size of an earthquake as described above supplements the earthquakes prediction studies. As an example it may be mentioned that in the recent prediction of a major earthquake in the Koyna region by Gupta and Rastogi (1974) from a study of correlation of water level and frequency of earthquakes, they tried to study only the triggering force and not the accumulated reserve of strain and hence, their prediction failed.

In evaluating a site of engineering projects it is proposed to apply this method in two stages :

(1) Prepare a strain accumulation and relaxation curve for a circular area of 100 km as radius taking the project site as centre, and

(2) Repeat the operation (1) by enlarging the area and taking the radius equal to 500 km.

This will give a better picture of the tectonic activity of the area as in general the rate of strain generation for the two areas will be different.

6. Conclusion

In general, every tectonic unit is characterised by a uniform rate of strain generation which may be used in preparing the strain accumulation and relaxation curve. These curves show a reference or minimum strain level which may be used to estimate the amount of stored strain and hence the maximum possible size of an earthquake if the entire accumulated strain is released at a time. Accordingly, the maximum possible magnitudes of earthquakes that may occur in the near future in Assam, Kashmir and Kutch regions are 8.3, 7.5 and 6.4 respectively.

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DISCUSSION

S.N. BHATTACHARYA (I.M.D) : Why minimum magnitudes are different in different blocks?

2. In Kutch region minimum mag. is 4.8. Is it possible to find magnitude so accurately in determining mag. of order of 4.8 since 1928? What is the basis of determining mag. since 1928?

AUTHOR: Minimum magnitude for each region is selected keeping in view the fact that all the events of that magnitude have been adequately recorded. Therefore, the minimum magnitudes for various blocks are different as they represent different levels of seismic activity. This magnitude may be as low as 2.0 (Chouhan 1975) depending upon the location areal extent and seismic activity.

2. Regarding the second point raised by Shri Bhattacharya, the author shares the view expressed by him regarding the possibility of determining accurately the magnitude of the order of 4.8 for the Kutch earthquakes since 1928, when we had very few seismological observatories in our country. Further, the magnitude scale itself was established by Richter in the year 1935 when most of the seismographs used in our country were Miline-Shaw. Therefore some of the values of magnitudes used in the present studies may be in error especially in the minimum magnitude level. However the contributions made by these lower magnitude events are so small that materially the conclusion arrived here may not be affected. In the absence of seismological records, macroseismic data was used to determine the magnitude values by using Gutenberg and Richter's (1956) relation. :

$$M_s = 1.3 + 0.6 \, I_{max}$$

where M_s is surface wave magnitude and I_{max} = maximum intensity observed in an earthquake.

V.S.Krishnaswamy (G.S.I): Instead of taking of the whole of Assam or whole of Kutch as a big block for strain accumulation/strain release studies, would it not be more realistic and fruitful from the point of view of earthquake prediction to chooe smaller blocks with identified tectonic lineaments and study the matter of strain release etc. Then, it may be possible to relate questions of magnitude of future shocks in terms of length of fault, geological nature of terrain etc.

Otherwise the excercise may remain largely academical. The author may consider.

Author: I would like to elaborate some of the observations made in connection with the areal extent of the region and duration of the data used in the following three phases:

(a) By taking a large area (as in the present case) for the strain release studies involving different tectonic blocks, it has been found that the regional strain release pattern behaves in such a way that the irregular strain release pattern is observed provided the time span is small. But, if we stretch the data for longer duration, then most of the irregularities are evened out and we can determine the rate of strain accumulation with a linear pattern of strain accumulation and relaxation curve. Such curves yield rate of strain accumulation and an idea of residual strain level. However it is difficult to set the time which we may need to get linear pattern of seismic activity. Depending upon the geological complexities the time also increases.

(b) When the area is comparatively small (Chouhan 1975) then many of the complexities appearing in (a) disappear. Actually this method of analysis was originally proposed to investigate, those areas, as has been proposed by Shri Krishnaswamy, with identified tectonic lineaments; latter this approach was extended to larger areas also. The present approach may prove very useful in earthquake prediction problems in estimating the size of future earthquakes.

(c) The same method when applied to a local area such as a coal mine or any other mine susceptible to rock bursts, the result obtained is very encouraging. This approach is being used in the prediction of rock bursts in many Polish coal mines with very good results. We are also planning to make a move in this direction by recording the microseismic events in the Indian coal mines. The main advantage of this method in a localised area is that a very short duration of the order of a month or so is enough to give an idea of the rate of strain accumulation and the residual strain level. The behaviour of a localised area is akin to the elastic hysteresis of a rock sample.

In addition, as has been mentioned in the paper for the selection of power projects it is desirable to make two pronged attack, one for the localised area and the other to include larger events in the neighbourhood (covering fairly large area with about 500 km radius with the power project as the centre)

G.S. Murty (B.A.R.C) : The rate of strain of accumulation computed in different areas is the same or different ?

Author : The rate of strain accumulation is different in various parts of our country as they represent different levels of seismic activity and hence they cannot be the same.