The strain rebound during an earthquake is taken to be proportional to the square root of its energy release. The relationship between energy $E$ (in ergs) and magnitude $M$ of an earthquake has been given by Gutenberg and Richter (1956) as,

$$\log E = 11.8 + 1.5 M$$  \hspace{1cm} (5.1)

According to Benioff (1951) and Ritsema (1954) the rate of strain release by the world's shallow earthquakes is approximately constant since 1907 (Chouhan, 1979). Regional strain release characteristics of Indian earthquakes have been studied by Chouhan (1966) who observed two non-linear segments followed by a linear one. Chouhan et al. (1966) have also studied, in detail, the strain release characteristics of Assam (the northeast Indian region). The importance of strain release studies, according to them, is that in a tectonic block, the characteristic features and trends of stress field can be investigated by examining the pattern of strain release over it and assuming a linear probability of earthquake occurrence over a period of few years, a direct extrapolation.
of the pattern of strain release into the immediate future can throw some light on the future earthquake activity expected in a given region. Although it is rather a crude forecast, yet it offers a valuable basis for general statistical seismic risk prediction.

In this chapter, strain release characteristics of the earthquakes of the northeast Indian region have been studied. Similar studies have been made by Chouhan (1966) for this region. But in this study the period of observation and the boundaries of the study region are different from those of Chouhan. In addition detailed studies of strain release characteristics have been made for each of the six tectonic blocks (Chapter IV) into which the whole region have been divided.

l. The theory and method of application:

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

\[
E_p = 0.5 \mu W S^2
\]

(6.2)

where \( \mu \) is the co-efficient of shear and \( S \) is the average strain just before the earthquake. Thus the energy released by seismic waves is given by,

\[
E_T = 0.5f \mu W S^2
\]

(6.3)
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, \( x_f \)

\[
S = C x_f
\]

\( \text{or,} \quad S = C x_f \tag{6.4} \)

where \( C \) is another constant.

Hence,

\[
k_T = 0.5 f \mu \omega C^2 x_f^2 = C_1^2 x_f^2 \tag{6.5}
\]

where \( C_1 = (0.5 f \mu \omega C^2)^{\frac{1}{2}} \)

Thus the displacement on a fault is seen to be proportional to the square root of the energy released as seismic waves. Hence using the magnitude-energy relationship given by equation 6.1 and the equation 6.5,

\[
\log k_T^{\frac{1}{2}} = \log C_1 x_f^2 = 5.9 + 0.75 M
\]

\( \text{or,} \quad x_f = \frac{1}{C_1} 10^{5.9 + 0.75 M} \tag{6.6} \)

This gives the relation between the fault displacement, \( x_f \) and earthquake magnitude \( M \). Thus if magnitudes of all earthquakes occurring in any one fault system over a period
of years are known, one can plot fault displacement (strain that may occur during that time period. Such plots, which
give strain rebound characteristics represents spurts of
seismic activity separated by relatively quiescent periods.
The resulting curve will be a saw toothed curve. Its upper
peaks will represent the exhaustion of accumulated strain
caused by earthquakes. A line drawn through these peaks will,
therefore, represent the rate of strain generation in a given
region. Assuming this rate of strain generation in a region,
it is then possible to illustrate the probable strain levels
obtained at different times by means of a strain accumulation
and relaxation curve. In the beginning of the period of study,
the strain accumulation and relaxation curve starts from an
arbitrary level which represent the store of strain at that
time. It is then made to follow a slope equal to the rate of
strain generation obtained from strain rebound characteristics
until an earthquake takes place which represent release of
strain. At this point, on the time axis, the curve drops
vertically by an amount equivalent to the strain of that
earthquake. Thereafter the curve again follows the slope of
mean rate of strain generation until the occurrence of next
earthquake.

Chouhan (1979) has remarked that although the strain
level following an earthquake or a series of earthquakes may
fluctuate from one active period to another, every region is
characterised by a certain minimum level of strain which is
seldom crossed. He suggests that this minimum level of strain which may or may not be zero, perhaps represents the residual strain that may persists 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 it is possible 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 of the earthquake if the accumulated strain is released instantaneously.

2. Application of the method to the northeast Indian region:

To apply the method to the northeast Indian region, as well as to the six tectonic blocks separately, the earthquakes which occurred during the period from 1897 to 1978 (both years inclusive) has been considered. The lower limit of earthquake magnitude has been taken as 5.0 in $M_s$ scale. Owing to the non-uniform record of seismic activity, specially in the earlier periods, some smaller earthquakes might have been missed. However the errors involved due to the omission of a few small shocks would be small because of the smaller contributions made by the shocks of lower magnitudes.

The strain release characteristic curve for the northeast Indian region using all earthquakes of magnitudes 5 or greater from 1897 to 1978 is shown in Figure 6.1(a). Here each vertical line represents the release of earthquake energy
in \( \frac{1}{2} \) which again represents the strain factor \( S \) in (erg)\(^{\frac{1}{2}} \), since \( S = \frac{1}{2} \) (equation 6.3). The continuous line represents the secular strain generation showing that strain accumulation is linear and may be represented by an equation of the form:

\[
\frac{1}{2} \int E^2 = A + Bt \tag{6.7}
\]

where \( A \) and \( B \) are constants and \( t \) is the time in years.

The observations made from this figure indicate that, after the occurrence of the great Indian earthquake of 12th June, 1897, the earthquake activity was sporadic. But between 1917 to 1950, the activity was found to be nearly uniform. In the year 1950 another great earthquake occurred (the Assam earthquake of 15th August, 1950) in this region. Thereafter minor tectonic activities are noticed for about two decades. After 1970, the tectonic activity of the region is relatively less.

Figure 6.1(b) shows the strain accumulation and relaxation curve for the northeast Indian region. This figure has been drawn, using the rate of strain generation from Figure 6.1(a), where the inclined lines represent strain accumulation and the vertical lines, the strain release. A horizontal line drawn through the lowest points of the strain accumulation and relaxation curve is the reference strain.
Figure 6.1  (a) Strain release characteristics and (b) Strain accumulation and relaxation curve, for the earthquakes of the northeast Indian region.
level, which may be used to determine the accumulated strain at any time. This figure shows that the strain level reaches its minimum (reference strain level) in the years 1897, 1951 and 1952. The highest amount of stored energy by the year 1947 was almost completely released in 1950 with the occurrence of an earthquake of magnitude 8.5 and its aftershocks. After 1952 to 1956, strain accumulation and release was nearly uniform. Thereafter, strain energy accumulation continues with minor release. The amount of accumulated strain until 1978 will be equivalent to an earthquake of magnitude 8.8, if released instantaneously. Similar results were also obtained by Chouhan (1979), who showed that the accumulated strain by the year 1971 would be equivalent to an earthquake of magnitude 8.3 if released, instantaneously. The minor release of accumulated strain since 1956 is a clear indication that the strain build up is fairly high in the northeast Indian region which may result in a big earthquake in the near future.

The eastern Himalayas: The strain rebound characteristic curve for this tectonic block is shown in Figure 6.2(a). It is observed that the seismic activity of this region was relatively low before 1940. There may be omission of fewer earthquakes in the earlier periods because of the incomplete reporting. The seismic activity, however started to increase gradually from 1940 to 1950-51. This indicates that the strain energy generation was more during the early years which
Figure 6.2 (a) Strain release characteristics for the earthquakes of the eastern Himalayas.
gradually started to be released after 1940. The rate of energy released has been seen to increase gradually and almost all the stored energy was released in 1950-51, due to the earthquake of 15th August, 1950 and its aftershocks. Thereafter the seismic activity in this region is again decreasing, indicating gradual increase in stored strain energy. The Figure 6.2(a) does not indicate any linear strain generation as in the case of the whole of the northeast Indian region (Figure 6.1(a)). Hence no linear strain generation line of the form of equation 6.7 can be drawn for the eastern Himalayas. Therefore, without the knowledge of strain generation rate, no strain accumulation and relaxation curve of the form shown in Figure 6.1(b) can be drawn for this tectonic block. However, since 1955, the accumulation of strain is more than its release. So it is possible that the stored strain energy in this region will be released sometime in future causing a major earthquake or a number of intermediate earthquakes, if the release is in instalments.

The Brahmaputra Valley: The strain release characteristics of the Brahmaputra valley is shown in Figure 6.3(a). The Figure 6.3(b) shows the strain accumulation and relaxation of this tectonic block. This figure shows that the accumulated strain reaches its maximum value in the year 1945, although there was alternate release and accumulation of strain since 1931. The strain level becomes low in 1950. Thereafter there was gradual accumulation of strain which again released in
THE BRAHMAPUTRA VALLEY

(a)

(b)

Figure 6.3  (a) Strain release characteristics and  
(b) Strain accumulation and relaxation curve,  
for the earthquakes of the Brahmaputra  
valley
1959 causing an earthquake of magnitude 6.5. The accumulated strain in the year 1971 was such as would be produced by an earthquake of magnitude 6.4, if the entire strain was released at a time. But, the only notable earthquake in 1971 had a magnitude of 5.0. The accumulated strain until 1978, if released at once, will be an earthquake equivalent to magnitude 6.8. This indicates that the stored strain energy in this region is fairly high. However the highest magnitude earthquake recorded in the Brahmaputra valley was only of magnitude 6.5.

The Naga hills and Patkai synclinorium:

The cumulative strain release characteristics for the earthquakes of the Naga hills and Patkai synclinorium are shown in Figure 6.4(a). This figure indicates a linear strain generation rate and nearly uniform earthquake activity. The strain accumulation and relaxation curve shown in Figure 6.4(b) clearly depicts three high peaks of stored energy in the years 1906, 1926, and 1950. The accumulated strain in the year 1906 resulted in a major earthquake of magnitude 7.0 and in 1908 another earthquake of magnitude 7.5 brought down the strain level practically to the reference strain level. The stored energy by the year 1926 resulted in a number of intermediate magnitude earthquakes until a few years later. Thereafter the stored energy till 1950 resulted in a number of intermediate and smaller magnitude earthquakes.
Figure 6.4 (a) Strain release characteristics and (b) Strain accumulation and relaxation curve, for the earthquakes of the Naga hills and Patkai synclinorium.
bringing down the energy level again to the reference strain level. After that the earthquake activity was almost continuous till 1978. In the year 1978, the accumulated strain energy was enough to produce an earthquake of magnitude 7.6. Thus in this tectonic block also, there is probability of occurrence of a large magnitude earthquake in near future, if the stored energy is released instantaneously.

The Shillong plateau and Mikir hills:

The cumulative strain release characteristics for the Shillong plateau and Mikir hills are shown in Figure 6.5(a). This figure also indicates a linear rate of strain generation. After the great earthquake of 1897 a major part of accumulated strain was released in the years 1923 and 1930 in two major earthquakes. The strain accumulation and relaxation curve shown in Figure 6.5(b) clearly depicts that the high level of stored energy in the years 1923 and 1930 resulted in an earthquake of magnitudes as high as 7.0. The stored energy in the year 1951 resulted in an earthquake of magnitude 6.8 and a few smaller shocks which bring the energy level down. Thereafter the release of accumulated strain in this tectonic block was very low indicating a high level of accumulated strain till 1978. Accumulated strain by that year if released instantaneously may result in an earthquake of magnitude 7.7 - a size of a devastating earthquake. But if the accumulated strain is released in instalments, it may
Figure 6.5  (a) Strain release characteristics and  
(b) Strain accumulation and relaxation curve  
for the earthquakes of the Shillong plateau  
and Mikir hills
give rise to more than one earthquakes of relatively lower magnitudes.

The Bengal basin and Surma valley:

The Figure 6.6(a) shows the strain release characteristics of the earthquakes of the Bengal basin and the Surma valley. This figure also indicates a linear rate of strain generation. The corresponding strain accumulation and relaxation curve is shown in Figure 6.6(b). This figure shows two distinct high peaks of stored strain, one in 1918 and the other in 1949. The stored energy by the year 1918 was released by a major earthquake of magnitude 7.6. Thereafter the seismic activity was nearly uniform and the stored energy by the year 1949 resulted in a number of smaller earthquakes in 1949 and 1950, bringing the strain level down to the minimum reference strain level. Again in 1955 the stored energy was released by an earthquake of magnitude 6.5. Thereafter till 1978, there was linear generation of strain and the accumulated strain by that year will be equivalent to an earthquake of magnitude 7.0, if released at a time.

The Arakan Yoma ranges:

The cumulative strain release characteristics of the earthquakes of the Arakan–Yoma ranges are shown in Figure 6.7(a). This curve clearly shows that the earthquake activity
Figure 6.6 (a) Strain release characteristics and (b) Strain accumulation and relaxation curve for the earthquakes of the Bengal basin and Surma valley.
THE ARAKÁN YOMA RANGES

Figure 6.7 (a) Strain release characteristics and (b) Strain accumulation and relaxation curve for the earthquakes of the Arakan-Yoma ranges
63

in this tectonic block is relatively high and almost uniform since 1920. The corresponding strain accumulation and relaxation curve is shown in Figure 6.7(a). This curve shows three distinct high energy peaks, in 1931, 1937 and 1953. All these stored energy resulted in earthquakes of large and intermediate magnitudes. It is important to note from this figure that the low levels of strain were recorded in the years 1938, 1956 and 1964. After 1964 till 1978, there were little release of stored strain indicating fairly high amount of accumulated strain. The stored energy till 1978 is equivalent to the energy that would be released by an earthquake of magnitude 7.8.

3. Discussion and conclusion:

Regarding the origin of strain producing forces Chouhan (1979) pointed out that the seat of these forces is in the upper mantle. According to Galanopoulos (1972) these strain producing forces can not change in time interval of some hundred years. Based on these evidence, Chouhan (1979) again assumed that in a geological unit the rate of strain generation and probabilities of strain storage per unit volume are everywhere the same. Benioff (1951), Hitzema (1954) and Galanopoulos (1972) reported that the total amount of strain accumulated in a given region is constant for many years.

As regard the pattern of strain accumulation and relaxation curve, it has been shown by Bath and Benioff (1958),
Hedervari (1963) and Chouhan (1968) that the uniform pattern of strain accumulation does not imply a uniform pattern of strain release. The pattern of strain release has a correlation with the block structure of the geological unit. Chouhan (1979) showed that an area of block faulting is characterised by sporadic seismic activity while an area of complex faulting is characterised by continuous seismic activity. The resulting strain release characteristics and the strain accumulation and relaxation curves for the northeast Indian region as well as for the six tectonic blocks separately, have also shown that the seismic activity in this region is more or less continuous. This tends to indicate that the region is characterised by complex fault system. Tectonic evidences of this region also tend to confirm the above fact.

The strain accumulation and relaxation curves, obtained in the above analysis, in each of the six tectonic blocks and the northeast Indian region as a whole, provide a very useful means of estimating the size of the future earthquakes. These curves show a reference and minimum strain level which is used to estimate the amount of stored strain and hence the possible size of earthquakes if the entire stored strain is released at a time. The maximum possible magnitudes of earthquakes that may occur in the near future in the northeast Indian region as a whole and in the six tectonic blocks separately are shown in Table 6.1.
Table 6.1 Maximum possible magnitude earthquakes that occur in near future.

<table>
<thead>
<tr>
<th>Region</th>
<th>Maximum possible magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>The northeast Indian region</td>
<td>8.8</td>
</tr>
<tr>
<td>The eastern Himalayas</td>
<td>8</td>
</tr>
<tr>
<td>The Brahmaputra valley</td>
<td>6.8</td>
</tr>
<tr>
<td>The Naga hills and the Patkai synclineorium</td>
<td>7.6</td>
</tr>
<tr>
<td>The Shillong plateau and the Mikir hills</td>
<td>7.7</td>
</tr>
<tr>
<td>The Bengal basin and the Surma valley</td>
<td>7.0</td>
</tr>
<tr>
<td>The Arakan Yoma ranges</td>
<td>7.8</td>
</tr>
</tbody>
</table>

(Maximum possible magnitude cannot be assigned. Explanation is given in the text.)

These results show that the earthquake risk in the northeast Indian region is high. The sizes of the maximum magnitude earthquakes that may occur in each of the six tectonic blocks as well as for the region as a whole indicate that they are big enough to cause large scale devastation in the region. The possibility of occurrence of such a large earthquake in future can not be ruled out, because of the occurrence of two earthquakes of magnitude greater than 8 during the last one hundred years causing large scale devastation in the region.