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Seismic Characteristics and Energy Release of Aftershock Sequences of Two Giant Sumatran Earthquakes of 2004 and 2005

R. K. Jaiswal*, Harish Naswa and Anoop Singh
Oil and Natural Gas Corporation, Vadodara

Summary

The giant Sumatra-Andaman earthquake of December 26, 2004 (Mw 9.3) ruptured the Sunda Arc from northern end of Sumatra to Andaman for a length of 1300 km. March 28, 2005 (Mw 8.7) rupture occurred south of it in north Sumatra. We studied seismic characteristics and energy release of the aftershock sequences of these two earthquakes. The energy released in aftershocks of 2004 and 2005 earthquakes was 0.135% and 0.365% of the energy of the respective mainshocks while the strain release in aftershocks was 39% and 71% for the two earthquakes, respectively. The b-value (slope of the frequency-magnitude relation), the p value (decay rate of aftershocks) and strain energy release are computed for both aftershock sequences.

Introduction

Two great earthquakes of magnitude 9.3 and 8.7 occurred in northern Sumatra region in quick succession on December 26, 2004 (3.3N 95.98E, 30km) and March 28, 2005 (2.09N 97.11E, 30km). Location of March 28, 2005 earthquake was about 190 km SE of the mainshock of December 26, 2004.

The first one caused the largest tsunami in the history killing about 300,000 people. The 2005 earthquake caused a minor tsunami. A large number of aftershocks, including some strong ones, that occurred after the two earthquakes enticed lot of interest. Study of these aftershocks is expected to throw light on tectonics of the region. In view of this we studied depth distribution, b and p values and the energy release of aftershocks. The aftershock duration, b value, p-value and energy release are all showing normal distribution. We read some comments that the 2004 earthquake has shown an unusually strong aftershock activity with lot of energy released by them. But we estimate that the energy release by aftershocks is not much. However, the strain release in aftershocks is substantial.

Data

Aftershock data for this study have been collected from USGS catalogs for the period up to May 20, 2006 covering the region between Lat. 0°S to 15°N and Long. 90^0 to 99^0E. Rupture of the 2004 earthquake propagated northward for 13,000 km up to Andaman (from Lat. 3°N to 15°N) while rupture of the 2005 earthquake propagated southward for 300 km (from 3°N down to 0°S). Aftershocks are considered to have occurred in the respective rupture zones. It is noticed that there were a few aftershocks of 2004 earthquake between lat 2.5 to 3°N. Hence, shocks between latitude 2.5 to 3°N until March 28, 2005 are considered as aftershocks of 26 Dec. 2004 event while shocks at and below latitude 3°N after 28 March, 2005 are considered as aftershocks of March 28, 2005 mainshock (Fig. 1). A similar pattern is shown by Ammon (2006). The focal depths of most of the aftershocks are between 20 to 50km (Fig. 2).

GP-16, Geophysical Services, ONGC, Makarpura – 390 009, Vadodara, Gujarat
Email: rajeev_ngri@rediffmail.com

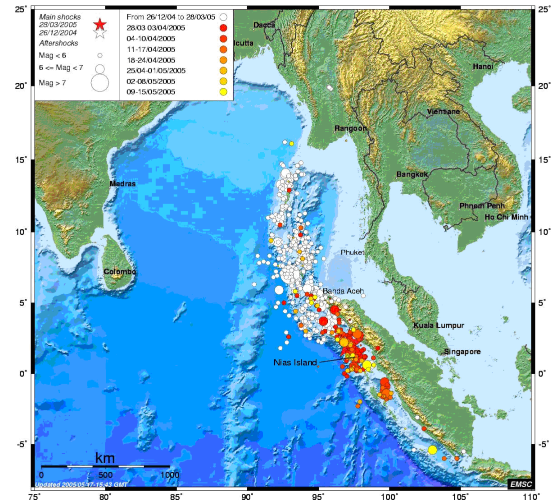

Fig. 1. Aftershocks of December 26, 2004 earthquake are shown by white patch of epicenters and a few red ones from Lat. 3°N and northward and that of the earthquake of March 28, 2005 are shown by red epicenters about 3°N and southward. The red patch of epicenters south of Lat 0° are not aftershocks of March 28, 2005 earthquake. Location of the earthquake of March 28, 2005 was about 190 km SE of the location of mainshock of December 26, 2004.

A total of 3460 aftershocks of December 26, 2004 mainshock are compiled in the magnitude range 3.5 -7.5. On the other hand 1835 aftershocks of March 28, 2005 earthquake are compiled in the magnitude range 3.6 - 6.9. For the December 26, 2004 earthquake the two largest aftershocks were of magnitude, Ms 7.5. The first one occurred a few hours after the mainshock near Nicobar Islands (Lat. 6.91^{0}E, Long. 92.96^{0}N). The second one occurred 150 km further NW on July 24, 2005 (Lat. 7.92^{0}E, Long. 92.19^{0}N) (Not shown in Fig. 1).

Due to large number of strong aftershocks the perception among many persons was that the aftershocks have released unusually large energy. The study here reveals that it is not so.

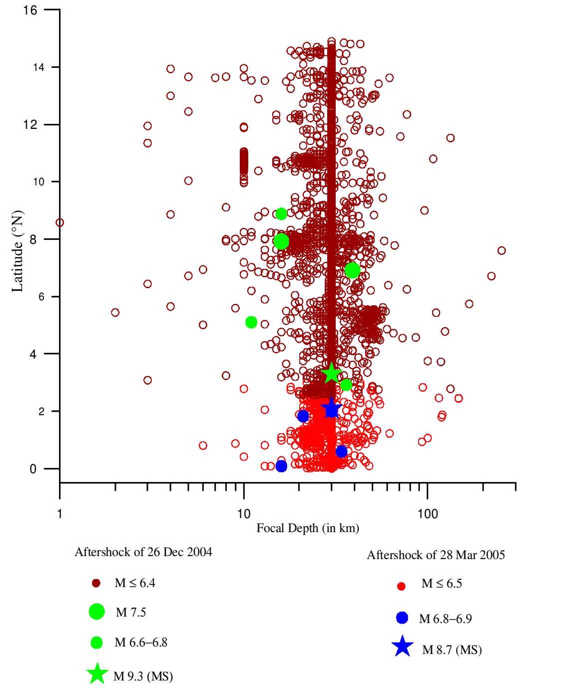

Fig. 2. Focal depth distribution of aftershocks with latitude for 2004 earthquake (maroon and green circles, 3° - 15°N) and of 2005 earthquake (red and blue circles, 0 - 3°N). Concentration at 30 km depth is artefact of the location progarm. Most of the aftershocks are in depth range of 20 to 50 km. Mainshock for 2004 and 2005 earthquakes are shown by stars.

Histograms of magnitude vs. frequency of aftershocks for the December 26, 2004 and March 28, 2005 earthquake sequences are shown in Figs. 3a and 3b, respectively.

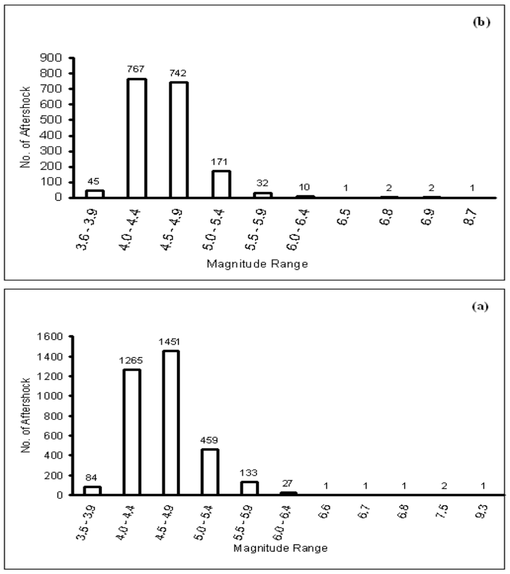

Fig. 3. Magnitude distribution of the aftershocks of (a) December 26, 2004 earthquake and (b) March 28, 2005 earthquake.

The b & p Values of Aftershock Sequences

Slope of the frequency-magnitude relation (b-value) and rate of decay (p-value) of aftershock sequences reveal the information about the heterogeneity of the rocks and stress conditions in the earthquake zones. The magnitude-frequency (Gutenberg-Richter) relation is given by:

$$\text{Log } N = a - b M$$

where, N is cumulative number of shocks, constant 'a' depends upon level of seismicity and slope b reflects upon the heterogeneity of the medium and level of stress. The b-values have been determined with least square and maximum likelihood methods. Using least-square method, for the sequence pertaining to the December 26, 2004 earthquake we obtained Log N = 8.87 - 1.21 M (Fig. 4a) and for March 28, 2004 we obtained Log N = 7.74 - 1.08 M (Fig. 4b). The b-values are obtained to be 1.21 ±0.04 for 2004 sequence and 1.08 ±0.03 for the March 28, 2004 sequence from least-square method.

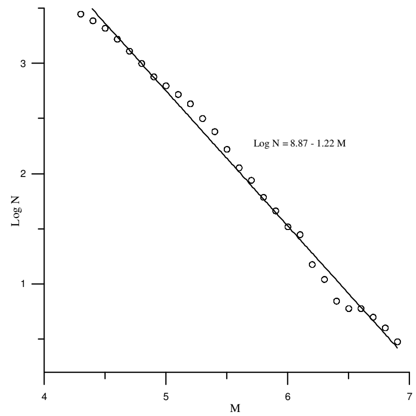

Fig. 4(a) The b value of December 26, 2004 sequence.

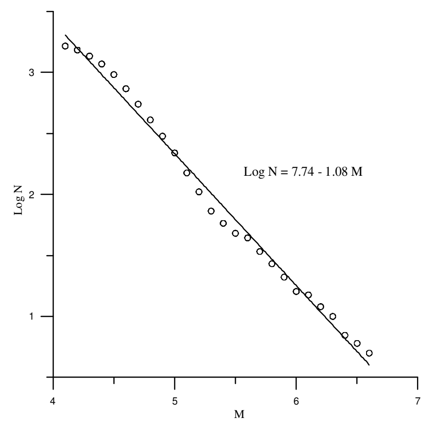

Fig.4(b) The b-value for the March 28, 2005 sequence.

The b-values have been determined by maximum likelihood method (Utsu, 1965; Aki, 1965) using the relation:

$$b = 0.4343 / Ma\text{-}Ms$$

where, Ma is the average magnitude and Ms is the threshold value (lower limit) of the magnitude for which the dataset is complete. The lowest magnitude is 4.2 for both the sequences. The December 26, 2004 and March 28, 2005 sequences show b values of 0.92 and 1.07, respectively by maximum likelihood method. The values nearly 1 indicate normal values.

Omori's (1894) law is used to study the frequency of occurrence of aftershocks n(t) at time t after the mainshock.

Utsu (1961) has given the modified version for Omori's law as:

$$n(t) = k / (t+c)^p$$

where k, c, p are parameters and n (t) is the frequency of aftershocks per unit time t. The constant k depends on the number of aftershocks during the first time interval, while c (taken zero in our case) is a constant. The decay in aftershock activity with time reflects a decrease of stress in the region. The constant p is determined from this relation and gives the rate of fall of aftershock activity. The frequency of occurrence of aftershocks n(t) at time t (weekly) after the mainshock is given as:

$n(t) = 725\ t^{-1.1}$ $R^2 = 0.75$ for December 26, 2004 Eq.
$n(t) = 281\ t^{-0.9}$ $R^2 = 0.68$ for March 28, 2005 Eq.

For Sumatran aftershocks 'p' value comes out to be 1.1 and 0.9 (Figs. 5a & 5b). It shows a normal decay and decrease of stress with time in the region.

Energy Release and Tectonic Strain Release in Mainshocks and Aftershocks

Energy released during an earthquake is proportional to its magnitude. The energy release, E in ergs is estimated from the relation:

$$\text{Log } E = 9 + 1.8M$$

The values of E have been calculated for the mainshocks and their aftershock sequences. Cumulative energy release for the two sequences is shown in Figs. 6a & 6b.

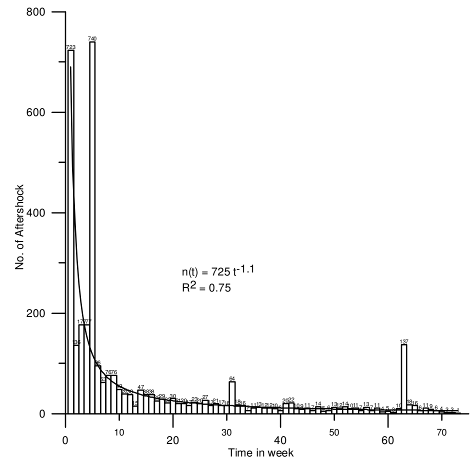

Fig. 5a. Decay rate of aftershocks of December 26, 2004 earthquake.

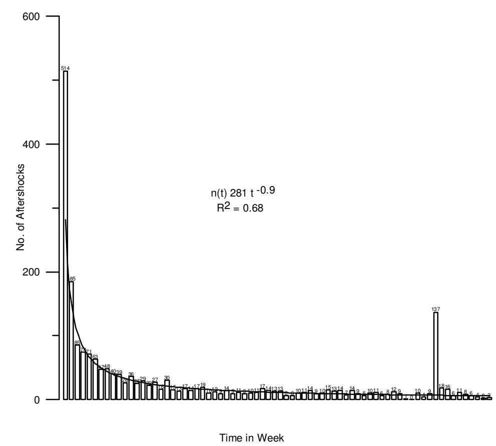

Fig. 5(b) Decay rate of aftershocks of March 28, 2005 earthquake.

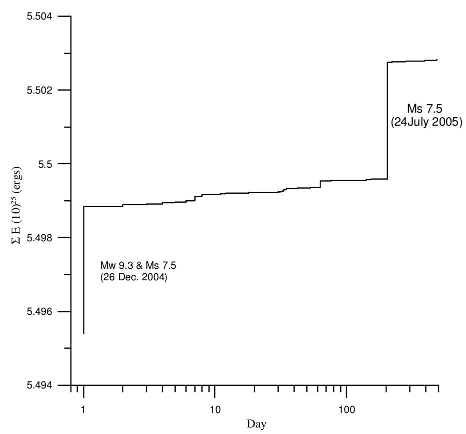

Fig. 6(a) Cumulative energy release of December 26, 2004 sequence.

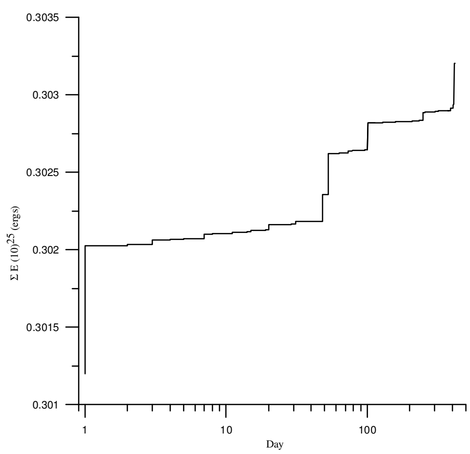

Fig. 6(b) Cumulative energy release of the March 28, 2005 sequence.

The energy released in the earthquake of December 26, 2004 was 5.49E+25 ergs, while the total aftershock energy was only 7.42E+22 ergs. That reveals only 0.135% energy of the mainshock was released in the aftershocks of earthquake of 26 Dec. 2004. On the other hand energy released in the earthquake of March 28, 2005 was 4.57E+24 ergs while the total aftershock energy was only 1.67E+22 ergs. This means only 0.365% energy of the mainshock was released in the aftershocks of earthquake of March 28, 2005.

The square root of energy for an individual earthquake is proportional to the strain release (Gutenberg and Richter, 1956) and is given by

$$\text{Log } E^{1/2} = 4.5 + 0.9M$$

Since energy unit is in ergs, strain release will be in the units of $(\text{ergs})^{1/2}$. Cumulative strain release for the two sequences is shown in Figs. 7a & 7b. The major strain release in the aftershock sequence of December 26, 2004 earthquake is by two major earthquakes of Ms 7.5 on December 26, 2004 and July 24, 2005.

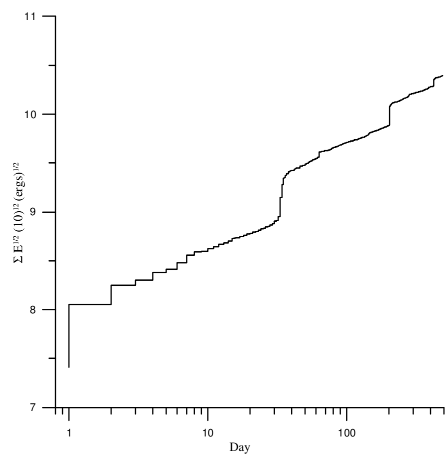

Fig. 7(a) Cumulative Strain release of the sequence of December 26, 2004 earthquake.

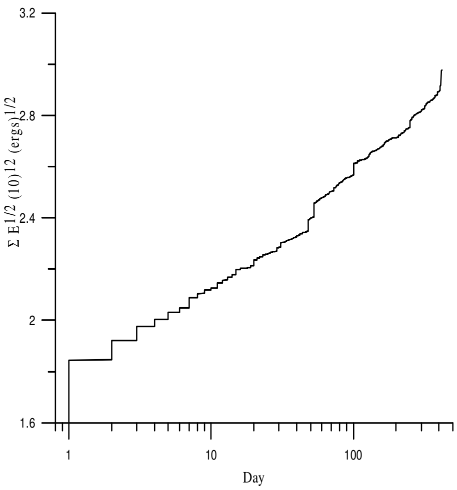

Fig. 7(b) Cumulative strain release of the sequence of March 28, 2005 earthquake.

The December 26, 2004 earthquake released strain of 7.41×10^{12} ergs$^{1/2}$, while its aftershocks released 2.98×10^{12} ergs$^{1/2}$ making 39% in the aftershocks. This figure is matching with the 30% slip in aftershocks for 1.5 months derived by GPS and seismic methods by Subarya et al. (2006). The March 28, 2005 earthquake released strain of 1.74×10^{12} ergs$^{1/2}$, while its aftershocks released 1.24×10^{12} ergs$^{1/2}$ making it 71% strain release in aftershocks.

Discussion

Occurrence of M8.7 earthquake just after 3 months of M 9.3 earthquake in an adjacent area indicates that it was most likely triggered by change in static stress due to the first earthquake. Aftershocks of the two earthquakes are confined to the respective rupture zones. The large shocks are confined upto Nicobar (9°N). The aftershock zone at 10°-15°N is narrow and confined to west of Andaman Islands along the zone of convergence.

Due to occurrence of two M 7.5, some 30 of M6 to 6.8 and about 600 of M5 to 5.9 aftershocks of December 26, 2004 earthquake it was perceived by many that it is an unusually strong aftershock activity with lot of energy released by them. However, the percentage of energy released by aftershocks with respect to 2004 and 2005 mainshoks is only 0.135% and 0.365%, respectively. The magnitude difference of the mainshocks and respective largest aftershocks is within two magnitude units, which is as expected for large earthquakes in the Indian region. The b and p values are also in the normal range of about 1, indicating normal heterogeneity, stress distribution and normal rate of decay of aftershocks. However, the strain release in aftershocks of 2004 and 2005 earthquake is 39% and 71%, respectively, which are quite large amounts.

Conclusions

Seismic characteristics of the aftershock sequences of giant/great Sumatra earthquakes of 2004 and 2005 have been studied. The energy released in aftershocks of 2004 and 2005 earthquakes was 0.135% and 0.365% of the energy of the respective mainshocks while the strain release in respective aftershock sequences was substantial being 39% and 71%, respectively. The b-value (slope of the frequency-magnitude relation), the p value (decay rate of aftershocks) indicates normal values of about 1. The difference in magnitudes between mainshocks and largest aftershocks are 1.8. All these parameters are in normal range and indicate normal stress patterns and mechanical properties of the medium. Only the strain release in aftershocks was substantial.

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