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Original Article

Magnitude analysis of aftershocks of the M_w 9.3 Sumatra-Andaman Earthquake recorded at the temporary PSU Seismic Station in Phang nga, Thailand

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Abstract

After the M_w 9.3 Sumatra-Andaman Earthquake on 26 December 2004, a temporary broadband seismic station was set up at the Khao Chang Telecommunication Station in Phang nga Province, Southern Thailand, in order to monitor aftershocks in an area bounded by 0°-20° N, and 90°-100° E. Altogether 98 events were identified during the study period from 1st to 12th January 2005; but six of these events are not listed in the catalog of the United States Geological Survey (USGS/NEIC). Body wave magnitudes (m_b) and moment magnitudes (M_w) of the events were determined and compared with USGS magnitudes. For m_b, the PSU values are 0.215 higher than the USGS values, whereas for M_w, the PSU values are 0.268 lower than the USGS values. Differences in m_b may result from differences in time windows chosen for the maximum amplitude determination, or from accuracy of the Q-value. Differences in M_w may result from assumptions made on velocity, attenuation and determination of the low-frequency part of the seismic spectrum. However, these differences are comparatively small considering that the USGS data are network values whereas the PSU data are from a single station.

Keywords: Earthquake, body wave magnitude, moment magnitude, Sumatra-Andaman Earthquake, tsunami warning

1. Introduction

The M_w 9.3 Sumatra-Andaman Earthquake occurred at 00:58:53 UTC (07:58:53 Thailand time) on 26 December 2004 at 3.316°N and 95.854°E off the West coast of Northern Sumatra, Indonesia. The earthquake triggered a series of devastating tsunamis that spread throughout the Indian Ocean and inundated coastal communities across South and Southeast Asia, including parts of Indonesia, Sri Lanka, India, and Thailand. The United States Geological Survey (USGS) reported a death toll of 157,577 people, 26,763 missing, and 1,075,350 people displaced (USGS, 2005).

The earthquake occurred at the interface of the Indian and Burma Plate, a small plate south of the Eurasian Plate. A sudden uplift of parts of the ocean bottom started the tsunami with devastating effects to Thailand's west coast (USGS, 2005).

The characteristics of the seismicity related to the subduction zone in the Sumatra-Andaman region and the nature of stresses and strains were previously not well understood (USGS, 2005). With the amount of digital seismological data worldwide recorded during this devastating earthquake and the subsequent aftershocks, ongoing and future research will provide further understanding of the processes during and after this earthquake (e.g. Lay *et al.*, 2005; Gahalaut *et al.*, 2006; Mignan *et al.*, 2006).

Furthermore, the analysis of the earthquake magnitudes and locations, including depths, are important for any future tsunami warning system, as only a fractional amount of all earthquakes trigger a tsunami. The Indian Ocean Tsunami Warning System is currently set up under the umbrella of the UNESCO (IOC, 2007). Reliable magnitude estimations are es-

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Table 1. Earthquake magnitudes and depths of the hypocenter as criteria for a tsunami warning system in Thailand (Khovadhana, 2005).

Magnitude	Depth of Hypocenter	
	Less than 100 km	More than 100 km
5.0-6.4	Low possibility to generate Tsunami **Advisory**	
6.5-6.9	Possibility to generate Tsunami **Alert / Watching**	
7.0-7.9	High possibility to generate Tsunami **Alert / Watching**	Possibility to generate Tsunami **Alert / Watching**
>8.0	Very high possibility to generate Tsunami **Warning**	High possibility to generate Tsunami **Alert / Watching**

essential for the efficiency of the warning system, as they are a key trigger parameter for the different warning levels, like *alert*, *advisory*, *watch,* and *warning* (see Table 1). The main goal is to minimize false alarms and warnings in order to ensure the reliability of the warning system among the public.

2. PSU seismic station

After the 26 December 2004 Earthquake, the Geophysics Group of the Prince of Songkla University deployed a temporary seismic station in Phang nga Province, Southern Thailand. The PSU Station consist of following main parts: a three-component Trillium 40 broadband seismometer, a Trident 24 bit digitizer, the Janus communication controller, a Global Positioning System (GPS) receiver, a modem and a computer with analysis software, all from Nanometrics, Canada (see Figure 1).

The PSU Station was set up at a telecommunication station in Muang District, Phang nga Province. The location of the Station Phang nga (PNG), was at 8.43^{o}N and 98.51^{o}E (UTM: Zone 47, 932283 445715, WGS-84) with an elevation of 85 meters. The PSU seismic station was located approximately 500 to 600 km east of the Sunda Subduction Zone in the Andaman Sea, the area of the interest for the earthquakes measurement, between 0^o-20^{o}N and 90^o-100^{o}E.

The main criterion for choosing the telecommunication station was the exposure of hardrock and the safety of the station. On the site of the telecommunication station there was an outcrop of hardrock, a sandstone-shale sequence of Lower Permian-Ordovician age, which was found with the support from the Department of Mineral Resources, Thailand.

The telecommunication station is located on a small hill surrounded by a fence and a family is permanently living there (Figure 2a). Besides the hardrock outcrop, another

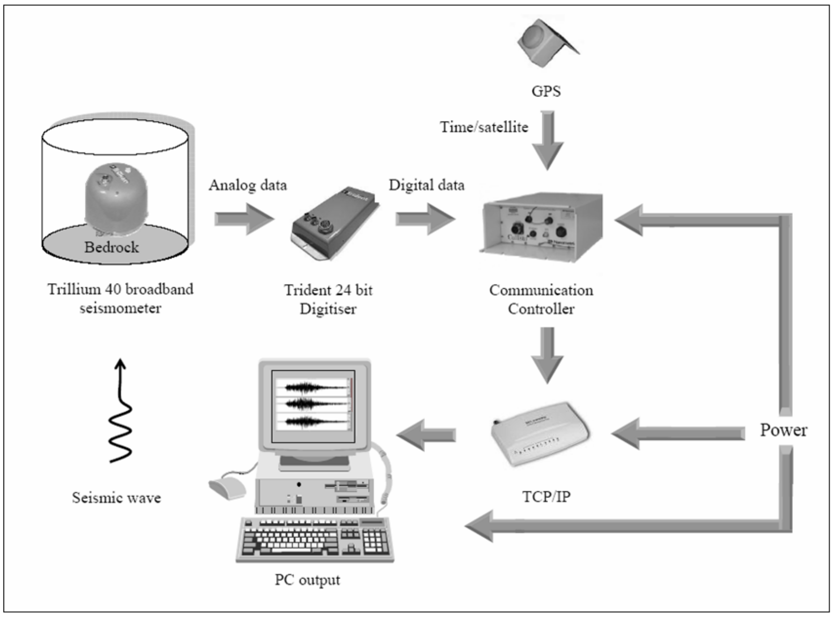


Figure 1. Schematic diagram of the PSU Broadband Seismometer Station, with data flow and power requirements.

Figure 2. The PSU temporary seismic station at the Khao Chang Telecommunication Station in Phang nga Province. (a) The station on the hill at the telecommunication station, (b) the sensor is placed on the outcrop and enclosed in a concrete ring with top, (c) the Trident 24-bit digitizer, the Janus communications controller, and TCP/IP at a house of the telecommunication station, and (d) the computer for data processing inside a building.

advantage was the access to continuous power supply, including a power backup generator, and the distance from urban activities and roads. The first housing is at the bottom of the hill near a highway. A disadvantage of the station was the disturbance from the power backup generator, which is tested every week. A further disadvantage was the location on the top of a hill, as the station is subject to more seismic noise generated by wind.

Before the seismometer was placed on the hardrock outcrop, concrete was added on the exposed sandstone in order to get a smooth surface. After that, a concrete ring with a plate on top was put around the seismometer for wind, rain, and sun protection (Figure 2b). The cables from the seismometer to the digitizer and Janus communication device were covered with cement tiles for protecting against animals, as they can cause severe damage to cables and other plastic parts of the station. The Trident 24-bit digitizer, the Janus communications controller, and TCP/IP modem were installed inside a building close to the seismometer site, which had a roof for rain and sun protection (Figure 2c). The GPS receiver, which provided location information and universal time coordinates (UTC time), was connected to a wooden panel about two meters above the surface. The computer for data collection and interpretation was operated inside another building of the telecommunication station (Figure 2d). A communication cable connected the Janus device with the computer via the modem. The station was fully operating with continuous and real time data recording from the 1^{st} to the 12^{th} January 2005.

3. Earthquake data

As the seismometer records any earthquake in any distance, depending on the magnitude, the earthquakes in the study area had to be identified among all events. Aftershocks of interest are in the area between 0^o-20^oN and 90^o-100^oE, and have epicenter distances of about 4^o to 8^o (Figure 3). Because of this distance, all seismic waves can be considered as refracted waves at the Crust/Upper Mantle boundary (Mohorovicic Discontinuity or Moho).

In the first step, the compressional wave (refracted P-wave, Pn) and the shear wave (refracted S-wave, Sn) arrival were identified in the seismogram of the vertical (Z-) component, with the corresponding arrival times (t_{Pn}, t_{Sn}). Then the time difference between both arrival times was calculated. With this time difference (t_{Sn} - t_{Pn}) the epicenter distance of each event was approximately determined using following rule of thumb (Havskov *et al*., 2002):

$$D\ [km] \approx 10\ [km/s] * (t_{Sn} - t_{Pn})\ [s]$$

This linear equation is based on the seismological tables by Kennett (2005) where the travel time of different phases (e.g. P-wave, S-wave) are listed for given epicenter distances (in degree) and depths (in km), and it is applicable only for distances up to about 1000 km. It is based on a velocity model with Vp=5.80 km/s and Vs=3.46 for the crust, and Vp=8.10 km/s and Vs=4.51 km/s for the Upper Mantle, and a Moho depth of 31 km. However, for the oceanic crust of the Andaman Sea area Curray (2005) estimates a depth of 20 km.

For the period from the first to the twelfth January 2005 altogether 293 earthquakes are listed in the earthquake data base of the United States Geological Survey, the National Earthquake Information Center (NEIC catalog; USGS, 2006a). The earthquake data can be retrieved from

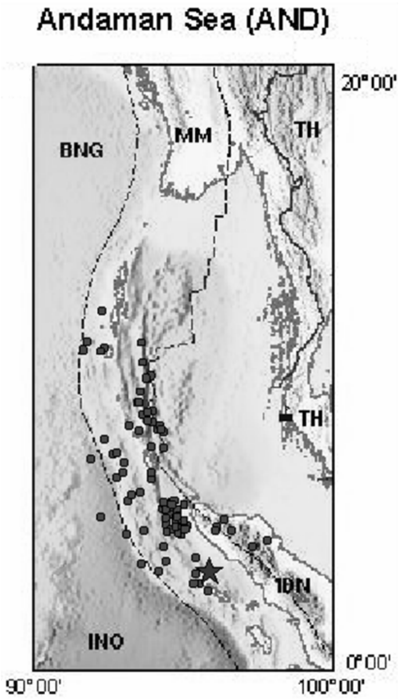


Figure 3. Epicenters of ninety-two aftershocks in the Andaman Sea Area from 1st to 12th January 2005. Star: epicenter of the 26 December 2004 Earthquake. Flag: location of PSU Station. TH: Thailand, MM: Myanmar BNG: Bengal and INO: Indonesia.

the database online via a web based interface. For each event, the following data are provided: origin time (date and time) in UTC (Thailand time is UTC+7 hours), location in degree longitude and degree latitude, depth in km, and the magnitude value for different magnitude types. The information listed is combining several individual station data from around the globe, which are all contributing to the USGS database (USGS, 2007).

For this study, 92 events that were identified from the recorded data at the PSU Station were used for a further magnitude analysis. The corresponding information of these events was also retrieved from the USGS earthquake database, in order to compare the data with the results of the PSU seismogram analysis (USGS, 2006a). Six earthquakes identified from the PSU Station could not be correlated with events recorded neither in the USGS earthquake catalogue nor in the database of the European Mediterranean Seismological Center (EMSC, 2006). This is subject of further investigations.

4. Earthquake magnitudes

Earthquake magnitudes provide information about the size of earthquakes and they are derived from ground motion amplitudes and periods or from signal duration measured from instrumental records. Varieties of different magnitude scales, which are all in logarithmic scale, are presently used, but all magnitude scales should yield approximately a similar value for any given earthquake (Stein and Wysession, 2003).

A body wave magnitude (m_b) is a logarithmic measure of the size of an earthquake or explosion based on instrumental measurements of the maximum motion and corresponding period recorded by a seismograph. The moment magnitude (M_w) scale is based on the concept of seismic moment, and so it is directly related to earthquake source processes. However, this magnitude requires more analysis of the seismogram than the body wave magnitude (Stein and Wysession, 2003).

5. Body wave magnitude (m_b)

The body wave magnitudes were determined from the highest amplitude, A, of the whole P-wave train, but before

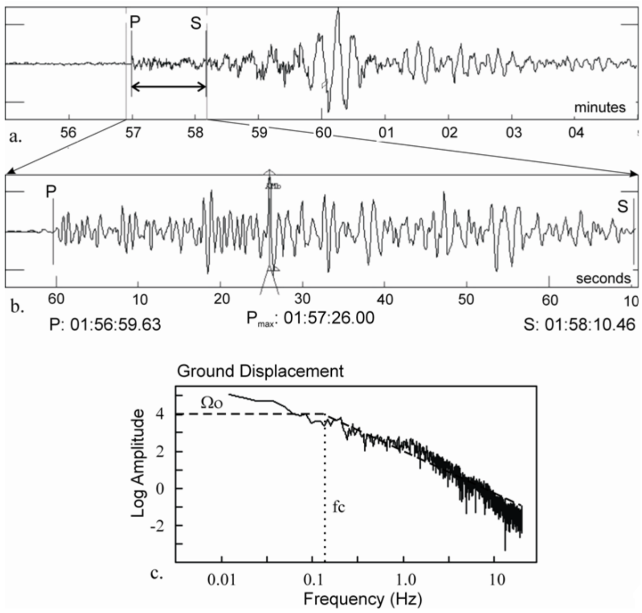


Figure 4. (a) Seismogram of the vertical (Z-) component of the 1 January 2005, 1:55:28.46 UTC earthquake recorded by the broadband seismometer at the PSU station. Amplitudes in counts, time in minutes, P: P-wave arrival, S: S-wave arrival. Arrow indicates the time difference between first P- and S-wave arrival, used for determining the epicenter distance, and for the amplitude spectra analysis, see (c).
(b) Seismogram of the P-wave train from (a), between P- and S-wave arrival. Amplitudes in ground displacement (nm), time in seconds. Mark of the maximum ground displacement P-wave amplitude (200.8 nm) with a period of 0.94 seconds at 01:57:26.00 UTC used to estimate the body wave magnitude. This earthquake has m_b 5.8.
(c) Seismic spectrum of the displacement amplitudes of the P-wave train shown in (a) in log frequency (Hz) versus log amplitude (nm s). This is used to estimate the low and high frequency asymptotes which are depicted as straight lines. The low-frequency part of the spectrum has a value of $\Omega_0 = 10^4$ nm s. The corner frequency, f_c, between the plateau and the high frequency $1/\omega^2$ decay (following Brune, 1970) is also shown for the spectrum. This earthquake has an M_w 5.4.

the S-wave arrival, and from the period, T, of the highest amplitude, following Gutenberg and Richter (1956). Following the USGS (2006b), the highest amplitude should be in a range from $0.1\ s \leq T \leq 3.0\ s$, whereas Gutenberg (1945a, b) originally suggested a period between 0.5 s and 12 s. In this study, the seismic records were filtered between 0.2 s and 5.0 s following Havskov and Ottemöller (2005), which is closer to the USGS filter. However, no maximum amplitude used in this study has a period above 3 s, usually around 1 s. Finally, the body wave magnitude of an earthquake is calculated with following formula defined by Gutenberg and Richter (1956):

$$m_b = \log(A/T) + Q(D,h),$$

where A is the maximum ground amplitude in micrometers for events of different period, T (in seconds). Q is the correction function of the body wave phase, depending on the focal depth (h) and the epicentral distance (D) in degrees ($D \geq 5^{\circ}$). For the analysis of the PSU Station data, the values for the epicentral distance were calculated from the location of the earthquake and the seismic station, and the depth for each event were taken from the USGS earthquake database. The determination of these values using data from one seismic station is possible, but contains higher uncertainties. Further, no correction for attenuation or geometric spreading of the ray path has been applied to the PSU data.

Figure 4a shows the seismogram of the vertical Z-component of the 1-Jan-2005 01:55:28.46 (origin time in date-month-year hour:minute:second:hundreds of a second) event with the P-wave and the S-wave phase identified, using SEISAN software (Havskov and Ottemöller, 2005). The time difference between the P-wave arrival (01:56:59.63) and the S-wave arrival (01:58:10.46) is 70.83 s (Figure 4). The calculated direct distance between the PSU Seismic Station and the earthquake location (2.91° N, 95.623° E), which is

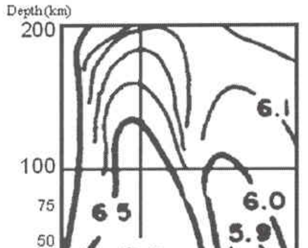


Figure 5. The Q (D,h) values for the vertical component for the determination of the body wave magnitude, with D = distance (degree) and h = depth (km). For example, here an earthquake has an epicentral distance of 5.22 degrees and a depth of 24 km. The Q-value for this event is 6.2 (after Gutenberg and Richter, 1956).

reported in the USGS database, is 687 km (6.23°); further a depth of 24 km for this event was reported. The maximum amplitude of 0.2008 mm with a period of 0.94 s was determined at 01:57:26.00 (hh:mm:ss.ss) shown in Figure 4b. The Q (D,h)-parameter for this event is 6.5, using the above-mentioned distance and depth (see Figure 5). The resulting body wave magnitude for this earthquake using the PSU waveform is 5.8. For the same event, the m_b of 5.3 was retrieved from the USGS database.

For 35 events (38 %) with a distance of less than 5 degrees, the Q (D,h) value had to be extrapolated. This increases the uncertainty and in sensu stricto violates the definition of the body wave magnitude. However, in order to correlate the data of this study with USGS data, either an m_b or an M_w magnitude value had to be determined. An extrapolation of one degree below the lower limit seems to be a fair solution (see Figure 5).

6. Seismic moment and moment magnitude (M_w)

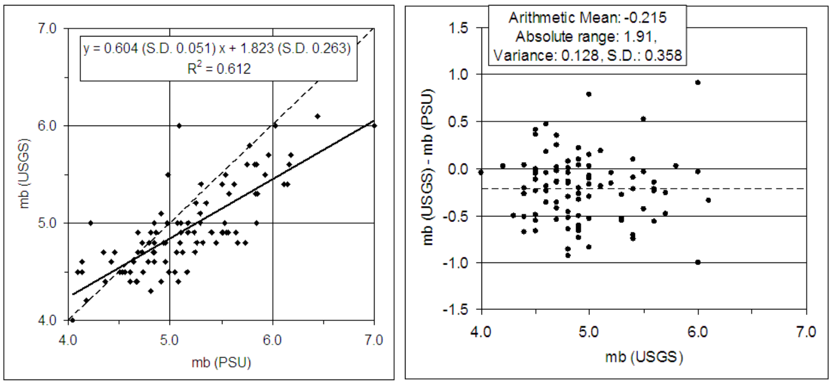
The seismic moment was calculated from the P-wave train, and before the S-wave arrival (e.g. Tsuboi *et al.*, 1995, Ottemöller and Havskov 2003), based on spectral parameters following Brune (1970):

$$M_o = \frac{4\pi\rho v^3 R\Omega_0}{F\Re_{\theta,\phi}},$$

where ρ is the rock density, Ω_0 is the low frequency spectrum level in m s, v is the P-wave velocity at the source, R is the hypocentral distance between source and receiver, $\Re_{\theta,\phi}$ accounts for the radiation pattern coefficient for the P-waves. An average value is used if the radiation pattern is not know, here $\Re_{\theta,\phi} = 0.52$ for P-waves following Boore and Boatwright (1984). $F = 2$ is the free surface correction factor (Nuannin, 2006). The moment magnitude then is calculated from the seismic moment using the relationship from Kanamori (1977)

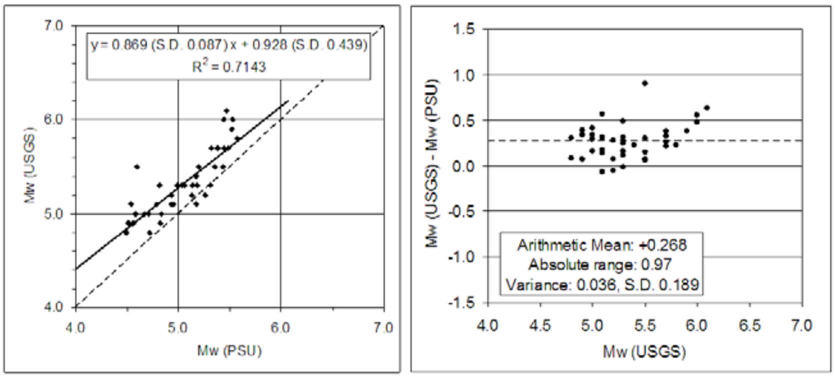
$$M_w = (2/3) \log Mo - 6.06, \text{ with } M_o \text{ in Nm.}$$

The earthquakes used in this magnitude analysis are all located in the Andaman Sea, which can be considered as oceanic crust. Therefore, $\rho = 3{,}300\ kg/m^3$ and a P-wave velocity of $v = 8{,}100$ m/s can be seen as reasonable values. Figure 4c shows the instrument corrected displacement spectrum (P-waves) for the 1-Jan-2005 01:55:28.46 event, with amplitudes (nm·s) versus frequency (Hz) in log-log scale. The flat spectral level or low frequency plateau was determined, giving a value of $\Omega_0 = 10^4$ nm·s ($\log \Omega_0 = 4$ nm·s). At the corner frequency, here 0.2 Hz, the amplitudes decay with increasing frequency. From these values, the calculated seismic moment is $1.457 \cdot 10^{17}$ N·m, resulting in a calculated moment magnitude of M_w 5.38, reported as 5.4. In the USGS database, a value of M_w 5.7 is given. No correction for anelastic attenuation was done, as no values are available for the travel path in the study area.



(a) (b)

Figure 6. (a) Correlation between m_b (PSU) and m_b (USGS); the linear regression line (solid line) with the statistical data are given. (b) Deviations between the m_b (USGS) and m_b (USGS) minus m_b (PSU). The arithmetic mean (dashed line) with the statistical data are given.



(a) (b)

Figure 7. (a) Correlation between M_w (PSU) and M_w (USGS); the linear regression line (solid line) with the statistical data are given. (b) Deviations between the M_w (USGS) and M_w (USGS) minus M_w (PSU). The arithmetic mean (dashed line) with the statistical data are given.

7. Magnitude correlation

Altogether ninety-two events, which occurred from January 1 to 12, 2005 in the Andaman Sea area, were used for the magnitude correlation. The epicenters of these after-shocks, obtained from the USGS database, range from 450 to 790 km, with a focal depths 8 to 107 km (Figure 3). All ninety-two earthquakes could be used for the correlation of the body wave magnitudes, whereas only forty-two events out if these 92 events could be used for the moment magnitude correlation. For all 92 events, an m_b value was listed in the USGS database, but only for 42 events, an M_w value was listed.

The body wave magnitudes of the ninety-two earth-quakes ranging from m_b 4.0 to m_b 7.0 corresponding to m_b 4.0 to m_b 6.1 reported by the USGS database. Correlations of the ninety-two events in Figure 6a and b show that the m_b (PSU) values are in general higher than the USGS magni-tudes, however with several earthquakes having an equal or lower magnitude than the USGS values (Figure 6b). The arithmetic mean of the correlation between m_b (USGS) and m_b (USGS) - m_b (PSU), shown in Figure 6b, gives a value of -0.215, with an absolute range of 1.91 magnitudes. The linear trend line of the PSU versus the USGS body wave magnitudes in Figure 6a, with m_b (USGS) = 0.604 * m_b (PSU) + 1.823, suggests, that the PSU magnitudes are increasing in comparison to the USGS values with increasing magnitude values. The six events recorded at the PSU station, but not listed in the USGS databases, have m_b values ranging from 4.4 to 5.2.

For the 42 events, the moment magnitudes retrieved from the USGS database range from M_w 4.8 to M_w 6.1 while the M_w values calculated from the PSU Station data range from M_w 4.2 to M_w 6.0 (Figure 7a). The arithmetic mean of the correlation between M_w (USGS) and M_w (USGS) - M_w (PSU), shown in Figure 7b, gives a value of +0.268, with an absolute range of 0.97 magnitudes. This indicates that the USGS values are in general higher than the PSU values. The linear trend line of the PSU versus the USGS moment mag-nitudes in Figure 7a, with M_w (USGS) = 0.869 * M_w (PSU) + 0.928, suggests, that the USGS values are slightly higher, but the linear trend lines are nearly parallel. The six events recorded by the PSU station that were not listed in the USGS database have M_w values between 5.2 and 6.3.

8. Discussion

The correlation between the magnitude data from the temporary PSU Station and from the USGS database for the same events have revealed remarkable agreements, as in average m_b from the PSU Station is only 0.215 higher than from the USGS, and in average M_w (USGS) is 0.268 higher than M_w (PSU).

In order to assess the quality and quantity of the remaining differences in the magnitude values presented, following issues have to be considered:

1) During the deployment of the broadband seismometer, additionally a short period seismometer was installed at the same site for recording local earthquakes in the southern part of the Thai Peninsula (Dangmuan *et al.* 2006). For the event on January 2, 2005 at 08:27:41 UTC, the broadband data give an m_b of 6.2, whereas the analysis of the short period records gives an m_b 6.1. This is a good agreement considering that two different seismometers, a short period and a broadband, and two separate recoding systems were used.

2) The seismic stations and networks providing m_b data to the USGS database might follow the recommendation by the USGS to determine the maximum P-wave amplitude in a five to twenty second long time window from the P-wave arrival. If the maximum P-wave amplitude arrives after the first twenty seconds of the P-wave train, the analysis will miss it, and so would determine a lower m_b value. In this study, the whole P-wave train is used for the magnitude analysis, around 50 to 80 seconds, depending on the distance, following Gutenberg (1945a,b). For the 1-Jan-2005 01:55:28.46 events shown in Figure 4b the maximum P-wave amplitude is about 26 s after the P-wave arrival (01:56:59.63 UTC).

3) An error of ±0.05 in the values of the body wave magnitudes has to be considered from the interpolation of the Q-value as shown in Figure 5. Further, the Q-values for distances between 4 and 5 degrees are extrapolated and in sensu stricto not defined.

4) The USGS m_b magnitude values are network data calculated from all magnitude values provided by USGS network stations and other networks who contribute to the USGS database. The final m_b magnitude in the USGS report and database is the 25 % trimmed mean of all m_b magnitude values provided to the database. Individual station magnitudes can vary by plus and minus one order of magnitude or more from the 25% trimmed mean value. The USGS believes, that this variation is mainly related to focal mechanism of individual earthquakes and to geologic structures of the travel paths of the seismic waves, rather than to errors in the data themselves (USGS, 2007).

5) For the determination of $M_{w,}$ several assumptions were made, like the homogenous half space, the P-wave velocity, the average value for the radiation pattern, and the free surface correction factor. Further, no attenuation correction was made for the PSU data. In addition, the determination of the low frequency plateau in the displacement spectrum is subjected to the interpreter's experience. All these factors can contribute to the difference in the moment magnitude between the USGS and PSU.

6) The magnitude correlations presented here rely on calculated distance data from the earthquake hypocenter, as listed in the USGS database, and the location of the seismic station. Therefore, the PSU and USGS magnitude values are not independent from each other. However, the earthquake location determination, with depth assumption, is possible with one three-component seismometer (e.g. Bormann and Wylegalla 2002), using the delta time between the S-wave and P-wave arrival time for the distance determination and additionally the back azimuth method. However, the distance determination is based on a velocity model, like the AK 135 global model (Kennett, 2005). The crust and Upper Mantle velocities and depths in the Andaman Sea area might differ from the global model, as this area represents an extensional back-arc basin (Curray, 2005). Therefore, the main reason to calculate the distance data rather then to measure them was to minimize the number of assumptions and to focus on the amplitudes.

9. Conclusion

For this study, a broadband seismometer station has been successfully deployed in Phang nga Province, in Southern Thailand at the beginning of 2005. For twelve days this stations operated in real time mode and continuously recorded events without any major problems and disturbances. The body wave and moment magnitudes determined from the PSU Station data show in average a difference of +0.215 for m_b and -0.268 for M_w in comparison to USGS database values. These differences are comparatively small considering all the issues discussed above, especially for the body wave magnitude. The main point is that the USGS magnitudes are network values, whereas the PSU magnitudes are from a single station.

For the moment magnitudes, further research are necessary on the input parameters in order to minimize the assumptions used here (Setapong *et al.*, 2006). Ongoing work is also looking into the earthquake location determination using one three-component seismometer, with all the uncertainties involved, e.g. phase identification, velocity model and back azimuth method (see Bormann and Wylegalla, 2002).

This study further shows that for earthquakes with short epicentral distances, 5^o to 8^o, and even down to 4 degrees, reliable body wave and moment magnitudes can be achieved. This distance range applies for all seismic broadband stations that are located on the Thai Peninsular in relation to the subduction zone earthquakes in the Andaman Sea. However, accurate earthquake magnitude values are not only important for scientific purpose, but they are essential for any Indian Ocean Tsunami Warning System. Magnitudes are a main parameter for any tsunami warning, as they are used as a trigger value for a tsunami warning, in combination with the location and depth of the earthquake.

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