CHAPTER 2

RESEARCH METHODOLOGY

In this study, a seismic network with four seismic recording systems was established in Southern Thailand during the first half of the year 2005. The data were processed and analyzed in order to determine the location and magnitude of the seismic events.

2.1 Equipment

The seismic recording system consists of following main parts: a seismometer, which is recording the ground motion, a seismograph, which is digitizing and filtering the analog data before storing them on a hard drive, a global positioning antenna, which is receiving the time information, and a power supply system.

2.1.1 Seismometer

For this study, Mark L-4-3D seismometers from Sercel (2002) have a frequency of 1 Hz. The waterproof cylinders, 20.32 cm in diameter, 18.19 cm in height, 9.1 kg weight, contain three geophones in three perpendicular directions: north-south (N-component), east-west (E-component), and vertical (Z-component). Figure 2.1 shows the seismometer form the outside and inside.

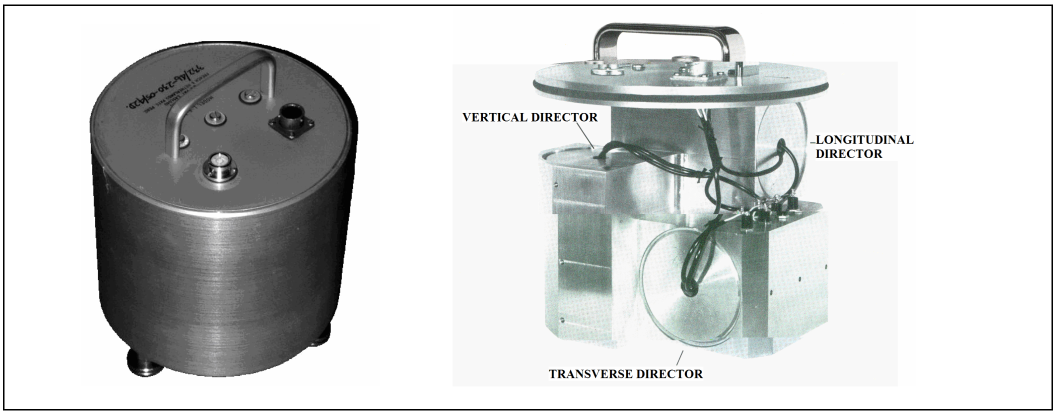


Figure 2.1. Exterior view of the Mark L-4-3D seismometer (left) and after removing the cover the three measuring components in the perpendicular arrangement are visible (right, from Sercel, 2002)

The seismometer has a pendulum or mass mounted on a spring attached to the fixed base. During ground velocity measurements, the base moves but the mass not. The movements of the base result in the generation of electrical voltage, which is recorded in a digital file. The voltage is proportional to the motion of the seismometers mass in relation to the ground, and can be mathematically converted to absolute motion of the ground.

2.1.2 Seismograph

The seismometer was connected via a data cable to a Orion short-period seismograph, manufactured by Nanometrics, Canada. This seismograph, with the appearance of a yellow hard plastic suitcase, is a portable seismic data logger of 47 cm in length, 37 cm width, 19 cm depth and 10.9 kg weight with 24-bit digitizer and 100 sampling rate. A GPS antenna (coaxial) for time rectification is directly connected to the seismograph. The device can either be operated with 6V-12A internal batteries or with a household power supply (Figure 2.2). See Appendix D for more detailed information.

2.1.3 Data cartridge

Inside the Orion data cartridge is a recording hard disk of 22 cm in length, 6 cm height, 14 cm width and 0.5 kg weight. It contains a hard-disk drive of altogether 1.99 GB memory space, for each component 697 MB (Figure 2.2). In the continuous recording mode of the seismograph during this study the memory space lasts for about two to three weeks.

Therefore, during this study each seismic station was visited every two weeks. The data on the Orion data cartridge were transferred via an SCSI-cable to a personal computer. A data set from one station consist of three 697 MB-files, one for each component. Additional files contain the State-of-the-Health (SOH) of the seismic recording system, and a file with all seismic events listed.

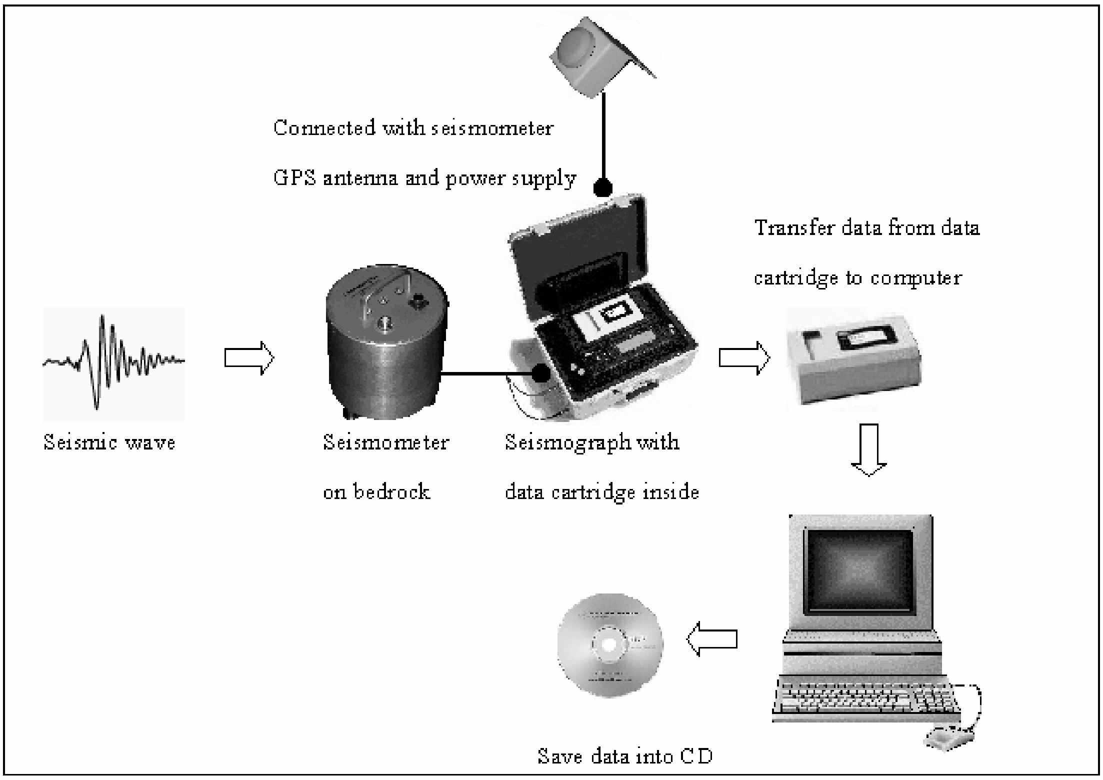


Figure 2.2. Schematic diagram of the data flow: The seismic waves travel through the solid earth, with the movement recorded by the seismometer. Then these analog data were transferred to the seismograph via cable. Additionally time information came from a GPS antenna connected with a cable to the seismograph. There all data were digitized and stored on the data cartridge. The data were regularly moved to a personal computer and additionally saved on CD.

2.2 Site selection

After the 26 December 2004, members of Geophysics Group at PSU and staff of the Department of Mineral Resources (DMR) operating in Pang Nga and Krabi made a survey for suitable places in establishing a temporary seismic network in the area. Many possible locations were visited. The main criteria for the site selection were (a) the exposure of hard rock, (b) a further distance to anthropogenic activities, and (c) the access to external power supply. Additional criteria were (d) the land ownership, and (e) security of the seismic station and the equipment.

After all, three sites were selected (Table 2.1), while the seismic station on the Phuket Campus of the Prince of Songkla University was already established in May 2002. After the places were prepared, hard rock was exposed and a small hut build, the seismic equipment was installed. All stations were active for about 6 months, from 14 January to 30 July 2005.

Table 2.1: Names and locations of the 4 temporary seismic stations. The one in Phuket already existed since May 2002. UTM in reference to WGS-84.

Station	Longitude	Latitude	UTM (Zone 47)	Elev. (m)	Location
Station 1 (PSUHY)	98°30’24.48”	8°26’3.84”	445708 E 932356 N	85	Kao Hua Chang Telecommunication Station , Mueang District, Pang Nga Province
Station 2 (PNG02)	98°39’37.44”	8°33’27.36”	462628 E 945958 N	55 m	Khok Charoen Village , Thap Put District, Pang Nga Province
Station 3 (PSUNM)	98°21’3.96”	7°53’97.76”	428474 E 874458 N	4.3 m	Prince of Songkla University Phuket Campus ,Kathu District, Phuket Province
Station 4 (TBK)	98°44’24.00”	8°23’24.00”	471376 E 927422 N	60 m	Tarnboke Koranee National Park, Ao luek District, Krabi Province

2.3 Seismic stations

2.3.1 Station 1 (PSUHY)

Station 1 is at the Kao Hua Chang Telecommunication Station in Mueang District, Phang Nga Province. The location is at 98°30'24.48" E and 8°26'3.84" N at an elevation of 85 m above sea level. The telecommunication station is located on a small mountain, respectively hill, with Lower Permian-Ordovician sandstone outcrops.

In order to make a smooth surface on the rock a concrete base was established before the seismometer was placed (Figure 2.3). A concrete tube and a wooden cottage were built to protect the seismometer and the seismograph from environmental perturbations (Figure 2.4). The GPS antenna was mounted at the wooden cottage. Electrical power was accessible from the telecommunication station. A family living at the station provided assistance for the security of the equipment. A backup generator for the telecommunication station was about 15 meters from the seismic station, which was tested every Monday morning for a 45-minute period.

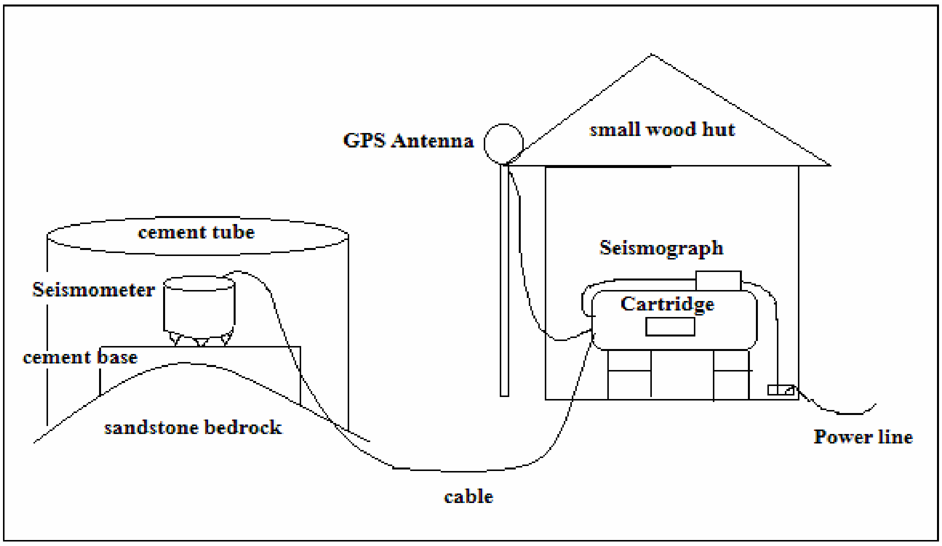


Figure 2.3. Schematic layout of Station 1. A concrete tube protected the seismometer and the seismograph was located in a wooden cottage nearby.

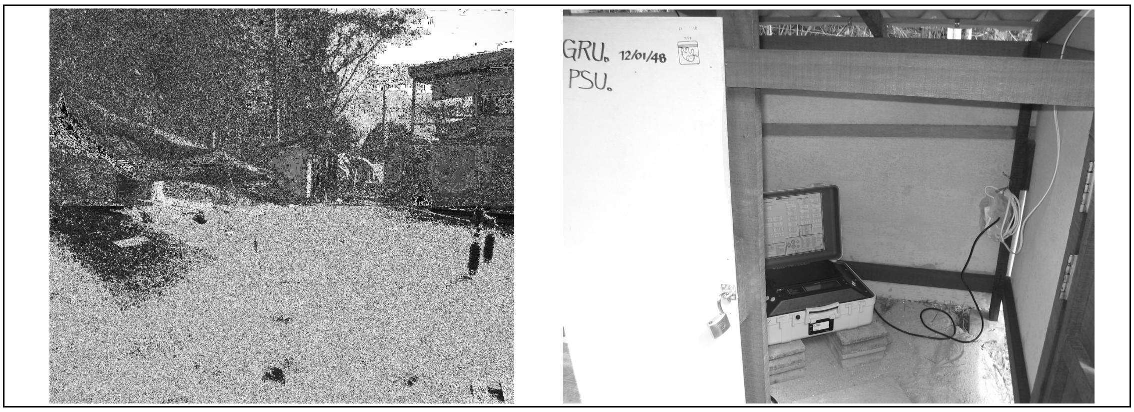


Figure 2.4. Left: Concrete tube on the left, with the seismometer inside. Inside a small wooden cottage is the seismograph, shown in the center back. To the right the backup power generator can be seen. Right: Inside the wooden cottage is the Orion portable seismograph located.

The seismic noise at Station 1 was quite low during the whole measurement period. An example of the noise power density spectrum shows relative higher noise levels at lower frequencies and lower noise levels at the higher frequencies (Figure 2.5), Noise levels were higher on Monday mornings when the power backup generator was tested for a 45 minute and period of windy days as the seismic station is located near the telecommunication tower.

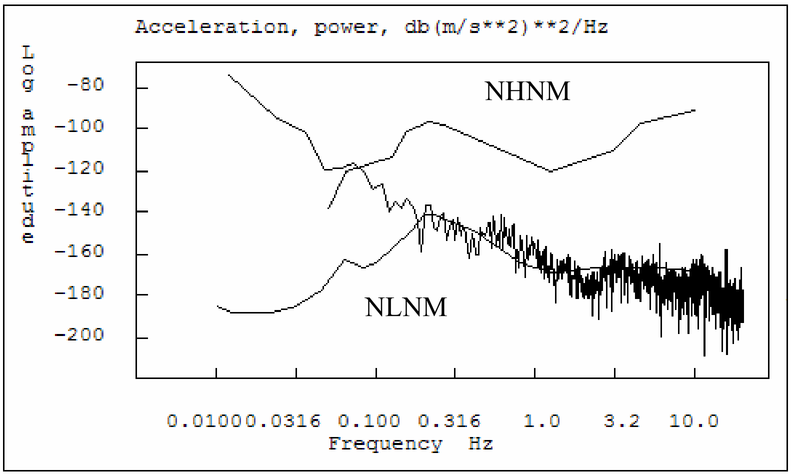


Figure 2.5. Seismic noise of the vertical component from 3 March 2005. The acceleration power is in db relative to 1 $(m/s^2)^2$ / Hz. The limit of the Peterson noise model is indicated by NHNM and NLNM (Peterson, 1993). The noise spectrum from Station 1_PSUHY has a low noises level (-160 db at 1.0 Hz).

2.3.2 Station 2 (PNG02)

Station 2 is in Khok Charoen Village, Thap Put District, Phang-Nga Province. The location is at 98°39’37.44” E and 8°33’27.36” N. The elevation is 55 m above sea level. The geology of the site is Lower Permian-Ordovician sandstone (bedrock outcrop). A concrete tube and small concrete cover were built to protect seismometer and seismograph from environmental perturbations (Figures 2.6 and 2.7). The location was remote from human settlements and close to a stream. Power was provided by a community nearby, about 20 m away. Local residents were responsible for the equipment safety.

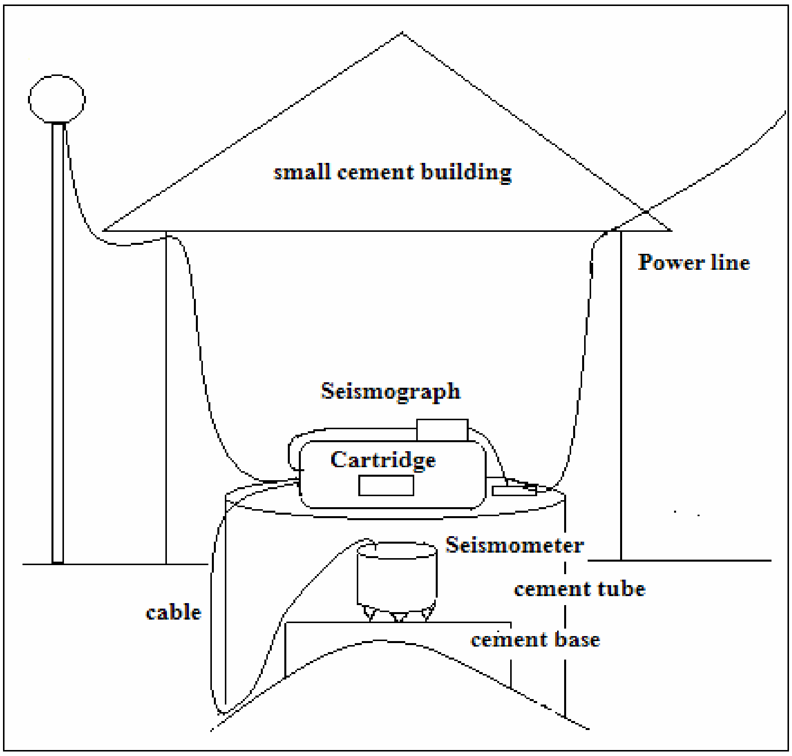


Figure 2.6. Schematic layout of Station 2, equipments is protected under a small concrete cover.

Figure 2.7. Left: Station is located near the waterside. There is a small concrete shelter containing a concrete tube and the Orion portable seismograph and a GPS antenna in front. Right: Concrete shelter where the Orion portable seismograph is protected in the concrete tube.

Show the seismic noise at Station 2 is relatively low. The noise power density spectrum higher noise levels at lower frequencies and lower noise levels at higher frequencies, with a noise level of -160 db above 1.0 Hz (Figure 2.8).

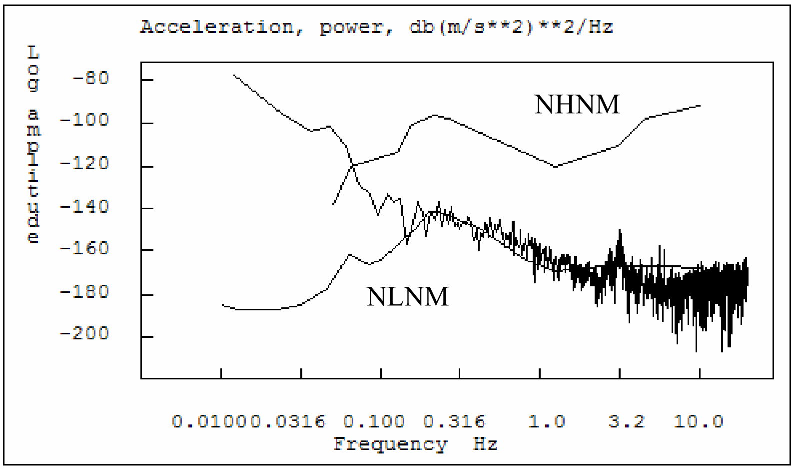


Figure 2.8. Seismic noise of the vertical component from 3 March 2005. The acceleration power is in db in relation to 1 $(m/s^2)^2$ / Hz. The limit of the Peterson noise model is indicated by NHNM and NLNM (Peterson, 1993). The noise spectrum from Station 2_PNG02 has -160 db at 1.0 Hz.

2.3.4 Station 3 (PSUNM)

Station 3 is at the Prince of Songkla University, Phuket Campus, at Kathu District, Phuket Province. Formerly a tin mine. The location is 7°53'97.76" E and 7°53'97.76" N. The elevation is 4.3 m above sea level. The geology of the site is Triassic-Cretaceous, coarse-grained biotite-granite, generally porphyritic. Seismometer and seismograph were mounted on a concrete base in a small wooden cottage located adjacent to the residential housing and Power supply was from the residential building (Figures 2.9 and 2.10).

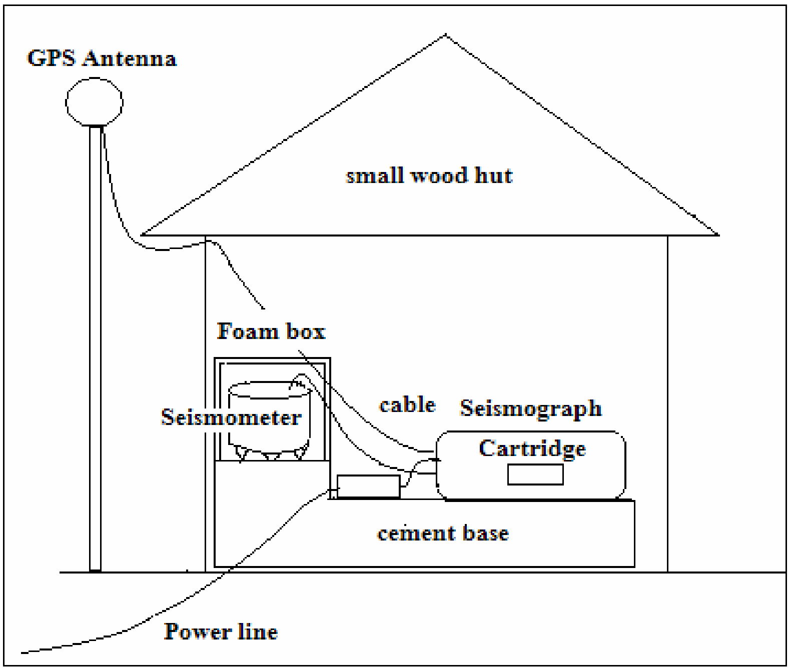


Figure 2.9. Schematic layout of Station 3; the equipment was protected in a small wooden cottage.

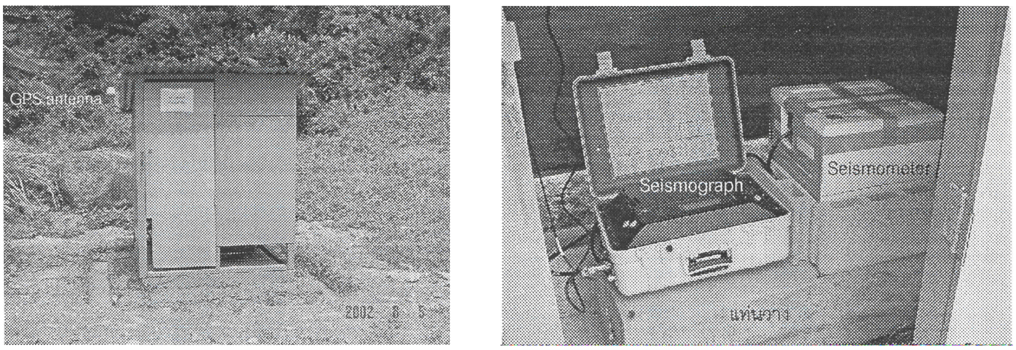


Figure 2.10. Left: Small wooden cottage with a protective concrete tube and Orion portable seismograph inside and exterior GPS antenna. On both sides of the cottage are dormitories surrounded by hilly area. Right: Inside the wooden cottage, seismometer and Orion portable seismograph were mounted on concrete.

The station 3 is located in between dormitories for staff members. The local inhabitants and their traffic cause a noise disturbance (Figure 2.11). The noise power density spectrum is shows higher noise levels at lower frequencies and lower noise levels at higher frequencies. The noise level above 1.0 Hz is -150 db with a peak at 3.2 Hz with –140 db.

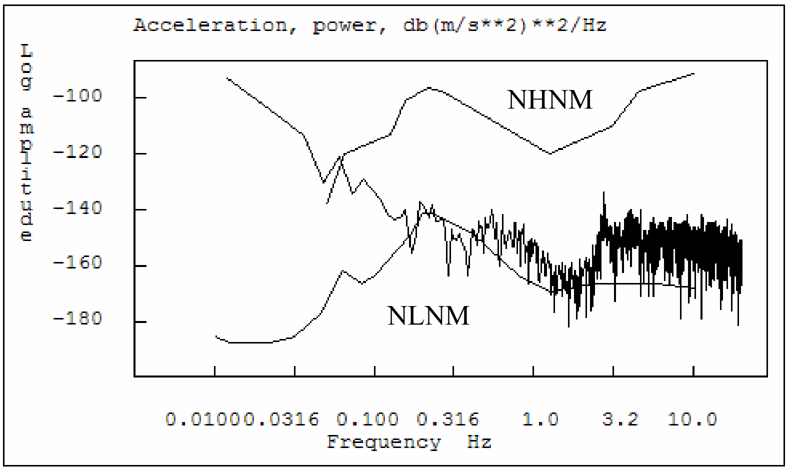


Figure 2.11. Seismic noise of the vertical component from 3 March 2005 .The noise power density spectrum is in db in relation to 1 $(m/s^2)^2$ / Hz. The limit of the Peterson noise model is indicated in NHNM and NLNM (Peterson, 1993). The noise spectrum from Station 3_PNGNM was higher than other the stations (-150 db at 1.0 Hz).

2.3.3 Station 4 (TBK)

Station 4 is located in the vicinity of the Tarnboke Koranee National Park at Ao Luek District, Krabi Province. The site is at latitude 8°23’24.00” N, longitude 98°44’24.00” E, at elevation of 60 m above sea level. The geology of the site is limestone with caves and waterfalls. Noise disturbances prevail from visitors and thus the equipment were kept away from the noise sources and hence placed in a limestone cave on the hill, and the plastic sheet-covered Orion portable seismograph was sheltered in a cage (Figure 2.12), providing security against monkeys (Figure 2.13). The power was supplied from the National Park area down the hill. Unfortunately, the GPS experienced communication problems as the area is completely surrounded by mountains. The results were data with relative longer errors in absolute time. However, the relative time signal for each data set was still very good.

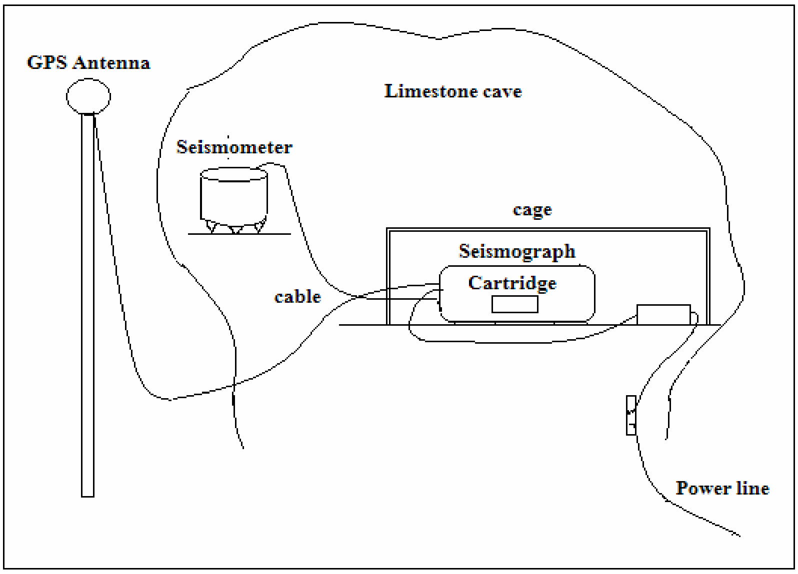


Figure 2.12. Schematic layout of the equipment at Station 4; equipment were sheltered inside a limestone cave.

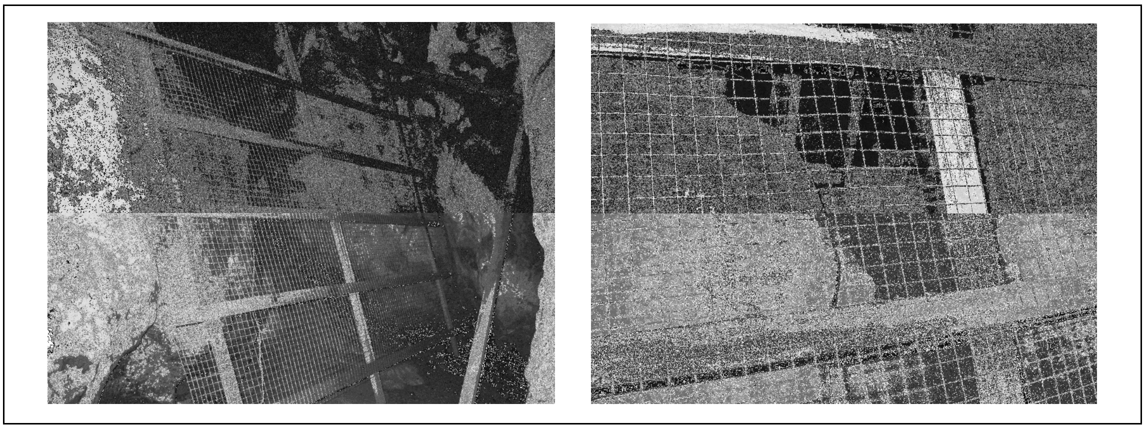


Figure 2.13. Left: Limestone cave protected with wire meshes. Right: Seismometer and Orion portable seismograph were mounted in the cage.

At Station 4 the noise power density spectrum show higher noise levels at lower frequencies and lower noise levels at high frequencies. The noise level above 1.0 Hz is -180 db with a peak at 3.2 Hz which a noise level of –150 db (Figure 2.14).

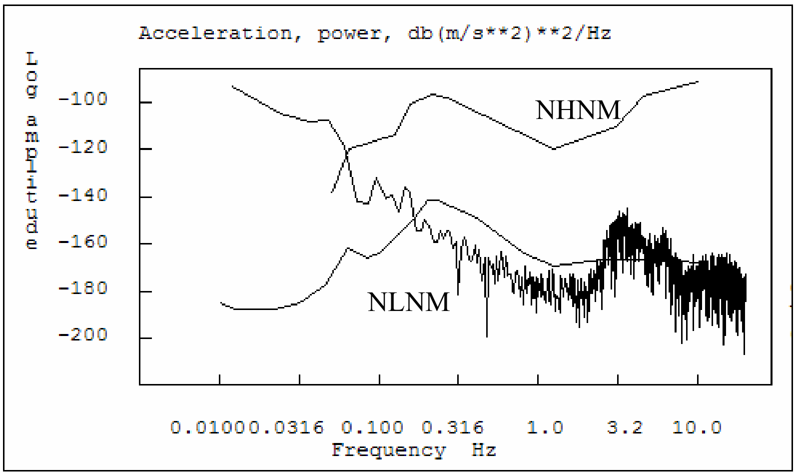


Figure 2.14. Seismic noise of the vertical component from 4 January 2005. The noise power density spectrum is in db relative to 1 $(m/s^2)^2$ / Hz. The limit of the Peterson noise model is indicated in NHNM and NLNM (Peterson, 1993). The noise spectrum from Station 4_TBK has -180 db at 1.0 Hz.

2.4 Measurements

After the December 26, 2004 Earthquake the short-period recording system was installed for measurements of the seismicity in the Southern Thailand. The equipment was installed at four stations for a month period, from 14 January to 30 July 2005. After the installation, the data were collected at an interval of one or two weeks and transferred to a computer where, the data were stored and additionally copied on CDs. The Station 4 is surrounded by high mountains, resulting in GPS communication problem. At Station 3, problems occurred with power supply, noises from human living nearby and wind. In 2006 the wooden house of Station 3 collapsed due to strong winds. The equipment was already removed at that time for maintenance (Figure 2.15).

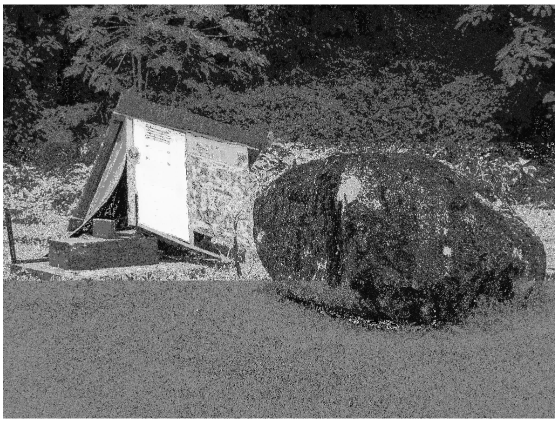


Figure 2.15. Collapse of Station 3 in May 2006, due to strong winds.

2.5 Data processing

2.5.1 Data processing steps

The data were transferred and processed as shown in Figure 2.16. The data from the Orion cartridge were in different files: the ringbuffer files x.she, x.shn, and the x.shz store the data of the E, N, and Z component. The x.soh file contains data about the state of health information of the seismological equipment.

The **soh file** was segregated using the **sohextrp** playback program in nmx/bin. The seismological time series data were separated from the ringbuffer files. The output file is in X-file format.

The program **response** generates a system response file, which corresponds with the station response information in the SEED file header (standard exchange of earthquake data).

The makeseed uses seed.rsp (output program) and X- file to generate the system response information.

The seed is read by rdseed program. IRIS, Incorporated Research Institutions for Seismology, developed the original UNIX-version of this program. Rdseed uses the seed data to create sac file and response file (RESP).

The WinQuake software deploys sac files to locate the earthquake location.

The Seisan software utilizes seed file and response file to earthquake parameter, like magnitude.

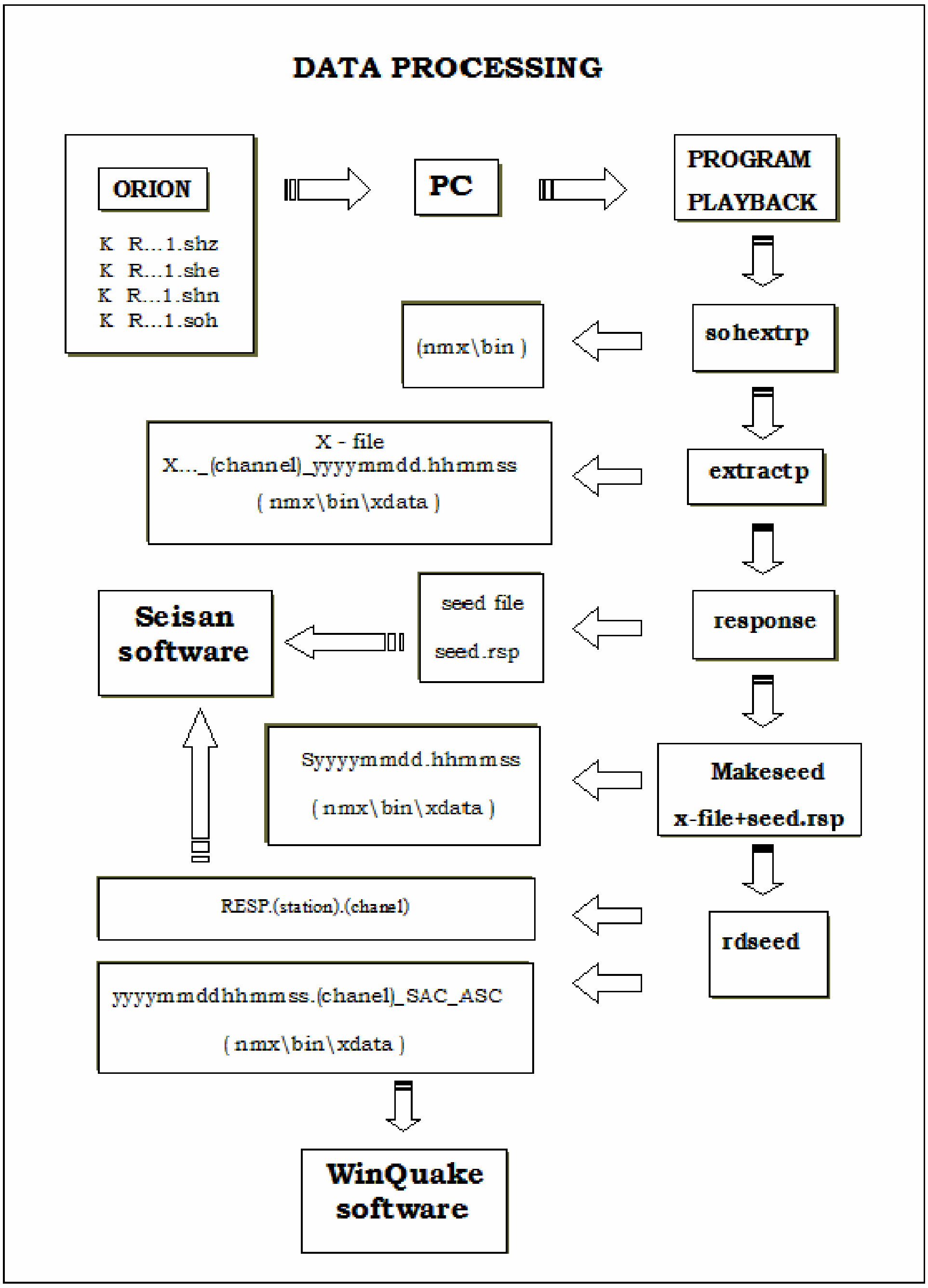


Figure 2.16. Flowchart of the stepwise processing of the seismological data.

2.5.2 Response file

The response file contains the mathematical expression of the physical seismometer and all filter and digitizing steps of the seismograph, presented in poles and zeros of different subsequent stage sequence numbers. Figure 2.17 shows part of a response file from Station 2, Z-component.

The stage sequence number 1 provides the information about the seismometer in poles and zeros (see Chapter 1.1.4) and their normalization factor (A0) in ms^{-1}/s. Here, this factor was internally calculated wrong from the seismographs and set as 1 ms^{-1}/s; however the right and later corrected value has to be 1.413999 ms^{-1}/s. For a detailed description, see Chapter 2.5.3. Further, here the gain is given with $1.705*10^2$ V/ ms^{-1}.

Stage sequence number 2 gives information about the Analog Digital Converter, also with a A0 normalization factor, a normalization frequency, and a gain.

Stage sequence numbers 3 through 9 are the filter coefficients for the anti alias filter and other subsequent filters.

The last sequence number 0 is the system sensitivity in counts/ms-1, which is all gain coefficients from the previous steps multiplied. However, the normalization frequency of all sequences should have the same value. A full version of a response file is given in Appendix D.

Figure 2.17. (next page) Parts of the response information in Z component from Station 2.

```
                     << IRIS SEED Reader, Release 4.15 >>
                   ======== CHANNEL RESPONSE DATA ========
                        B050F03     Station:     PNG02
                         B050F16     Network:     PN
                        B052F04     Channel:     BHZ
              B052F22     Start date:  2000,032,07:53:40.0000
              B052F23     End date:    2006,082,04:20:04.0000
                   =======================================
                   --------------------------------------------------
                   Response (Poles & Zeros), PNG02 ch BHZ
                   --------------------------------------------------
B053F03     Transfer function type:          A [Laplace Transform (Rad/sec)]
B053F04     Stage sequence number:           1
B053F05     Response in units lookup:        M/S - Velocity in Meter Per Second
B053F06     Response out units lookup:       V - Volts
B053F07     A0 normalization factor:         1.413999    [Following Seisan program]
B053F08     Normalization frequency:         1
B053F09     Number of zeroes:                2
B053F14     Number of poles:                 2
Complex zeroes:
i  real              imag                 real_error          imag_error
B053F10-13    0  0.000000E+000  0.000000E+000  0.000000E+000  0.000000E+000
B053F10-13    1  0.000000E+000  0.000000E+000  0.000000E+000  0.000000E+000
Complex poles:
i  real              imag                 real_error          imag_error
B053F15-18    0 -4.442210E+000  4.442210E+000  0.000000E+000  0.000000E+000
B053F15-18    1 -4.442210E+000 -4.442210E+000  0.000000E+000  0.000000E+000
B058F04     Gain:                            1.705000E+002
                   --------------------------------------------------
                   Response (Poles & Zeros), PNG02 ch BHZ
                   --------------------------------------------------
B053F03     Transfer function type:          A [Laplace Transform (Rad/sec)]
B053F04     Stage sequence number:           2
B053F05     Response in units lookup:        V - Volts
B053F06     Response out units lookup:       V - Volts
B053F07     A0 normalization factor:         1.40568E+012
B053F08     Normalization frequency:         1
B053F09     Number of zeroes:                0
B053F14     Number of poles:                 3
B058F04     Gain:                            7.533000E+000
                   --------------------------------------------------
                   Response (Poles & Zeros), PNG02 ch BHZ
                   --------------------------------------------------
B053F04     Stage sequence number:           3
B053F05     Response in units lookup:        V - Volts
B053F06     Response out units lookup:       COUNTS - Digital Counts
B053F07     A0 normalization factor:         1
B058F04     Gain:                            7.880330E+005
B058F05     Frequency of gain:               1.000000E+001 HZ
                   ------------------------------------------
                   Channel Sensitivity, PNG02 ch BHZ
                   ------------------------------------------
B058F03     Stage sequence number:           0
B058F04     Sensitivity:                     1.012130E+009
B058F05     Frequency of sensitivity:        1.000000E+001 HZ
```

2.5.3 Normalization factor correction

The normalized response can be calculated from the pole and zero data. At the normalization frequency, here 1 Hz, the normalized response should be 1 (normal). If the normalized response differs from the value 1 at 1 Hz, it indicates some inconsistencies in the response file information.

With the POL_ZERO program, the consistency of the response file information can be verified (Wielandt, 2001). Figure 2.18 and 2.19 show a window of POL_ZERO program with the given input values from the response file in Figure 2.17. Using the original normalization factor A0 with 1 to calculate the normalized response, it is not 1 at 1 Hz as it should be (0.707214 at 1 Hz, Figure 2.18). However, with a normalization factor A0 of 1.41399 the normalized response is 1 at 1 Hz as shown in Figure 2.19.

The Seisan program is doing this analysis automatically as shown in Figure 2.20, and even further, it makes an automatic correction of this internal inconsistency. Therefore, no further correction was necessary.

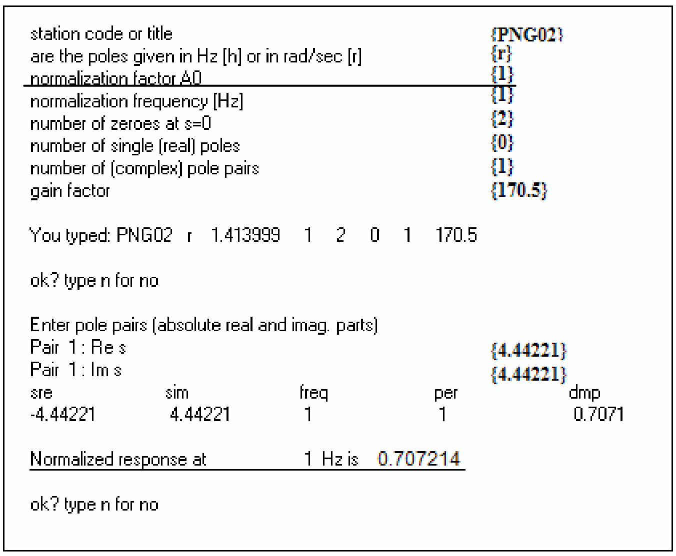


Figure 2.18. Window of the POL_ZERO program. Normalized response was 0.707214 at 1 Hz frequency, calculated using data from Station 2 (PNG02) in Z component. Here the original normalization factor A0 of 1 was used.

```
station code or title                                   {PNG02}
are the poles given in Hz [h] or in rad/sec [r]         {r}
normalization factor A0                                 {1.413999}
normalization frequency [Hz]                            {1}
number of zeroes at s=0                                 {2}
number of single (real) poles                           {0}
number of (complex) pole pairs                          {1}
gain factor                                             {170.5}

You typed: PNG02  r   1.413999   1   2   0   1   170.5

ok? type n for no

Enter pole pairs (absolute real and imag. parts)
Pair  1 : Re s                                          {4.44221}
Pair  1 : Im s                                          {4.44221}
sre            sim            freq           per            dmp
-4.44221       4.44221        1              1              0.7071

Normalized response at            1 Hz is  1

ok? type n for no
```

Figure 2.19. Window of POL_ZERO program with normalized response of 1 at 1 Hz frequency, based on data from Station 2 (PNG02) in Z component. Here the normalization factor of 1.413999 was used.

```
seed response
found date and time:        2006          3          23          4
        20   4.000000
paz not normalized, stage =          1
amplitude at     1.000000     Hz =    0.7072139
a0 changed to     1.413999
```

Figure 2.20. Part of the window of the Seisan program showing the automatically correction of the normalization factor A0 from 1 to 1.413999 after an internal calculation and verification of the response file information.

The response curve in Figure 2.6 shows the relation between amplitude and frequency of response data, which is the graphical representation of the poles and zeros in the response file. Figure 2.21 shows the response curve with the original normalization factor A0 of 1 (left) and the corrected on with 1.41399 (right). The shape of the curve has not been affected by this correction, but the amplitudes of the y-axis. The corrected curve is shifted further up as shown in Figure 2.21.

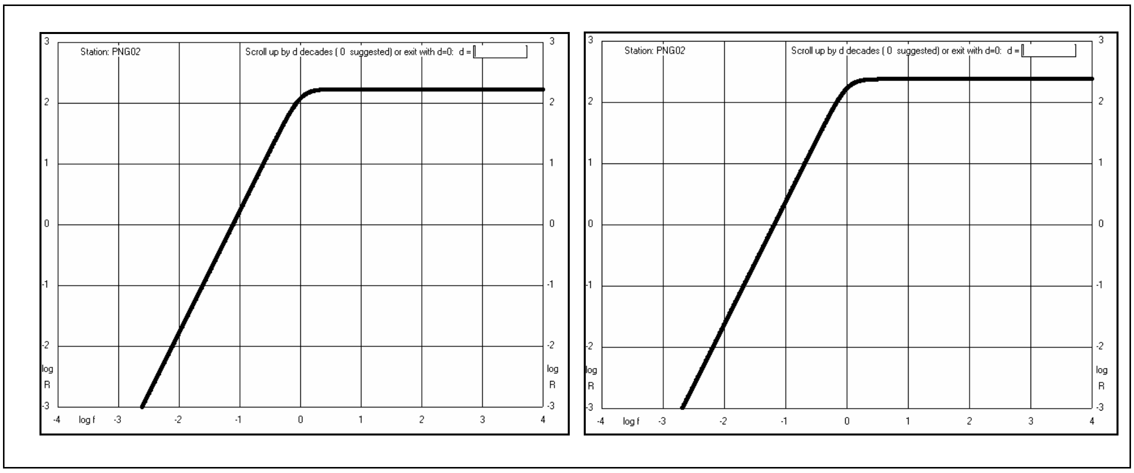


Figure 2.21. Response curve from the Station 2, Z component, using the same response data, except a different normalization factor A0. Left: response curve with the original value of 1. Right: Response curve with a corrected value of 1.413999. Plots made with POL_ZERO program (Wielandt, 2001)

2.6 Earthquake analysis software

For the analysis and interpretation of the seismic events, two programs running on Windows platform were used: the WinQuake software (Cochrane, 2002), which uses sac files to determine the earthquake location; the Seisan software (Havskov and Ottemöller, 2005) utilizes seed files and response files.

2.6.1 WinQuake software

The WinQuake software, version 2.8.9, copyright 1994-2002 by Larry Cochrane, is written for viewing and analyzing seismic events in the Public Seismic Network (PSN), Princeton Earth Physics Project (PEPP). The software can read input data in following formats: SAC Binary, GSE2.0, and in SEED-format. Data volumes are accessible from the Internet (Cochrane, 2002).

Figure 2.22 shows a window of the WinQuake software with a seismic event on display. The seismogram is shown in amplitude (Y-axis in counts) versus time (X-axis in hours, minutes, or seconds). The menu provides several options for the further analysis of seismic events.

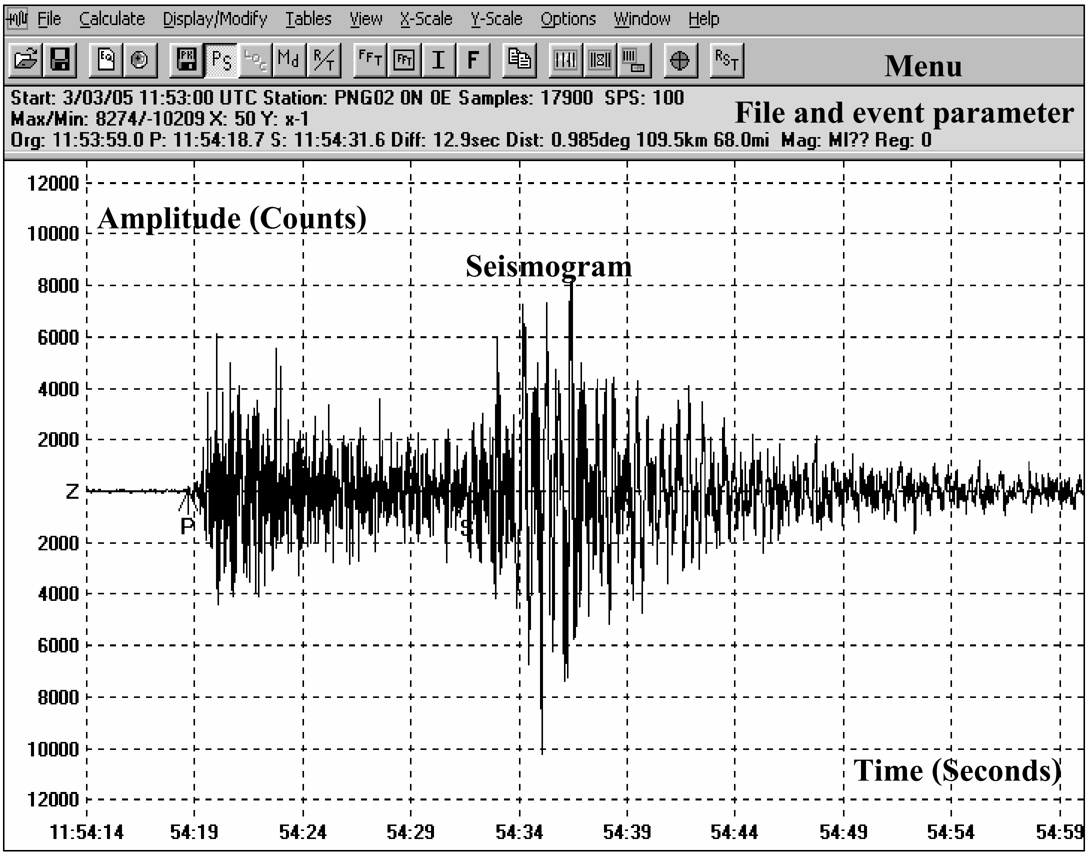


Figure 2.22. WinQuake window showing the seismogram of the Z-component of a local seismic event recorded at Station 2 (PNG02) on 3 March 2005 (UTC time 11:53:59.0).

2.6.2 Seisan software

The Seisan software is earthquake analysis software by Havskov and Ottemöller (Havskov and Ottemöller, 2005). The software can be freely downloaded from following website: ftp.geo.uib.no (129.177.554) for different operating platforms. The latest version is 8.3. For this study the version 8.1 was used.

The Seisan window has an option menu on the top, followed below by file information (Figure 2.23). The seismogram is displayed in the window below. A more detailed part of this seismogram can be additionally shown at the same time in a second window further below. The x-axis for both seismograms windows is time in hours, minutes or seconds, which can be changed accordingly. The Y-axis shows the amplitude in counts.

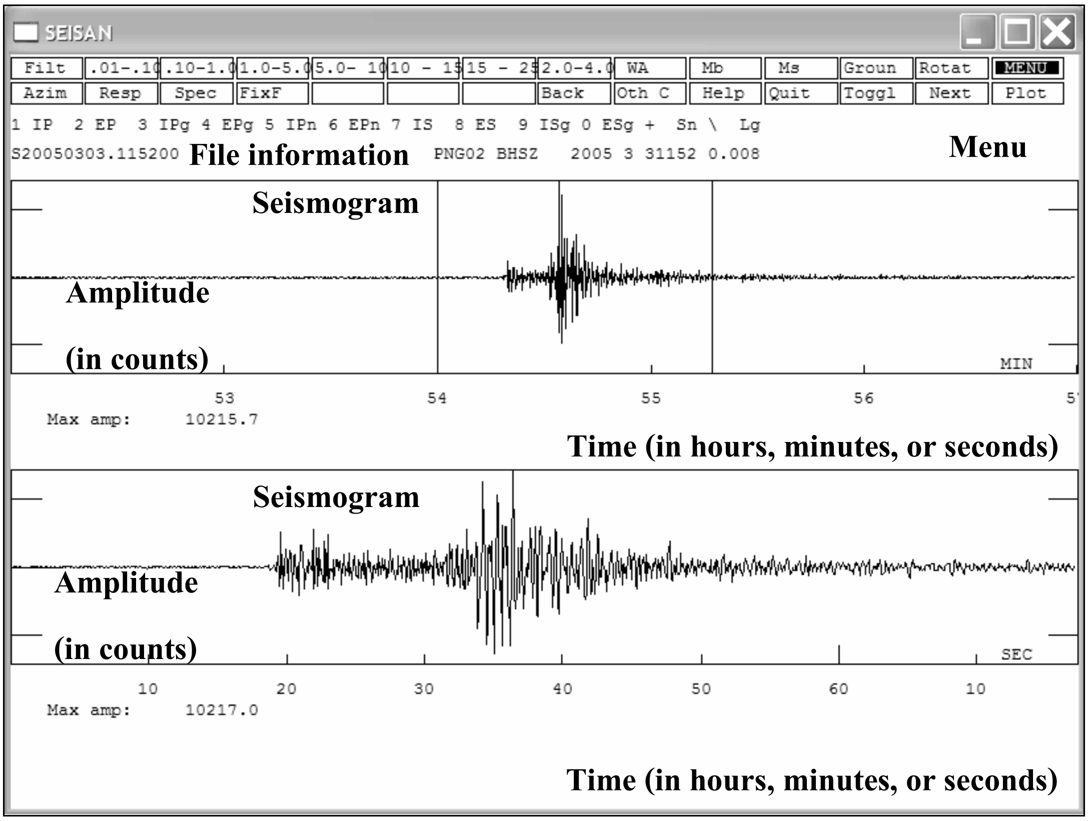


Figure 2.23. Seisan window showing the Z component of a seismic event recorded at Station 2 on 3 March 2005 (UTC time 11:53:59.0).

2.7 Seismograms

After the data processing, the seismograms of the seismic events could be displayed in the WinQuake and Seisan software. Figure 2.24, 2.25, 2.26 and 2.27 show examples of seismograms from each station and for each component displayed with Seisan software.

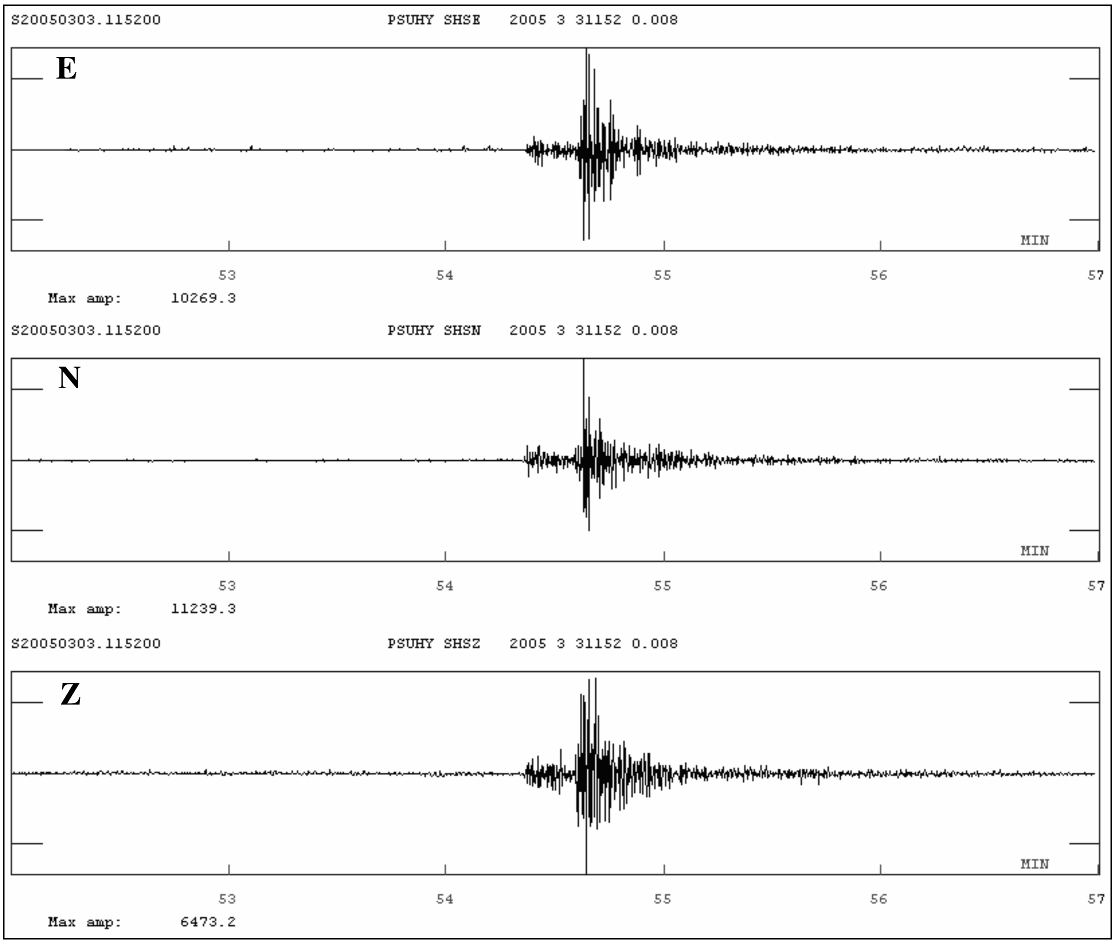


Figure 2.24. Seismic Station 1 (PNGHY); Seismograms of the N-, E, and Z-component of a seismic event recorded at Station 1 on 3 March 2005 at 11:53:59.0 UTC time. The x-axis is the time (here in minutes), the y-axis is the amplitude (here in counts). The y-scale is different for each component, whereas the x-scale is the same.

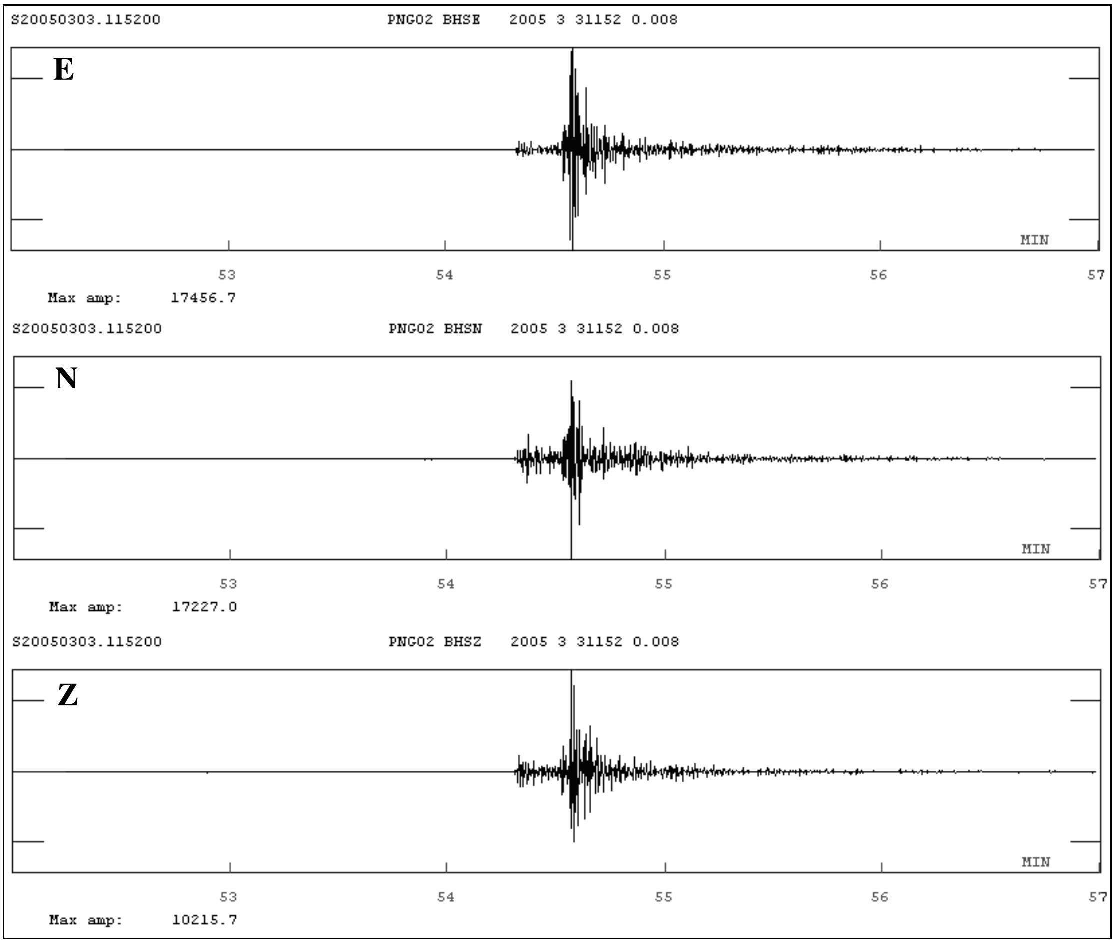


Figure 2.25. Seismic Station 2 (PNG02); Seismograms of the N-, E, and Z-component of a seismic event recorded at Station 2 on 3 March 2005 at 11:53:59.0 UTC time. The x-axis is the time (here in minutes), the y-axis is the amplitude (here in counts). The y-scale is different for each component, whereas the x-scale is the same.

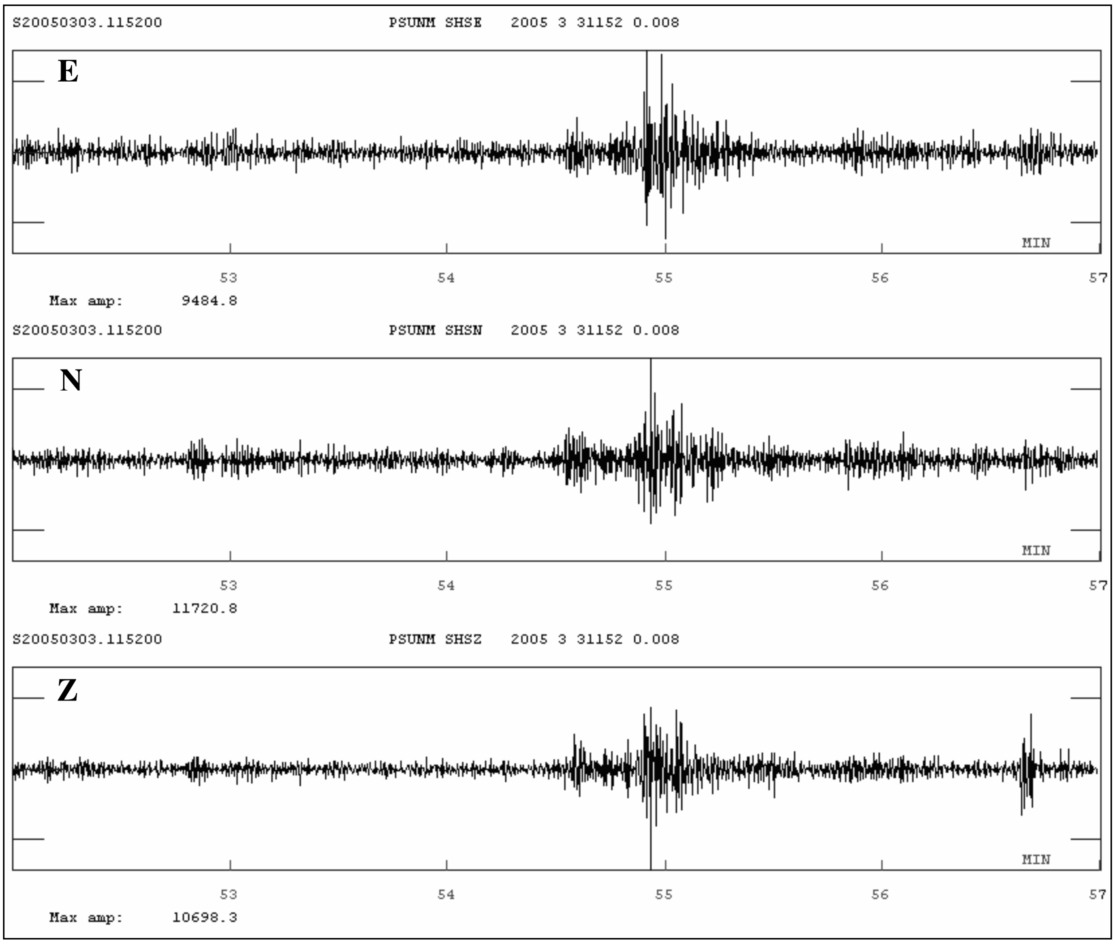


Figure 2.26. Seismic Station 3 (PSUNM); Seismograms of the N-, E, and Z-component of a seismic event recorded at Station 3 on 3 March 2005 at 11:53:59.0 UTC time. The x-axis is the time (here in minutes), the y-axis is the amplitude (here in counts). The y-scale is different for each component, whereas the x-scale is the same.

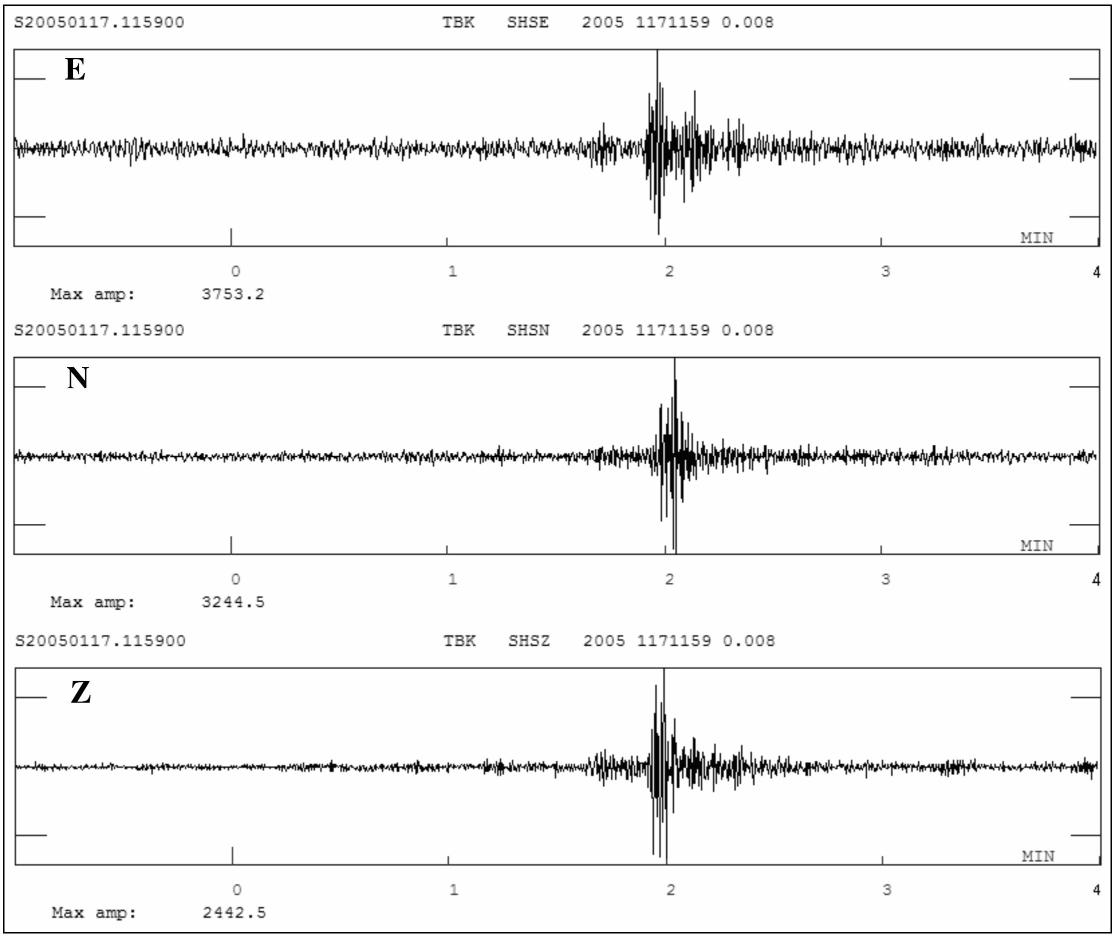


Figure 2.27. Seismic Station 4 (TBK); Seismograms of the N-, E, and Z- component of a seismic event recorded at Station 4 on 17 January 2005 at 11:59:00 UTC time. The x-axis is the time (here in minutes), the y-axis is the amplitude (here in counts). The y-scale is different for each component, whereas the x-scale is the same.

2.8 Phase identification and arrival time determination

The first step in the data analyzing process was the phase identification and determination of wave arrival time (Figure 2.28). The primary wave arrival is marked by first break from the zero line.

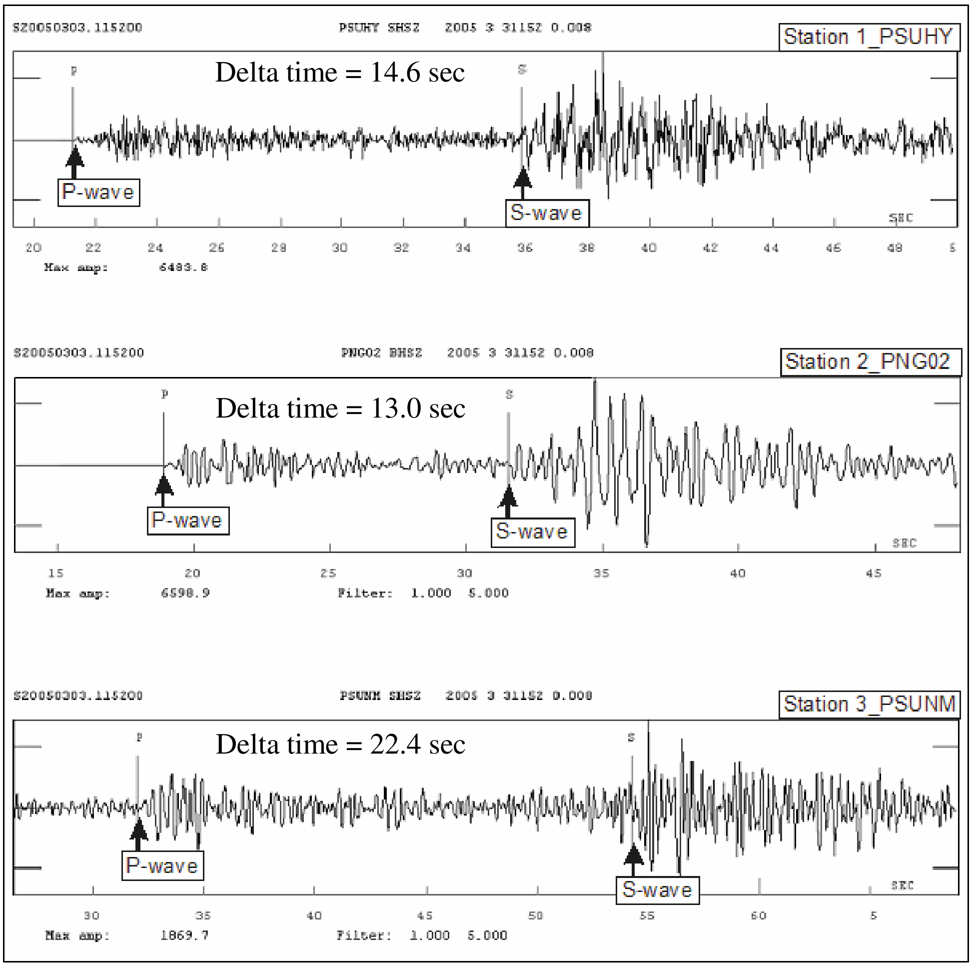


Figure 2.28. Seismograms of the Z component from PSUHY Station (Station 1), PNG02 Station (Station 2) and PSUNM Station (Station 3) respectively, for a seismic event on 3 March 2005 (UTC time 11:53:59.0). The arrival of the P- and S-wave are shown and the delta time determined from the difference in arrival time.

As most of the stations had a low seismic noise, this first break was usually quite clearly identifiable. The time of this first break is the arrival time of the primary wave. The later arriving secondary wave was more difficult to determine, because there were still P-wave signals in the seismogram when the S-wave arrived. The arrival of this wave was identified by an increase of the amplitude and/or a change in the waveform (see Figure 2.28). The filter options in the Seisan program were helpful during this task.

After the phase identification and determination of the traveltime for the primary and secondary wave the time difference between both arrival times has been calculated, the so-called delta time (Δt), which then is used for the determination of the distance between the seismic event and the station.

2.9 Identification and separation of seismic events

The seismometer recorded all seismic events during the study time, teleseismic, regional earthquakes in the Andaman Sea, local earthquakes, man-made seismic events and seismic noise. Therefore, the second step of the data analysis was the separation of the different types of events.

After the P- and S-phase identification and arrival time determination the regional seismic events related to the subduction zone in the Andaman Sea area and the teleseismic events were separated from local seismic events by using delta time, respectively distance. The regional and teleseismic events were usually located more than 500 km from the seismic stations (Setapong, 2006), which is equivalent to more than 50 seconds delta time using the refracted Pn- and Sn-phases, or other related phases, following the travel time tables given by Kennett (2005). Therefore, all seismic events with more than 50 seconds delta time were separated and not further analyzed in this study (see Figure 2.29).

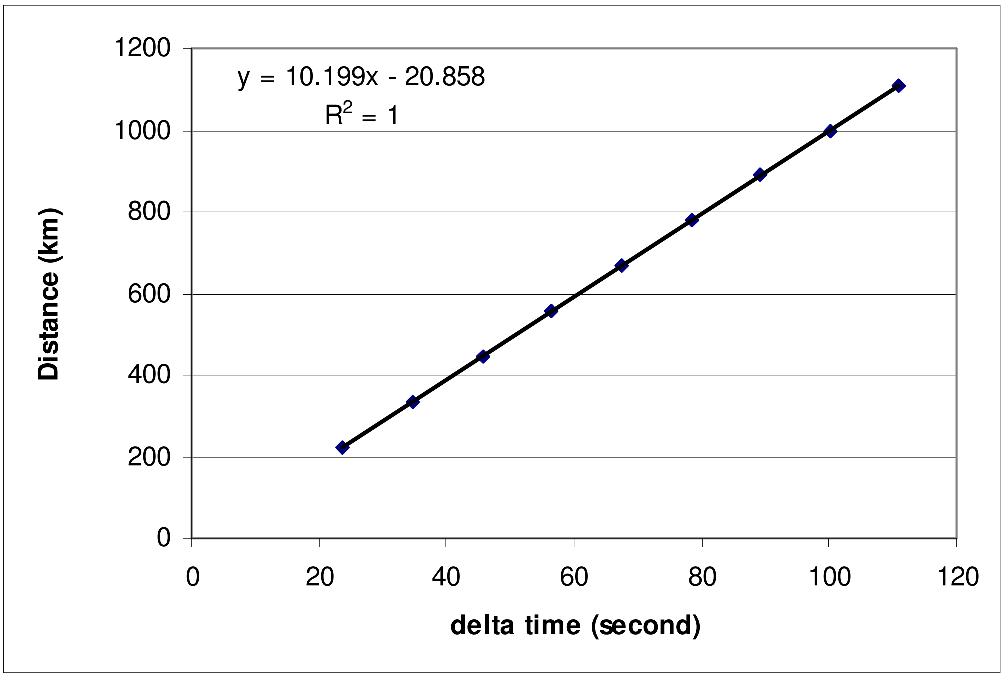


Figure 2.29. Relationship between delta time (in seconds) and the distance (in km) for regional earthquakes at 35 km depth based on the traveltime tables of Kennett (2005). A distance of 500 km relates to 51.07 seconds delta time, as the relationship is linear, with *distance (km) = 10.2 km/s * delta time (seconds) - 20.858 km.*

After the separation of the regional and teleseismic events, the remaining seismic events were considered as local seismic events. However, these events can include local earthquakes, local man-made seismic events and seismic noise. Seismic noise was separated by waveform and frequency analysis, as they were often single sharp high amplitude events or longer term higher frequency events.

Man-made seismic events like quarry blasting was separated by waveform analysis, especially using the surface Rayleigh waves (Rg), together with location and origin time determination (see also Nilsuwan, 2006). Figure 2.30 shows a blasting event with larger amplitude Rg-waves following shortly after the S-wave.

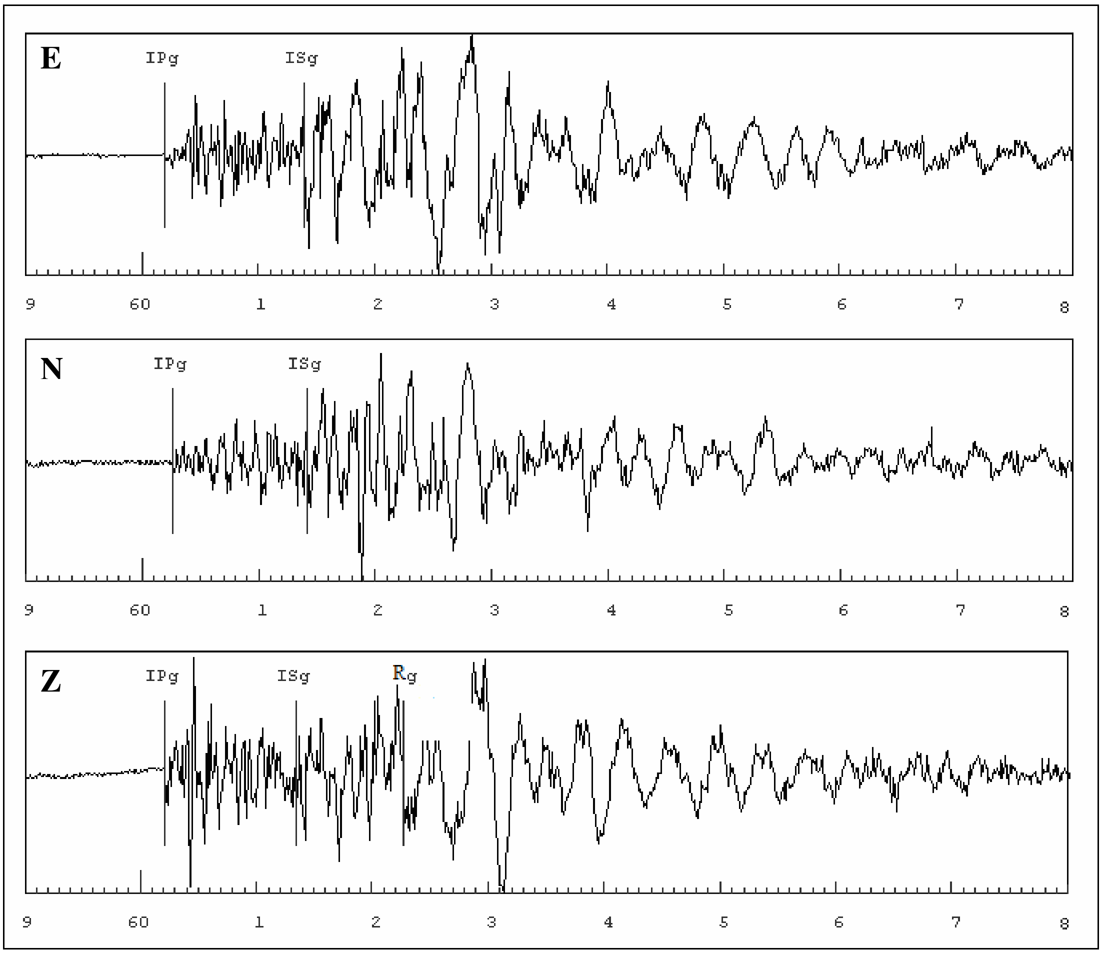


Figure 2.30. Seismograms of a man-made event from 7 April 2005 at Station 2 in E, N and Z component (after Nilsuwan, 2006). Pg: direct P-phase, Sg: direct S-phase, Rg: Rayleigh (surface) wave.

2.10 Distance determination for local seismic events

The distance between a seismic event and the station was determined using the delta time between the S- and P-wave arrival times, and using the *Jeffreys and Bullen Seismological Tables*, respectively velocity model (Table 2.2, Jeffreys and Bullen (1967, 1970). The P- and S-wave arrival times were usually determined using seismograms of the vertical Z-component (see Figure 2.28).

Table 2.2: Traveltime versus distances of different phases near earthquake after Jeffreys and Bullen (1967, 1970, JB tables).

Seismological Table
Near Earthquake Phase
Time of Transmission for Surface Focus

Pg			Pn			Sg			Sn		
Distance (degree)	Travel-time m	s	Distance (degree)	Travel-time m	s	Distance (degree)	Travel-time m	s	Distance (degree)	Travel-time m	s
0.00	0	0.000	0.80	0	18.355	0.00	0	0.001	0.80	0	31.275
0.28		5.507	1.05		21.894	0.34		11.378	1.12		39.255
0.55		11.014	1.30		25.433	0.69		22.755	1.43		47.236
0.83		16.521	1.54		28.973	1.03		34.133	1.75		55.217
1.10		22.028	1.79		32.512	1.38		45.511	2.07	1	3.198
1.38		27.535	2.04		36.051	1.72		56.888	2.39		11.179
1.66		33.042	2.29		39.591	2.07	1	8.266	2.70		19.160
1.93		38.549	2.54		43.130	2.41		19.644	3.02		27.140
2.21		44.056	2.79		46.669	2.76		31.021	3.34		35.121
2.48		49.563	3.03		50.209	3.10		42.399	3.66		43.102
2.76		55.070	3.28		53.748	3.45		53.777	3.97		51.083
3.03	1	0.577	3.53		57.287	3.79	2	5.154	4.29		59.064
3.31		6.084	3.78	1	0.827	4.14		16.532	4.61	2	7.045
3.59		11.591	4.03		4.366	4.48		27.910	4.92		15.025
3.86		17.099	4.28		7.905	4.83		39.287	5.24		23.006
4.14		22.606	4.52		11.445	5.17		50.665	5.56		30.987
4.41		28.113	4.77		14.984	5.52	3	2.043	5.88		38.968
4.69		33.620	5.02		18.523	5.86		13.420	6.19		46.949
4.97		39.127	5.27		22.063	6.21		24.798	6.51		54.930
5.24		44.634	5.52		25.602	6.55		36.176	6.83	3	2.911
5.52		50.141	5.77		29.141	6.90		47.553	7.14		10.891
5.79		55.648	6.01		32.681	7.24		58.931	7.46		18.872
6.07	2	1.155	6.26		36.220	7.59	4	10.309	7.78		26.853
6.34		6.662	6.51		39.759	7.93		21.686	8.10		34.834
6.62		12.169	6.76		43.299	8.28		33.064	8.41		42.815
6.90		17.676	7.01		46.838	8.62		44.442	8.73		50.796
7.17		23.183	7.26		50.377	8.97		55.819	9.05		58.776
7.45		28.690	7.50		53.917	9.31	5	7.197	9.37	4	6.757
7.72		34.197	7.75		57.456	9.66		18.575	9.68		14.738
8.00		39.704	8.00	2	0.995	10.00		29.952	10.00		22.718

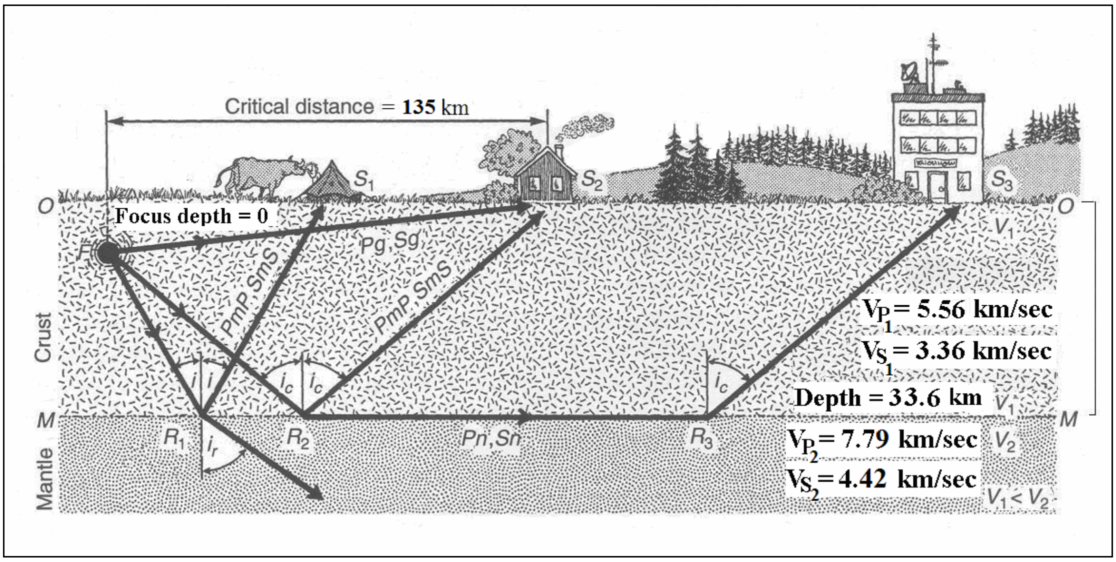


Figure 2.31. Modes of wave propagation from the focus of earthquake (**F**) through a simplified one-layer crust model. Symbols ***O*** and ***M*** represent the earth's free surface and Moho discontinuity, respectively. $\mathbf{S}_k$ is the ***k***th recording seismographic station, $\boldsymbol{i}$ is angle of incidence, $\boldsymbol{i_r}$ is the angle of refraction, $\boldsymbol{i_c}$ is critical angle, and **V** is velocity of propagation for P or S. From above, Vp_1 = 5.56 km/s, Vs_1 = 3.36 km/s, Vp_2 = 7.79 km/s, Vs_2 = 4.42 km/s. R_k are the points of redirection at the Moho discontinuity for wave that travels to the ***k***th station (modified after Kulhánek, 2002)

For this study, no velocity model for Southern Thailand was available, so the depths and velocities of the Crustal and Upper Mantle layers were unknown. Therefore, the Jeffreys and Bullen (JB) tables were used in this study for the distance determination of the local seismic events (see Table 2.2).

The JB velocity model for local events comprises two crustal layers and the crust-mantle boundary at 33.6 km depth (see Chapter 1.1.7). For this study, the two crustal layers were treated as one layer, with Vp_1 = 5.56 km/s and Vs_1 = 3.36 km/s, because the interface between the Upper and Lower crustal layer could not been identified in the seismograms. The Upper Mantle velocities were Vp_2 = 7.79 km/s and Vs_2 = 4.42 km/s (see Figure 2.31). Therefore, in this study only direct phases (Pg and Sg) and refracted phases at the Moho discontinuity (Pn, Sn) were used.

The crossover distance between the Pg- and Pn-phase is at 135 km; the cross over distance between the Sg- and Sn-phase is at 158 km. A distance of 135 km relates to a delta time of 15.95 s (between Sg-Pg and Sg-Pn); a distance of 158 km corresponds to a delta time of 19.72 s (between Sg-Pn and Sn-Pn). From these relationships between delta time and distance for the different phases the distance was determined for each seismic event and each station (see Figure 2.32a and 2.32b, see also Box 1).

The depth for all seismic events in this study is set at 0 km or surface focus. The main reason was that the seismogram analysis did not allow a resolution of the depth. Because the depth of an earthquake is generally more accurate, where the distance from the epicenter to the closest station is less than the calculated focal depth and the accuracy of focal depths usually increases as the number of picked S-phase arrivals increases (Trnkoczy et al., 2002a). For this study, the local earthquakes were assumed crustal earthquakes with depths less than 30 km. The distances to the seismic stations were usually more than that. Further, l data from maximal four seismic stations were available, often only from three stations. For a further discussion, see Chapter 4.1.3.

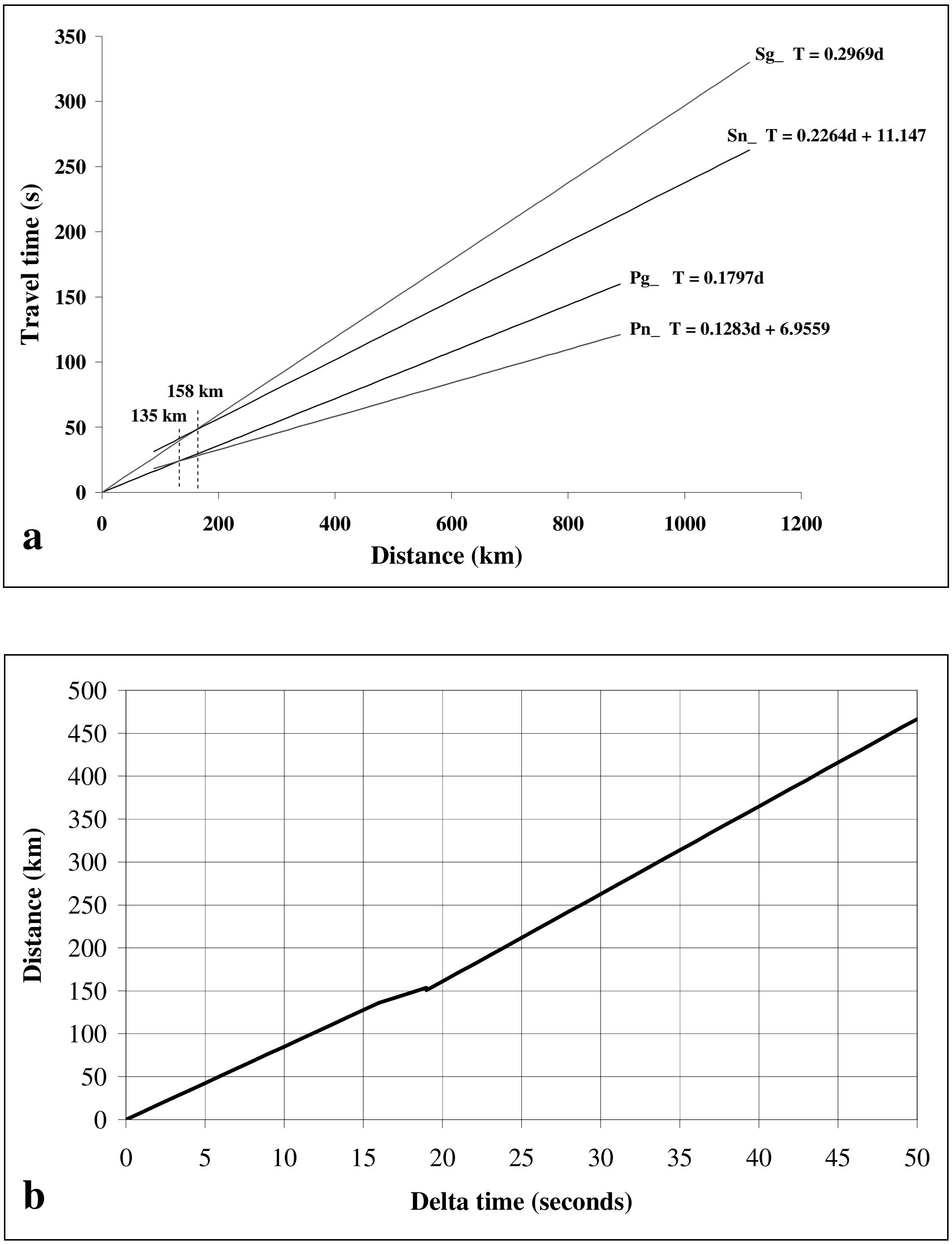


Figure 2.32. Relationship between delta time and distance for local seismic events based on JB tables (Table 2.2). (a): The travel time (T) versus distance (d) for the different phases that the cross over of Pg and Pn phase is at 135 km, Sg and Sn is at 158 km. (b): The distance versus delta time that the slope changes are related to the different phases, they are at delta time 15.95 s (between Sg-Pg and Sg-Pn) and at 19.72 s (between Sg-Pn and Sn-Pn).

2.11 Location determination of local seismic events

The locations of seismic events are determined from the epicenter distances of three seismic stations. In case, data from only two or even one seismic stations was available, the back azimuth technique was used. This was possible, as for each seismic station data from three components were available.

2.11.1 Location determination with data from three seismic stations

In case that for a seismic event distance data from three seismic stations were available, the circle and cord method was used. The epicenter is the point where all three circles intercept. This was done automatically with the WinQuake program. An example of the calculations involved is shown in Box 1 and the results in Figure 2.33.

Seismic event on 3 March 2005 (11:52:59.0 UTC time), see Figure 2.28.

Delta time (Δt)- distance (d) relationship for different phases (see Figure 2.32):

Sg and Pg phase ($\Delta t < 15.95$ s):	d (km) = 8.501 (km/s)*Δt (s)
Sg and Pn phase ($15.95 < \Delta t < 19.72$ s):	d (km) = 5.931 (km/s)*Δt (s) + 41 km
Sn and Pn phase ($\Delta t > 19.72$ s):	d (km) = 10.192 (km/s)*Δt (s) – 42.7 km

Find the epicenter distances from delta time:

PSUHY Station (Station1)

Pg arrival time: 11:54:21.4 (UTC)

Sg arrival time: 11:54:36.0 (UTC)

Δt (Sg – Pg) is 14.6 s d = 8.501 km/s*14.6 s = 124.2 km.

PNG02 Station (Station 2)

Pg arrival time is 11:54:18.7 (UTC)

Sg arrival time is 11:54:31.7 (UTC)

Δt (Sg – Pg) is 13.0 s d = 8.501 km/s*13.0 s = 110.3 km

PSUNM Station (Station 3)

Pn arrival time is 11:54:31.1 (UTC)

Sn arrival time is 11:54:53.5 (UTC)

Δt (Sn – Pn) is 22.4 s d = 10.192 km/s*22.4 s - 42.7 km = 185.6 km.

Box 1. Example of distance calculations for a seismic event and data from three seismic stations as part of the location determination (see Figure 2.33).

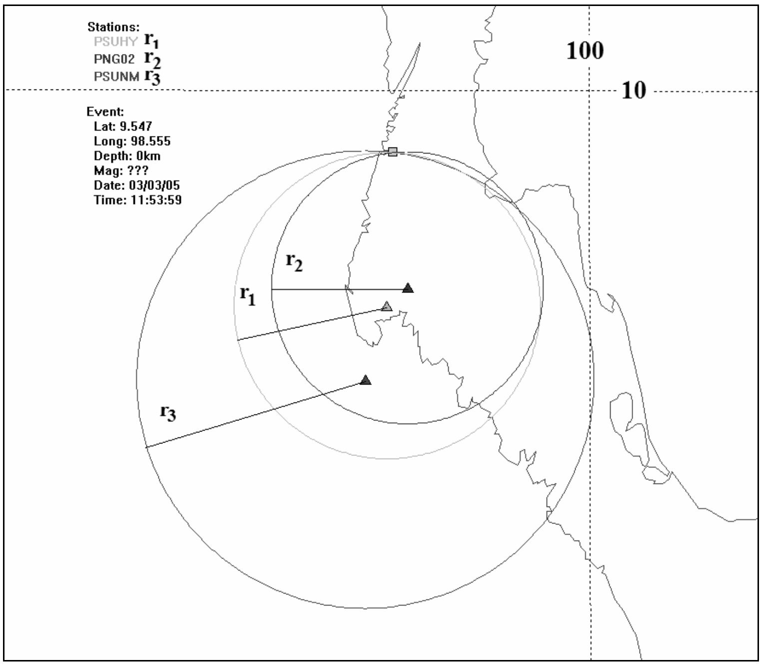


Figure 2.33. Earthquake on 3 March 2005 at 11:53:59.0 (UTC time): Location (epicenter) at longitude 9.547 degree north and latitude 98.555 degree east (local magnitude Ml = 2.2, see Chapter 3.1)

2.11.2 Location determination with data from two seismic stations

In case data from two seismic stations were only available, the circle and cord method was still used, but the circles crossed in two locations. To identify which of the two locations is the real one, the back azimuth from one seismic station with three components was determined (see Chapter 1.1.8).

Determination of (back) azimuth from three components of one seismic station:

If + represents a positive first peak

If – represents a negative first peak

East-West component	: (+) to the East, (-) to the West
North-South component	: (+) to the North, (-) to the South
Z (vertical) component	: (+) up = push, (-) down =pull
AZI = arctan (AE/AN)	AE and AN are the first amplitudes in E- and N- component

Seismic event on 30 May 2005 at 09:05:23.5 UTC time.

Data only from two seismic stations available (see Figure 2.34 and 2.36).

Back azimuth determination data from Station 2 (PNG02), see Figure 2.34.

East - West component is up (+)	→	East
North - South component is down (-)	→	South
Z (vertical) component is down (-)	→	pull.

AE = 23.9 counts

AN = 42.3 counts

AZI = arctan (23.9/42.3)

AZI = 29.47 degrees

Back azimuth is 180 minus 29.47 degrees = 150.53 degrees.

Determining the event location from one seismic station (Station 2):

The epicenter distance = 22.6 km (calculated from delta time).

The azimuth from N is 29.47 degrees (see Figure 2.35)

N = cosine 29.47 * 22.6 km = 19.676 km = 0.1771 degrees

E = sine 29.47 * 22.6 km = 11.118 km = 0.1001 degrees

Station 2 location: 8.5576 N, 98.6604 E

Event location: N : 8.5576 - 0.1771 = 8.3805 degree

E : 98.6604 + 0.1001 = 98.7605 degree

Event location from back azimuth from Station 2: 8.3805 N, 98.7605 E

The event location from circle method using and Winquake program is slightly different at 8.368 degree north, 98.720 degree east (see Figure 2.36).

Box 2: Example of back azimuth determination for a seismic event with data from one seismic station with three components (see Figure 2.34).

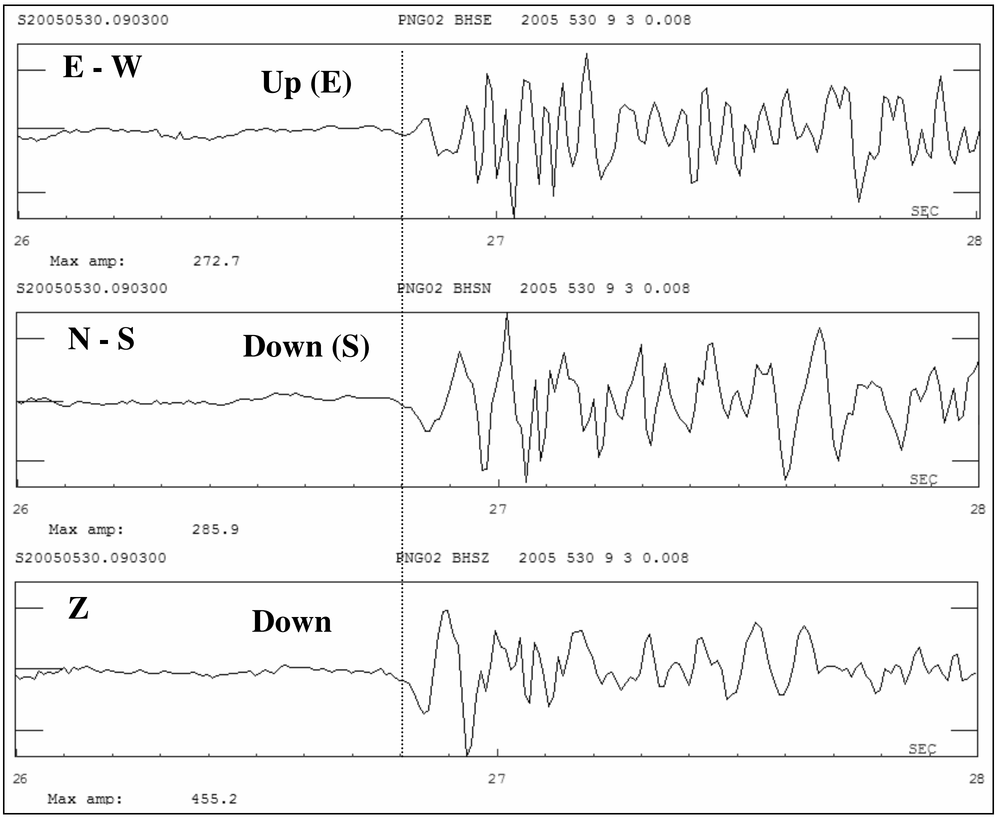


Figure 2.34. Determination of first peak from the first wave (P wave) arrival in three components from PNG02 Station (Station 2) at 09:05:23.5 (UTC time) on 30 May 2005.

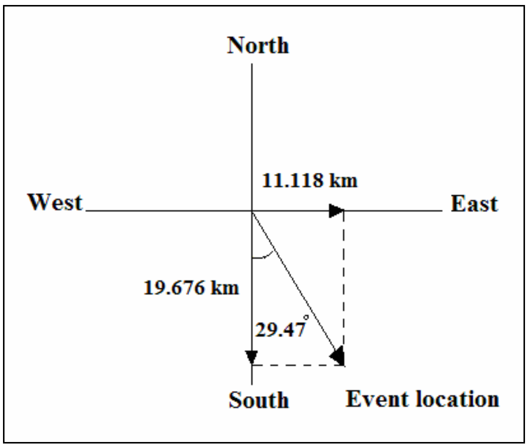


Figure 2.35. The location of the event on 30 May 2005 at 09:05:23.5 (UTC time) is in the South-East sector, based on data from PNG02 Station with three components.

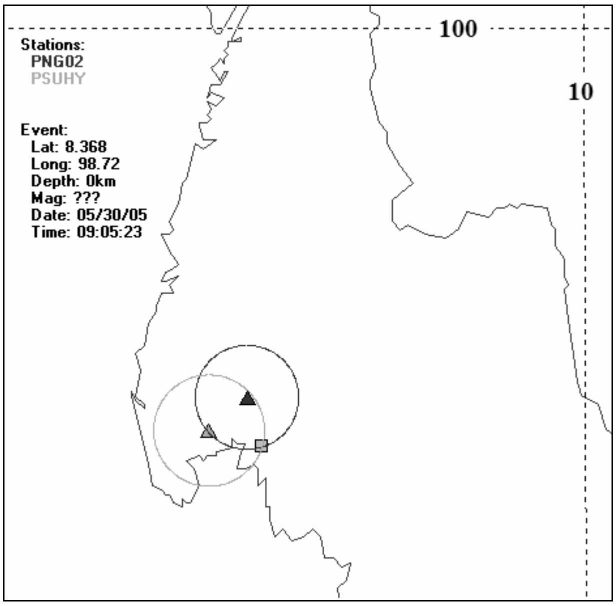


Figure 2.36. Event on 30 May 2005 at 09:05:23.5 UTC time: Location (rectangular symbol) at 8.368 degree north, 98.720 degree east (Ml = -0.6), based on data from two stations (PSUHY and PNG02 Stations: triangles symbol) and back azimuth determination from Station 2 (see Box 2, Figure 2.34, Figure 2.35).

2.11.1 Location determination with data from one seismic station

In case data from only one seismic station was available, the circle and cord method could no be used anymore. The event location was determined with the back azimuth method from one seismic station with three components. The results are less reliable than for the previous examples (for discussion see Chapter 4.1.5)

2.12 Determination of origin time

The origin time of seismic event is determined from the P- or S- wave arrival time and the traveltimes in the JB traveltime table. After the distance is determined from the delta time the traveltime for each phase and distance can be found in the JB traveltime tables (see Table 2.2). See Box 3 for an example calculation.

The earthquake origin time is calculated from :

EQ_origin time + P wave travel time = P wave arrival time,

EQ_origin time = P wave arrival time – P wave travel time

or

EQ_origin time + S wave travel time = S wave arrival time

EQ_origin = S wave arrival time – S wave travel time

P wave and S wave travel times are taken from the travel time-distance table for the relevant distances that are derived from the delta times between S-wave and P-wave arrival times (see above).

Earthquake origin time for earthquake on 3 March 2005 (Figure 2.28):

PSUHY Station (Station 1)

Pg wave arrival time is 11:54:21.4 (UTC)

Pg wave travel time is 00:00:22.3 (UTC)

EQ_origin time = P wave arrival time – P wave travel time

EQ_origin time = (11:54:21.4)-(00:00:22.3)

EQ_origin time = 11:53:59.1 (UTC time)

PNG02 Station (Station 2)

Pg wave arrival time is 11:54:18.7

Pg wave travel time is 00:00:19.8

EQ_origin time = P wave arrival time – P wave travel time is

EQ_origin time = (11:54:18.7) – (00:00:19.8)

EQ_origin time = 11:53:58.9 (UTC time)

PSUNM Station (Station 3)

Pn arrival time is 11:54:31.1

Pn travel time is 00:0:30.7

Thus EQ_origin time = P wave arrival time – P wave travel time

EQ_origin time = (11:54:31.1) – (00:0:30.7)

EQ_origin time = 11:54:00.4 (UTC time)

The average origin time (from Station 1 and Station 2) for this event is 11:53:59.0 (UTC).

Box 3: Example of origin time determination for a seismic event with data from three seismic stations.

2.13 Determination of local magnitude

For all seismic events in this study, the local magnitude (Ml) was determined. The local magnitude is applied for epicenter distances less than 10 degrees (Bormann, 2002b). The local magnitudes are calculated as following

$$Ml = \log A_{max} - \log A_0 \quad (1)$$

With A_{max} is the amplitude sum in mm, measured as zero to peak in the horizontal component (East and North component, $A_{max} = \sqrt{(E_{max}^2 + N_{max}^2)}$) with a Wood-Anderson seismograms and – log A_0 is the correction or calibration values. In this study, the local magnitude was calculated following Hutton and Boore (1987):

$$-\log A_0 = 1.110 \log (R/100) + 0.00189 (R- 100) + 3 \quad (2)$$

With R is the hypocentral distance in km, R = $\sqrt{(\Delta^2 + h^2)}$, Δ is the epicentral distance in km, h is hypocenter depth in km. If h = 0, zero depth, then R = Δ. For data recorded on a Wood-Anderson seismograph the local magnitude can be calculated as

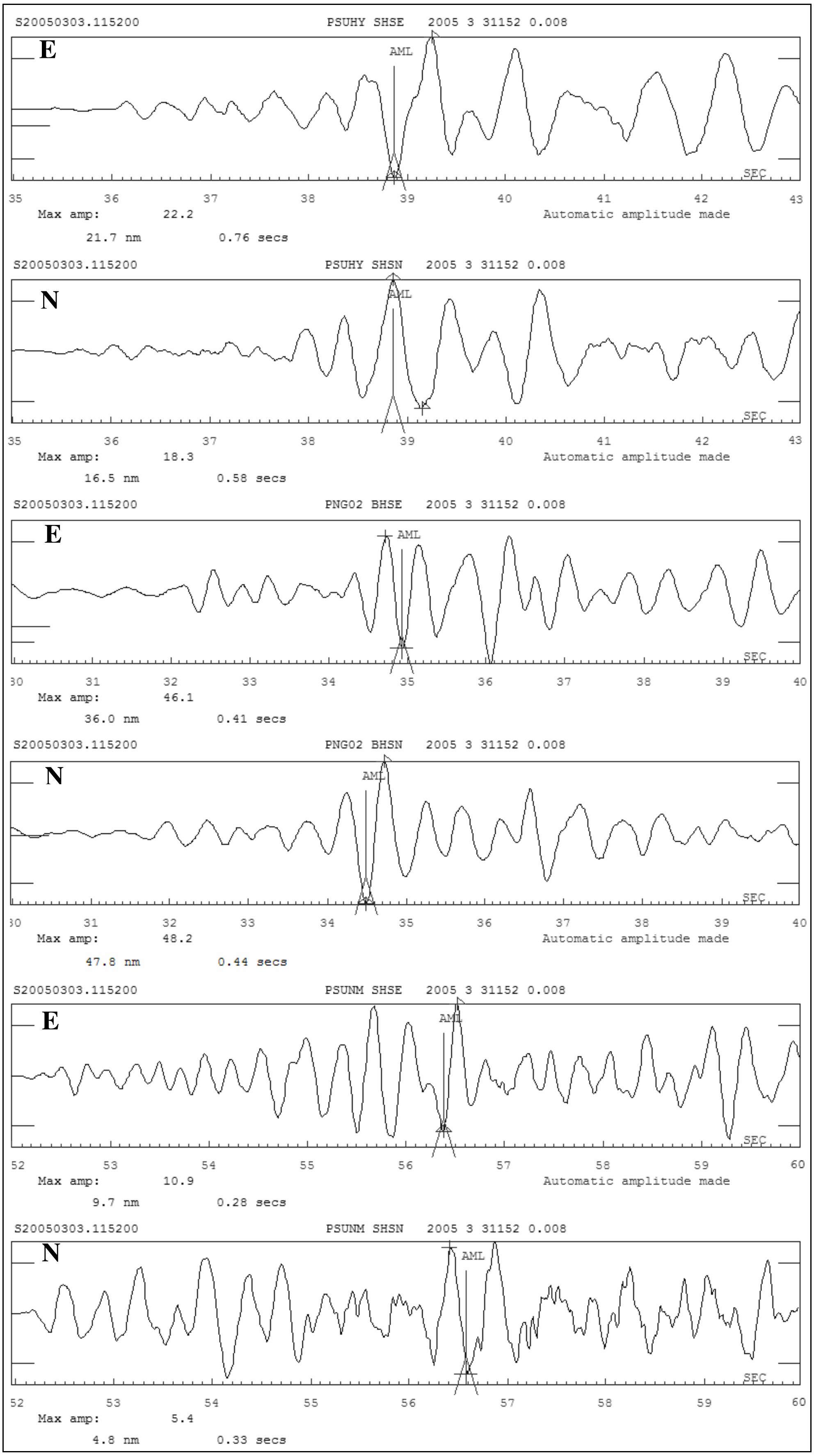
$$Ml = \log A_{max(mm)} + 1.110 \log (R/100) + 0.00189 (R- 100) + 3 \quad (3)$$

In the Seisan program, the real ground displacement is calculated from the seismogram and the response information, Havskov and Ottemöller (2005). In the real ground displacement window the amplitudes for the magnitude determination are measured. Therefore, the local magnitude in formula Equation 3 has to be changed for real ground displacement using the Wood-Anderson magnification of 2080 $\pm$ 60. Rewriting Equation 3 for real ground displacement amplitudes (A_{max}) in nanometers (10^{-6} mm = 1 nm) the magnitude formula is

$$Ml = \log (A_{max(nm)}) + 1.110 * \log (R) + 0.00189*R- 2.09 \quad (4)$$

Where A_{max} is the sum of the amplitude in the East and North component (in nm) measured at the same time, with $A_{max} = \sqrt{(E_{max}^2 + N_{max}^2)}$, and R the hypocenter distance (in km).

Figure 2.37. (next page) Maximum amplitude (nm) in the east (E) and north (N) component for a seismic event on 3 March 2005 at 11:53:59.0 UTC time from PSUHY Station (Station 1), PNG02 Station (Station 2), and PSUNM Station (Station 3), respectively. The amplitudes in the E- and N-component are determined at the same time. The location of this event is at 9.547 degree north, 98.555 degree east with ML 2.2.


S20050303.115200
PSUHY SHSE 2005 3 31152 0.008
E
AML
SEC
35 36 37 38 39 40 41 42 43
Max amp: 22.2
Automatic amplitude made
21.7 nm 0.76 secs
S20050303.115200
PSUHY SHSN 2005 3 31152 0.008
N
AML
SEC
35 36 37 38 39 40 41 42 43
Max amp: 18.3
Automatic amplitude made
16.5 nm 0.58 secs
S20050303.115200
PNG02 BHSE 2005 3 31152 0.008
E
AML
SEC
30 31 32 33 34 35 36 37 38 39 40
Max amp: 46.1
36.0 nm 0.41 secs
S20050303.115200
PNG02 BHSN 2005 3 31152 0.008
N
AML
SEC
30 31 32 33 34 35 36 37 38 39 40
Max amp: 48.2
Automatic amplitude made
47.8 nm 0.44 secs
S20050303.115200
PSUNM SHSE 2005 3 31152 0.008
E
AML
SEC
52 53 54 55 56 57 58 59 60
Max amp: 10.9
Automatic amplitude made
9.7 nm 0.28 secs
S20050303.115200
PSUNM SHSN 2005 3 31152 0.008
N
AML
SEC
52 53 54 55 56 57 58 59 60
Max amp: 5.4
4.8 nm 0.33 secs

Determination of the local magnitude (after Hutton and Boore, 1987)
for the earthquake on 3 March 2005 at 11:53:59.0 UTC:

Station 1: Maximum amplitude in E component = 21.7 nm

Maximum amplitude in N component =16.5 nm

Vector sum $= \sqrt{E^2 + N^2} = 27.3$ nm

Local magnitude (Ml)

A_{sum} = 27.3 nm, distance = 124.2 km

Ml $= \log_{10}A_{sum} + 1.11*\log_{10}D_{km} + 0.00189*D_{km} - 2.09$

Ml $= \log_{10} 27.3 + 1.11*\log_{10}124.2 + 0.00189*124.2 - 2.09$

Ml = 1.9

Station 2: Maximum amplitude in E component = 35.9 nm

Maximum amplitude in N component = 47.8 nm

Vector sum $= \sqrt{E^2 + N^2} = 59.8$ nm

Local magnitude (Ml)

A_{sum} = 59.8 nm, distance = 110.3 km

Ml $= \log_{10}A_{sum} + 1.11*\log_{10}D_{km} + 0.00189*D_{km} - 2.09$

Ml $= \log_{10} 59.8 + 1.11*\log_{10}110.3 + 0.00189*110.3 - 2.09$

Ml = 2.2

Station 3: Maximum amplitude in E component = 9.7 nm

Maximum amplitude in N component = 4.8 nm

Vector sum $= \sqrt{E^2 + N^2} = 10.8$ nm

Local magnitude (Ml)

A_{sum} = 10.8 nm, Distance = 185.6 km

Ml $= \log_{10}A_{sum} + 1.11*\log_{10}D_{km} + 0.00189*D_{km} - 2.09$

Ml $= \log_{10} 10.8 + 1.11*\log_{10}185.6 + 0.00189*185.6 - 2.09$

Ml = 1.8

Here the maximum value of the local magnitudes from the three stations is reported, Ml=2.2.

Box 4: Example of local magnitude determination for a seismic event with data from three seismic stations.

2.14 Summary and presentation of seismological parameters

The data from the seismogram analysis are presented in a table; an example is shown in 2.3 and Table 2.4. Table 2.3 provide all data related to a seismic event, with the event number, date, seismic stations, P-wave arrival time, S-wave arrival time, origin time (in UTC), delta time, distance, maximum amplitude in the North component, maximum amplitude in the East component, average amplitude from North and East component, local magnitude, longitude and latitude of the location of the event. For a complete list, see Appendix E. Table 2.4 provides only the relevant seismological data of a seismic event, event number, and origin time, location in longitude and latitude and local magnitude. From all magnitude values from the three different stations, the highest magnitude is reported. This is a conservative approach using this data in a seismic hazard analysis. A complete list for all events is presented in Chapter 3.

Table 2.3: Compilation of all data of an earthquake event, here for a local earthquake on 3 March 2005. T = time, Δt = delta time, Dist = distance in km, E = east component, N = north component, A max = maximal amplitude, A max (ave.) = average maximal amplitude, Ml = local magnitude. Long = longitude, Lat = latitude.

Event No.	Date dd/mm/yy	Stations	P-arrival T. hh:mm:ss.	S-arrival T. hh:mm:ss.	Origin T. hh:mm:s.	Δt (sec)	Dist. (km)	E A max (nm)	N A max (nm)	A max (ave.) (nm)	Ml	Long.	Lat.
44	03/03/05	1 (PSUHY)	11:54:21.4	11:54:36.0	11:53:59.1	14.6	124.2	21.7	16.5	27.3	1.9	98.555	9.547
		2 (PNG02)	11:54:18.7	11:54:11.7	11:53:58.9	13.0	110.3	36.0	47.8	59.8	2.2		
		3(PSUNM)	11:54:31.1	11:54:53.5	11:54:00.4	22.4	185.6	9.7	4.8	10.8	1.8		

Table 2.4: Relevant seismological data for the same event shown in Table 2.3.

Event	Origin Time dd/mm/yy hh:mm:ss.	Longitude	Latitude	Ml
44	03/03/05 11:53:59.0	98.555	9.547	2.2