LANDSLIDE MONITORING OF NATURAL TERRAIN AREA IN CENTRAL ACEH USING INTERFEROMETRIC SYNTHETIC APERTURE RADAR TECHNIQUES

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UNIVERSITI SAINS MALAYSIA

2021

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by

JEFRIZA

**Thesis submitted in fulfilment of the requirements
for the degree of
Doctor of Philosophy**

September 2021

ACKNOWLEDGEMENT

"**Bismillahirrahmanirrahim**"

"In the Mighty Name of ALLAH, The Most Beneficent, The Most Merciful"

I would like to express my sincere gratitude and love to my parents, Allahyarham Yulina (lost in Aceh Tsunami 2004) and Basyarmuddin; my wife Cut Linda Marheni, Lc. MA; my son and daughter, Allahyarham Mikal Sajjad (5.5 yr), Sabira Hurin Ien (post-liver transplant patient), Jibril Bassam, and the entire family for support, encouragement, and guidance have shown to me during the Ph.D journey. I would like to gratitude my appreciation to my supervisor, Professor Dr. Habibah Lateh, Dr. Izham Mohamad Yusoff, and Dr. Ismail Ahmad Abir for encouragement, guidance, critics, and friendship. Without their support and interest, this thesis would not have been the same as presented here. My deepest appreciation for these agencies for providing free SAR data for this research (Japan Aerospace Exploration Agency (JAXA) for ALOS PALSAR images and ESA for Sentinel-1). Also, I would like to acknowledge Dr. Perissin for providing a free trial of SARPROZ software which was vital for this research. My appreciation also goes to the Badan Pengembangan Sumber Daya Manusia (BPSDM) Aceh Government, Indonesia for the financial support. My appreciation also extends to all my colleagues and others who have assisted on various occasions.

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LIST OF ABBREVIATIONS

ALOS	Advanced Land Observing Satellite
ASAR	Advanced Synthetic Aperture Radar
APS	Atmospheric Phase Screen
BMKG	*Badan Meteorologi, Klimatologi dan Geofisika*, (Meteorology, Climatology, and Geophysical Indonesian Government agency)
DEM	Digital Elevation Model
ENVISAT	Environmental Satellite
ERS	European Remote Sensing
ESA	European Space Agency
GPS	Global Positioning System
InSAR	Interferometric Synthetic Aperture Radar
JAXA	Japan Aerospace Exploration Agency
JERS	Japan Earth Resources Satellite
LiDAR	Light Detection and Ranging
LOS	Line of Sight
SBAS	Small Baseline Subset
PALSAR	The Phase Array type L-band Synthetic Aperture Radar
PS	Persistent Scatterer
SAR	Synthetic Aperture Radar
SLC	Single Look Complex
SNR	Signal to Noise Ratio
SRTM	Shuttle Radar Topography Mission
USGS	United States Geological Survey
WGS	World Geodetic System

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ABSTRAK

Pengukuran deformasi permukaan tanah sangat penting untuk kajian tanah runtuh. Teknik *Interferometric Synthetic Aperture Radar* (InSAR) sangat penting untuk kajian tanah runtuh kerana ianya menyumbang kepada kaedah pemantauan deformasi permukaan tanah untuk kadar pergerakan perlahan sebelum berlakunya kejadian tanah runtuh. Teknik tersebut telah digunakan secara meluas di kawasan bandar dan luar bandar. Pergerakan tanah runtuh di kawasan kajian Aceh Tengah, Indonesia kebanyakan termasuk di bawah kategori klasifikasi kadar halaju. Hal ini disebabkan oleh empat faktor utama penyebab kejadian tanah runtuh, iaitu jumlah hujan lebat, zon tektonik, tanah lembut dan aktiviti manusia (pemotongan cerun). Objektif kajian ini adalah untuk mengukur dan menganalisis deformasi pergerakan perlahan tanah runtuh di kawasan ketinggian semula jadi. Teknik InSAR boleh memantau jenis pergerakan ini dalam kawasan yang luas. Pemantauan tanah runtuh di kawasan ketinggian semula jadi akan terbatas dengan masalah awan sekiranya penderiaan jarak jauh optik digunakan. Kumpulan data siri masa *Single Look Complex Synthetic Aperture Radar* (SLC SAR) yang terbaru dan dikemas kini dari satelit sensor Sentinel-1 dan data lama dari satelit sensor ALOS PALSAR digunakan dalam kajian ini. Analisis yang digunakan ke atas teknik InSAR ialah penggunaan *Persistent Scatterer* (PS), *Small Baseline Subset* (SBAS) dan *Quasi-PS* (Q-PS). Teknik PS digunakan secara meluas di kawasan bandar, manakala SBAS dan Q-PS dapat digunakan di kawasan bandar dan di luar bandar (kawasan semula jadi). Eksploitasi penggabungan setiap imej radar dan teknik InSAR (PS dan Q-PS) dengan laluan orbit

secara menaik dan menurun serta penggunaan imej-imej terkini Sentinel-1 SAR menjanjikan teknik yang baik untuk memenuhi jarak setiap jurang kecondongan radar berpunca dari kesan bayangan. PS dan Q-PS menggunakan data siri masa Sentinel-1, manakala SBAS menggunakan imej-imej siri masa ALOS PALSAR. Penemuan kajian menunjukkan corak perubahan bentuk penenggelaman (20 mm) dan kenaikan (16 mm) terhasil di kebanyakan kawasan utara Aceh Tengah. Penemuan kajian juga menunjukkan persamaan penenggelaman (2.3 mm – 15 mm) di Bandar Takengon berpunca daripada garis sesaran dan jenis tanih lembut. Hasil kajian ini sangat berharga dalam menggalakkan penggunaan teknik InSAR yang sahih dan boleh dipercayai terhadap pengukuran tanah runtuh dengan kecepatan yang sangat perlahan dalam pemantauan skala yang luas serta menyediakan ketepatan dalam skala millimeter.

LANDSLIDE MONITORING OF NATURAL TERRAIN AREA IN CENTRAL ACEH USING INSAR TECHNIQUES

ABSTRACT

Surface deformation measurements are critical for landslide studies. *Interferometric Synthetic Aperture Radar* (InSAR) technique is very important for landslide studies as it contributes to soil surface deformation monitoring methods for slow movement rates before landslides occur. The technique has been widely used in urban and rural areas. Landslides movement in the study area of Central Aceh, Indonesia, are mostly categorized as rapid landslides in terms of velocity rate classification. This is due to four factors which are; heavy rainfall amount, tectonic/fault zone, soft soil, and human activity (cut-slope). The objective of this study is to measure and analyze the slow deformation of landslides in the natural terrain areas. InSAR techniques can monitor this type of movement rate within large areas. Monitoring of landslides at natural altitudes will be limited to cloud problems if optical remote sensing is used. The time series of *Single Look Complex Synthetic Aperture Radar* (SLC SAR) of new and updated Sentinel-1 and historical data of ALOS PALSAR were used. The analyses of InSAR techniques used are Persistent Scatterer (PS), Small Baseline Subset (SBAS), and Quasi-PS (Q-PS). PS is widely used in urban, whereas SBAS and Q-PS can be applied in both urban (such as city center) and rural areas (such as undulating natural terrain areas). Exploitation and a combination of each radar image and InSAR techniques (PS and Q-PS) with an ascending or descending orbit pass with a new and an updated Sentinel-1 SAR images is a promising technique to fill the gap of each radar slant range due to shadow effect. PS and Q-PS technique uses Sentinel-1 time series, whereby SBAS technique uses

ALOS PALSAR time-series of images. The finding showed the pattern of deformation of subsidence (20 mm) and uplift (16 mm) occurs in most of the part of Northern Central Aceh. The finding also corresponds to the subsidence (2.3 mm -15 mm) in Takengon city due to faults and soft soil type. The results of this study are valuable in encouraging a valid and reliable InSAR technique for the measurement of slow landslides in wide-scale monitoring as well as in providing millimeter accuracy to enhance better InSAR techniques.

CHAPTER 1 INTRODUCTION

Landslide is a general term used to describe the movement of a mass of rock, debris, or Earth down a slope (Cruden, 1991). It is one of the natural land degradation processes that is continuously occurring in the hilly terrains and it is still unpredictable. It is hard to understand these movements without an obvious, consistent and continuous record with the landslide monitoring equipment.

The traditional method of landslide monitoring is a contact monitoring system, whereby equipment such as inclinometer, extensometer, piezometer, and Global Positioning System (GPS) are installed in the observation area. The benefit of this monitoring system is the availability to detect movement with very high accuracy. However, traditional monitoring is restricted and limited to cover a wide area. Moreover, when landslides occur, the costly monitoring equipment may be damaged (Lu et al., 2011).

Landslide monitoring without making physical contact with the object and also less or no equipment installation in the observation area can be done with the help of remote sensing technology. The term remote sensing generally refers to the use of satellite (spaceborne) and aircraft (airborne) based on electromagnetic radiation. In recent years, remote sensing played a key role in landslide monitoring (Di Martire, 2013). Based on the energy source, remote sensing is divided into two basic categories, optical (passive) and radar (active) remote sensing. The first one depends on the Sun, and the latter emits its energy. For landslide monitoring in natural terrain which is an undulating hilly area usually the presence of clouds restricts the use of optical remote sensing images. An active (radar) remote sensing uses Synthetic Aperture Radar (SAR) sensors, can penetrate the cloud cover and can capture either day or night could be the advanced technique to monitor landslide in such area. A complex of landslides on a regional scale can be achieved using SAR which gives the ability to detect surface deformation in millimeter level accuracy.

Centimeter to millimeter level surface deformation can be measured over a large area using space-borne Interferometric Synthetic Aperture Radar (InSAR) techniques (Bouali et al., 2017; Vassileva et al., 2017; Hrnčiar, 2018). InSAR techniques give a high accuracy and rapid mapping techniques over a wide investigated area compared to traditional ground monitoring techniques (Novellino, 2015). This technique helps ground detection and monitoring of slope instability due to rapid and easily updated SAR data acquisitions. The main advantages are less laborious field works and minimization of cost especially over wide areas (Ferretti et al., 2005; Bala et al., 2002).

Conventional InSAR, whereas only used two images (before and after), is a very useful technique for the detection of huge land deformation such as an earthquake. The clear deformation would be achieved by the conventional InSAR technique. However, for landslide monitoring with an extremely slow velocity in natural hilly terrain areas, the occurrence of an atmospheric noise is high due to water vapor. Then, the stacking or time series of images is necessary for removing the atmospheric phenomena using the Atmospheric Phase Screen (APS).

At present, there are many InSAR stacking techniques. The most common ones for the analysis of phase signals in interferometric time-series are Persistent Scatterer (PS), Small Baseline Subset (SBAS), and Quasi-PS (Q-PS) which is developed by Hooper, (2006); Berardino et al., (2002); Perissin and Wang, (2012) respectively.

PS analysis is carried out on stable scatterers to separate the atmospheric, topographical, and deformation components. The stability of the radar response, which occurs mainly in the presence of dominant point scatterers is the key assumption of

PS. Whereas, SBAS analysis is supposed to be Distributed Scatterer (DS) within the resolution cell and spatial multi looking is implemented to enhance the phase stability. SBAS spatial resolution is degraded concerning the PS approach (Cascini et al., 2010). While Q-PS technique is used partially coherent target for increasing the spatial distribution. Q-PS is successful for landslide monitoring in undulating areas whereas lacks coherence (Perissin et al., 2007). An application of Q-PS was also performed by Razi et al., (2018).

Most PS techniques are present in urban areas due to high coherence in the SAR perspective (a man-made building that can reflect SAR sensors). However, little attention to the PS technique is performed in natural terrain (rural areas) due to lack of coherence. By decreasing the coherence threshold, the number of stable scatterer points will increase for natural terrain areas. Ascending and descending of SAR image acquisition also contributes to landslide monitoring in the way of slope aspect. The direction of the slope influences the deformation map generation for natural terrain. If the slope is facing toward or away to the satellite, its can be monitored by the sensor with different angle of orbit pass. On the other hand, both Q-PS and SBAS techniques are applicable to detect movement in the natural terrain (rural with undulating areas) and it also works well in the urban area. Q-PS and SBAS techniques use a lack of stable coherence can detect movement in mostly landslide occurs.

To fill the gap of the limitation of using PS technique in the natural terrain and the benefit of using Q-PS or SBAS in the natural terrain, the exploitation of the combination of those techniques is focussed on this research. The combination also emphasizes the different angles of the sensor acquisition (ascending and descending). The effort of combining different sensors is attempted, however, the combination will not make sense since different properties of each sensor (C-Band and L-Band). The combination emphasizes on C-Band of the Sentinel-1 sensor due to its has complexities of the dataset (time-series) rather than the L-Band of the ALOS PALSAR sensor. Due to, only PS and Q-PS techniques can be analyzed and processing by certain application tools (SARPROZ which was developed by Perissin, 2019), then only PS and Q-PS techniques combination are presented in this research. The expectation of these combinations, either InSAR techniques (PS, Q-PS) or angle of the sensor (ascending and descending), can fill the gap with some area that cannot monitor due to shadow effect (SAR image slant range effect). The success of integrating/combining PS and SBAS techniques was performed by using the StaMPS/MTI application tool (Stanford Method for Persistent Scatterer/Multi Temporal Interferometry) (Bouraoui, 2013).

The come out of the InSAR techniques combination (PS and Q-PS) is the deformation movement pattern either subsidence or uplift (objective #1). Then the deformation pattern based on the deformation map will relate to local geological properties, rainfall amount, geological properties, and tectonic activities (local fault zone) (objective #2). The acceptable measurement means the deformation is showing a good agreement with another ground measurement or GIS interpretation (objective #3).

The study area was performed in Central Aceh District, Aceh Province, Indonesia. The justification of the study area was chosen based on Central Aceh has always experienced plenty of landslide events. This area is influenced by the geology, especially the faults, which is located in the tectonics activity, Central Aceh moved vertically 5 cm to the east (Fig.2.15 page 47). The landslide may be triggered due to the high-risk area of the fault zone, type of loose soil and human activity (cut-slope), and high amount of rainfall intensity (Rusydy et al., 2016). An example of landslides triggered by earthquakes such as the Gayo earthquake 02 July 2013, 6.2 M, is (one of the landslides triggered factor in Central Aceh) (Daryono & Tohari, 2016). The authors concluded that several landslides were widespread in the natural mountainous area. The landslides destroyed Serempah Village in the Ketol sub-district which was six people lost (See Figure 2.13 page 38) (Daryono & Tohari, 2016; Solikhin et al., 2016). Pamela et al., (2018) also stated that numerous landslides occur after the catastrophic earthquake. The authors estimated at least 43 deaths, 52,113 evacuees, and around 18,902 houses and buildings destroyed directly or indirectly by the catastrophe. An example of landslides induced by heavy rainfall is landslide occurrences after the accumulation of the rainfall amount in days or weeks. One of the disaster landslides occurred from 19 October to 01 November 2015 which 20 numbers landslide locations impact almost all sites in Central Aceh (Kompas, 2015). The peak of rain amount (October 2015) is very high 24 years back, which is 1,002 mm/month (See Appendix C. Rainfall Data). Landslides induced by a sequence of heavy rainfall also occurred in the main road Lut Tawar Lake (Serambi Indonesia, 2017a, 2017b, 2017c; Tempo, 2017; Toskomi, 2017). Based on the high risk of landslide occurs in Central Aceh, it is very important to understand landslide deformation and monitoring systems at a low cost and can cover large areas.

1.1 Problem Statement

There are many landslides in Central Aceh, mainly due to earthquakes or heavy rainfall. These types of landslides include rapid to extremely rapid categories based on velocity classification (Cruden & Varnes, 1996). However, there is a possibility of these landslides into slow to extremely slow categories. The ability to figure out the slow movement is the capability of InSAR techniques. Monitoring of the slow landslide movement (initial movement) before large movement is one of the benefits of InSAR techniques. This study focuses to figure out the slow movement before large movement. The landslide velocity classification is described on page 8 Table 1.1 Section 1.5.

The use of InSAR techniques is new in Aceh Province, however, the use of synthetic aperture radar (SAR) images, is only limited to post-disaster tsunami and earthquakes (Natsir, 2014; Rusdi et al, 2015; Schmitz & Lohmann, 2007). However, there is no quantification of the ground movement of using SAR images for landslide studies in Aceh. Although high occurrences of landslide in Central Aceh, less emphasis have been given on InSAR techniques to monitor landslide in this region. Landslide monitoring using InSAR techniques is necessary for this area.

The main focus of this research is the combination between InSAR techniques (PS and Q-PS) and different angles of the sensor (ascending and descending) that affect the deformation monitoring measurement (subsidence and uplift) in the natural terrain areas.

1.2 Research Aim

The main aim of this study is to monitor the deformation of ground movement in the potential landslide of the natural terrain area in Central Aceh using exploitation of InSAR techniques with different angle SAR sensors (ascending and descending), different SAR images (Sentinel-1 and ALOS PALSAR) and the combination of InSAR techniques (PS and Q-PS).

1.3 Research Questions

Based on the problem statement, the research questions are:

- What is the pattern of surface deformation based on the available archived SAR images of Central Aceh?
- Where are the potential areas for future landslides based on their deformation map and the relationship with rainfall intensity, local geology, and tectonics?
- Are the deformation measurements in agreement with existing landslide maps GIS) interpretation?

1.4 Research Objectives

There are three research objectives, which are:

1. To measure ground surface deformation (subsidence and uplift) using InSAR stacking techniques, PS, SBAS, Q-PS for the natural terrain areas of Central Aceh.
2. To analyze areas of the potential landslide based on rainfall intensity, local geology, and tectonic activities in Central Aceh based on the InSAR deformation map.
3. To verify deformation measurement (subsidence and uplift) with GIS interpretation.

1.5 Scope of the Study

This research is about landslide monitoring in the natural terrain area. It focuses on the deformation trend either subsidence or uplift, to see if it is possible to predict future landslides with a radar technique application for measuring surface ground movement.

According to Raspini et al., (2015) InSAR technique allows for achieving a result with high accuracy for slow to extremely slow velocity classification rate of the landslide that affecting in large areas, where the vegetation coverage is limited. Therefore, the type of landslide that will be monitored using InSAR techniques is only limited to slow to extremely slow velocity classification (Table 1.1). Cigna et al., (2013) stated that the maximum velocity measurable using PS is ~15 cm/year for C-Band. Rapid landslides cause temporal decorrelation (can not be measured by PS) (Casagli et al., 2017; Crosetto et al., 2016) and SBAS (Berardino et al., 2002). However, landslides with rapid movement due to earthquake-triggered, which is often triggered by heavy rain, are extremely difficult to be monitored by InSAR. This rapid movement velocity rate of landslide excludes from the scope of the study.

Table 1.1 shows the landslide velocity to the highest speed attained after the slope failure, according to the classification of (Cruden & Varnes, 1996). PS and SBAS techniques only can detect extremely very slow movements (velocity < 15 mm/year and < 1.6 m/year (Herrera et al., 2013). All types of landslides such as deep-seated, creep, slide, flows, and complex landslides, as long as their velocities in very or extremely slow can be detected using InSAR techniques.

Table 1.1 The landslide velocity classification and the corresponding potential damage (Cruden & Varnes, 1996)

Velocity Class	Description	Velocity (mm/sec)	Typical Velocity	Probable Destructive Significance
7.	Extremely Rapid	5×10^{3}	5 m/sec	The catastrophe of major violence; buildings destroyed by the impact of displaced material; many deaths; escape unlikely
6.	Very Rapid	5×10^{1}	3 m/min	Some lives lost; velocity too great to permit all persons to escape

5.	Rapid	5 x 10^{-1}	1.8 m/hr	Escape evacuation possible; structures; possessions, and equipment destroyed
4.	Moderate	5 x 10^{-3}	13 m/mth	Some temporary and insensitive structures can be temporarily maintained
3.	Slow	5 x 10^{-5}	1.6 m/yr	Remedial construction can be undertaken during movement; insensitive structures can be maintenance work if total movement is not large during a particular acceleration phase
2.	Very Slow	5 x 10^{-7}	15 mm/yr	Some permanent structures undamaged by movement
1.	Extremely SLOW			Imperceptible without instruments; construction possible without precautions

Another certain limitation of InSAR techniques is the availability of images, an expensive of radar images (e.g. ALOS PALSAR 2 (Advanced Land Observing Satellite The Phase Array type L-band Synthetic Aperture Radar) and TerraSAR-X), the requirement of enough radar time series, long time of processing, a high specification of the computer and the commercial of software for processing tools.

For image acquisition, initially, ALOS PALSAR 2 was commercially provided by JAXA (Japan Aerospace Exploration Agency) is available with high-resolution SAR products, such as range and azimuth (3 x 3) to (8.7 x 5.3) meter of Stripmap Mode. However, the acquisition of multiple resolutions SAR products is an expensive process. One SAR image may cost around 240.000 Japanese Yen (for achieving of Stripmap SAR mode) – 390.000 Yen (new acquisition). Attempts were made to acquire several products of this type (http://en.alos-pasco.com/offer/price.html). Considering the benefit of other SAR images, a SAR Sentinel-1, which is an updated and highly available image acquisition is used for the main radar data. Another benefit of the Sentinel-1 (C Band and 5.6 cm wavelength) is more frequency of revisiting time than ALOS PALSAR (Sentinel-1, 12 days and ALOS PALSAR, 46 days).

For PS analysis the number of images needed is at least 15 - 20 images, the larger the number of available images the better quality and longer monitoring the PS deformation accuracy (Crosetto et al., 2016). Obtaining other than Sentinel-1 was beyond the scope of the available research budget. Hence, this research was a time-series of Sentinel-1A Single Look Complex images which are freely accessed and downloaded from the European Space Agency (ESA). Controlling landslides is not taking consideration in this study. To deliver maximum data with research limited in time, the territory of the research is narrowed, which is located in Central Aceh District, Aceh Province – Indonesia.

The study area is in Central Aceh District, Aceh Province – Indonesia. Landslides in the natural terrain (undulating and rural) areas are associated with steep topography and human activities (deforestation and unplanned farming on steep slopes). Landslides were also induced by an earthquake and high intensity of rainfall amount. Landslide-prone areas, which are located in hilly terrain, are very productive for agricultural purposes whereas the inhabitants depend on agriculture for their livelihood. Hewawasam (2010) stated that deforestation for diversification of vegetation in agricultural fields can increase the landslide occurrences. Extensively growing agriculture on the steep slope such as in the study area can expose to severe landslides.

According to Kolodziejek and Tey (2016), the Silih Nara sub-district of Central Aceh occurred large-scale landslides. Landslides destroyed the irrigation systems 40 years ago. This leads the water from the river can not to reach the village and the agricultural plantation just depend on the rain. Clean water is also hard to find in those districts. Silih Nara and Ketol sub-district is the most destructive village due to landslides induced by Gayo Earthquake, 02 July 2013.

Therefore, landslide monitoring using the InSAR technique uses Central Aceh District, Takengon (capital city) in northern Sumatra Island, Indonesia. Figure 1.1 shows the study area (either small of red or yellow rectangle) with the lake inside. Figure 1.1 also shows the ascending (red) and descending (yellow) of Sentinel-1 with sensor direction and line of sight (LOS) direction. More detail about the study area is explained in Chapter Two Section 2.2 and Section 2.3.

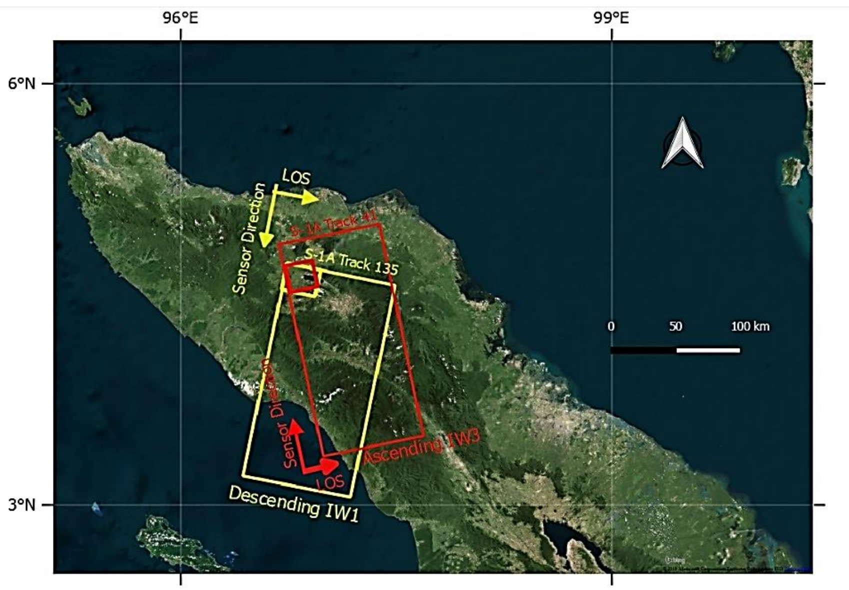

Figure 1.1 Sentinel-1A ascending, track 41 (red) and descending, track 135 (yellow) with Line of Sight(LOS) and sensor direction. A small rectangle of the red and yellow means study area (area of interest) which is Takengon city and a small part of Lut Tawar Lake**.**

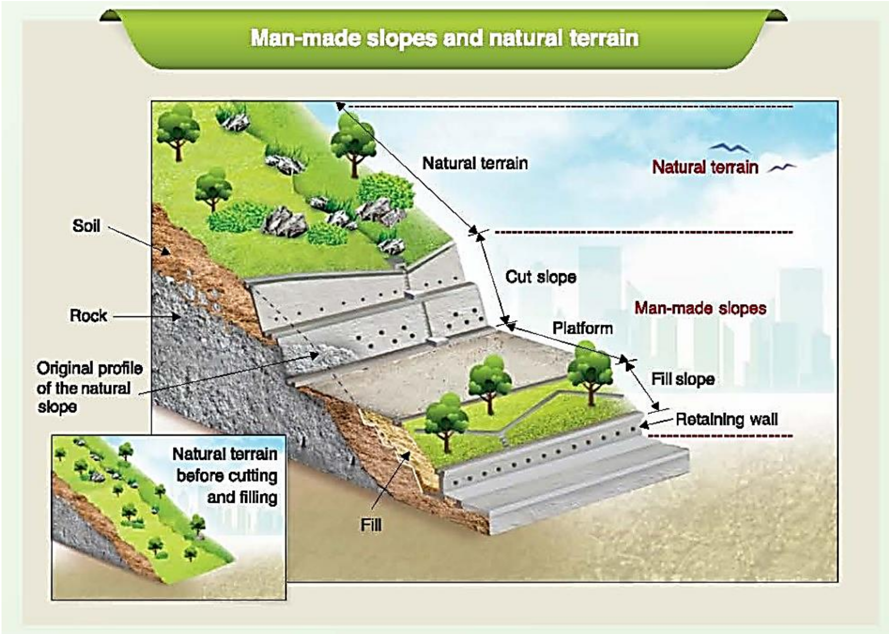

Figure 1.2 Man-made slopes and natural terrain (Geotechnical and Engineering Office, 2016)

The natural terrain for landslide monitoring in this research is described in Figure 1.2. The demand for housing and other infrastructure means that urban development is influenced further into areas of steeper natural terrain. The natural terrain landslide is a natural phenomenon due to its potential threat to urban development.

1.6 Novelty of Study

PS is a suitable technique in urban areas since the technique computes the higher energy reflected more in the urban areas than rural areas. Building and other man-made structures often act as PS due to scattering behavior and high radar reflectivity. Several studies have highlighted and successful for monitoring landslides in an urban area using InSAR techniques (PS, SBAS, and combination method of both techniques) (Bouraoi, 2013;Agram, 2015). However, due to lack of coherence in natural terrain or rural area with the undulating areas. The use of PS techniques in a natural area is limited compared to the SBAS technique. Therefore, there are two approaches to use the PS technique in natural terrain, using PS point density threshold (Hooper, 2006) and using low coherence threshold (Ferretti et al, 2000; Colesanti et al, 2003; Kampes, 2006). The first approach is appropriate in either urban or rural areas. It can be used by InSAR tools, namely StaMPS (Stanford Method for Persistent Scatterer) (Hooper, 2006). StaMPS technique uses a coherence threshold up to 0.4. The application of using this approach has been done by Di Martire, (2013). The study used an archive of SAR images, namely ENVISAT (Environmental Satellite), ERS (European Remote Sensing) and ALOS PALSAR-1. Perissin, (2019) also developed an application tool for deformation monitoring, SARPROZ. The tool can analyze PS and Q-PS techniques, which uses CPT (Partially Coherent Target) approach. Q-PS can detect deformation (subsidence or uplift) in natural terrain (Perissin et al 2007; Razi et al, 2018). In other side, most of the landslide monitoring studies appointed capabilities of using SBAS techniques (Feretti et al, 2002; Hooper et al, 2007). Nevertheless, very little attention on the Q-PS technique (Perissin 2007, Razi et al, 2018).

Nevertheless, very little attention is given or none of the studies performs PS and Q-PS combination techniques with a new and updated Sentinel-1 Satellite, using a different combination of satellite angle (ascending and descending). This study could impact quality and enhance the measurement of deformation in the landslide monitoring of the natural terrain.

The findings of this study are recommended, focus on the application of using combining current radar data in this case Sentinel-1 with many benefits compared to others radar data using different angles (ascending and descending) and different InSAR techniques (PS and Q-PS) for landslide monitoring the natural terrain area.

This study (combining InSAR techniques) can be used for other natural terrain areas with specific similar to the study area.

1.7 Thesis Outline

This thesis consists of five chapters. The first chapter briefly depicts the landslide monitoring systems with InSAR techniques, a general introduction of each common InSAR technique which is PS, SBAS, and Q-PS, and provided landslides related problems in the study area of Central Aceh, Indonesia. The purpose of the research, which is the monitoring landslides in natural terrain areas using InSAR techniques. The second chapter explains the basic elements of landslides. The historical landslides in the study areas are also described with the SAR remote sensing techniques about both platforms and sensors characteristics and different data processing systems. Chapter three shows the research methodology of InSAR techniques for monitoring landslides in natural terrain. Exploitation and a combination of each radar image with an ascending or descending orbit pass with new and an updated Sentinel-1 SAR images have been described. Chapter four describes the application of Sentinel-1 and ALOS PALSAR using SARPROZ and ENVI SARscape application tools, respectively. The measurement of deformation either subsidence and uplift is verified with ground measurement and GIS interpretation. The pattern of surface movement, then connected with geological and tectonic (fault zone) properties. It shows an agreement between radar measurement and geological and tectonic activities. The fifth chapter illustrates the conclusions and recommendations. The appendices are radar dataset selection, daily rainfall amount in 24 years and a short tutorial of PS and Q-PS uses SARPROZ application.

CHAPTER 2 LITERATURE REVIEW

This chapter describes the historical hazards, geology, previous studies of landslides, basic concepts of landslides (Highland & Bobrowsky, 2008), and landslide triggering factors in Central Aceh. The application of landslide monitoring uses an active radar remote sensing in Interferometric SAR (InSAR) techniques which are Permanent Scatterer (PS), Quasi-PS (Q-PS), Small Baseline Subset (SBAS), and previous combined InSAR techniques in the natural terrain area. Space-Borne satellite sensor acquisition and image type were also described. An explanation and an overview of, potential and limitations of the InSAR technique will also be described in this chapter.

2.1 Historical Hazard of Central Aceh

Administratively, Aceh Province is one of the 34 provinces that is a part of Indonesia located in the north of Sumatra Island, Indonesia. Central Aceh, located in the highland area, which is one of twenty-three sub-district/cities in Aceh Province. It lies on Gayo Plateau (which consists of three districts namely Central Aceh, Bener Meriah, and Gayo Lues) has 14 sub-districts with 295 villages. Central Aceh has the second largest lake after Toba Lake in the north of Sumatra, namely Lut Tawar Lake. This lake is surrounded by natural terrain area. Takengon city is located in the western part of the lake. The elevation of the Central Aceh region is about 2000 m above sea level. The area experiences heavy rainfall of 2000 - 2500 mm annually. The maximum annual mean temperature is about 23ºC while the minimum is about 10ºC (BPS, 2016). In Chapter 1, Figure 1.1 shows the Central Aceh (small rectangle) in and Aceh Province of image acquisition. Figure 2.3 (b) shows the Aceh Province, which Central Aceh is in the middle of Aceh Province. Central Aceh has a slope classification of less than 8%, 8-15%, 16-25%, 26-40%, and more than 40%. Based on the slope classification, the dominant slope in Central Aceh is 8-15 % with an area of 167,501 Ha or 36 % of the total area of the regency which is used for plantation and agriculture purposes (BPS, 2016). The most popular is coffee and sugarcane plantation. The forest of the area has been largely destroyed by farmers to increase coffee, sugarcane, and other plantation.

Central Aceh suffers extremely high occurrences of landslides. According to Badan Pusat Statistik (BPS, 2016), the total number of landslides was almost 1240 locations recorded up to 2016. Based on Rusydy et al., (2016), landslide triggered factors in Central Aceh are divided into four factors which are high amount of rainfall intensity, loose type of soil, human activity (cutting slope), and tectonic (local fault) activity. Recently, Central Aceh has built a hydropower station for electricity generation. The tunnel that has been built across the mountains by the government may trigger a landslide.

While other districts in Aceh Province, on the west or north coast, suffer flood and flash floods. Landslide in this area is relatively low, except areas near the toe of the mountain. In Aceh Tamiang District, catastrophic hazards such as landslides and flash floods often occur after heavy rainfall intensity. The major factor of these natural disasters is due to depletion of forests. Environmental damage because of human activity such as illegal logging, mining, and land conversion leads the disaster of the natural environment (Rachman & Harry, 2018).

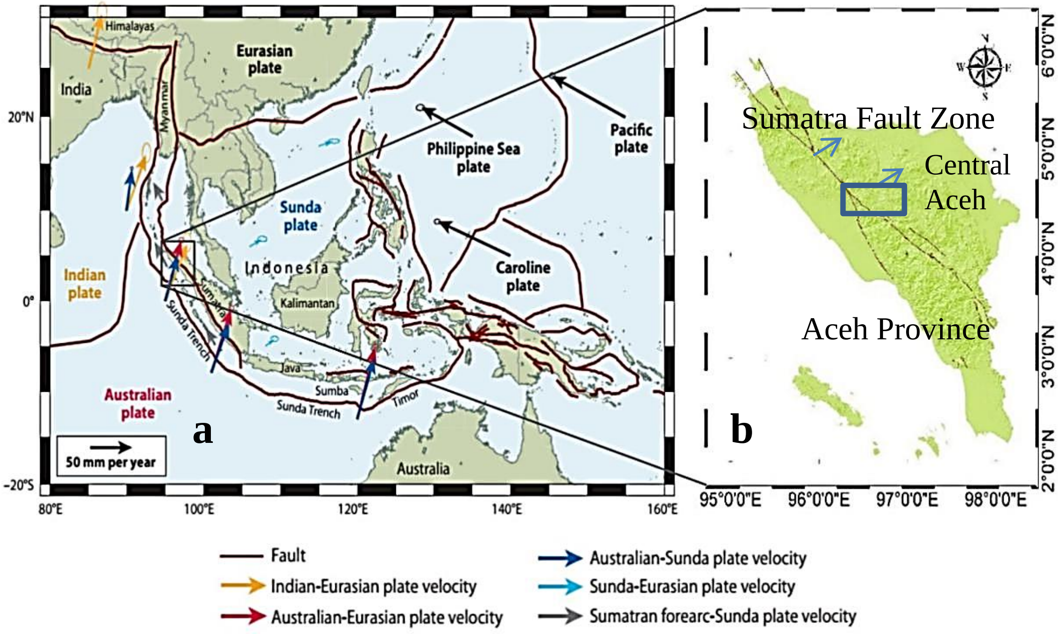

Figure 2.1 a). Plate tectonic setting of Indonesia. Arrows show relative velocities of plate pairs as labeled. b). Aceh province map (Modified from McCaffrey, 2009)

Geographically, Sumatra island lies within the Sumatra Fault Zone, which ruptures from the Semangko Bay to the Andaman Sea. Figure 2.3 shows the fault appears to separate Sumatra Island into two parts (Sieh & Natawidjaja, 2000). The subduction zone as described in Figure 2.3 (a) between the Indo - Australian Plate with the Eurasian Plate exists in the southern part of Sumatra Island (western part of Aceh Province). The Indo - Australian plate moves northward and subducts beneath the Eurasia plate at rates of about 5 cm/year (McCaffrey, 2009).

Figure 2.3 also shows Aceh Province (b) is in the north part of Sumatra Island with Sumatra Fault Zone and Central Aceh is in the middle of the Gayo Plateau. This area has potential deformation due to its Sumatra Fault Zone (SFZ). Based on Sieh & Natawidjaja (2000), the Sumatra Fault Zone in Aceh Province is divided into four segments namely; Seulimum, Aceh, Tripa, and Batee (Figure 2.4). Those segments crossed over Gayo Highland. These segments may be contributed to slope failure in Aceh province. Faults and the structural complexity of an area are often the main factors characterizing landslide-prone conditions. The segments and epicenter of the earthquake near the city of Takengon were described in Figure 2.4.

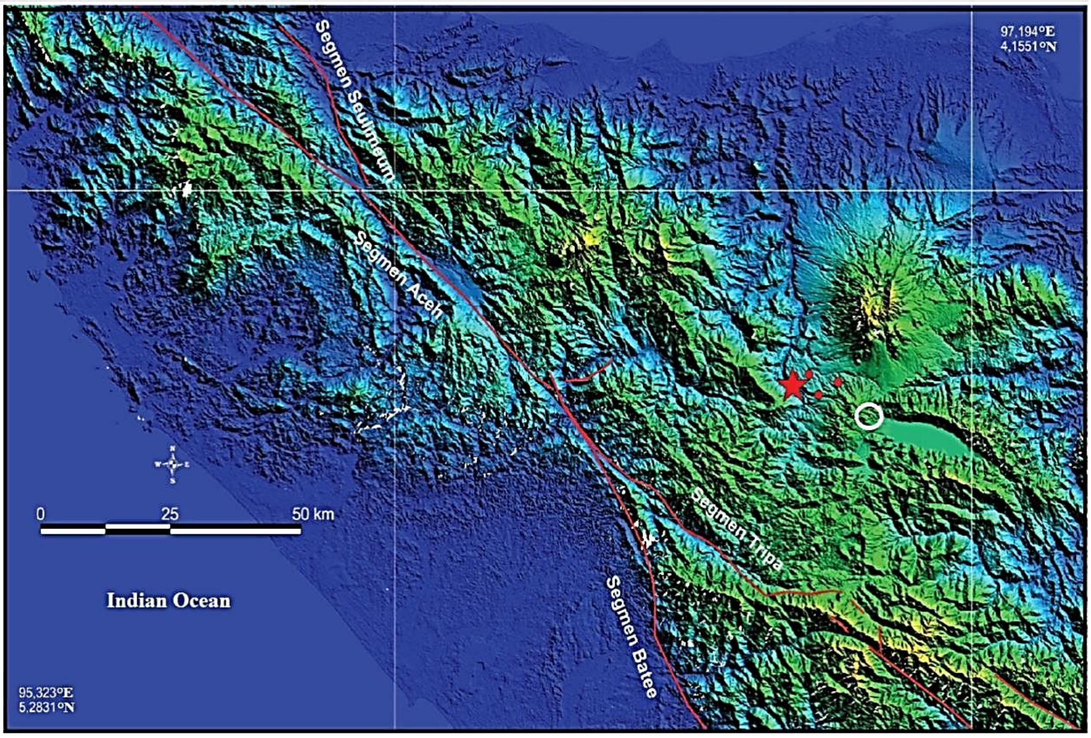

Figure 2.2 Red star is the epicenter of the main earthquake, continuation earthquake (red dots), and Sumatra Fault Zone (red line) and its segments in Aceh Province. The white circle is Takengon city (Modified from Hidayati et al., 2014)

2.1.1 Geology of Central Aceh

The geological structures of Central Aceh consist of faults and folds. Folds and faults are characteristic of a weak zone with the possibility of water saturating the surface layers of soil and rock or soil moving on the sliding plane (Rusydy et al., 2016). Fold axes have a general north to south (N-S) direction. East to the west (E-W) oriented faults indicate a right-lateral strike-slip fault (dextral) with the offset being visible along the cut fold axis. The fault has a younger age compared to the fold (syncline) because it was offset by the fault (Rusydy et al., 2016).

Figure 2.5 shows a geological map of Central Aceh and Bener Meriah Districts. Before becoming a new district, in the past, Bener Meriah is a part of Central Aceh. Geologically, these two districts (Central Aceh and Bener Meriah) have the same geological condition.

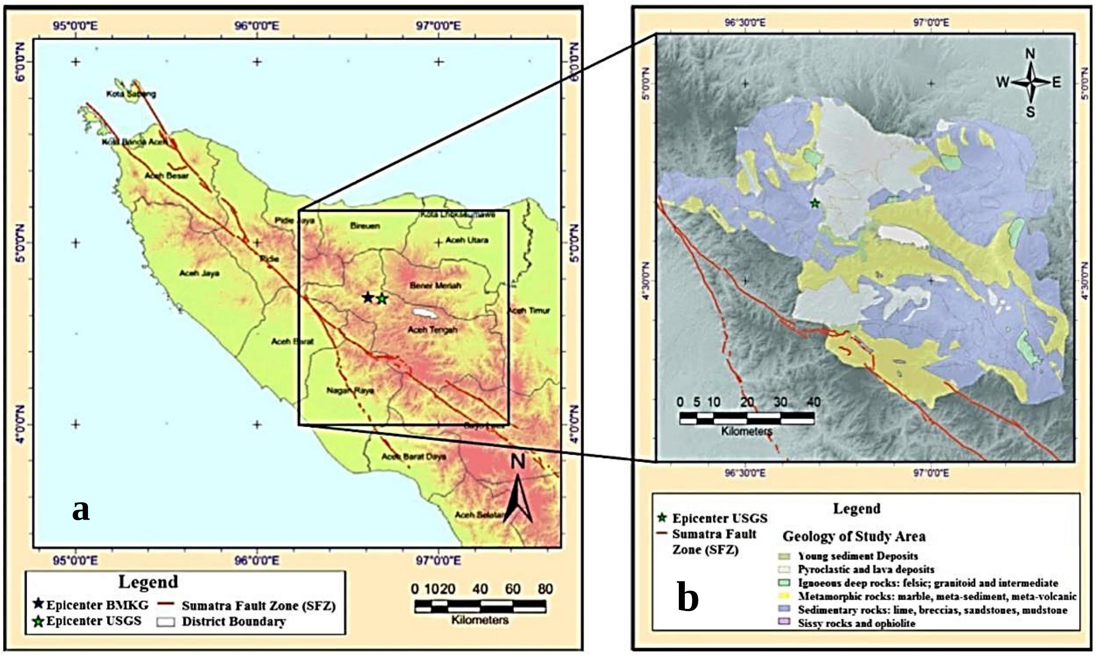

Figure 2.3 a). The epicenter of the Gayo Earthquake is based on USGS (green star) and BMKG (blue star) and Sumatra Fault Zone (SFZ) in red line based on Sieh & Natawidjaja (2000). b). Geological map of Central Aceh and Bener Meriah District (Cameron et al., 1983) (Modified from Rusydy et al. 2016).

According to the local geology map scale of 1:250,000 which was developed by Cameron et al. (1983), Central Aceh and Bener Meriah Region were a part of the geological map of Takengon Quadrangle, Sumatra Island (Indonesia). Both regions have similar complexity in geological conditions. On the west of the site of Lut Tawar Lake, there are deposits of alluvium and deposition of the volcanic fan in quarter periods in specific of Holocene epoch (Qh) or formed about 10,000 years ago. These deposits are found in Kebayakan, Bebesen, Bies and some part of Pegasing. The first two are a sub-district in Takengon city, while Bies and Pegasing are part of the Central Aceh District. The sediments in the Holocene epoch (Qh) are categories as young sediment on the geological time scale. This sediment is loose and soft sediment and less consolidated. In addition, in Ketol and Silih Nara Subdistricts, it is found that the ancient pyroclastic deposit is consists of sand, tuff, breccia, and conglomerates that formed in the Quarternary period which indicates as the soft and loose sediment (Cameron et al., 1983). The oldest rocks found in Central Aceh formed during the Carboniferous at late Paleozoic (248 million years ago). These rocks are from the hilly side of the southern part of Central Aceh. This includes metamorphic rock consisting of quartzite, phyllite, and schist. The intrusive and extrusive igneous rocks were found in Central Aceh that is composed of andesite, rhyolites, basalts, and tetra fine-grained and coarse. This igneous rock was formed about 206 million years ago in the Jurassic Mesozoic era and is a part of the Woyla group. Overall, sedimentary rocks are dominated in Central Aceh. Sedimentary rocks that formed the hillside consist of sandstone, shale, siltstone, mudstone, conglomerate rock, and limestone in the age of the Quaternary and Tertiary period (Cameron et al., 1983).

In the Bener Meriah district, there are Bur Ni Telong and Bur Ni Geuredong volcanoes. Most of the area consists of volcanic rock such as andesite, basalt, and fine-grained and coarse tetra, which is known as an Enang Enang unit (QVee). On the western side of the Bur Ni Telong volcano, it consists of the Lampahan sub-district and on the eastern side of the volcano, it consists of the Pondok sub-district, whereas young volcanic deposits were presented due to past eruption that occurrence about 1.8 million years ago. These deposits consist of sand, tuff, breccia, and conglomerate that formed in the Quarternary period. The western side recognizes as the Lampahan unit (QVL) and the eastern side is the Pepanji unit (Qvp).

In addition, in the Bener Meriah district, some mountains were dominated by metamorphic rocks formed during the Late Permian, Paleozoic era (about 290 million years ago). This metamorphic rock consists of quartzite, phyllite, and schist located in the southern part of the district near the Central Aceh boundary. These metamorphic rocks are immediately adjacent to the limestone at Tawar Unit (MPt). On the eastern side of Bener Meriah, it found the mountains formed by sedimentary rocks such as sandstone, shale, siltstone, mudstone, conglomerate, and limestone.

According to Hidayati et al., (2014), the destruction due to Gayo Earthquake on 2nd July 2013 was not related to the Sumatra Fault but was due to an activity of a new fault in Central Aceh. Morphology analysis showed that dominant lines from the east to the west (NW –SE) around the epicenter of the earthquake (USGS) (Figure 2.6). The lines disappeared with the “ruined” of the young volcano which is consisted of andesite, pumice, breccious, conglomerate, and lava (Cameron et al., 1983).

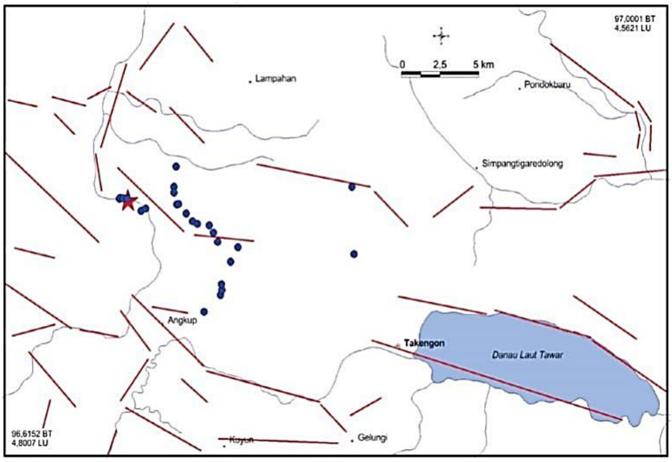

Figure 2.4 Dominant pattern (red lines) based on combination SRTM and topographic map, overlaid with the devastation of the building. The red star is the epicenter of an earthquake (USGS) (Hidayati et al., 2014)

Rusydy et al. (2017) found a new fault in Central Aceh (thick green line in Figure 2.7. It relies on between Pantan Terong Highland to Takengon City near Lut Tawar Lake.

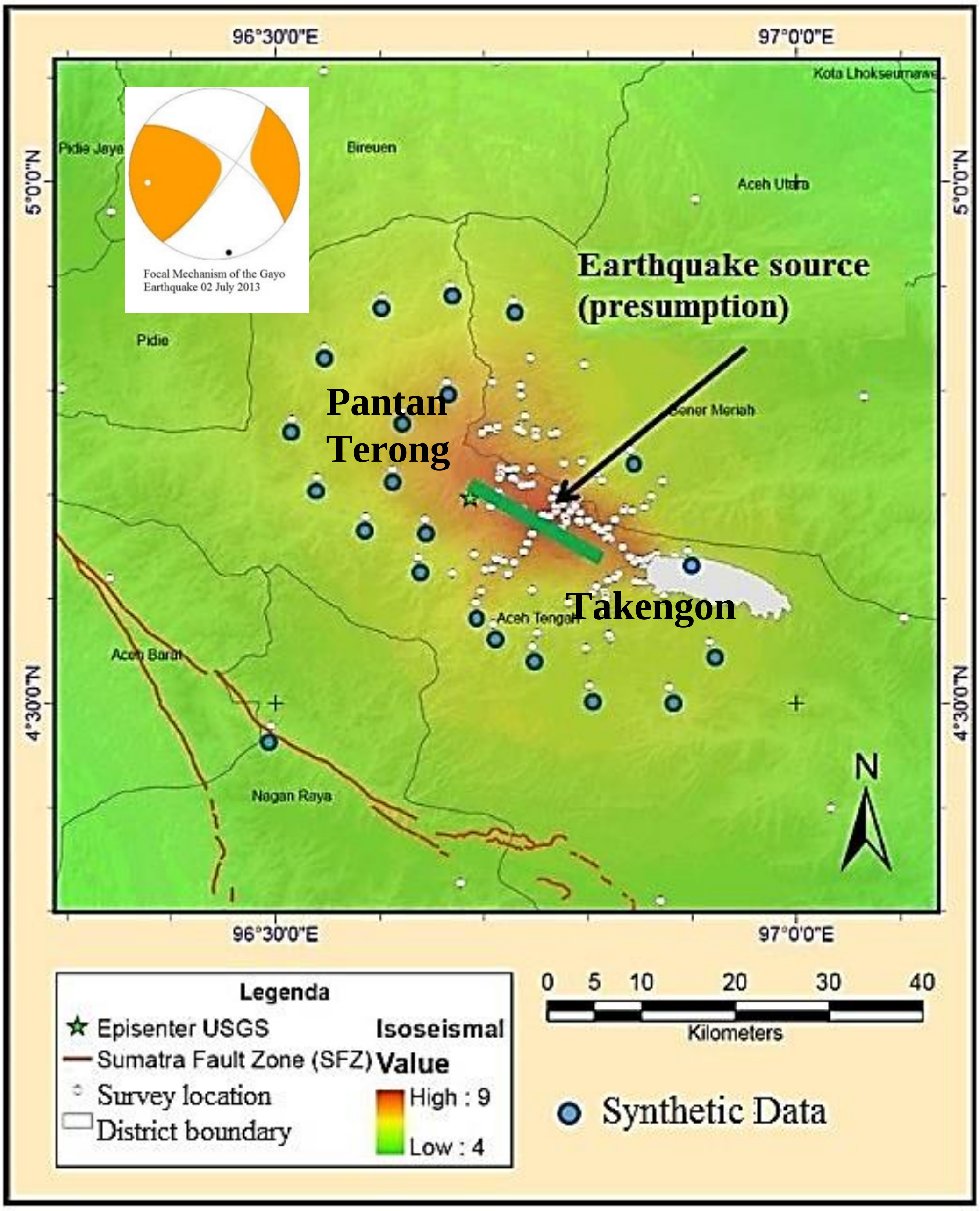

Figure 2.5 Isoseismal map based on the macroseismic and focal mechanism (inset) of the Gayo Earthquake 2nd July 2013 (USGS Source) (Modified from Rusydy et al., 2016)

2.2 Previous Studies of Landslide in Central Aceh

According to Rusydy et al., (2016), there are four types of landslide triggering factors in Central Aceh District, which are landslides induced by the earthquake, landslides induced by the high amount of rainfall (high precipitation), landslides induced by human activity (cut slope) and landslides induced by soft soil type.

2.2.1 Landslides induced by Earthquake

Aceh Province, due to its complex and hazardous location, is known as the laboratory of all research about natural hazards in Indonesia. The most destructive hazard was on Sumatra Andaman Earthquake, which occurred on the 26th December 2004 00:58;53 UTC (Coordinated Universal Time), followed by a giant tsunami causing 108,100 casualties and 127,700 people missing in Indonesia (NOAA = National Oceanic and Atmospheric, Center for Tsunami Research, 2005). In total, at least 283,100 people were killed by the earthquake and subsequent tsunami in 10 countries in South Asia and East Africa (USGS, 2005). The magnitude of the earthquake is 9.1 on the Richter scale with the epicenter located at a latitude of 3.295° North and longitude of 95.982° East. The tsunami wave came from the west coast of northern Sumatra (NOAA, 2005). However, the magnitude of the earthquake from Jet Propulsion Laboratory (JPL) was 9.0 (JPL, 2005). The tsunami caused more casualties than any other in recorded history. Many earthquakes followed after December 2004, such as the Central Aceh Earthquake (Gayo Earthquake) in July 2013 and Pidie Jaya Earthquake in December 2017.

The epicenters of those earthquakes were not only in the ocean but also on the mainland. The epicenter of the December 2004 Earthquake was in the ocean while both the Central Aceh earthquake and the Pidie Jaya earthquake epicenters were in the mainland of Sumatra. The 2004 earthquake was followed by a tsunami and landslide in the submarine (Setyonegoro, 2016) while the earthquake in Pidie Jaya was not, it was a pure earthquake (Syahreza et al., 2018). However, the Central Aceh earthquake has triggered many landslides in areas around the Gayo Plateau (Daryono & Tohari, 2016). Those landslides occurred due to the shallow epicenter depth of 10 kilometers for the Central Aceh earthquake and the distribution of the epicenters of the earthquake in the natural terrain (Daryono & Tohari, 2016). Moreover, the landslides in Central Aceh are specifically due to the area's proximity to the Sumatra Fault (Hidayati et al., 2014). Figure 2.8 shows Sumatra Fault Zone (SFZ) in the mainland that passes the Central Aceh district and the subduction (megathrust) line zone in the Indian Ocean.

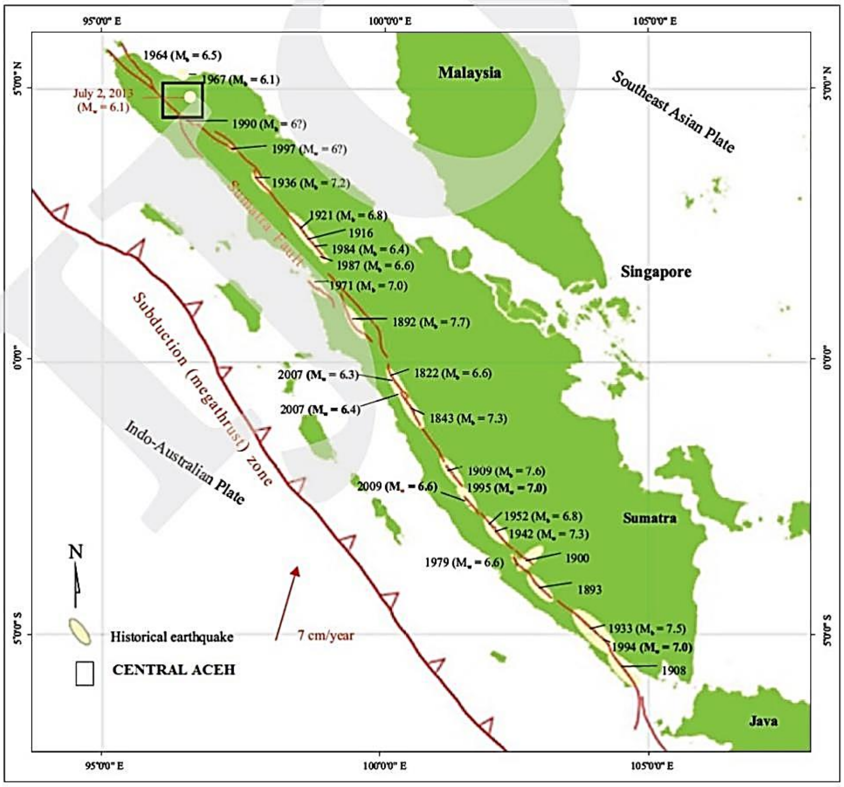

Figure 2.6 Historical of Sumatra Island Earthquake and Sumatra Fault Zone. The black rectangle is the study area (yellow dot inside is the Gayo Earthquake epicenter) (Modified from Daryono & Tohari, 2016)

Table 2.1 shows the parameter of the Gayo Earthquake in 2013. These parameters are; the source (latitude and longitude), magnitude, and depth of the quake.