ASSESSMENT OF GROUND DEFORMATIONS USING INSAR TECHNIQUES AND SHALLOW SUBSURFACE IMAGING IN PULAU PINANG, MALAYSIA

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by

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TABLE OF CONTENTS

CONFERENCES

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF SYMBOLS

A	Absorption
B	Noise bandwidth
G_r	Receiver gain
G_t	Transmitter gain
k	Boltzmann constant
R	Reflection
T	Transmission
T_p	Transmitter power
T_s	Receiving system noise temperature
Ωm	Ohm meter
λ	Wavelength
Σ	Cross-section

LIST OF ABBREVIATIONS

ALOS	Advanced Land Observing Satellite
AOI	Area of Interest
APS	Atmospheric Phase Screen
ASAR	Advanced Synthetic Aperture Radar
ASF	Alaska Satellite Facility
ASI	Amplitude Stability Index
BF	Batu Ferringhi
DC	Direct Current
DEM	Digital Elevation Model
DInSAR	Differential Interferometric SAR
DS	Down Sampling
ER	Electrical Resistivity
ERS	European Remote Sensing
ESA	European Space Agency
ENVISAT	Environmental Satellite
EW	Extra Wide Swath
GIS	Geographic Information System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GRD	Ground Range Dataset
GUI	Graphical User Interface
InSAR	Interferometric SAR
ISA	International Standard Atmosphere
IWS	Interferometric Wide-Swath
JRC	Joint Research Centre
JWTC	South China Joint Typhoon Warning Centre
LOS	Line of Sight
LULC	Land Use Land Cover
MISP	Multi-Image Points Processing
ML	Multi-Looking
MST	Multi-Spanning Tree
PC	Personal Computer

PH	Penang Hills
PRF	Pulse Repetition Frequency
PS	Persistent Scatterers
PSC	Persistent Scatterer Candidate
PS-InSAR	Permanent Scatterer Interferometric SAR
PT	Paya Terubong
QPS	Quasi Permanent Scatterer
ROI	Region of Interest
S-1A	Sentinel-1A
SBAS	Small Baseline Subset
SAR	Synthetic Aperture Radar
SLC	Single Look Complex
SM	Strip-map
SRTM	Shuttle Radar Topography Mission
TB	Tanjung Bungah
TOPS	Terrain Observation with Progressive Scans
WV	Wave

LIST OF APPENDICES

PENILAIAN NYAHPEMBENTUKAN TANAH MENGGUNAKAN TEKNIK INSAR DAN GAMBARAN BAWAH TANAH DI PULAU PINANG, MALAYSIA

ABSTRAK

Deformasi tanah memberi ancaman yang ketara terhadap nyawa dan harta benda penduduk di Pulau Pinang, Malaysia. Ia biasanya berlaku apabila terjadi hujan lebat yang berterusan. Kaedah-kaedah terdahulu mengenai bahaya ini adalah berdasarkan kepada simulasi, pemodelan dan isu-isu kejuruteraan geo. Namun, tiada yang mengukur pergerakan menggunakan teknik *Interferometric Synthetic Aperture Radar* (InSAR). Dalam penyelidikan ini, gabungan teknik InSAR dan geofizik diperkenalkan untuk menilai potensi dan sebab-sebab kemungkinan zon-zon bahaya di Pulau Pinang. Kawasan ini dipilih untuk penyelidikan kerana mempunyai daya reflek dan potensi anjakan tanah yang tinggi. Teknik *Permanent Scatterer- InSAR* (PS-InSAR) dan *Small Baseline Subset- InSAR* (SBAS-InSAR) digunakan untuk memantau, mengukur, dan memetakan deformasi kawasan. Enam puluh set data *Sentinel-1A* (S-1A) menaik dan lima puluh enam set data *Sentinel-1A* (S-1A) menurun diperoleh antara 2016 dan 2019 dan sembilan belas *ENVISAT ASAR* menurun diperoleh dari tahun 2003 hingga 2010 diproses dan dianalisis. Tinjauan *Electrical Resistivity* (ER) dan *Ground Penetrating Radar* (GPR) dilakukan di beberapa laman web terpilih berdasarkan hasil peta deformasi InSAR. Akhir, *Geographical Information System* (GIS) and *Statistical Package for the Social Sciences* (SPSS) digunakan untuk menganalisis hasil InSAR secara spasial dan mengaitkannya dengan beberapa parameter luaran seperti pemendakan, pembandaran, tanah dan geologi, analisis tanah yang diambil semula di kawasan kajian . Hasil InSAR mengenal pasti beberapa deformasi tanah aktif dengan nilai penurunan tertinggi antara -10.00 mm/thn dan -15.16 mm/thn dan nilai kenaikan dari 5.00 mm/thn hingga 12.25 mm/thn untuk set data S-1A dan ASAR. Teknik InSAR disahkan dengan menggunakan pemerhatian Sistem Pendudukan Sejagat yang dilakukan pada tahun 2015 di Pulau Pinang. Kawasan dengan nilai rintangan yang rendah antara 0 dan 20 Ωm dikelaskan sebagai zon tepu. Anomali GPR sepadan dengan penurunan titik PS. Penggabungan InSAR dan hasil geofizik sesuai dengan gangguan di bawah permukaan. Aplikasi teknik InSAR dan geofizik telah meningkatkan kefahaman kedua-dua mekanisma permukaan dan permukaan bawah, mengurangkan ketidaktentuan di dalam hasilnya, dan menyelidik kawasan deformasi tanah yang aktif.

ASSESSMENT OF GROUND DEFORMATIONS USING INSAR TECHNIQUES AND SHALLOW SUBSURFACE IMAGING IN PULAU PINANG, MALAYSIA

ABSTRACT

Ground deformation presents a significant threat to people's lives and properties in Pulau Pinang, Malaysia. It usually occurs when there is continuous heavy rainfall. Previous methods on this hazard were based on simulation, modelling, and geo-engineering issues. Still, none of them quantified the movements using the Interferometric Synthetic Aperture Radar (InSAR) technique. In this research, a combination of InSAR and geophysical techniques is introduced to assess the potential hazard zones and the possible causes in Pulau Pinang. This region was chosen for this research as it has high reflectivity and ground displacement potential. Permanent Scatterer- InSAR (PS-InSAR) and Small Baseline Subset- InSAR (SBAS-InSAR) techniques were used to monitor, quantify, and map the region’s deformations. Sixty ascending and fifty-six descending Sentinel-1A (S-1A) datasets obtained between 2016 and 2019 and nineteen descending ENVISAT ASAR acquired from 2003 to 2010 were processed and analysed. Electrical Resistivity (ER) and Ground Penetrating Radar (GPR) surveys were conducted at some selected sites based on InSAR deformation maps' results. Finally, Geographical Information System (GIS) and Statistical Package for the Social Sciences (SPSS) were used to spatially analyse the InSAR results and relate them to some external parameters such as precipitation, urbanisation, soil, geology, reclaimed land analyses of the study area. InSAR results identified some active ground deformation with the highest subsidence values ranging between -10.00 mm/yr and -15.16 mm/yr and uplift values from 5.00 mm/yr to 12.25 mm/yr for the S-1A and ASAR datasets. InSAR techniques were validated using Global Positioning System (GPS) observation conducted in 2015 in Pulau Pinang. The areas with low values of resistivity ranging between 0 and 20 Ωm were classified as saturated zones. The GPR anomalies correspond to the subsidence PS points. The integration of InSAR and geophysical results correspond well with disturbances in the subsurface. The application of InSAR and geophysical techniques has improved the understanding of both the surface and subsurface mechanisms, reduced uncertainty in the results, and investigated active ground deformation areas.

CHAPTER 1

INTRODUCTION

1.1 Background

Three hundred million people (4-5 %) of the world population live in hillside areas, and sixty-six million people live in high-risk zones (Di Martire et al., 2016). Ground deformation such as sinkhole, landslides, subsidence, etc., is considered as a high risk-zone. Ground deformation monitoring is essential to mitigate natural hazards. Recently, ground deformation activities have dramatically increased globally and in Malaysia in particular. It has affected lives and properties (Pradhan et al., 2014). Pulau Pinang is one of Malaysia's regions with the highest landslide occurrences (Ahmad and Lateh, 2012). Weather conditions (e.g., heavy rainfall), human activities (urbanisation, deforestation, and hill cutting), and soil composition are the main reasons for these occurrences (Ahmad and Lateh, 2012; Pradhan et al., 2014). Pulau Pinang is composed of residual soil formed under tropical weathering conditions from accumulating organic material and staying where it was formed (Ahmad et al., 2006). The island is underlain by granitic rock (Tan, 1994; Hashim et al., 2018).

Landslide is one of the most significant natural geohazards driven by gravity (Ahmad and Lateh, 2012; Bekler et al., 2008; Kavzoglu et al., 2014; Saadatkhah et al., 2016). It is estimated to cause almost 1000 deaths every every year, where properties worth 4 billion US Dollars are lost globally (Lee and Pradhan, 2006; El-rahman, 2017). The failures of landslides are inevitable around steep slope areas (Borghero, 2017; Di Martire et al., 2016; Mirzaee et al., 2017), especially during the rainy season when water adds weight to the upper layer of soil and lubricates it (Chowdhury and Flentje, 2014; Nikolaeva and Walter, 2013). The consequences vary depending on the number of activities, such as the presence of people, the number of buildings, constructed roads, and agricultural farming in the area.

On the other hand, subsidence is the downward movement of the earth's surface, mostly caused by water pumping, fracking of hydrocarbons, and mining mineral resources from the ground (Chen et al., 2018). The amount of soil moisture is also a concern. Leaking drains can weaken the soil or wash the soil away, making the ground susceptible to subsidence patterns. Also, during the hot weather, clay soil will compress, crack, and move, creating all sorts of instability on the ground. Subsidence can occur over a large area and be detected using field based methods (extensometer, inclinometer, GPS, remote sensing methods (InSAR).

The economic and population growth with limited flatlands in Pulau Pinang leads to the exploitation of hill slopes for road construction and infrastructure building. The need to expand the island has necessitated the state government to allow high-rise buildings (condominiums and apartments) on artificial islands, reclaimed land, and hill slopes (not exceeding 76 m above sea level (asl) and 25^{o} in gradient) (Majid et al., 2020). However, some developers build infrastructure and other modern amenities on unstable, unsuitable, and dangerous rocks without considering the subsurface conditions (Meteorological Malaysia Department, 2018). The activities above have increased the area's impact of ground movement, leading to heavy road traffic, damages to properties, and sometimes loss of lives. A worthy example was the landslide case in Tanjung Bungah in 2017 when the earth swallowed eleven people after reducing a slope of 18^{o} in gradient to 67^{o}, which led to ground instability (Chacko, 2019). Another incidence was a collapsed retaining wall protecting the road at a newly completed housing area built on a hillslope, a water catchment area, at Tanjung Bungah, Pulau Pinang. Because of heavy and persistent rainfall, the soil became soft and unable to sustain the concrete barrier. Another worthwhile example was the subsidence and sinkhole events in Mount Erskine, Tanjung Tokong, in 2017, where eight families lost their houses to heavy rain that lasted for hours. The rain caused the soil to lose its cohesion and sink, which caused some buildings to shift after weakening their structural strength (Yahaya et al., 2019).

There have been several works on landslide but few on subsidence in studying the dynamics of ground deformation in Pulau Pinang (Lee and Pradhan, 2006; Pradhan and Lee, 2010; Pradhan et al., 2012; Khodadad and Jang, 2015). The ground movement needs consistent and continuous recordings using monitoring systems (Perissin and Wang, 2012). It can be monitored using the global positioning system (GPS), extensometer, and inclinometer. They have the advantage of high accuracy for monitoring but only cover small areas and are susceptible to damages during the occurrence of ground movements (Bayer et al., 2017; Thuro et al., 2010).

Optical and radar remote sensing data are widely used for ground deformation detection and monitoring (Richard et al., 1993; Tofani et al., 2013; Cigna et al., 2013; Tymchenko et al., 2016). Field surveys have been applied for ground deformation identification and characterisation because they are useful for investigations at the local scale and known deformation areas. However, remote sensing imagery covers large spatial and temporal scales for ground deformation detection, monitoring, and mapping (Tofani et al., 2013; Di Martire et al., 2016). The Synthetic Aperture Radar (SAR) system of remote sensing techniques is the most concern in this work. This research focuses more on Interferometry Synthetic Aperture Radar (InSAR) technique as it offers the following advantages

i. it has been used for measuring ground deformation for a few decades (Nikolaeva and Walter, 2013; Devanthéry et al., 2016; Razi et al., 2018)
ii. it provides accurate measurements of the radiation travel path due to its coherent feature (Karila et al., 2013; Costantini et al., 2014)
iii. it gives background information about the study areas through the exploitation of archived and historical satellite imagery to recognise potential zones of landslides activities (Yang et al., 2014)
iv. it is free of geotechnical ground-based surveys (Di Traglia et al., 2018), offers global coverage (Luo et al., 2014), and enables researchers to study past unreachable areas (Chen et al., 2018; Eriksen et al., 2017).

InSAR creates an opportunity to extend the knowledge obtained to the more massive landslide and subsidence areas by setting up a field laboratory to carry out geophysical studies to describe subsurface mechanisms that might trigger landslide and induce subsidence occurrences.

Multi-temporal InSAR techniques have recently been established to calculate the deformation signal from pixels with various scattering properties. There are currently two types of multi-temporal InSAR algorithms: Persistent Scatterer (PS) and Small Baseline Subset (SBAS). PS technique exploits multiple SAR images (slave) over the same region at different acquisition times, relating to one adequately chosen master (Ferretti et al., 2001). It has been used to overcome the errors introduced to the results via atmospheric conditions on the radar pulses and changes in the ground reflectivity due to differences in the ground's vegetation or moisture content (Hung et al., 2011). SBAS technique is a popular approach in slow deformation detection (Virk et al., 2019).

A geophysical survey is a powerful approach that has been used for a few decades in different fields (Perrone et al., 2006; Wilkinson et al., 2012; Giocoli et al., 2015). It is used to provide accurate data on the subsurface characterisation. Some of the available geophysical methods are the Ground-penetrating Radar (GPR), gravity, seismic, resistivity, and magnetic.

However, electrical resistivity (ER), with the advantage of determining the depth to shallow subsoil and ground-penetrating radar (GPR) used to locate underground anomalies without disturbing the ground, is used in this research. The ER measurement has been applied to investigate ground deformation areas (Perrone et al., 2006; Muztaza et al., 2012; Nouioua et al., 2013; Gance et al., 2016). It offers rapid and cost-effective subsurface valuable information about the geological setting and water-saturated ground deformation areas (Gance et al., 2016).

GPR has also been used extensively to characterise subsoil structures and processes (Gutiérrez et al., 2009; Anchuela et al., 2009; Nouioua et al., 2013). It is a non-destructive technique that generates vertical cross-sectional images of the shallow subsurface (radargram) (Nouioua et al., 2013). Its operation is based on transmitting a signal of high-frequency microwave electromagnetic energy into the ground. The antenna receives the reflected energy, where the results depend on the soil type and the equipment used.

These two techniques (remote sensing and geophysical methods) are applied to investigate ground movement and image subsurface of the earth to detect potential displacement regions and provide possible triggering mechanisms in Pulau Pinang, Malaysia. This research presents the potential of InSAR techniques and geophysical surveys to detect and monitor two types of ground deformations (subsidence and landslides) in the study area.

1.2 Study Area

Pulau Pinang was chosen as the study area because it is a landslide-prone area due to its terrain and weather conditions (tropical rainfall) (Pradhan and Lee, 2010). The high reflectivity (due to ground cover by tall buildings and constructions along the hills), different topography (high elevated hills in the centre and flat areas to the east and west), ground displacement potential, and the abundance of previously performed geotechnical studies make the research area credible.

It is located on the Northwest coast of Malaysia Peninsula (Figure 1.1) with a geographical coordinate of (between latitudes 5° 15’ 30” N and 5° 29’ 0” N, and longitudes 100° 20’ 0” E and 100° 29’ 0” E) (Figure 1.1). It is one of the most developed regions in Malaysia. The prevalence of natural resources, rapid urbanisation, and adequate security encouraged a high population influx into Pulau Pinang (Chee et al., 2017; Paradella et al., 2015). Plantation forest, peat swamp forest, inland forest, scrub, ex-mining site, and grassland are predominantly land use (Pradhan and Lee, 2010).

The landmass of Pulau Pinang is approximately 300 km^2, with an estimated population of 720,000 people. More than half of the land is hilly, coupled with a maximum rainfall of 647 cm per year (Chee et al., 2017; Ooi, 2015; Meteorological Malaysia Department, 2018). Due to the high annual rainfall, the region is vulnerable to severe land hazards like subsidence, landslides, and the collapse of human-made buildings (Ooi, 2015). Uphill houses, deforestation, and natural erosion also form part of urban soil instability (Chee et al., 2017).

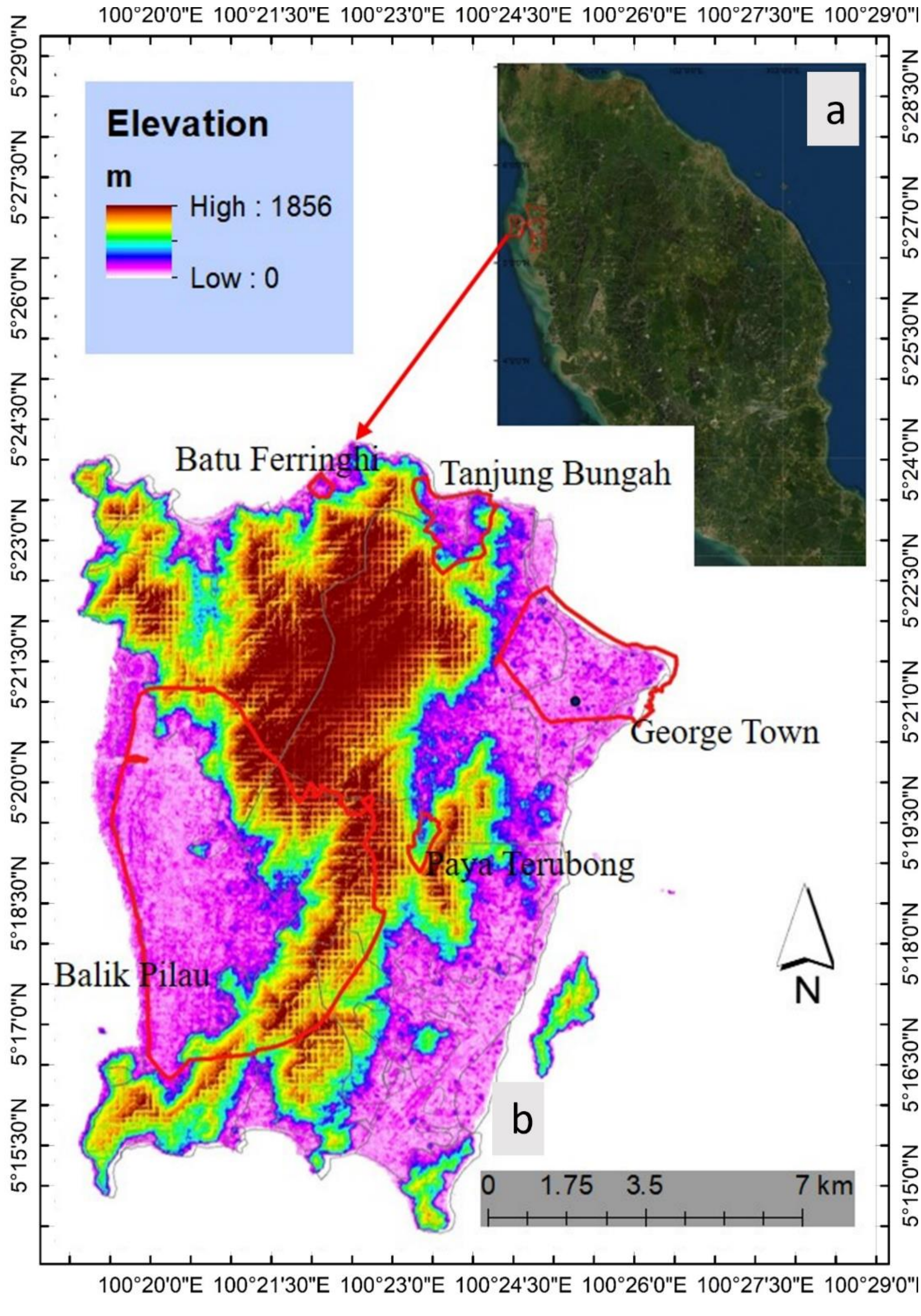

Figure 1.1 (a) Map of Malaysia Peninsula and (b) Map of Pulau Pinang with its Digital Elevation Model (DEM). The areas where field surveys were performed are highlighted in red colours.

The study area's topography based on the Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) with a 30 m resolution is shown in Figure

1.1. The elevation ranges from 0 to 420 m above sea level (asl), with the highest in the northern part and lowest in the western region. The island's slope varies between 25° and 87° in gradient (Pradhan et al., 2012).

1.3 Problem Statement

There is an increase of population growth in Pulau Pinang due to developments of infrastructure and other modern amenities. The government allows expansion on hills and reclaimed lands due to limited flat lands to cater for the increase in population influx and urbanisation. The development activities on hills and reclaimed lands usually lead to various slope failures and ground deformations particularly in the rainy and most times lead to heavy road traffic, damages to properties, livestock, cars, agricultural produce, businesses, and even cause loss of lives.

Various approaches have been applied to predict ground movements in Pulau Pinang using different models and methods. Past studies focused on observations of ground deformation hazards using GIS. Previous studies also focused more on engineering and environmental issues. Most of the studies were concerned about the modelling, prediction and simulation (Pradhan and Lee, 2010; Pradhan et al., 2012) of ground movements after the hazards. The probabilistic model was applied by constructing a spatial database using available digital maps (topographic, soil, drainage, geology, land cover). A lot of landslide data is required for the model to be implemented more widely.

Other studies (Hussein et al., 2010; Bery, 2016; Ismail et al., 2018) also focussed on subsurface characterisation using geophysical methods. These methods can only be applied to characterise certain selected areas unlike InSAR that can map and quantify the ground movements of the entire island. Past studies never worked on the time series of the movements; instead, they were more specific in a small area. None of the applied approaches quantified the rate of the ground movements in the area. Still, a combination of InSAR and geophysical methods has not been applied in Pulau Pinang.

Therefore, the displacement rate of ground deformations can be known through the remote sensing (InSAR) technique, and some causes for the movements can be studied using geophysical methods. The integration of the two (InSAR and geophysical) techniques give a better opportunity to assess the potential hazard zones and know the possible causes of the hazards in Pulau Pinang. Some external factors are analysed and related to the existence of the deformation.

1.4 Research Objectives

The aim is to assess active movements in Pulau Pinang and provide possible causes of the movements.

The objectives are to:

v. assess ground deformations using the InSAR (PS and SBAS) techniques and validate the results using the existing GPS result
vi. detect saturated zones and subsurface structures with the application of geophysical (ER and GPR) methods
vii. spatially analyse and integrate both results (InSAR and Geophysical method) to understand the influence of urbanisation, rainfall trend, geology, and topography on ground deformation in the study area

1.5 Scopes and Limitations

The scope of this research focuses on InSAR and geophysical techniques to identify and map the ground movement of Pulau Pinang (between 2003 and 2019). The geophysical methods are limited to certain selected areas (that show high subsidence trends) based on InSAR analyses, although the entire island was mapped. InSAR techniques give excellent information about deformation activities on the surface. The geophysical method images subsurface regions and extracts physical information. The satellite imageries used in this research are limited to Sentinel-1A (S-1A) and ASAR datasets.

1.6 Novelty and Significance of the Study

This work has assessed, quantified, and reported some potential ground deformation areas for Pulau Pinang, Malaysia, using two different InSAR techniques (PS and SBAS) with two different satellite imageries (S-1A and ASAR datasets). The time-series results has been created to reveal the ground displacement activities of Pulau Pinang. This work also integrates InSAR and geophysical methods for the first time in Pulau Pinang to investigate potential ground deformation areas and state some possible causes for the deformations. The results show that the combined methods are powerful tools for studying ground deformation areas.

1.7 Thesis Outline

The arrangements of the thesis are explained in this part. The thesis has five chapters.

Chapter 1 contains the introduction to the study, where the background of the research is described. The study area, problem statement, research objectives, scopes and limitations, and the study's novelty and significance are also stated.

Chapter 2 presents a general introduction on ground deformation, landslides' basic concepts, classifications, factors affecting it, landslides in Malaysia, landslides of Pulau Pinang, and previous studies on landslides. The basic background, causes and effects, and earlier studies of subsidence are explained. This chapter also deliberated Radar and SAR systems. InSAR's basic concept, its applications, and Multi-temporal InSAR are explained. Finally, the introduction, essential components, applications, mode of operation, and the theoretical background of geophysical methods are described.

Chapter 3 explains the materials and methods of the two techniques (InSAR and geophysical methods) to investigate the ground deformation areas. The datasets (S-1A and ASAR) and the methods (PS and SBAS) used to process them are discussed. The geophysical methods (ER and GPR) used for mapping the subsurface features on the Island are explained.

In Chapter 4, the results from InSAR techniques and subsurface imaging are discussed. The statistical analyses of InSAR results using SPSS software are also discussed. The results from both the GPS and borehole data are discussed accordingly to validated our studies. The obtained results from the two (InSAR and Geophysical) methods spatially analysed using GIS are presented.

Finally, Chapter 5 concludes this research. Some recommendations for future research and the challenges encountered during the study are stated.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the last two decades, remote sensing and geophysical methods have steadily improved our ability to detect and monitor ground deformation, mainly landslide and subsidence areas (Perrone et al., 2006; Schrott and Sass, 2008; Roque et al., 2014; Büyüksaraç et al., 2014; Barla et al., 2016; Declercq et al., 2017). The basic concept of landslides and subsidence trends are discussed in section 2.2 and section 2.3, respectively. Ground deformation studies have increased dramatically in recent years to reduce the socio-economic harm they cause (Wasowski and Bovenga, 2014; Azadnejad et al., 2019). The causes of ground displacement include urbanisation, reclaimed land, hill-cutting, and deforestation. Increased rainfall also plays a vital role because of changes in weather patterns, tectonic activity, and volcanic eruptions (Thuro et al. 2010). Since ground deformation monitoring is essential to minimise these natural hazards, the basic concepts of the modern technique (remote sensing) used in this research are presented in section 2.4. As this study utilises InSAR and geophysical techniques, their basic concepts are discussed in sections 2.5-2.7.

2.2 Landslides

Landslide is the most dominant natural hazard causing significant loss of lives and damages to buildings, roads, waterways, livestock farms, and powerlines every year across the globe (Kundu et al., 2013). It is one of the most pronounced ground movements in Pulau Pinang, Malaysia. It is the downward movement of rock, soil, and organic material under the effects of gravity (Cruden, 1991). There are five types of landslides: slides, topple, fall, flow, and spread. The failures can occur within minutes and range from a single to tens of thousands if triggered by earthquakes and range between days and weeks if triggered by heavy rainfall (Malamud et al., 2004). Generally, most landslides cannot be prevented, but the nature of the slides that fail, when, where, how, and why they fail can be studied. Early warnings and predictions based on the observations and analyses are essential to reduce subsequent occurrences and the losses they usually cause (Inada and Takagi, 2010).

2.2.1 Classification of Landslides

The main criterion for classifying the various types of landslides involves the nature of the movement associated with rockfall, deep-seated slides, or internal debris flow and mudflow that takes place (Perski et al., 2009). Landlside can also be classified as topples, lateral spreads, and, flow, slides- rotational and translational (shallow and depth) (Rahman and Maqjabil, 2017). The type of material that moves is also necessary, precisely if it is solid rock or unconsolidated (weaker) sediments. Unconsolidated sediments are not cemented and have not been significantly compressed by overlying materials.

Slopes made of clayey formations (which are fragile and weak and allow the passage of water) can be affected by slow-moving landslides (Casagli et al., 2016; Lari et al., 2014). The movement (usually controlled by external factors like rainfall, temperature, snowmelt) is the main criterion for characterising landslide (Chalkias et al., 2014; Iverson et al., 2015). As previously stated, any landslide can be characterised and described using the materials and movements (e.g., rock fall, debris flow) shown in Table 2.1.

Table 2.1 Classes of landslides (Source: Rahman and Maqjabil, 2017)

S/N	Type of movement	Type of materials		
		Bedrock	Engineering Soils	
			Predominantly Coarse	Predominantly Fine
1	Fall	Rock Fall	Debris Fall	Earth Fall
2	Topple	Rock Topple	Debris Topple	Earth Topple
3	Slide	Rock Slide	Debris Debris	Earth debris
4	Spread	Rock Spread	Debris Spread	Earth Spread
5	Flow	Rock Flow	Debris Flow	Earth Flow
6	Complex	Combination of two or more principle types of movement		

Similarly, Figure 2.1 describes the different types of landslide. Falls (Figure 2.1a) are the abrupt separation of geologic elements (rocks and boulders) from steep slopes.

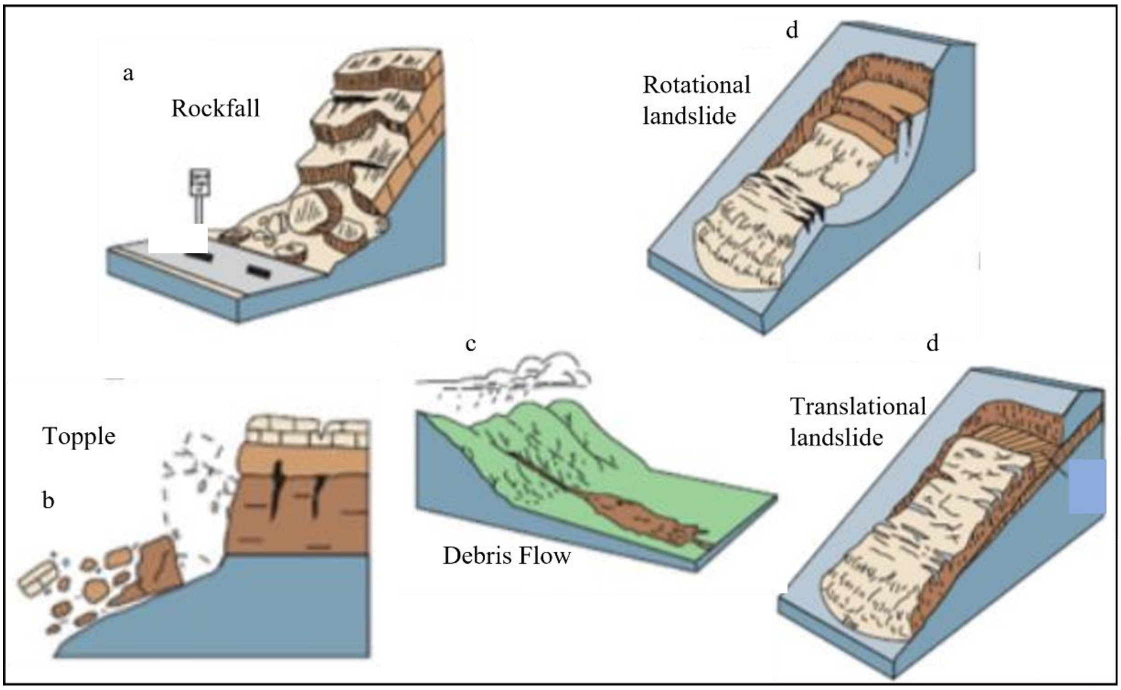

Figure 2.1 Schematic diagram of the types of landslide

The forward rotation under the influence of gravity is identified as toppling failures (Figure 2.1b). A flow (e.g., debris) is a type of rapid mass movement in which a slurry containing loose soil, rock, organic matter, air, and water mobilises and flows downslope (Figure 2.1c). Spread movement usually occurs on very moderate slopes or flat terrain (Figure 2.1d-e).

2.2.2 Factors affecting Landslides

There are many factors that can trigger landslides. Table 2.2 shows some of the factors that trigger landslides.

Table 2.2 Landslides causative factors (Source: Rahman and Maqjabil, 2017)

S/N	Geology	Morphology	Human Activities
1	Weathered materials	Tectonic eruption	Excavation of slope
2	Sheared, materials	Subterranean erosion	Deforestation Irrigation
3	Discontinuity materials	Deposition loading slope	Mining

Deforestation (which weakens the tree root structure, thereby making the land liable to slide) (Radutu et al., 2017), cirque landform, and lateral slope-cutting for high rise buildings (Ooi, 2015) are among the factors affecting landslides. Other phenomena like volcanic activities, gravity, earthquakes (Roque et al., 2014), snow melting, changes in groundwater disturbances, and heavy rainfall can generally cause landslides (Mostafa, 2012). Similarly, extraction of ground oil (Marco et al., 2014) and vibrations from heavy machinery for construction (Virk et al., 2019) can trigger landslides. The compacted soils become looser and weaker and allow the passage of water through the slope. The geological condition of an area also influences the formation, acceleration, and development of landslide.

2.2.3 Landslides in Malaysia

This section of the thesis examines the history of ground deformation (landslides and subsidence) in Malaysia where various techniques and methods have been applied in different areas to study and monitor landslide occurrences and subsidence patterns. Landslide is a consistent threat to residents, settlements, and infrastructures. It claims lives and devastates valuable properties in Malaysia and, particularly, in Pulau Pinang. It arises from steep slopes, hilly areas, near high-rise housing areas, edges of roads, and highways (Sulaiman et al., 2019). Malaysia is split into two major parts, namely Peninsula Malaysia and Borneo Island with an area of 330,200 km^2 (Majid et al., 2020). Multiple natural disasters, such as landslides, subsidence, mudslides, and floods, are common in Malaysia due to heavy rainfall, rapid urbanisation, socio-economic development (such as road network, highways, dams, high rise buildings on hills, etc.), and poor slope management (Rahman, 2017). Peninsular Malaysia accounts for 76 % of landslide events in Malaysia's 21000 landslide-prone zones, whereas Sabah and Sarawak account for 14 % and 9 %, respectively. In Malaysia's highlands, hill development is also a causative factor that triggers landslides whenever there is a technical defect (e.g., inadequate design, poor building, or poor maintenance) (Jamaluddin, 2006). The most major categories of landslides in Malaysia are shallow landslides, which occur during or shortly after torrential rainfall and usually have a depth of less than 4 metres. A few examples of various methods used to tackle the hazard are present in Table 2.3.

According to Majid et al., 2020 (Journal & Science, 2020), who used secondary data from the National Slope Master Plan to fully investigate landslides in Malaysia between 1993 and 2019, several landslides' occurrences were observed in Selangor and Kuala Lumpur due to increased development. The collapse of the 14-story block A of the Highland Tower in Ulu Klang, which killed 48 lives, was one of Malaysia's most devastating landslides (Rahman, 2017). Landslide incidences and risk regions were mapped and located using GIS software based on their research. In these two regions, landslides have caused many losses of lives, perished various properties, and impacted directly and indirectly the economy (Shazrin et al., 2013). According to existing evidence, development in hilly areas has been the primary cause of landslides in the areas (Selangor and Kuala Lumpur). Another landslide incidence in Malaysia was the Bukit Tanjan, Kuala Lumpur landslide on 9 May 2014, where a road major was blocked (Johari et al., 2019). In Sabah, there have also been many instances of disastrous landslides. On the 26th of December 2001, and the 30th of June 2006, landslides in Lok Bunuq village claimed many lives and assets (Roslee and Jamaluddin, 2012). The level of landslide disasters is steadily rising due to slope failure, usually caused by localised rainfall. It is usually triggered when there is continuous heavy rainfall, which sometimes lasts for hours. This rise in water volume raises the soil's weight, and the seepage pressure, however, reduces the soil's cohesion, which significantly affects the slope (Pradhan and Lee, 2010). Urban development has recently increased landslide activities substantially due to the hill cut for construction (Hashim et al., 2018).

Table 2.3 Various landslides occurrences in Malaysia with their applied methods

Authors	Location	Materials and Methods	Finding
Pradhan & Lee 2010	Pulau Pinang	Frequency ratio, logistic regression, and artificial neural network models	Landslide hazard was modeled
Pradhan et al., 2012	Pulau Pinang	Remote sensing data and GIS Software. universal soil loss equation (USLE) method.	Soil erosion and landslide events were modelled
Oh & Pradhan 2011	Pulau Pinang	Neuro-fuzzy model	Landslide was mapped
Abd Majid, et al., 2018	Pulau Pinang	Artificial Neural Network (ANN)	Various types of slope failure were modelled
Jebur et al., 2014	Perak	L-band InSAR technique	Detection of vertical slope movement in highly vegetated tropical landslide area
Jebur et al., 2015	Cameron Highlands	ALOS PALSAR	Detection and mapping slow-moving landslides
Elmahdy et al., 2016	Pulau Pinang	Weighted spatial probability model in GIS	Analyses landslides
Nhu et al., 2020	Cameron Highlands	Machine Learning Algorithms and Remote Sensing Data	Landslide Susceptibility Mapping
Lee and Pradhan, 2006	Pulau Pinang	GIS modelling	landslide studies using probabilistic models

2.2.4 Landslides of Pulau Pinang

Malaysia is a tropical country with abundant rainfall, which causes landslides in Pulau Pinang's mountainous locations on steep and cutting slopes. This type of landslide is common on Pulau Pinang and has resulted in excessive traffic (Elmahdy et al., 2020). One of the incidents was a landslide that struck a worksite's social housing project in Lengkok Permai, Tanjung Bungah; on 21st October 2017, therein eleven workers lost their lives. Similarly, between 4th and 5th November 2017, the Island witnessed severe weather events due to a tropical depression that induced rainfall in the northern region of Peninsula Malaysia, resulting in catastrophic flooding that later produced countless landslides in Pulau Pinang river valleys (Meteorological Malaysia Department, 2018).

The South China Joint Typhoon Warning Centre (JWTC) predicted that this tropical depression would go through southern Thailand and trigger a continuous rainfall in Kelantan and northern Terengganu. Unfortunately, the movement shifted to the north of Peninsula Malaysia, which led to major disasters in Penang and Kedah before leaving for Thailand (Meteorological Malaysia Department, 2018). It triggered significant traffic chaos for a few days as dozens of roads were blocked, thousands of houses flooded, and hundreds of trees were uprooted. Different landslides had occurred in some places, particularly in the northeast and southwest regions on the Island (Weijie et al., 2018). Other landslide failures in the area happened in Penang hills, Paya Terubong, and Tanjung Bungah. Penang hills is a protected forest reserve and world-famous tourist attraction site on Pulau Pinang. It experienced over 194 different landslides (including rapid earth flows and slow-moving landslides) in 2017 alone due to heavy rain and strong winds (Chacko, 2019). The rail service operation, which has been operating for nearly a century, was disrupted.

These interruptions were due to the earth mounds that fell on the orbit near the middle station and massive boulders that damaged the railway track and hauling cables and caused two funicular trains to get stuck.

Similarly, between September and November 2017, many lives and properties were lost, and several houses were inundated due to days of continuous rainfall. The retaining walls that collapsed in Paya Terubong claimed nine lives.

2.3 Subsidence

Globally, land subsidence is one of the environmental issues and frequent geological hazards associated with the bedrock dissolution and the gradual sinking of the ground due to waterbody's withdrawal (Elmahdy et al., 2020). Urban areas and agricultural industries are affected by land subsidence's consequences (Pradhan et al., 2014). This hazard has been an environmental challenge in Malaysia (Lee and Pradhan, 2006) and strongly affects any society's economic situation (Julio-Miranda et al., 2012). It is perceived as groups of catastrophic occurrences (Pradhan et al., 2014). Therefore, it is good to determine some areas prone to subsidence for future prevention in Pulau Pinang.

2.3.1 Causes and effects of land subsidence

The two leading causes of land subsidence include human-made activities (e.g., groundwater extraction, mining, and tunnel construction) and natural causes (e.g., tectonic motion) (Wan et al. 2012; Hu et al., 2013; Hu et al. 2014; Wan and Lei 2009;

Lee and Pradhan 2006). Evidence of subsidence patterns has been identified in some areas (e.g., Tanjung Tokong, George Town) of Pulau Pinang. Therefore, to prevent potential land subsidence occurrences and reduce its damage, it is essential to identify vulnerable places on the island.

2.3.2 Past studies on land subsidence

Adequate monitoring and attention from the researchers and governments are required on this disaster to mitigate its impacts on properties and lives (Hu et al., 2013). It is essential to choose the most suitable, low-cost, time-efficient, and accurate method to determine land subsidence patterns to reduce its effects on lives and properties. However, many researchers have worked on different subsidence topics and used various approaches because it is a widespread phenomenon (Wu et al., 2009). Some of the topics include subsidence sources, monitoring, evaluation methods, and concept mapping.

Several approaches have recently been introduced to study land subsidence mapping, as each method has its attributes. For instance, many researchers have worked on land subsidence modelling because models can precisely predict. Also, remote sensing technology (RS) has transformed subsidence studies due to its effectiveness in acquiring, processing, analysing, and validating SAR data. Many researchers have used the InSAR technique (Calderhead et al., 2011; Jebur et al., 2014), the fuzzy operator (Choi et al., 2010), artificial neural network (ANN) (Kim et al., 2009), and probabilistic simulations (Galve et al., 2009; Kim et al., 2006), etc. to evaluate the risk of land subsidence.

Different approaches have been combined to identify land deformations in densely vegetated areas (Jebur et al., 2014). As probabilistic regression is not as robust as the NND method, the highest predictive potential was shown by the NND method. Moreso, using frequency ratio (FR), logistic regression (LR), the weight of evidence (WOE), and the artificial neural network (ANN) methods, Oh and Lee (2011) developed a ground subsidence hazard map in Samcheok, Korea. Based on these previous studies, it is evident that two or more techniques can be combined. In this research, InSAR and shallow subsurface imaging are combined to study the ground deformation in Pulau Pinang. InSAR was used to map the entire island as there is no previous studies on such. None of the past studies quantified the displacement rate of ground deformation (landslide and subsidence) in Pulau Pinang. Most of the models used in the past studies tackled engineering and environmental issues successfully. Therefore, it is essential to know the displacement rate of ground deformation via the remote sensing (InSAR) technique.

Table 2.4 Subsidence occurences with their applied methods

Authors	Location	Materials and Methods	Finding
Jebur et al., 2014	Perak	L-band InSAR technique	Detection of vertical slope movement in highly vegetated tropical landslide area
Calderhead et al., 2011	Mexico	InSAR and field data	Simulation of pumping-induced regional land subsidence
Pradhan & Hasan 2014	Korea	Application of a fuzzy operator	Estimations of coal mine subsidence
Pradhan & Hasan 2014	Kinta Valley	GIS modelling	Land subsidence hazards was mapped
Setan & Othman, 2006	Malaysia	Application of GPS	Monitoring of Offshore Platform Subsidence

2.4 Interferometric Synthetic Aperture Radar (InSAR) Techniques

InSAR techniques are discussed in this section. It consists of interference of two or more SAR images at different times over the same ground target to measure precise distances between the satellite antenna and ground resolution elements to derive landscape topography and its subtle elevation change (Bayer et al., 2017; Perrone et al., 2006). Each of these radar images contains amplitude and phase information (Nikolaeva and Walter, 2013). The InSAR's ability to measure small changes in the topography allows it to monitor slow ground deformations. It is classified into across or along-orbit interferometry. Across-orbit interferometry can be achieved either with a one-antenna platform, e.g., ERS, ENVISAT, ALOS, or a two-antenna sensor, e.g., Shuttle Radar Topography Mission (SRTM). Meanwhile, in the along-orbit technique, the interferometry is made with two antennas, and they are directed parallel to the flight direction (Ferretti et al., 2000; Şahin, 2013; Tapete and Cigna, 2012).

2.4.1 Applications of InSAR

InSAR has been used for mapping and monitoring ground deformation for the past few decades (Zekber, 1986). InSAR has been widely applied to monitor urban landslide and subsidence patterns in various part of the world include Beijing (Jiming Guo et al., 2016), Mexico (Castellazzi et al., 2016; Le et al., 2016), Shanghai (Dong et al., 2014; Wu and Hu, 2016), and Jinan (Liu et al., 2016). Some of its applications are presentaed in Table 3.1

Table 2.5 Applications of InSAR techniques

S/N	Authors	Titles	Applications
1	Zekber, 1986	Topographic Mapping From Interferometric Synthetic Aperture Radar Observations	Mapping of topography and small elevation changes over large areas
2	Tantianuparp et al., 2013	Characterisation of landslide deformations in three Gorges area using multiple InSAR data stacks	Characterising landslide deformation areas
3	Dai et al., 2016	Monitoring activity at the Daguangbao mega-landslide (China) using Sentinel-1 TOPS time series interferometry	Monitoring of landslide
4	Krieger et al., 2010	Interferometric Synthetic Aperture Radar (InSAR) missions employing formation flying	Monitoring of ocean currents
5	Marco et al., 2014	Remote Sensing for Landslide Investigations: An Overview of Recent Achievements and Perspectives	Monitoring of slower movements
6	Handwerger et al., 2013	Controls on the seasonal deformation of slow-moving landslides	Slow landslides monitoring
7	Schmidt and Bürgmann, 2003	Time-dependent land uplift and subsidence in the Santa Clara Valley, California, from a large interferometric synthetic aperture radar data set.	Land subsidence monitoring
8	Ruiz-Constán et al., 2018	SAR interferometry monitoring of subsidence in a detritic basin related to water depletion in the underlying confined carbonate aquifer (Torremolinos, southern Spain)	Land subsidence monitoring
9	Chen et al., 2018	Detection of land subsidence associated with land creation and rapid urbanisation in the Chinese Loess Plateau using time series InSAR: A case study of Lanzhou New District	Detecting ground deformation connected with natural phenomena, such as earthquakes and volcanic eruptions
10	Bakon et al., 2016	nfrastructure Non-linear Deformation Monitoring Via Satellite Radar Interferometry	Measuring the rate of displacement of human-made structures including buildings, bridges, and dams