LOCAL LAND SUBSIDENCE ANALYSISI IN PENANG ISLAND (MALAYSIA) BASED ON INSAR MAPS

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LOCAL LAND SUBSIDENCE ANALYSISI IN PENANG ISLAND (MALAYSIA) BASED ON INSAR MAPS

by

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Time is a bird forever on the wing. For the past two years, I had a fulfilling life in the USM. Now my study at the school of physics will soon come to an end and the completion of my graduation thesis. I'd want to convey my heartfelt gratitude to everyone who has assisted me in any way throughout my two years of master's studies at USM.

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LIST OF ABBREVIATIONS

ATI	Along Track Interferometry
CTI	Cross Track Interferometry
DEM	Digital elevation model
DInSAR	The Differential Synthetic Aperture Radar Interferometry technology
GPS	Global Positioning System
InSAR	Interferometric synthetic aperture radar
IPCC	United Nation's Intergovernmental Panel on Climate Change
IW	Interferometric Wide swath
MT-InSAR	The time series InSAR
NOAA	The National Oceanic and Atmospheric Administration
PS-InSAR	Persistent Scatterers method
PSs	Point-like stable reflectors
RAR	Real aperture radar
RTI	Repeat Track Interferometry
SBAS-InSAR	Small Baseline Subset method
SLC	Single look complex
SLR	Sea level rise
SRTM	Shuttle Radar Topography Mission
USGS	The United States Geological Survey

ANALISIS PENURUNAN TANAH TEMPATAN DI PULAU PINANG (MALAYSIA) BERDASARKAN PETA INSAR

ABSTRAK

Pulau Pinang merupakan pusat ekonomi penting di Malaysia yang mengalami penenggelaman tanah sejak beberapa tahun ini. Dalam kajian ini, teknik PS-InSAR dan SBAS-InSAR digunakan untuk memantau penenggelaman Pulau Pinang berpandukan imej radar Sentinel-1 SAR untuk menjejaki peningkatan dan penurunannya. Hasil InSAR menunjukkan bahawa seluruh wilayah mengalami kadar penenggelaman yang berbeza. Buat pertama kali, penganalisis geostatistik dan kaedah penguraian 3D digunakan untuk menjana peta ubah bentuk tanah menegak untuk menghasilkan pemahaman peneggelaman tanah yang lebih baik di kawasan kajian. Menurut kepada hasil penenggelaman tanah, keseluruhan garis pantai di timur pulau mempunyai tahap penurunan yang sederhana berbeza, terutamanya di kawasan penambakan tanah dan kawasan pembangunan. Penurunan maksimum bagi Kawasan barat Pulau Pinang adalah sebanyak 26.4 mm setahun. Kemudian kawasan kajian dibahagikan kepada beberapa kawasan kecil untuk menganalisis lebih lanjut berkaitan dengan punca penenggelaman tanah. Keputusan menunjukkan jenis tanah merupakan punca utama penyebab penenggelaman tanah serta aktiviti manusia yang lain, projek pembinaan, dan pengakutan telah mempercepatkan kadar penenggelaman. Tambahan, kajian ini mewakili masalah dalam menggunakan kaedah MT-InSAR untuk memantau perubahan bentuk tanah pada kawasan tersebut. Akhir sekali, penenggelaman tanah digabungkan dengan projek peningkatan permukaan laut wilayah menunjukkan kesan penenggelaman tanah akan bertambah teruk. Dalam senario terburuk, lebih kurang 14.8% bahagian pulau akan mengalami

tenggelam. Oleh itu, kami berharap kajian kami dapat membantu mereka bentuk pengeluaran yang lebih cekap dan langkah yang sesuai untuk penggubalan dasar dan perancangan bangunan.

LOCAL LAND SUBSIDENCE ANALYSIS IN PENANG ISLAND (MALAYSIA) BASED ON INSAR MAPS

ABSTRACT

Penang Island is an important economic centre in Malaysia that has experienced land subsidence in recent years. In this study, the PS-InSAR and SBAS-InSAR techniques are used to monitor land subsidence of Penang Island based on Sentinel-1 SAR radar images in both ascending and descending tracks. The InSAR results demonstrate that the entire region is sinking at different rates. For the first time, the geostatistical analyst and 3D decomposition method are used to generate vertical land deformation maps in order to better understand land subsidence in the study area. According to the land deformation results, all of the coastlines in the east of the island have differing medium levels of subsidence, especially in reclaimed lands and building areas. The maximum subsidence rate of – 26.4 mm/yr can be found in the west of the island, where is a rural area. Then, the study area is divided into several sub-areas to further analyse the reasons for land subsidence. The results indicate the soil type is the main driver for land subsidence, as well as other human activities, construction projects, and transportation accelerate the subsidence rate. In addition, this study represents the problem of using MT-InSAR techniques to monitor land deformation in such areas. Finally, land subsidence is combined with regional sea level rise projection, indicating the effect of land subsidence would be devastating. In the worst scenario, about 14.8 % of the island would be submerged. Therefore, I hope our study could help to design more efficient production and adaptation measures for policymakers and development planners.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Generally speaking, land deformation refers to the total influence of a variety of natural and human-related activities. The natural reasons for land deformation are always related to the various geophysical processes, such as the diagenesis process of loose or semi-loose sediments on the ground from soft to fine under the influence of gravity, earthquakes, landslides, and geological structure adjustment (Bense et al., 2003; Long et al., 2019; Marra et al., 2016; Niu et al., 2020). Most of these deformations are commonly uncontrollable and unpredictable, and they are more likely to happen in places where few people live. However, the human-related land deformations are more often associated with large construction projects, such as reclaimed lands, mining industries, variations of groundwater and intensely artificial buildings (Amelung et al., 2000; Du et al., 2016; Ou et al., 2018). Although these deformations always have a lower rate, most of them are visible and around us. Therefore, it is critical to establish regional early warning mechanism to prevent such disasters.

In urban areas, one of the most prominent characteristics of land deformation is land subsidence. In most regions, land subsidence has been occurring at a lower rate for a long time, but without being noticed by most people. To some extent, uniform land subsidence has a limited effect on buildings and infrastructures on the ground. However, uneven land subsidence or deformation rates that exceeded the critical threshold would emerge severe hazards, such as collapse of buildings, road subsidence, and rupture of underground pipelines. Except for land subsidence could increase the cost of construction protection and road transportation, as well as it poses a threat to human survival. More importantly, these issues are difficult to control or recover with existing capabilities and techniques. However, monitoring land subsidence is essential to the sustainable development of cities.

As one of the manifestations of urban geotechnical hazards, which are normally related to the soil types, reclamation projects, population explosion and over-exploited energy resources, and it has been recorded in many cities around the world. For example, according to the United States Geological Survey (USGS) investigation, land subsidence has directly affected over 17,000 square miles in 45 states across the United States, with some parts of California experienced a cumulative settlement of about 9m between 1925 to 1977 (Galloway, Jones, & Ingebritsen, 1999); In Mexico City, long-term groundwater extraction and aquifer-system compaction have caused widespread land subsidence, destroying colonial-era structures, buckling highway roads, as well as disrupting water supply and waste-water drainage systems (Sowter et al., 2016); In Jakarta, it has been named as the fastest-sinking city in the world. The North part of Jakarta has sunk 2.5 metres within 10 years, and some areas are continuing to sink with a subsidence rate of more than 25 cm/yr (Moe et al., 2017). Owing to rising sea levels and significant land subsidence, this massive city is gradually vanishing into the ground; In Singapore, although there is only slight land subsidence, it also could increase the risk of being submerged in the city centre due to sea level rise (Catalao et al., 2020b). All these studies indicate land subsidence have the potential to be major economic threats. Furthermore, the rapid growth of the population and economy in coastal cities has resulted in increased demand for land, water resources and other forms of natural energy over the last century. According to the report of the United Nation's Population Division, roughly 83 million people are added to the world per year. In this context, the population is expected to reach 9.8 billion by 2050, and 10.9 billion by 2100 (DESA, 2019). Of these, two third of the population will live in the city, and half will live along the coastal zone, these areas accounts for just 10% of the total land area on the planet. Therefore, these factors would pose a challenge to provide a stable land, and land subsidence is likely to worsen in the future.

Penang Island is an important economic centre in Malaysia, with a 90.8% urbanization rate and most people living on the coast areas according to the Development of Statistics Malaysia Official Portal (Mok, 2016). Because of rapid urban expansion, it has experienced land subsidence in the last few years. Unlike land subsidence in other cities, which is often related to the extraction of underground water, a shortage of land resources and large-scale construction projects could pose a much greater challenge in Penang Island. Since 1960, the reclaimed lands have increased from 0.4 km^2 (0.1%) to 9.5 km^2 in 2015 (3.2%), and it is expected to reach 32.3 km^2 in 2030 with new construction projects completed (Chee et al., 2017). In order to face growing demand to traffic, Light Rail Transit (LRT) and several highway roads in the urban planning procedure have been approved, as shown in Figure 1.1. Previous studies have proved these artificial islands and highway projects are closely related to the land subsidence, which has a negative impact on the sustainable development of the city (Jing et al., 2018; Sun et al., 2018).

Figure 1.1 The urban planning procedure of Penang Island, the proposed three island projects with a total area of18.21 km^2; Bayan Lepas Light Rail Transit (LRT) and Pan Island Link Highway passes through the whole island (TheStar.com.my).

In addition, unconsolidated soil cover 19% of the island and are home to 80% of the population, which has been proved to be the primary driver for land subsidence in coastal areas (Gong, Li, & Yang, 2009). However, in such tropical area, although soft soil is vulnerable to sink during the soil compaction process, heavy rainfall may also speed up the process. Figure 1.2a shows a structural damage of home, which relates to the heavy rain loosened soil and caused it to sink, many families were forced to relocate to temporary quarters. Figure 1.2b shows land subsidence in a newly completed housing area, where the soft land was unable to support the retaining wall. Meanwhile, since half of the island is mountainous, land subsidence and landslides can occur simultaneously, resulting in massive financial losses.

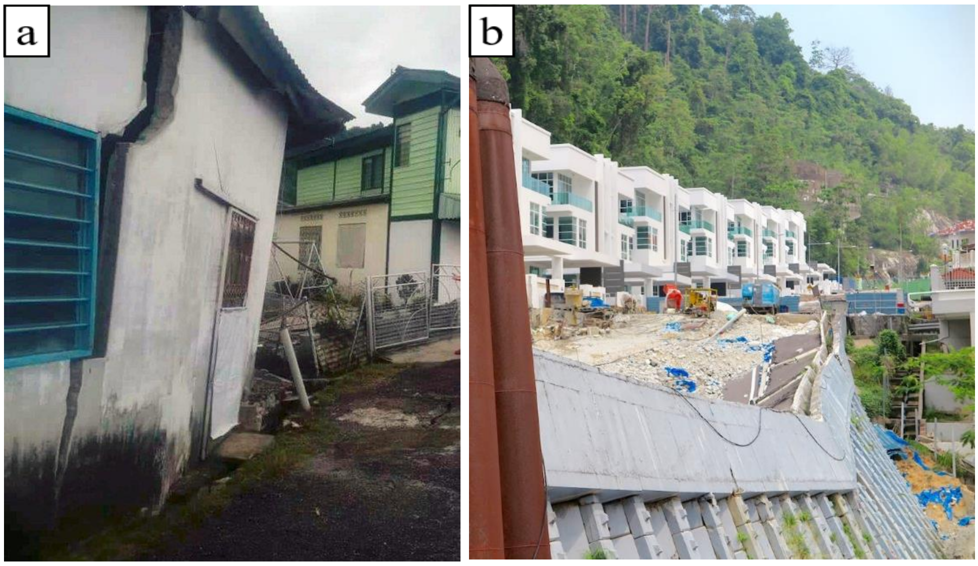

Figure 1.2 Penang homes suffer structural damage as soil sinks and roads collapse (nst.com.my).

Although the water supply on Penang Island is adequate, it also must be addressed urgently in the future. The first issue is that the per capita domestic consumption is 291 liters/capita/day (2019), which is higher than the target of the federal government (180 liters/capita/day) by 2025. According to the report of PENANG HAS TO TACKLE 3 KEY WATER SUPPLY ISSUES from Perbadanan Bekalan Air Pulau Pinang Sdn Bhd (PBAPP), the main raw water source on Penang Island (the Sungai Muda River) may only be able to satisfy demands until 2025. As one of the most important manufacturing hubs in Malaysia, manufacturing makes a major contribution to the state's overall GDP. Nevertheless, inadequate or insufficient water supply would result in revenue losses for all parties involved. In that case, the government would have to exploit groundwater, which has been proved closely related to severe land subsidence (Cigna & Tapete, 2020; Moe et al., 2017). Therefore, searching for appreciating techniques to monitor land subsidence especially in high-risk areas is very significant in Penang Island, which can help the government take appropriate mitigation measures in advance and minimize losses.

In Penang Island, another issue is land subsidence would exacerbate the effect of rising sea level. A previous observation-based study shows that the extent of sea level rise between 11cm to 15cm from 1900 to 1990, while the radar satellite altimetry measurement reveals a treble acceleration from 1993 to 2017 (Sweet et al., 2017). The latest report from the United Nation's Intergovernmental Panel on Climate Change (IPCC) indicates global sea level would likely rise during 0.29m to 1.1m by the end of this century under different greenhouse gas concentrations (Church et al., 2013). According to the coastal risk screening tool of CLIMATE CENTRAL, some main areas, such as the commercial centre and international airport in Penang Island, would be submerged, as shown in Figure 1.3. Nevertheless, one drawback for this model is the influences of local land subsidence had not been taken into consideration. Therefore, the inundation areas would several times than previous forecast after quantifying land subsidence (Anzidei et al., 2017; Eggleston & Pope, 2013; Stanley & Clemente, 2017).

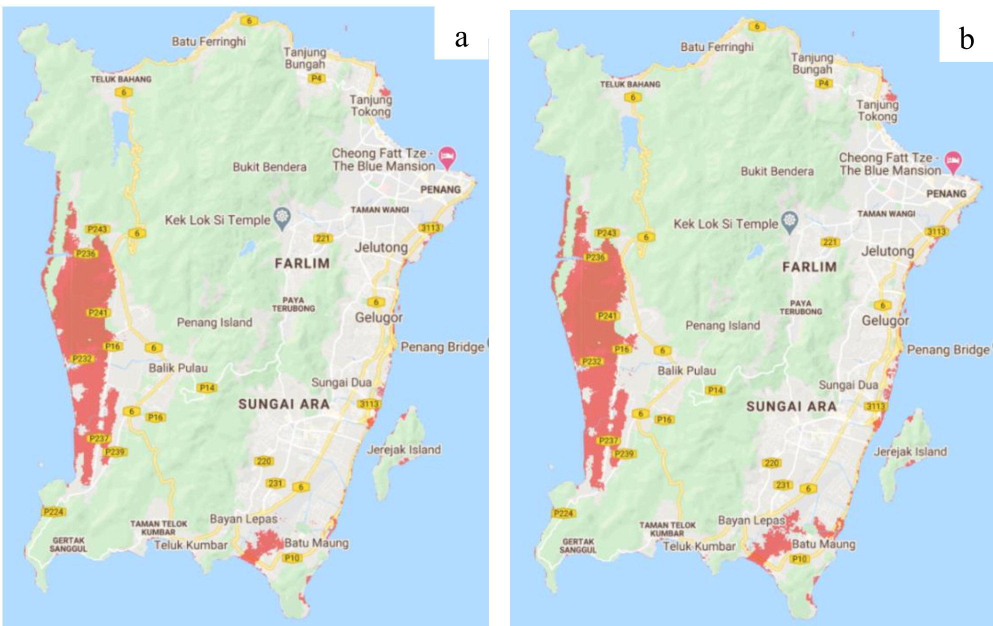

Figure 1.3 Land projected to be below annual flood level in 2050 (a) and 2100 (b) in Penang Island (red colour), respectively (coastal.climatecentral.org).

Over the past few decades, traditional point-based measurements are commonly used in monitoring land deformation, such as benchmark data, Global Positioning System (GPS) and geophysical investigation methods. These methods commonly have two significant characteristics: one is the requirement for building observation stations; another is that each observation cycle takes a long time and many people to complete. Therefore, although these methods have a lot of advantages in terms of measurement accuracy, their implementations are constrained by insufficient spatial and temporal sampling rate of monitoring results, time- and labour-intensive, and high in costing (Ito, Susaki, & Anahara, 2019; Poland et al., 2006; Psimoulis et al., 2007).

For SAR radar images, which contains amplitude and phase information two parts. Backscattering is one of the main forms of amplitude information, which is primarily used for ground target identification and classification by analysing various backscattering factors. While the phase information refers to the round-trip propagation distance between the sensor platform and the ground target. In this context, standard Differential InSAR (DInSAR) method adopts a phase difference between at least two images to evaluate where the objects travelled and how far it is, these radar images are acquired at the same areas but different times. In other words, InSAR as a valuable remote sensing technique, which has a prominent ability to work on all-weather, all-day and mapping slow land motion with large area (Benattou, Balz, & Liao, 2018; Zhou et al., 2017). This method was firstly proposed by *Graham* to map deformation of surface elevation by mounting SAR sensors on the airplane platforms, its result indicates using SAR and interferometer techniques can generate high-accuracy topographic maps from the all-weather collection of data (Graham, 1974). In recent years, with a series of high-accurate radar satellite launches, such as

Sentinel-1, ALOS, ENVISAT and TerraSAR, InSAR technique has been widely used in monitoring geological disaster.

However, although the DInSAR technique has demonstrated great advantages in monitoring land deformation, there are still some drawbacks that need to be noted. As we all know, most SAR satellites operate in repeat-pass mode, the special imaging mechanism of radar satellites often results in temporal and spatial decorrelation, which can cause the artefact and affect measurement accuracy (Osmanoğlu et al., 2016; Zhao et al., 2020). In addition, due to relatively long-time interval of SAR images, atmospheric delay is one of the most difficult components to estimate. Therefore, these issues pose a challenge to the accuracy of the DInSAR technique. In this context, Multi-Temporal InSAR (MT-InSAR) technique was applied to minimize these effects and provide a finer deformation precision. The principle of the MT-InSAR technique is to obtain a series of interferograms by multiple SAR radar images that have high-quality coherent points. Then, land deformation is inverted by phase differences between radar images. Therefore, if there are table ground control points (GCPs) in the study area, land deformation can be accurately measured. Normally, these GCPs could be identified even on a long-time span and maintain stability to the radar waves, such as on the road, building, roof, rock, and other corner reflectors. Currently, the commonly used MT-InSAR technique have Stacking (Sandwell & Price, 1998), Least Square (Usai, 2002), Coherent Point target (Blanco-Sanchez et al., 2008), Temporal Coherence Point (Zhang et al., 2012), Persistent Scatterers method (PS-InSAR) and Small Baseline Subset method (SBAS-InSAR). Of these, the SBAS-InSAR and PS-InSAR technique have been widely used to urban land subsidence and crustal movement, with significant benefits.

In addition, due to most of the radar satellite are on near-polar orbits, it means SAR satellites mainly has two flight tracks: the descending track refers to as satellite travels from the north pole towards the south pole, while ascending track refers to as satellite travels from the south pole towards the north pole. Unlike commonly used optical sensors that look directly down, SAR sensors have a special right-looking imaging geometry, which causes InSAR results to be in the line-of-sight (LOS) direction. Typically, LOS deformation velocity is composed of the 3D velocity with components d_U , d_E and d_N in up-down, east-west, and north-south directions, respectively. Therefore, single track can often differ noticeably from the real movement, the horizontal displacement might be wrongly assumed vertical movement, as shown in Figure 1.4.

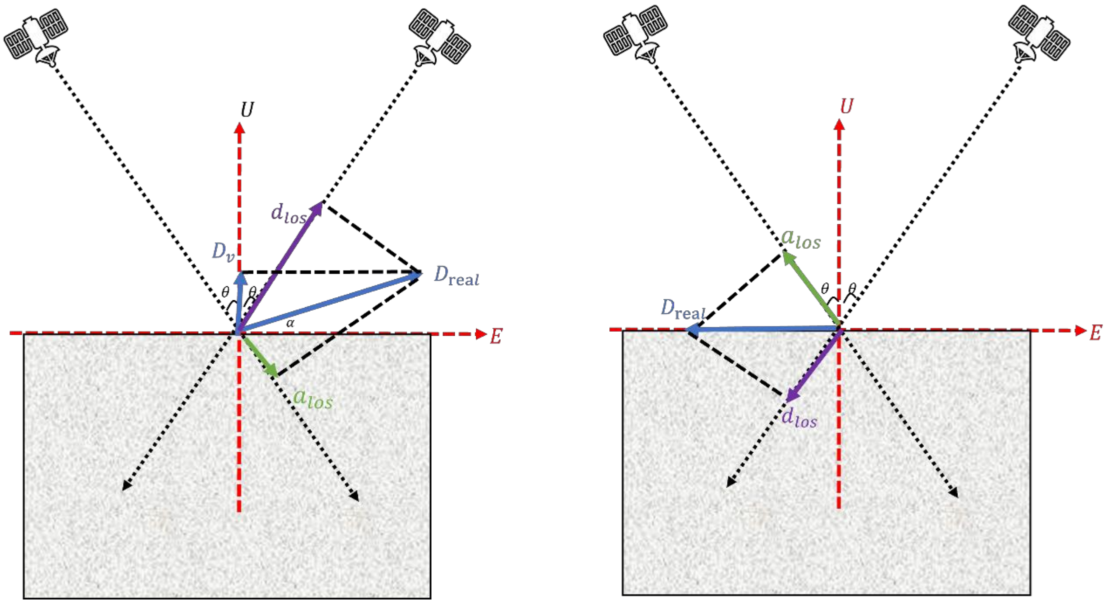

Figure 1.4 LOS acquisition geometry of radar sensors. D_{LOS} is the ground target deformation in the LOS direction; D_{real} is real deformation of ground target; U and E indicates vertical and horizontal direction; a_{los} and d_{los} represents land deformation in LOS direction.

In order to obtain accurate measurements, the most common post-processing of InSAR measurement methods is to decompose 3D displacement fields according to ascending and descending track data (Foroughnia et al., 2019; Ng et al., 2011; Wright, Parsons, & Lu, 2004). However, although it is possible to obtain a real estimation of the vertical and vertical components, there are also some issues that remain unsolved: (1) The InSAR derived results in different tracks must be obtained from the same ground points, instead of the same pixels. Because a single pixel in an InSAR image could represent several square meters and a large number of ground targets. This means that all of these ground targets may be contributing to the same pixel; (2) The second is only part of the pixels can be used for deformation monitoring because of the lower correlation in such densely vegetated areas and some deformations are only acquired by one of tracks. Therefore, conventional 3D decomposition methods also could derive misleading results, and these errors are difficult to correct. So how to use different track results need more effectively to be further discussed.

1.2 Statement of Problem

In the past, Penang Island has posed a threat to land subsidence, and worsening conditions is underway. However, there are only little public attentions. Although InSAR methods have many advantages, most previous studies concentrated on temperate zone. While in tropical areas, there are several confounding factors, such as dense vegetation coverage and unstable house structures. Therefore, only using single technique or track may be unable to achieve an accuracy measurement, we must integrate various techniques. Meanwhile, another problem is using different technique and track to calculate vertical deformation. Because of special imaging principle of SAR images, most conventional 3D decomposition methods also have some issues need to be addressed.

1.3 Research Questions

MT-InSAR technique plays a significant role in retrieving topography information, which has been successfully applied in those areas with less vegetation and dry climates. However, fewer study focusses on these tropical developed islands, which is covered by dense vegetation. In addition, how to select adequate polarization modes for SAR radar images is an important issue. More importantly, it is crucial to know how to effectively extract vertical land subsidence using various technique results. Therefore, this research is developed to better understand the status of land subsidence in study area, the research questions of this study are:

Questions 1

Are these InSAR techniques effective for land subsidence monitoring?

Questions 2

How to minimize the errors of InSAR results in different tracks and techniques?

Questions 3

What effect does land subsidence have on rising sea levels?

1.4 Research Objectives

The use of spatial high-resolution SAR radar images to measure land deformation is a new field of geography. In some of developing cities, land subsidence is always closely related to rapid urbanization and always represents a potential threat to human survival. In addition, studying land subsidence is important for potential inundated areas related to rising sea level in the future. Therefore, the general purpose of this paper is to explore the land subsidence status in Penang Island based on SBAS-InSAR and PS-InSAR techniques.

The specific objectives of this study are:

Objectives 1

To monitor land subsidence in Penang Island based on InSAR maps.

Objectives 2

To analyse the reasons for land subsidence in Penang Island.

Objectives 3

To create inundation scenarios according to local land subsidence models and sea level rise projections.

1.5 Scope of Study

With the fast development of society, land subsidence already became one of the most challenging disasters in recent years in Malaysia. However, little attention has been paid to these phenomena, whether government or the general public. In view of this situation, the present study analyzes land deformation status in Penang Island (within latitudes 5.40°N to 5.48°N and longitudes 100.17°E to 100.34°E). To this end, this study also demonstrates inundation projections by 2100 that relates to both sea level rise and land subsidence, which can help to better understand the effect of land subsidence.

During the study, other limitations are also stipulated for limiting the scope for this study. The scopes are:

1) The Sentinel-1A radar images cover from January 2018 to August 2020, and also only Interferometric Wide swath (IW) single look complex (SLC) products are used.

2) The CoastalDEM that will used in the research is 90m in spatial resolution, and Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) with a spatial resolution of 3 rad/s.

3) During calculating inundation area, the static bathtub model and average land subsidence values are utilized.

4) Only PS-InSAR and SBAS-InSAR techniques are used to estimate land deformation, and all processing are implemented at SARscape software.

1.6 Significance of the Study

Monitoring land subsidence is very important for sustainable development of cities. Penang as one of the states of Malaysia, which has made great contributions to the national GDP construction and employment. However, the state government has to develop infrastructure due to the rapidly growing economy and population in the past several decades. In the next few years, there are some ongoing and planned construction projects, such as reclaimed lands and LRT, all of them have a great influence on the environment and the stability of geology. In addition, special geographical environment and human intervention makes this area easily occur land subsidence. In recent years, the government has spent a lot of money on land subsidence and landslide, more than 1 billion (Alkhasawneh et al., 2012).

Besides, sea level rise because of climate change is also a great challenge in Penang Island, because a large proportion of the population and economic activities are concentrated along the coastlines. Previous studies tend to analyse the potential effect of rising sea level (Ghazali et al., 2018; Ong, 2001; Paw, Thia-Eng, & Management, 1991), while land subsidence also is a major factor in coastal flooding prevention and management (Catalao et al., 2020b; Wang et al., 2018; Yin et al., 2013). Therefore, this thesis is going to study land subsidence status in Penang Island based on InSAR techniques, which would help to create more accurate inundated scenarios.

In order to obtain a continuous land deformation map, geostatistical analyst method is applied to integrate various InSAR results. Geostatistical analyst is an effective spatial analysis tool in natural phenomena and can create accurate predictions for other unmeasured locations within the same area from identifying variation. This method provides a possibilistic framework for quantifying uncertainties in data that are incomplete or subject to error (Johnston et al., 2001; Kamble & Aggrawal, 2011; Nas, 2009). This study indicates the geostatistical analyst method can help to create more accurate land subsidence models and reduce errors of various InSAR results. Then, its results are used to calculate vertical deformation rate.

According to the previous studies, the following conclusions has been drawn:

1) Comparing to the DInSAR technique, the MT-InSAR is suitable for obtaining slight land deformation. Meanwhile, the decoherence influence can be adequately weakened.

2) Land subsidence commonly relate to the soil types, such as reclaimed lands and unconsolidated soil.

3) Various tracks and methods may drive differ in the vicinity of mountain and reclaimed lands.

4) In coastal areas, combining land subsidence model to estimate the inundation map is efficient.

1.7 Organization of the Thesis

The outline of this thesis is shown as follows:

Chapter 1: This chapter introduces the report outlining the background of the study, research status, the specific research objectives, research questions, scope of study, and significance of this study.

Chapter 2: The second chapter is about literature reviews. In this chapter, the history of SAR radar sensors is firstly described, followed by compared with RAR. This chapter also indicates the advantages and disadvantages of DInSAR, PS-InSAR, and SBAS-InSAR. In addition, the past and present SAR satellites are also listed.

Chapter 3: The third chapter discusses the methodology and its procedures to fulfil the objectives of the research together with an overview of methodology for validation of results. The principle of radar imaging process, DInSAR (two-pass, three-pass, and four-pass), PS-InSAR, and SBAS-InSAR are described in detail in this chapter. In addition, the materials and study areas also included in this chapter together with the software.

Chapter 4: Chapter 4 are on the basis of PS-InSAR and SBAS-InSAR result in the study areas both contain ascending and descending orbit data. Then, selecting several sub-areas for further analysing the reasons for land subsidence according to the InSAR result. In addition, it also indicates the inundated areas in the future by combining local land subsidence and SLR data.

Chapter 5: Chapter 5 draws the conclusion and outlines future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

To achieve accurate measurements, effective land subsidence monitoring techniques should be widely deployed across the whole study area and to provide continuous monitoring. Therefore, conventional methods require the installation of a large number of instruments as well as many technique staff to manage, all of which can be expensive. In recent years, remote sensing techniques have been proven to be an effective analysis method in land deformation monitoring due to broad spatial and temporal coverage as well as low costs. As the rapid development of radar satellites and theories, InSAR techniques play an important role in various natural phenomena monitoring and provide a millimetre-level precision, such as land subsidence, earthquakes, landslides, and volcanic eruptions.

Before using InSAR technique to detect land subsidence, it is essential to understand the fundamental principles of SAR imaging, and I provide a simple comparison with RAR in this thesis. In addition, DInSAR, PS-InSAR, and SBAS-InSAR techniques are discussed in terms of their benefits and drawbacks. After a general introduction about InSAR techniques, the fundamental principles of 3D decomposition methods and the bathtub model also are given in this chapter.

2.2 Synthetic Aperture Radar

Spatial resolution refers to an ability to measures small objects and is generally divided into two parts: azimuth resolution (along the radar flight direction) and range resolution (perpendicular to the radar flight direction). In real aperture radar (RAR), if radar antenna is a uniform rectilinear movement, the beamwidth can be calculated by follow:

$$d = \frac{\lambda}{D} \tag{2.1}$$

where d is the beamwidth of RAR; λ is the wavelength; D is the real aperture. Then, assuming the slant range between the radar antenna and ground target is R, the azimuth resolution (R_α) can be expressed as:

$$R_\alpha = d \times R = \frac{\lambda}{D} \times R \tag{2.2}$$

In this Equation, the azimuth resolution is proportional to wavelength and fly height, but inversely proportional to the real aperture. As a result, the length of physical antennas must be increased in order to improve azimuth resolution. Spaceborne SAR systems, such as the C-band Sentinel-1 radar, have a wavelength of just 5.66cm. To obtain a 10m resolution, the slant range must be 530km, which means the physical antenna must be 1.5km. Clearly, designing such a long antenna in a real-world setting is improbable. However, the physical antenna length limits the development of RAR, regardless of whether the radar is airborne or satellite.

In this context, the SAR technique was designed to address the poor azimuth resolution of RAR. According to the forward movement of flight platform, using a small -aperture antenna to synthetic a virtual large-aperture linear antenna array, thereby increasing the resolution of radar system. Alternatively, it also can be understood that a moving platform can collect different echoes in all directions when electromagnetic waves are reflected sequentially from ground targets, while a static radar can only accept partial information. Therefore, it can obtain a similar effect by large-aperture antenna.

Figure 2.1 shows the operating principle of the SAR technique, T_1 is the earliest position of using radar to observe ground target, while T_m is the latest position. During this period, the radar can transmit and receive signals in any position. If we assume the radar antennas will continue moving with constant speed in a straight line, the azimuth resolution of synthetic aperture can be calculated:

$$R_a = \frac{D}{2} \tag{2.3}$$

where *D* is the real aperture; R_a is the azimuth resolution. Therefore, the azimuth resolution of SAR is completely dependent on antenna aperture. Then a 10m antenna would suffice for a 20m resolution.

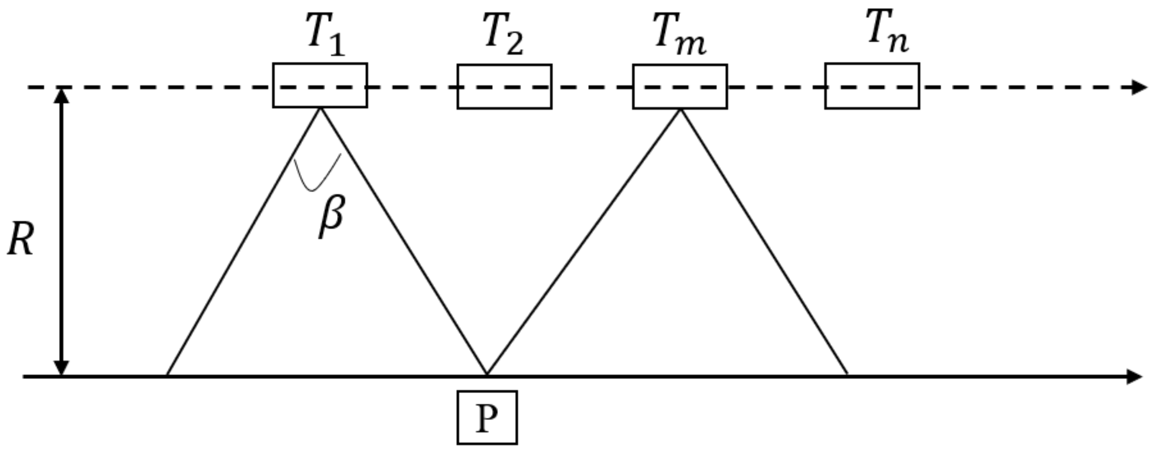

Figure 2.1 The operating principle of the SAR technique. *R* is the height of antennas.

Basic Properties of SAR Satellite

Over the last 60 years, SAR techniques have been highly regarded and developed by many nations around the world. Sensors, signal processing, application technology and other technologies are all constantly evolving and improving, from preliminary to laboratory and airborne to spaceborne. It has been one of the most influential and fast-growing microwave remote sensing radar sensors till now. As a kind of active remote sensing sensor, which combines pulse compression, synthetic aperture, and digital signal processing techniques, and utilizes a smaller aperture antenna to generate high-resolution radar image in range and azimuth direction. The radio waves used in the SAR technique usually have a wavelength of about 3cm to a few meters, which is much longer than the visible light wavelength that is always used in producing optical imaging. Therefore, SAR technique has distinct advantages over optical sensors because smaller wavelengths are less affected by clouds, glare, and smoke, even though both are designed for using radio waves to generate images. In addition, the radar side-imaging mechanism is a commonly used method in SAR technique, which generates radar images by measuring the echo energy from both transmitted and received signals.

Meanwhile, SAR as an active sensor, which can produce and transmit radio waves to ground targets from its own antenna. The small aperture antenna can be treated as a single radiating unit that travels along a straight line in various positions and receives the radar echo signal in turn. In this way, the characteristics of ground targets are scanned in range (refer to the across-track dimension perpendicular to the flight direction) and azimuth (refer to the along-track dimension parallel to the flight direction) dimension. Therefore, this technique is often used to monitor land deformation in the radar flight direction and reconstruct 2D or 3D images of the objects. Such characteristics have unique advantages over conventional approaches, especially in areas of traditional optical sensors or other methods are difficult to image.

Basic Imaging Modes of Synthetic Aperture Radar

As a microwave active imaging radar, SAR techniques can produce 2D high-resolution images of the ground targets that cover the study region, close to images obtained by optical satellites. According to the different interferometry modes and geometric positions between antennas, SAR sensors are mainly classified into the following three imaging modes:

2.2.1(a) Cross Track Interferometry (CTI)

CTI (also known as vertical track method) technique requires mounting two sensing antennas in the flight direction on the same platform that perpendicular to each other, one antenna is in charge of transmitting and receiving radar waves, the other is mainly responsible for receiving echoes from multiple ground targets at the same time, the geometric principle of CTI mode is shown in Figure 2.2. This mode was firstly used to observe Earth by *Graham et al.* (Graham et al., 1974). According to different distances from two antennas to ground targets, radio echoes can be used to calculate phase difference by interferometry technique. In addition, because interferometric phase differences are sensitive to the topographic change, it is primarily used in airborne platforms for topographic mapping, such as SRTM mission. However, there is an intractable error in estimating the result due to the roll of the aircraft or the impact of the sloping terrain (Rudiger et al., 1996).

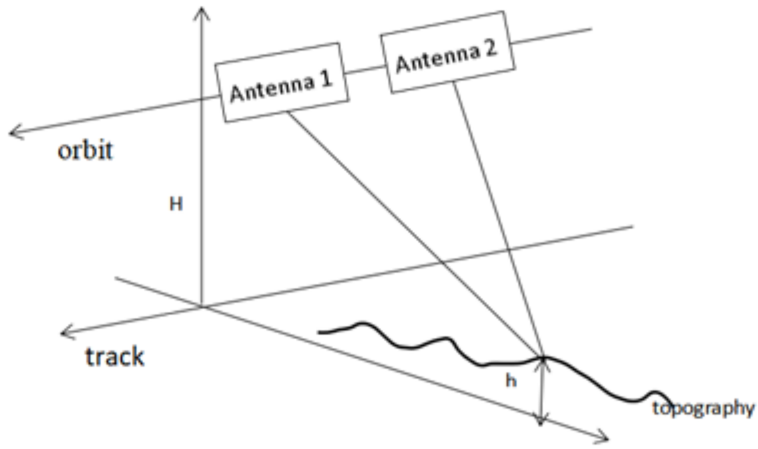

Figure 2.2 The Geometric Principle of CTI. H is the height of satellite; h is the elevation of ground target.

2.2.1(b) Along Track Interferometry (ATI)

Goldstein & Zebker are the first to show that ATI technique can be used to calculate land deformation (Goldstein & Zebker, 1987). As shown in Figure 2.3, two sensing antennas are parallelly mounted on a standard SAR platform along the moving path, one behind the other. In this case, the phase differences can be calculated using two complex SAR images that cover the same area even though they are acquired with a 0.5ms time lag, identical backscattering coefficients and excellent coherence also can be obtained. Then, utilizing phase difference to detect land displacement. Meanwhile, because two echoes are received from the same ground, which decreases the operational difficulty of registration. Therefore, this mode is suitable for estimating the velocity of moving targets on the ground, mapping ocean current water flow diagram and the measurement of directional wave spectra (Mastro et al., 2020; Romeiser et al., 2005). But there are also some drawbacks, such as high demand for hardware and flight conditions.

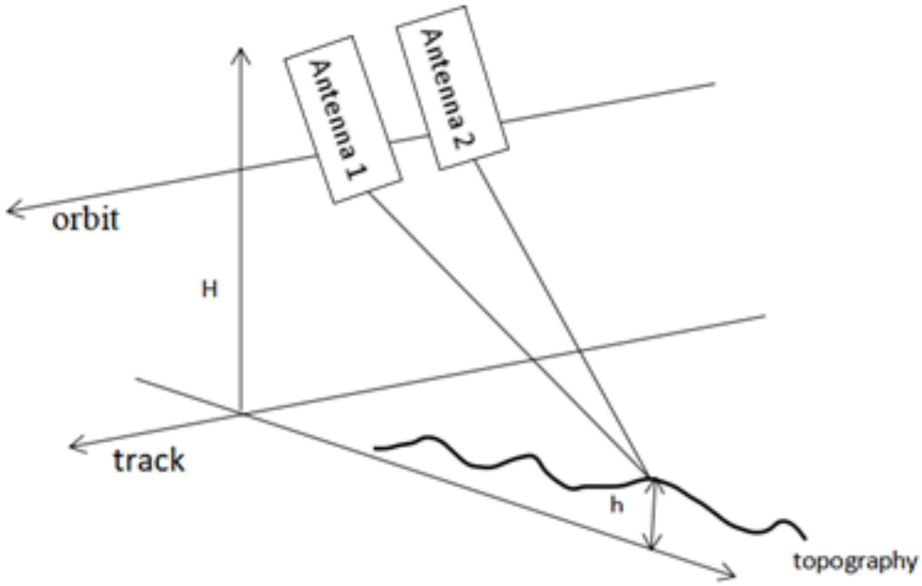

Figure 2.3 The Geometric Principle of ATI. H is the height of satellite; h is the elevation of ground target.

2.2.1(c) Repeat Track Interferometry (RTI)

Gabriel et al. is the first to employ the RTI method to collect data by using SIR-B satellite (Gabriel et al., 1988). The geometric principle of the RTI mode is shown in Figure 2.4. On the contrary to the ATI, this mode only has one antenna. In this way, the interferometry method is used to process two SAR images that acquired in the same area but at different times (one can be assumed obtained to have been taken form orbit 1 and the other from orbit 2). Because slightly different in look angles, this mode is more suitable for spaceborne SAR system that has a stable orbital path, such as RADARSAT, Sentinel-1. Currently, most SAR systems are implemented this mode due to low cost and hardware requirements. In addition, this mode is often used to measure geomorphological characteristics using temporal and spatial coherence, such as changes in surface topography induced by volcanoes and earthquakes, land cover classification, and mapping flooding areas (Antonia Pepe, 2017; Ferretti et al., 2007).

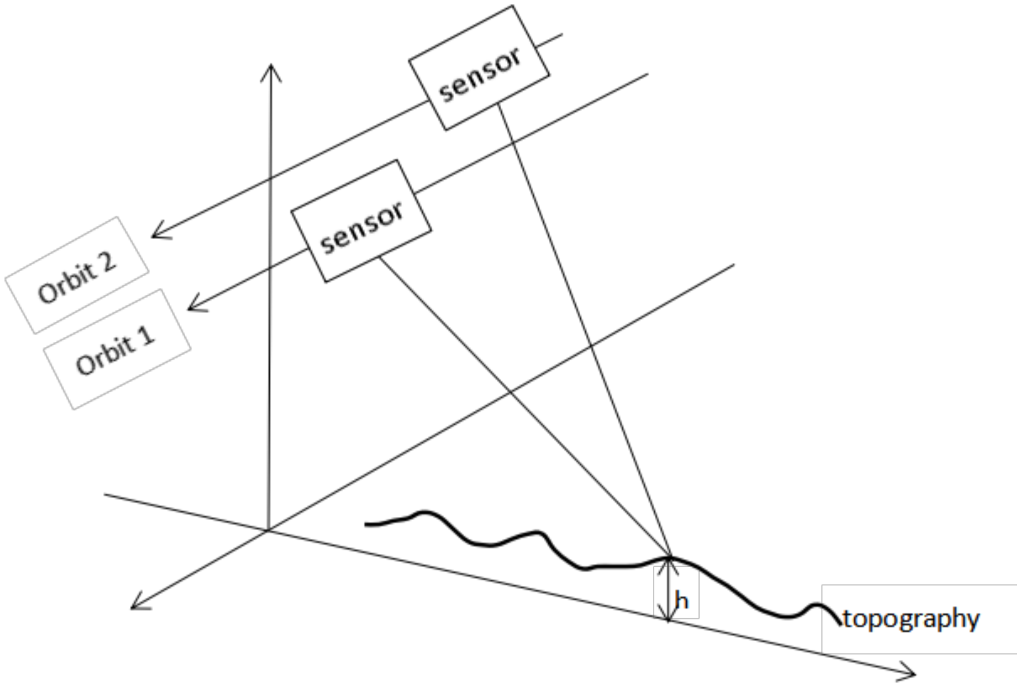

Figure 2.4 The Geometric Principle of RTI. H is the height of satellite; h is the elevation of ground target.

Currently SAR Satellites

SAR is an active microwave sensor with less cloud, light or fog sensitivity than optical sensors. With the development of the InSAR technique, spaceborne SAR has risen rapidly, and the number of satellites continues to rise. The conventional SAR satellite system, which began in 1978 with the launch of the first satellite, as shown below.

Table 2.1 The Conventional SAR Satellite System

Satellite(s)	Band	Operation	Country	Polarization	Resolution
SEASAT	L	1978-1978	USA	HH	30m
SIR-A	L	1981-1981	USA	HH	40m
SIR-B	L	1984-1984	USA	HH	40m