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APPLICATION OF INSAR TECHNIQUE FOR THE DETECTION OF GROUND DISPLACEMENT IN PENANG ISLAND, MALAYSIA

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ABSTRACT: Slope failure is Penang Island's most critical geohazards that inflict significant economic damage each year. Penang landslide is considered one of the most disastrous landslide regions in Malaysia. The threat to lives and property had been associated with the slope instability issues for decades and continuous rain that usually lasts for hours/days. Earlier research employed simulation and modeling to address this hazard, but InSAR technique has not been fully utilized to quantify Penang Island's movements. It now requires proper monitoring using satellite techniques. Sentinel-1A S-1A images acquired enables Synthetic Aperture Radar (SAR) processing technique looks very promising. The data were processed using a versatile and powerful tool called SARPROZ software. The Permanent Scatterer Interferometric SAR (PS-InSAR) technique was applied to monitor ground deformation in Penang Island, Malaysia, as various deformations have been reported for years. The results of S-1A data show slow ground deformation values ranging between −9.19 mm/yr and -10.00 mm/yr for subsidence pattern and from 5.00 mm/yr to 4.66 mm/yr for uplift behavior. The results with S-1A data confirmed a trend of deformations around the regions. This reflects the improvement of the S-1A datasets for the PS-InSAR analysis in the region. InSAR result was validated using available GPS analysis. The results were also related to some works on physical parameters such as rainfall, slope, geology, and soil properties of the region for comparison. However, the detailed spatial pattern of surface displacement in the middle of the island is not clear as persistent scatterer has a limitation in the vegetated and rural areas.

Keywords: Slope failure, Landslide, Deformation, Instability, SARPROZ, PS- InSAR

1. INTRODUCTION

Landslide is a common geohazard induced when gravity overcomes the frictional forces keeping the layers of rocks in place on the slope [1]. The ground we stand on is made of different layers of different materials. A weak geological layer like shale often forms a ‘failure plane’ that makes the slope unstable. The upper layer slides away if there is any disturbance on balance (e.g., heavy rain, earthquake). Such movements also lead to rock falls, severe slope collapse, and shallow debris flow [2]. Landslide can be triggered by intense flash floods [3, 4]. It poses critical natural hazards and causes substantial loss of lives and harm to properties worldwide [5]. There has been a significant rise in landslide frequency over the past decades, combined with climate change and urbanization growth [6]; thus, monitoring and early forecasts are essential to reduce this effect.

Penang Island remains one of the fastest-growing and industrializing states in Malaysia. The significant growth activities by the Penang State Government have placed tremendous pressure on the limited flat land resources. Overcoming this constraint, the developers have chosen to expand the hill areas that are abundantly available on the island [7]. Recently, global problems such as landslides, deforestation, water contamination, soil erosion, and flooding are described as consequences of hill growth. This growth has caused lax destructions to human lives, transportations, communication networks, buildings, infrastructures, etc. [3, 8]. Due to topography, illegal clearing, and weather conditions, there have been numerous reports of regular landslides and slope failures, especially during the rainy season in Penang Island. An excellent example of landslide incidence was the one that happened in 2017 in Tanjung Bungah when eleven people were crushed to death after a natural slope of 18º was reduced to a 67º, resulting into ground instability [7]. In addition, a freshly constructed housing area built on a hillslope collapsed in 2017 owing to strong and persistent rains that softened the soil and rendered it incapable of supporting the concrete barrier. Field surveys like groundwater sampling, material characterization, and geophysical studies have been used to identify and predict landslides. However, landslide detection with ground-based instruments (e.g., Global Positioning System GPS, Extensometer) is not commonly feasible due to economic factors [9]. Although these systems have high accuracy, they can only cover small areas.

Different models and methods have also been used to predict and simulate landslide occurrences in Penang Island. Past works focused on engineering and environmental issues. They also focused on using Geographic Information Systems (GIS) and Landsat images [8, 10, 11] to predict hazards. One of the previous studies includes applying a probabilistic model by constructing a spatial database using available digital maps like topographic, soil, drainage, geology, and land cover [8]. A lot of landslide data are required for the model to be implemented more widely. 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. Therefore, the displacement rate of ground deformations can be known through the application of remote sensing. It is the science that utilizes the concept of electromagnetic scattering to obtain information about any object without being in contact with it [6, 12, 13]. Microwave remote sensing is one of the most promising sub-categories of remote sensing techniques [14]. It is being carried out in the microwave region of the electromagnetic spectrum [15]. The microwave region of the spectrum is quite large, relative to the visible and infrared. The platforms like airborne and space-borne are used for mounting sensors [6]. Interferometry Synthetic Aperture Radar InSAR is one of the fastest-growing fields in remote sensing techniques [16], developed from theoretical perception to a method that transforms a wide range of Earth science fields for over four decades to measure ground surface movements (millimeter-to-decimeter) across large areas [13, 17]. It involves phase difference between two or more SAR images acquired at different times in the same area [18]. The phase difference is measured along the satellite line of sight (LOS) of the reference (master) SAR image and determined by the distance between the satellite antenna and the ground targets. InSAR has been used for monitoring surface deformation [15, 16]. In the 1980s, it was used for mapping topography and small elevation changes over large areas [18, 19]. It has been used for seismic analysis [20] and landslide monitoring [21]. Noise (from geometric distortion, radar and wave propagation) is the main drawback of the InSAR technique. Manipulations of data products and system design improvements can be used to circumvent the constraint. This study aims to apply the Permanent Scatterer Interferometric Synthetic Aperture Radar PS-InSAR technique for the first time to monitor, quantify, and map the instability of the slope in Penang Island. The application of InSAR technique has improved the understanding of the surface displacement of the study area. The satellite imageries applied for this research are limited to Sentinel-1A datasets.

2. STUDY AREA AND ITS GEOLOGICAL SETTINGS

Penang Island, which has experienced significant landslide devastation due to heavy rainfall, was considered an attractive study area for mapping and monitoring landslide analysis. The region is positioned on the northwestern coast of Peninsular Malaysia (Fig 1), with approximately 300 km^2. It has longitudes 100° 8'E and 100° 32' E and latitudes 5° 8' N and 5° 35' N and witnesses an equatorial climate which is sunny and warm annually [11]. The slope of the area varies from 25^o to 87^o. Its temperature ranges between 29 and 32°C, with the highest temperature between April and June [22]. The mean relative humidity fluctuates from 65 to 96% [23, 24]. The knowledge of the geology of the study area cannot be overemphasized. It is used in remote sensing techniques for the investigation of ground displacements [25]. Penang Island is underpinned by an igneous rock when graded according to the fraction of alkali feldspar compositions into total feldspars, as shown in Fig. 1a [26, 27]. The landscape includes hills, mountains, and coastal plains. The granites have mineralogical and textural deviations and form a distinct plutonic complex [28].

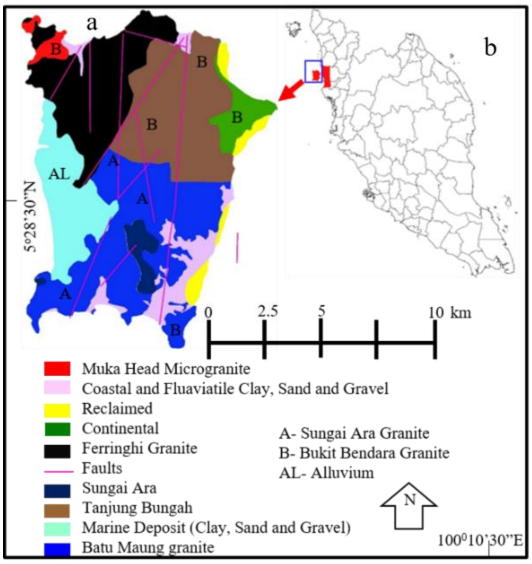

Fig.1 Location of the study area (a) in north-west of Peninsular Malaysia with the footprint of S-1A datasets (b).

Similarly, the island's soil comprises feldspar, quartz grains, and clayey substance with the potential to slide when there is heavy rainfall due to clayey material. The thickness of the soil material varies [23]. The soil pattern consists of residual soil categorized under granite soils between an average dry density of 1.41 kN/m^3 and 2.31 kkN/m^3, depth to bedrock 2.1 m and 40 m [29]. It is formed by the deposition of organic material without transportation [24]. The bulk of the island is covered by the steep soil type where most landslides have occurred. There are two types of granitic rocks of Penang Island based on age differences (i.e., mineralogy and texture of the granites), namely: Type A: Sungai Ara, and Type B: Bukit Bendera, as shown in Fig. 1a [24]. The southern part of the island hosts Type A granite, while Type B is found in the island's northern part except for those in the Batu Maung region. A major fault cuts the island into two (from the north-south). This fault touches areas like Paya Terubong, Tanjung Bungah, Air Itam, etc., which could be the reason landslide occurrences are frequent in those areas.

2.1 Brief History of Penang Island Landslides

One of the extreme weather events was recorded between 4 and 5 November 2017 when a tropical depression caused heavy rainfall across the northern region of peninsular Malaysia, which resulted in severe floods that later triggered several landslides along the river valleys in Penang Island [10] (Fig. 2). The island recorded a daily rain of 213.80 mm on 04 November 2017, 74% of the highest daily rainfall (288.20 mm) ever registered on the island [22]. The Penang flash flood on the two days was a rare catastrophe that the residents will never forget. Due to the exceptional intensity of the rainfall, the island was ravaged by the worst floods ever. The region's landslide was triggered due to the tropical depression that was identified by the Joint Typhoon Warning Center (JWTC) in the South China Sea on 26 October 2017. Initially, this depression was projected to pass over southern Thailand, bringing heavy rain to northern Terengganu and Kelantan. Unfortunately, the flow was diverted to the northern part of Peninsular Malaysia before reaching Thailand, resulting in significant tragedies in Kedah and Penang [23].

Fig.2 Flood events in Penang Island [23].

3. DATA ACQUISITION AND METHODS

Table 1 shows some characteristics of the S-1A data used and summarizes its technical aspects.

Table 1. Descriptions of Dataset of Sentinel 1A

Characteristics	Description
Launched	2014
Azimuth Spacing	14 m
Range Spacing	2.3 m
Orbit	Near-polar
Polarization	VV
Incident Angle	39
Revisit Time	12 Days
Flight Altitude	Right looking
Band	C
Acquisition Pass	Ascending/Descending

Sentinel-1A, S-1A equipped with a C-band sensor, is a satellite that acquires images while orbiting the Earth [30, 31]. Sixty (60) and fifty-six (56) Sentinel-1A S-1A images (2017-2019) acquired from ascending and descending orbits between 20 February 2017 and 13 November 2019, and from 01 September 2017 to 30 December 2018, respectively were used for this research to measure, quantify, and map ground deformation in the study area. These images were acquired by the European Space Agency (ESA) using Terrain Observation by Progressive Scans TOPS imaging mode [32]. The images acquired on 16 April 2018 and 29 March 2018 were chosen as the master images for the ascending and descending orbits, respectively, as they are days without rainfalls. All other images were allocated to the processing images of the slaves. For this research, the acquired data were processed using SARPROZ software. The data were imported into the software, and the orbits were set to choose suitable subsets for further processing. The flow chart of the SARPROZ software is depicted in Fig. 3.

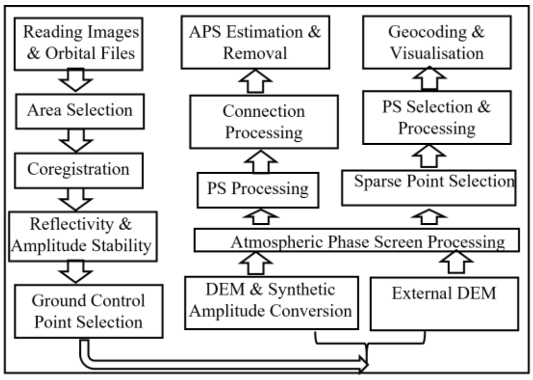

Fig.3. Flowchart for S-1A data processing.

The steps taken from the flow chart are as follows: the first step was the creation of a project folder SLC where the downloaded images were copied and saved into. The data were read, and the

Area of Interest AOI, such as latitude of 5.2651, the longitude of 100.1840, and radius area of 21 km were selected. Data were imported, and the master and slave images were extracted and finally coregistered in the data processing module to align all the images for comparison pixel-by-pixel without any positional errors. In generating interferograms, digital elevation model DEM was applied to remove the Atmospheric Phase Screen APS. Multi-looking interferograms were used to remove the long spatial wavelengths caused by atmospheric distortions due to some additional signals with various spatial frequencies [1, 5]. Three different Multi-Look ML factors were applied (15*15, 20*20, and 25*25), but the smoothest ML factors were chosen. Finally, the images were geocoded to Google Earth and projected to 3D orthophoto maps.

4. RESULTS AND DISCUSSIONS

Fig. 4 shows the steps in PS-InSAR processing.

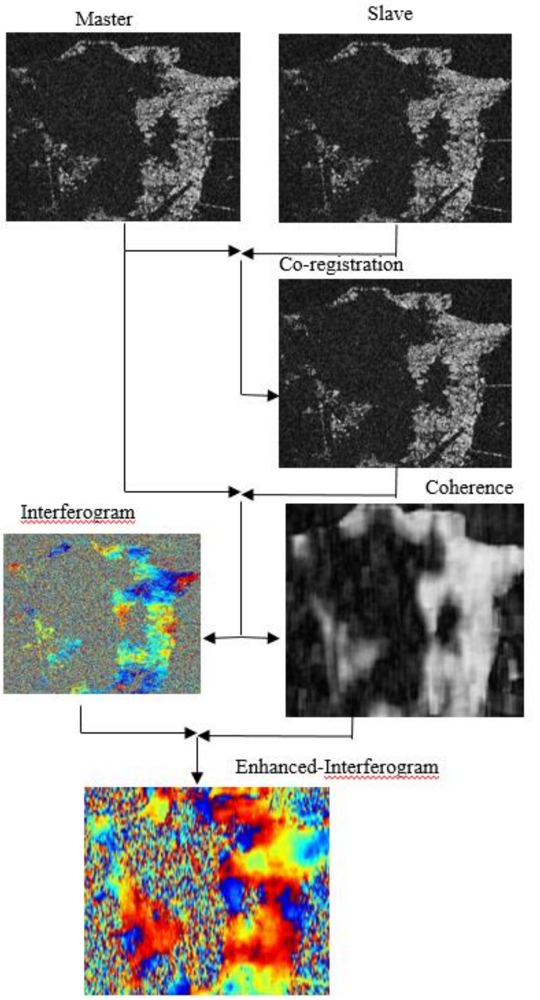

Fig.4. PS-InSAR method steps taken.

The temporal basis of the master scene is at the core of the acquisition period, where the degree of coherence specifies the master and slave pair connection. Good results were obtained using PS-InSAR technique with S-1A data and SARPROZ software to investigate ground displacements in Penang Island. The Goldstein mode was used to filter some additional signals with various spatial frequencies in the data. The average coherence of the dataset was calculated, and the results of the multi-looked interferograms (Fig. 4).

The one-star sensor graphs where the Persistent Scatterer (PS) technique is used to process satellite data were generated. All the interferograms produced in the star graphs are referred to as a single master acquisition. Furthermore, the PS points obtained are uniformly distributed over the entire study area because of the appropriate acquired data. Fig. 5 shows the velocity maps for both ascending and descending orbits using PS technique. The overall results of S-1A data indicate rapid slow land movement (subsidence) of around −9.19 and -10.00 mm/yr. Furthermore, the uplift values of 5.00 mm/yr and 4.66 mm/yr were calculated.

The InSAR results conform with the results obtained using the geophysical (i.e., electrical resistivity) method at Paya Terubong [5], though the results are not presented in this paper. The PS analyses are done for the entire Penang Island. Fig. 5 shows the PS points in the RGB color scale, where red color depicts extreme ground displacements, green color symbolizes moderate subsidence patterns, and blue color demonstrates uplift patterns. As the threshold value increases, the number of PS points decreases.

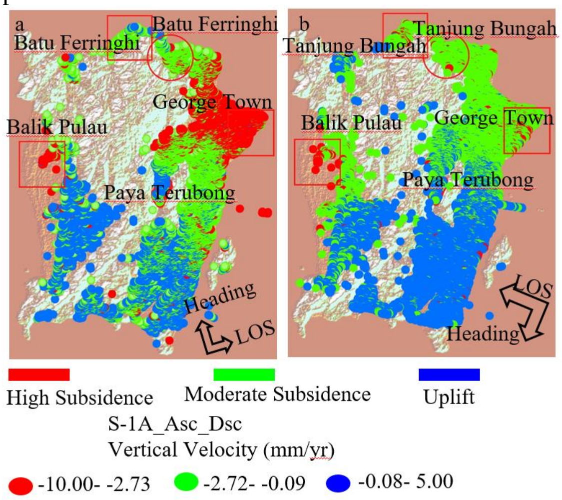

Fig. 5. Geocoded Time Series for Ascending (a) and Descending (b) orbits

The two orbits have identical deformation patterns, having the highest urbanization region in the core north and northeast. The persistent decrease in the velocity suggests that the PS points travel away from a LOS. This decline also shows that the area is subsiding and, therefore, susceptible to landslides. The threshold values (0.75 - 0.85) were used for the point detections, and the PS points values of 35961 and 37936 were obtained for the two orbits, respectively, to calculate the time series.

Fig. 6 represents the geocoded time series results for the descending dataset. Cumulative displacements and differential trends were observed. The time-series interpretations for PS points reveal that the landslides in the region are still active with high ground displacements in Fig. 6, where the x-axis represents the displacement in mm, and the y-axis depicts the date in yr. Thus, the graphs provide a better understanding of the displacement rate and linear trend. The declinations observed in the time series around November 2017 in Fig. 6 correspond to the landslide event triggered by heavy rain when tropical depression happened.

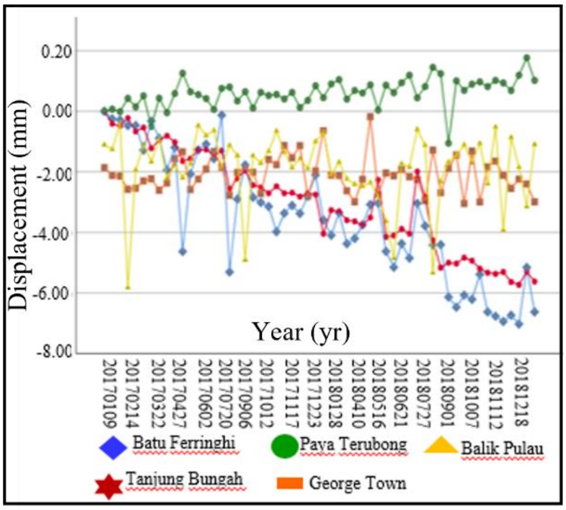

Fig. 6. Time series of the PSC at BF (diamond), TB (star), PT (circle), GT (square), and BP (Triangle) for the descending orbit.

4.1 PS-InSAR Validation

As several factors affect the accuracy of the InSAR technique, its validation is crucial. This was done using an existing analyzes of Global Positioning System (GPS), a high-precision technology. GPS has a long history of use in mass movement and landslide applications. However, its drawbacks include- inability to reach isolated locations and cover a large region and cost-effectiveness. Ami et al. [33] quantified Malaysia's vertical motion trend using GPS data (1999 to 2011) obtained from 87 different stations at the Department of Surveying and Mapping Malaysia (DSMM). The reported uplift values vary from 0.21 to 1.44 mm/yr, and subsidence values range from -0.04 to -34.41 mm/yr, with the subsidence rate at Penang Island (USMP station) -0.90 mm/yr as shown in Fig. 7a. The USMP station value in Fig.7a matches the values acquired simultaneously using the PS-InSAR approach shown in Fig.7b.

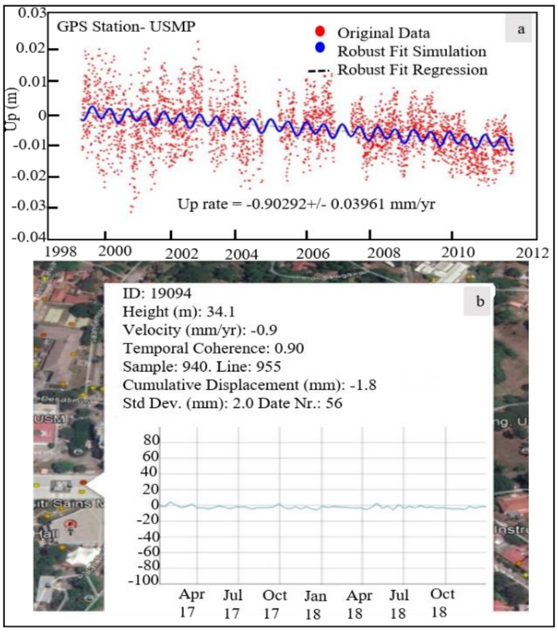

Fig.7 The vertical displacement of GPS measurement at USMP station [33].

4.2 Surface Deformation and Rain

Fig.8 shows the modified result of the rainfall classes by Khodadad and Jang [34].

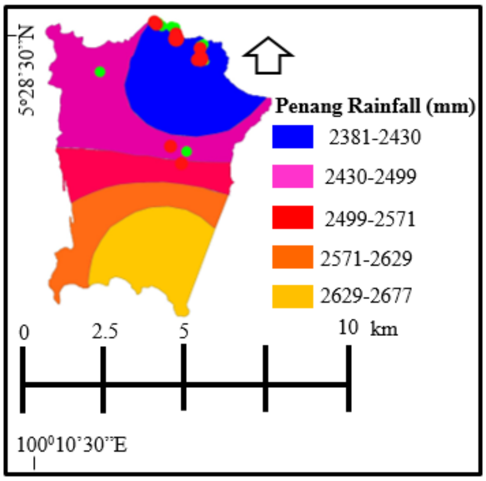

Fig. 8 PS points overlaid on rainfall map of Penang Island. The rain increases from the southwestern to the north-eastern part. It usually reaches its peak between October and January (Modified after [34]).

The results of 10 years (2003-2012) of rainfall data gathered and analyzed by Khodadad and Jang [34] on Penang Island are applied to validate the PS-InSAR analysis. InSAR techniques and rainfall results are found to have a linear relationship. The observed high rainfall intensity values in the northeast correspond to the deformation detected in the InSAR results. Additionally, the observed low rainfall values in the southwest correlate to the InSAR results (uplifting patterns). As a result, excessive rain is identified as one of the causes of ground displacement in Penang Island.

4.3 GIS Analysis

Geographical information system (GIS) is used to perform spatial analysis. It uses spatial analysis to create geographical data, and the information generated is explanatory. Figs. 9a-c shows the distribution of PS points overlaid on the slope (9a), elevation (9b), and geology (9c) maps of Penang Island.

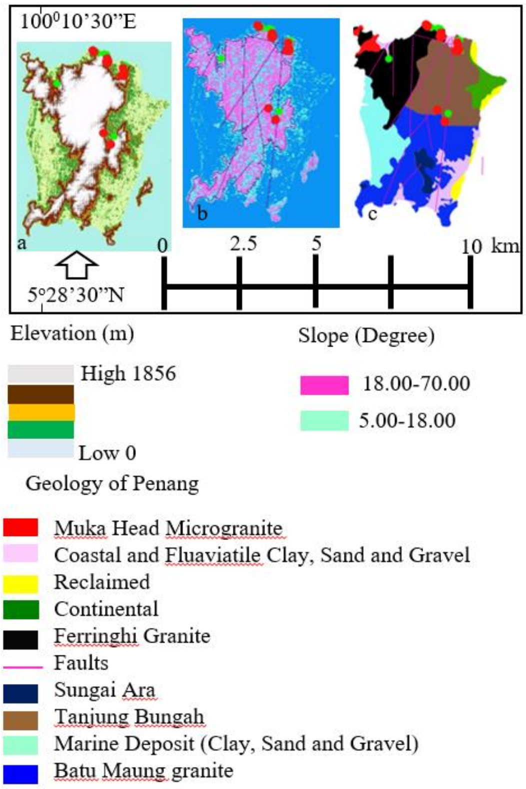

Fig. 9. PS points overlay on the slope

The deformation patterns are on the highest slope values (> 25°) (Fig. 9a), where various landslide events occur. Fig. 9b shows the elevation map of the area. The PS points are well distributed at the highest elevation edges, where different landslide occurrences usually happen. Various landslide events have been recorded in Batu Ferringhi and Paya Terubong areas. They are both respectively located on the northwestern coast and southeastern part of Penang Island. The geology of Paya Terubong (middle of the island) comprises South Penang Pluton (SPP) Fig. 9c. The area is underlain between coarse-grained and medium-grained porphyrite muscovite- biotite granite. The high records of landslide occurrences at Paya Terubong are due to the main fault, Fig. 9c, that crosses the area and weathering processes. Vegetation removal and illegal clearing of the hills also play crucial roles in the region's landslide events. Heavy rainfall makes the soil of the area become saturated and raises the flash flood risks downstream.

4.3 Surface Deformations with Soil and Geology

The steep soil type, which is made up of clayey, gravel, and silty components, covers the bulk of the island and has the tendency to slide in huge amounts when there is a lot of rain. Erosion of collected rainfall penetrates clayey materials, induces subsidence, and triggers old landslide fractures. Fig.10 depicts the main constituents of the soil series of the island- from north to south. The earth stiffens when coarse-grained soil is overlaid by fine-grained soil, linked to southern uplift trends. Likewise, when fine-grained material rests underneath the soil layer, it is loose at first and becomes dense with depth, and could be linked to subsidence patterns in the north [35].

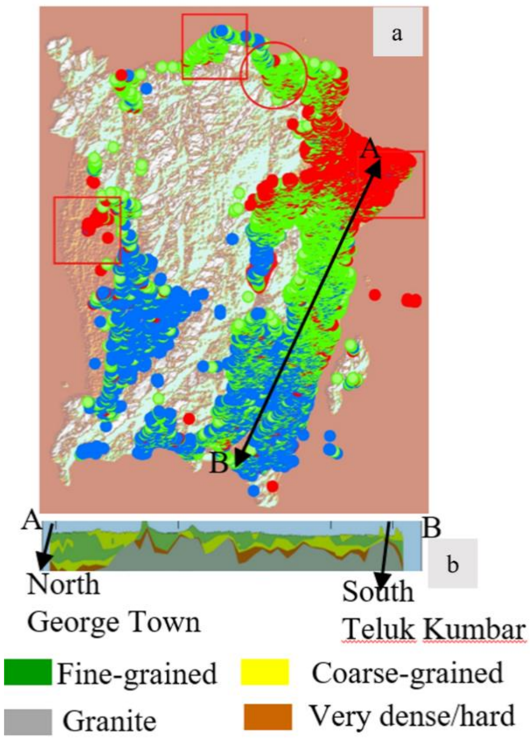

Fig.10 Deformation map of Penang Island and North-south stratigraphy along the island's east coast (Modified after [35]).

5. CONCLUSION

In this study, S-1A images have been applied to quantify the landslide occurrence and monitor the instability of the slope. The S-1A results show ground deformation values ranging between −9.19 mm/yr and -10.00 mm/yr for subsidence pattern and from 5.00 mm/yr to 4.66 mm/yr for uplift behavior. A consistent linear trend of ground deformation was detected with the application of PS-InSAR techniques across Penang Island. The public must be aware of the steps to be taken if a warning is issued about the devastating consequences, particularly for those living in hillside areas. At the same time, the potential use of the PS technique is prominent for monitoring surface displacements. Some ground movements detected in spatial time are shown on the created maps. Such maps will assist the government in getting a better understanding of the areas where ground displacements are ongoing during hill site allocations. The maps also indicate the potential landslide areas for engineers and scientists' awareness during construction and research.

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