Land subsidence detection in Jakarta Province using Sentinel-1A Satellite Imagery

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Abstract. The land surface in Jakarta Province is thought to have experienced relatively continuous subsidence because of natural processes and artificial activities. This research was carried out to evaluate the rate of land subsidence in Jakarta Province. Based on this research, it can be shown from the Sentinel-1A satellite images that there has been landed subsidence. The data used are two pairs of Sentinel-1A Single Looking Complex (SLC) images acquired in 2019 and 2020. The data was processed using the DInSAR method to examine the rate of land subsidence. The results show that the land subsidence rate in Jakarta Province during the 2019-2020 period varies from 1.8 cm to -10.7 cm/year. The literature data results in 2016 experienced a decrease in land subsidence with a significant value of -12.6 cm/year. Land subsidence in 2017 averaged -1.8 cm/year. The land subsidence results from 2019 to 2020 have a value that tends to be lower than in 2016 of -3.62 cm/year. Land subsidence occurs mostly in coastal areas and near estuaries caused by the nature of alluvial deposition materials. It has caused damages to road infrastructure in several regions of Jakarta Province, such as Mutiara Beach, West Cengkareng, and Pademangan.

Keywords: coastal areas, DInSAR, land subsidence, satellite imagery, Sentinel-1A

1. Introduction

The development of the Jakarta Province has grown very rapidly in the industrial, trade, transportation, tourist, and other sectors. This is expected to directly increase the rate of land subsidence in Jakarta Province since it is located in a coastal area. Data reported over the years shows there has been land subsidence in some places in Jakarta Province at different rates [1]. In general, the factors that can cause land decline that occurs in Jakarta Province include decreases caused by building loads, excessive groundwater extraction, tectonic forces and natural consolidation of alluvial soil layers. It is also caused by underground mining, fractures of the Earth’s crust, gas and oil extraction, and geothermal contraction in the lithosphere [2]. The impact of land subsidence in Jakarta Province has come into several forms, such as permanent construction cracks in some road infrastructure, changes in river canal flow, more comprehensive expansion of flood areas and damage to drainage systems. In addition, increased seawater intrusion and increased coverage of tidal flood areas. Several methods have been conducted to evaluate land subsidence in Jakarta. In 1980, land subsidence in several locations in Jakarta Province was measured using measurement techniques such as levelling surveys, extensometer measurements, groundwater level observations, GPS surveys, and Interferometric Synthetic Aperture Radar (InSAR) techniques [3, 4]. Results obtained in the previous studies prove that some places in Jakarta decreased by about -20 to -25 cm/year in 1900-2010 [5]. Direct research into the field requires a lot of time and cost. Over time, technology has developed that makes it easier to carry out monitoring in the field. Land subsidence can be detected using spatial data in the form of radar satellite imagery.
Satellite imagery is an effective way to obtain spatial information and the need for monitoring of land subsidence. Satellite imagery has a higher spatial and temporal resolution to detect changes quickly [6]. The choice of radar technology is the best solution in determining spatial mapping for estimating land subsidence. DInSAR is a RADAR image processing method that can provide good accuracy and minimize the effect of decorrelation. Microwaves emitted from active sensors such as Radio Detection and Ranging (RADAR) have advantages able to scan the earth's surface in various weather conditions, day and night, including through thick cloud cover and rain. The research purpose of mapping the rate of land subsidence from the Sentinel-1A radar satellite images using the DInSAR method in Jakarta Province.

2. Materials and Methods

2.1. Study Area and Materials
The study site is located in five administrative cities of Jakarta Province, namely North Jakarta, West Jakarta, Central Jakarta, East Jakarta and South Jakarta. Due to its particular location and geological conditions, the area is susceptible to various natural hazards, including flooding and landslides. However, the fast subsidence in several areas was also associated with the construction of large artificial structures, including residential, industrial, highways, airports and stations. To investigate ground movements in Jakarta Province, we collected Sentinel-1A of VV polarization data in ascending mode and Sentinel-1A data polarizations VV in ascending mode (incidence 14.1 m pixel spacing). Sentinel-1A was selected for the study because of the availability of archival data and the easy to extract the data. With 4 burst scenes acquired on January 7, 2019 and 4 burst scenes of acquired on January 2, 2020. This mode acquires 3 sub-tiles using Terrain Observation with Progressive Scan SAR (TOPSAR). Sentinel-1A provided good spatial and temporal coverage for DInSAR analysis in this study (Figure 1).

![Figure 1. Map of research locations in Jakarta Province.](image-url)
The materials used include two SAR Sentinel-1A type level 1 Single Look Complex (SLC) was acquired on January 7, 2019 and January 2, 2020, Digital Elevation Model (DEM) data, Jakarta Province shapefile maps, and data GPS Jakarta, 2002 to 2010.

2.2. DInSAR Processing
The proposed method for integrating DInSAR and analysis for urban land movement included, topography phase removal, multi looking, phase unwrapping correction, and a combination of DInSAR results to get phase to displacement imagery. DInSAR processing was applied to each track to generate the differential interferogram, coherence, and unwrapped phase. Spatial and temporal subsidence processing was carried out using the DInSAR method on the SNAP software. The data processing process consists of image data acquisition to remove of topographic and atmospheric influences, which will then be converted into an altitude phase. All the interferograms from one track were co-registered and resampled to the same reference image. The interferograms were improved using adaptive filtering and unwrapped using the Minimum Cost Flow algorithm with a well-known reference point. The same reference location is identified in each interferogram so that the phase is not wrapped and used for both polarization mode data. DInSAR products from both were georeferenced to the same resolution 5 x 20 m. The data obtained are in the form of two paired radar images and have master and slave data characteristics, which are shown in Figure 2.

The master and the slave data are then processed through aligning interferogram. Align interferogram is a process of merging to obtain phase and amplitude information from two SLC images that overlap and have a clear correlation, as shown in Figure 3. The baseline perpendicular estimation between the master and the slave data needs to be considered in determining the appropriate image pair so that it is not too high. Perpendicular baseline data used in image pairs can affect the coherence value. Coherence is the correlation coefficient of the SAR image in the smallest part. The longer the perpendicular baseline, the worse the coherence value will be. Perpendicular baseline data can be found on the DInSAR stack overview menu display on the SNAP software. Therefore, the perpendicular baseline data used in image pairs can affect the coherence value. The MCF algorithm is better in producing a Digital Surface Model (DSM) represented by the RMSE value lower and higher vertical accuracy. The difference between DEM and DSM is DEM can represent ground level, whereas DSM can present the elevation of the ground surface and objects seen from over the ground. The results obtained in the unwrapping process are still in \( \pi \) radians (phase). Combining several radar images can minimize interference effects and produce good geometric shape information.
Figure 3. Align of the master and slave images.

After filtering, the next step is multi-looking, which reduces the SAR image’s noise phase and is converted into a pixel phase. After that, issue multi-looking results with export unwrap tools to be entered into the next stage. The next process, phase unwrapping, is converting the ambiguity phase into an absolute phase. The resulting phase from the multi-looking stage is still ambiguous, so it needs to be converted into an absolute phase. At this stage, it is using additional tools in the form of SNAPHU. Conversion of unwrapping data from phase form to elevation value is done to determine the difference in height from the DInSAR process or convert from slant to height using the phase to displacement tool in SNAP software. The last stage is adjusting the position of the coordinates to the actual position or generally called geocoding—the results of the range doppler terrain correction used next to create a spatial map of land subsidence.

3. Results and Discussion

3.1. Display of Sentinel-1A Image on DInSAR Processing
A radar image is formed because of the amplitude measurement results from the radar system. Amplitude is the intensity value of the image colour obtained from the scattering reflection of the object received by the receiver. The interferogram phase and amplitude intensity in DInSAR processing are presented in Figures 4A and 4B.

Figure 4. Amplitude interferogram (A), phase interferogram (B) January 7, 2019 - January 2, 2020.

In Figure 4A, some areas show white as rough objects, while black areas show objects with flat or smooth surfaces. The black area in the interferogram image is water. Objects with a rough surface will reflect strong scattering, resulting in bright colours on radar images. In Figure 4B, fringes are formed.
because the orbits are not the same when taking the SAR image. Fringes are thin lines that show the phase values at the same value. The phase interferogram interval has a value of $-2.98\pi$ to $2.98\pi$. According to Ismullah [11], the interval between the first colour and the next one has a difference of $2\pi$.

The magnitude of the change in the phase value produced by the phase interferogram image is not visible, as shown in Figure 5. It is caused by the small value of the Signal to Noise Ratio (SNR) since there is a significant noise decorrelation in the phase interferogram image. A filtering technique can minimize SNR value. Filtering can increase SNR value on the interferogram image. The results of DInSAR processing filtering are shown in Figure 5.

![Figure 5. The phase of interferogram filtering January 7, 2019 - January 2, 2020.](image1)

The filtering process is carried out using the Goldstein filtering technique. It shows that the filtering process can significantly increase the visibility of the fringes in the interferogram image so that the fringes are easier to interpret visually [7]. The results of the phase interferogram image can show land subsidence with an indication of the density level of the fringes. Information on the filtering process is limited between the values of $-\pi$ to $\pi$, giving rise to the problem of phase ambiguity [12]. Therefore, an unwrapping phase is carried out to change the ambiguity of the phase values into absolute phases. The results of phase unwrapping processing are presented in Figure 6.

![Figure 6. The phase of the interferogram unwrapping January 7, 2019 - January 2, 2020.](image2)
The unwrapping phase is deleting the discontinuity of the integer $2\pi$ in the interferogram image [13]. The algorithm included in the unwrapping process uses Minimum Cost Flow (MCF). The formula for the MCF algorithm is presented in equation [9]:

$$\sum_{i,j}^{n} W_{i,j}^{(x)} (\Delta \Phi_{i,j}^{(x)} - \Delta \varphi_{i,j}^{(x)}) + \sum_{i,j}^{n} W_{i,j}^{(y)} (\Delta \Phi_{i,j}^{(y)} - \Delta \varphi_{i,j}^{(y)})$$

(1)

where:

$W_{i,j}^{(x)} = i,j$ horizontal pixel

$W_{i,j}^{(y)} = i,j$ vertical pixel

$\Delta \Phi_{i,j}^{(x)} = \text{absolute horizontal phase (abs\_phase)}$

$\Delta \Phi_{i,j}^{(y)} = \text{absolute vertical phase (abs\_phase)}$

$\Delta \varphi_{i,j}^{(x)} = \text{wrapped horizontal phase (2\pi)}$

$\Delta \varphi_{i,j}^{(y)} = \text{wrapped vertical phase (2\pi)}$

In Figure 6, it can be seen that after experiencing the unwrapping process, the interferogram image already has a deformation value in $\pi$rad units (phase). The phase unwrapping interval has a value of -6.71 $\pi$rad to 21.14 $\pi$rad indicated in purple and increases in blue colour. Conversion to get the metric unit value requires the displacement process. The displacement process aims to obtain the value of subsidence deformation. This process is a conversion from the absolute phase to metric units.

3.2. DInSAR Results of Land Subsidence in Jakarta Province

A Spatial map of land subsidence in Jakarta Province in 2019-2020 from DInSAR processing is shown in Figure 7. The value of subsidence is indicated by the colour indicated on the colour bar with a range of -10.7 cm/year indicated in red to 1.8 cm/year is indicated in blue.

The vertical distribution pattern of land subsidence in Jakarta Province is highest in the north of Jakarta and decreases towards the south of Jakarta. In the southern area of Jakarta Province, there is an uplift in the land surface that will be discussed in the analysis section of land subsidence. Statistical data on DInSAR processing in Jakarta Province in 2019-2020 shows that significant land surface subsidence has been detected in 5 cities in the Jakarta Province, presented in Table 1. The highest average land subsidence occurs in the City of North Jakarta, 4.9 cm/year with a maximum value of -10.7 cm/year of land subsidence, followed by land subsidence in the City of West Jakarta -9.9 cm/year. The lowest average land subsidence occurs in East Jakarta City, which is -2.5 cm/year.

The results obtained from data processing were compared with previous literature data in the study of Cyntia from 2016 to 2017. North Jakarta experienced an average high land decline, especially in North Jakarta, close to the sea, where land subsidence is affected by natural activity. Three rivers cross the city of West Jakarta with large water flows. This will cause the soil and water flow to be easily eroded, resulting in significant subsidence. Land subsidence in 2017 did not decrease as much as in 2016, namely an average of -1.8 cm/year. The results of land subsidence in 2019 until 2020 have a value that tends to be lower than in 2016, which is -3.62 cm/year. Comparison of average land subsidence data from DInSAR processing with literature data is shown in Figure 8.

Table 1. Extent of land subsidence and increase in Province of Jakarta land surface in 2019-2020.

| Location     | Minimum (cm/year) | Maximum (cm/year) | Average (cm/year) |
|--------------|-------------------|-------------------|-------------------|
| North Jakarta| 1.2               | -10.7             | -4.9              |
| East Jakarta | 1.2               | -7.0              | -2.5              |
| West Jakarta | -1.8              | -9.9              | -4.8              |
| Central Jakarta | -1.2          | -5.3              | -3.1              |
| South Jakarta | 1.8               | -7.5              | -2.8              |
Figure 7. Map of land subsidence in Jakarta Province 2019-2020.

Figure 8. Data results of average subsidence using the DInSAR method 2016-2017 in Jakarta Province [14].

The results of literature data in 2016 in Jakarta Province experienced a decrease in land surface with a significant value, namely -12.6 cm/year. Land subsidence in 2017 did not decrease as much as in 2016,
namely an average of -1.8 cm/year. The results of land subsidence from 2019 until 2020 have a value that tends to be lower than in 2016, which is -3.62 cm/year. Comparison of the spatial map of land subsidence for DInSAR processing in 2019-2020 with direct data collection using GPS for 2007-2008, 2008-2009, and 2009-2010 is shown in Figure 9.

![Figure 9. Land subsidence from GPS observations 2007-2008 (A) 2008-2009 (B) 2009-2010 (C), and DInSAR 2019-2020 (D) in Jakarta Province [15].](image)

DInSAR results are usually verified using levelling or GPS measurements [16, 17, 18]. GPS measurements for 2007-2008 have an interval of -6 to -28 cm/year. GPS measurements for 2008-2009 have a reduction interval of -3 to -14 cm/year, while the GPS measurements in 2009-2010 have a reduction interval of -6 to -16 cm/year. GPS measurement was used to build a model to kriging interpolate the missing records and predict the measurements corresponding to the DInSAR in this study. High land surface subsidence resulted in flooding that occurred in 2007. Observations made by the Meteorology, Climatology, and Geophysics Agency (BMKG) indicated that the rainfall on February 2, 2007, was the biggest. Rainfall occurs in Ciledug with an intensity value of 339.8 mm/day, Kemayoran is 235 mm/day, Pasar Minggu 220 mm/day, Pakubuwono 178 mm/day, and Tanjung Priok 168 mm/day.

The results obtained from DInSAR processing in 2019-2020 have an interval of 8 to -17 cm/year. High land subsidence, high rainfall, and the destruction of the sea barrier of the National Capital Integrated Coastal Development (NCICD) in Penjaringan, North Jakarta, at the end of 2019 exacerbated flooding in 2020. The rivers in Jakarta have a water level that exceeds the normal water level, resulting in an overflow along the river. The results of DInSAR processing shown in the image above have occurred in the Ancol area and its surroundings. According to geologists at the Indonesian Institute of Sciences (LIPI), canal system cannot solve flooding in Jakarta Province because Jakarta is a flood basin
geologically. The North Jakarta City Regency area (around Ancol and Jakarta Bay) is experiencing uplift due to tectonic activity. Therefore, the water flow from the 13 rivers that empty into Jakarta Bay cannot flow smoothly into the sea and is blocked in the large Jakarta basin [19].

3.3. Analysis of Land Subsidence in Jakarta Province

The Jakarta Province area consists of sedimentary rock layers that limit layers above is 50 meters below ground level. The process of land formation on the Jakarta Bay Coast is influenced by estuaries rivers with high sediment content and the formation of coastal lands faster than the low river sediment content. These deposits come from weathering and erosion carried by water rivers and settle in the river mouth. The components influence the characteristics of rock constituent materials in the rock. Alluvial constituent material is found in coastal areas and near river estuaries in sand coarse and macro-pore texture. This factor will make it easier for alluvial constituent materials to be filled with water and air media so that the bonds between the materials become weak [20]. The weak bond between soil particles is caused by the influence of the carbonate or oxide compound among these particles, or it can also be by the presence of minerals organic. This will result in the alluvial material being eroded more easily by streams of river water. Changes in land use in the Jabotabek area have changed hydrological functions in watersheds and have improved flood intensity for the Jakarta Province area [21]. Land use these are generally intended for the development of existing infrastructure in Figure 10.

![Figure 10](image)

**Figure 10.** Infrastructure near the river mouth at Tanah Rendah Street, Jatinegara, East Jakarta.

The existence of settlements causes the soil binding capacity to decrease around the river. Several damages evidence this phenomenon of land subsidence to road infrastructure that occurred in 5 districts of Jakarta Province as shown Figure 11.

![Figure 11A](image)
![Figure 11B](image)
![Figure 11C](image)

**Figure 11.** Damage to road infrastructure in Mutiara Beach (A), West Cengkareng (B), and Pademangan (C) [22].

This land subsidence has an impact on infrastructure damage roads and some have caused landslides in several areas. In figure 11A, located at Mutiara Beach, North Jakarta, there was damage to the sidewalk resulting from subsidence. Gaffara [23] indicates that land subsidence in coastal areas is due
to the correlation between alluvial soil texture, groundwater use, and building loads. In the West Cengkareng District, West Jakarta, as shown in Figure 11B, landslides in the road body area. Reporting from the Kompas media letter has been explained that land subsidence in West Cengkareng District has reached - 26.6 cm/year. Figure 11C is located on R.E Martadinata Street, Pademangan District, North Jakarta. There was damage to road infrastructure main/subsidence above the river flow. According to Wibowo [24], one of the causes of land subsidence is the consolidation or compression of soil and groundwater changes.

4. Conclusion

Overall, the Jakarta Province area has experienced a decrease in surface land during the study period in 2019 to 2020. By region, the city of North Jakarta experienced the largest land subsidence. From 2019 until 2020, the average land level subsidence in the Jakarta City area is North -4.9 cm/year, East Jakarta -2.5 cm/year, West Jakarta -4.8 cm/year, Central Jakarta -3.1 cm/year, and South Jakarta -2.8 cm/year. Factor infrastructure development near river estuaries is also increasing land subsidence in Jakarta Province. Further researchers need two-phase image processing with a hose in the same year and direct measurements to the field to increase the accuracy of data processing results.

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