Analyses of surface deformation with SBAR InSAR method and its relationship with aquifer occurrence in Surabaya City, East Java, Indonesia

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Abstract. Rapid development of Surabaya City requires space for industry and settlement. The city development is followed by increasing of water demand for various purposes. Large amount of groundwater extraction may cause ground subsidence. According to groundwater extraction, we tried to delineate the possibility of aquifer potential based on ground surface deformation using Interferometric Synthetic Aperture Radar (InSAR) and Electrical Resistivity methods. The InSAR is a method to estimate surface deformation in millimeter scale based on different phase of SAR data between acquisition times. In this paper, surface deformation combined with ground resistivity was used to analyse the potential of aquifer related to subsidence at Surabaya City, East Java, Indonesia. The Small Based Subset (SBAS) method was used to reduce phase delay in the interferogram due to atmospheric condition. Based on the SBAS InSAR the deformation was detected at Surabaya City in January 2007 to February 2008. The largest and lowest deformation about 40 mm/year and about 0 - 10 mm/year were located in North to Southeastern and Western part of the city, respectively. The geodetic Global Positioning System (GPS) campaign in Surabaya confirmed that the detected deformation correlated with the ground subsidence with correlation coefficient about 0.96. To obtain the subsurface structures at subsidence zones, the Electrical Resistivity survey with Schlumberger configuration was performed in Surabaya city. According to the SBAS InSAR and subsurface resistivity, the subsidence around Pabeancantikan, Kenjeran, Simokerto and Tenggilismejoyo sub-districts agreed to high resistivity about 7 - 18 Ωm. The Sandstone of Kabuh and Pucangan formations in this area served as ground water aquifer which used by more than 200 wells. Ground water extraction probably triggered the subsidence at ground surface. The high resistivity at subsidence zones originated from high porosity of rocks served as aquifer with high groundwater extraction.

Keywords: Subsidence, SBAS, Aquifer, Surabaya, GPS, Schlumberger

1. Introduction
Land subsidence is a common phenomenon in big cities of Indonesia, such as Bandung [1], Jakarta [2], and Semarang [3]. Each city has different subsidence characteristics and their causes. The excessive exploitation of ground water is one of the causes of the land subsidence [4].

The Interferometric Synthetic Aperture Radar (InSAR) is a method to determine the surface deformation based on the difference in phase signal [5]. This method is effective to detect subsided or uplifted zones [6]. To characterize the land subsidence caused by groundwater exploitation; we also conducted the Electrical Resistivity survey with Schlumberger configuration. The Electrical Resistivity method could be used to interpret the location of ground water aquifers in the depth based
on resistivity parameter of the rock formations. Characterizing land subsidence in Surabaya city has been being studied due to the amount of groundwater extraction. The connection between groundwater extractions with subsidence occurrence were analysed to interpret the cause possibilities of land subsidence in Surabaya city including groundwater extraction.

Based on Shaded map from SRTM 1 arc second, the Surabaya City is located at low topography between 0-30 m above mean sea level (amsl). Surabaya city have height of ground ranging from 0-10 m that is occupying about 25,919 hectares (80.72%) spreads in the east, north, south, and centre. In other areas of the city have ground height of 10-20 m (12.53%) and above 20 m above sea level (6.76%) which is generally present in the west and south of the city of Surabaya. The location of study area is depicted in Figure (1).

![Shaded map from SRTM 1 arc second](image1)

**Figure 1.** Study area at Surabaya city, East Java showed by the red line square (Shaded map from srtm 1 arc second)

The geomorphology of the study area is dominated by paneplain of alluvial about 80% from total area. Therefore, the outcrop is very limited. Subsoil has a grain size of clay to sand. Differences in soil color and gradation of soil grains found locally in the eastern part. Light brown soil with grain size of clay to sand and gravel, found in small amounts. Based the geological map (Figure 2), this soil is interpreted as weathering rock of Pucangan formations. The geological structures could not be found clearly at the field. Therefore, we used geological maps (Figure 2) to know structure of rock, in the location trending anticline is the east - west.

Based on Geological map of Surabaya and Sepulu [7] Surabaya has 4 lithologies with the youngest lithology are are Alluvium unit plains that has unconformity contact with all the older (Figure 2). Detail stratigraphy could be explained as follows:

1. Aluvium Unit
   Alluvium unit composed of clay to gravel sized loose material Alluvium unit composed of clay-sized material loosened up gravel, consisting of clay, sandy clay, sand gravel, loose, soft, water passing medium - high. This sediment is the result of the deposition of sediments by the river flow. Alluvial Deposition is spread in most areas of Surabaya starting from the north, south, east, and in the area around the coast. The maximum depth is 30 m and occupies a land area reaching more than 60% of the research area
2. Sandy mudstone unit
   This unit consists of sandstone, tuffaceous sandstone and conglomerate. Commonly, colored gray - brown, fine grained – rough, angled - rounded, disaggregated bad - medium, fragile, passing the water is medium - high, containing of conglomerate insertions This unit has weathered up generally in the form silty clay containing a bit of sand, brown, soft and plastic when it expands, friable when dry, less
than 1 m thick. Actually occupy several places in the southern part, approximately 17% of the area of mapping according to the distribution Pucangan Formation and Kabuh Formation.

![Geologic Map of the city of Surabaya scale of 1: 100.000](modified from [7]).

2. Data and Method

2.1. Data

The data used in this study consists of two main data. The first data is Synthetic Aperture Radar (SAR) from Advanced Land Observation Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) level 1.0. The second data is Electrical Resistivity from 20 measurement points. There are nine ALOS PALSAR data used and acquired on 3rd January 2007 to 21st February 2008. These data are HH polarimetric mode. We also used GPS campaign measurements from 20 stations in October to December 2010. The ALOS PALSAR data used in this study were listed in Table 1.

The correlation and interpretation of the ground surface deformation and electrical resistivity were used to evaluate and characterize the aquifer potential zones.

**Table 1.** Detail ALOS PALSAR data used in this study

| No | Name of data                  | Date of record | Direction |
|----|-------------------------------|----------------|-----------|
| 1  | ALPSRP050183770-L1.0         | 03-Jan-07      | Descending|
| 2  | ALPSRP056893770-L1.0         | 18-Feb-07      | Descending|
| 3  | ALPSRP063603770-L1.0         | 05-Apr-07      | Descending|
| 4  | ALPSRP070313770-L1.0         | 21-Mei-07      | Descending|
| 5  | ALPSRP083733770-L1.0         | 21-August-07   | Descending|
| 6  | ALPSRP090443770-L1.0         | 06-Okt-07      | Descending|
| 7  | ALPSRP097153770-L1.0         | 21-Nop-07      | Descending|
2.2. Method

The Small Baseline Subset (SBAS) InSAR algorithm was first demonstrated by [8] as a means to mitigate atmospheric artifacts and topographic errors in time-sequential interferograms and thus to obtain time-series deformation information. The algorithm uses only interferograms with small baselines that overlap in time in order to reduce spatial decorrelation. The SBAS technique relies on a proper combination of unwrapped interferograms characterized by a small normal baseline between the acquisition orbits and a short time interval (temporal baseline) between the acquisition epochs. Following [9], the SBAS processing work flows depicted in Figure 3 could be explained as follows:

1) Evaluation of the orbital parameters associated to each SAR acquisition (subsequently used within the estimation of the spatial baseline value) and reference Master image selection.
2) Generation of a set of single look SAR images (SLC) from the available raw data files (focusing).
3) DEM conversion into reference Master image SAR coordinates and computation of sensor to target distance files (range files) for each acquisition.
4) Optimal interferometric data pair distribution selection.
5) Co-registration of each SLC data pair with respect to the selected reference Master image
6) Differential interferograms and corresponding spatial coherence maps generation
7) Noise-filtering of the generated Differential InSAR (D-InSAR) fringes
8) Generation of the mean deformation velocity map and the corresponding time series, for each coherent pixel of the investigated area, via the inversion of the computed sequence of D-InSAR interferograms. At the same time, an estimate of the possible residual topographic components and the atmospheric contributions is also accomplished
9) Geocoding of the obtained results and projection onto a universal cartographic grid.

Resistivity method is one of geophysical exploration method that utilizes resistivity properties of medium to learn the situation subsurface. In principle, the current flowed / injected into the earth through a pair of the current electrodes and then the response received is the potential difference on pair of electrodes potential then the response received is the potential difference a pair of electrodes. From this response, can then studied the electrical properties of the media under the surface, thus enabling the geological interpretation to create a subsurface geological models based on the electrical properties of the medium (rock). In this study, the geological model used to determine the groundwater aquifer. Here are the steps performed in the resistivity method.

1) Measurement in the study area, the measurement is performed at 20 points using Schlumberger configuration. This configuration is already well known in determine the position groundwater (aquifers).
2) 1D modeling preparation with inverse modeling methods Ridge Regression (RR) which can be expressed by equation from [10] as follows:

\[ \delta g = (J^T J)^{-1} J \delta f \]  
(1)

Where \( \delta g \) is the difference between the initial parameters and allegations parameter, \( \delta f \) is the difference in pseudo resistivity model and pseudo allegations resistivity models, \( J \) is the Jacobian matrix.
3) From the 20 points 1D models correlated to become a 2D cross sections to determine the distribution of potential rock aquifers in the area of research.
4) From that 20 points, was made contour of thickness of potential aquifer areas on entire research area.
3. Result and Discussion

3.1. SBAS InSAR

- Orbit parameters extraction and Master selection

By exploiting the orbital information, it is possible to plot each normal baseline of SAR data pair, as shown in the Baseline plan, as shown by Figure 4.

By benefiting of this graphical representation, it is possible to properly select the reference master data with the shortest normal baseline. In order to help the subsequent co-registration step, it is useful to select as a reference the SAR image with a baricentrical position in the acquisition distribution plot. It implies that the normal of data pair are the smallest.

- Data Pairs Selection and co-registration

Data pair selection was obtained by imposing a threshold on the minima temporal and normal baseline. Therefore, only smallest perpendicular baseline interferograms would be generated. Each
interferogram corresponds to an arc connecting two green points, i.e., two SAR acquisitions. Blue arcs are relevant to interferograms belonging to the Triangulated Irregular Network.

For a generic point in the master image, the SAR coordinates of the same point in the slave image is given by:

\[ x'_s = x'_m + \delta x' (x', r') \]  \hspace{1cm} (2)

\[ r'_s = r'_m + \delta r' (x', r') \]  \hspace{1cm} (3)

wherein \((x'_m, r'_m)\) and \((x'_s, r'_s)\) are the coordinates of the point in the master and slave geometry, and \((\delta x', \delta r')\) is the difference coordinates in the SAR to be applied to the master image coordinates. The registration process can solve the problem of computing the geometric image transformation and the problem of re-sampling the second image with respect to the master one, in such a way that each ground point is located at the same position in the two different images.

**Figure 4.** The normal baseline for data pair distribution from nine scenes of ALOS PALSAR.

**Figure 5.** The ALOS PALSAR selected data pair distribution in the normal baseline plane.
Differential interferogram generation

The generation of the differential interferograms is carried out by subtracting the estimated topographic phase contribution from the interferometric phase term. The differential interferometric phase $\Delta \phi$ is related to the deformation occurred between the two passes of the SAR sensor by the following relation:

$$\Delta r = \frac{4\pi}{\lambda} \Delta \phi$$

where $\Delta r$ represents the slant range sensor-to-target difference (after removing the synthetic fringes) between the two passes and $\lambda$ is the sensor wavelength (Figure 6).

![Image of interferograms](image-url)

**Figure 6.** Time series of generated interferograms in regional scale of Surabaya.
Deformation time series generation

Deformation time series generation is the SBAS INSAR processing can be summarized as follows:

1) In order to extract from each generated differential interferogram an information relevant to the actual deformation, the computed differential phases, representing the modulo-2\pi restriction (wrapped) of the original interferometric phase signal.

2) The unwrapped interferograms, previously filtered from the residual topography artifacts, are used within the time series generation. Indeed, the selected DInSAR pairs are characterized by a small spatial and baseline as well as by a small frequency shift between the Doppler centroids [11]. As a consequence of these constraints, the SAR images involved in the interferogram generation could be grouped in several independent small baseline subset, thus an appropriate “link” of such subsets is required.

3) Finally, the atmospheric phase signal is evaluated and removed from the computed deformation time series uses the Singular Value Decomposition (SVD) approach based on a minimum-norm criterion of the deformation rate to derive time-series deformation estimates.

In this context, we just remark that by exploiting the previously unwrapped filtered interferograms \( \{\psi_j\}_{j=1}^M \) it is possible to obtain the phase values \( \{\varphi_i\}_{i=1}^{N+1} \) at each SAR epoch, i.e., the temporal evolution of the deformation for each investigated pixel.

Since interferometric products are differential measurements, before to start, it is necessary to select one of the identified points as a spatial reference for the whole interferogram set. It would be characterized by high spatial and temporal coherence and its deformation behavior should be a priori known (typically, it is located in a non-deforming zone). Indeed, note that any error affecting this reference point will also affect the overall results; in this context, particularly critical can be the impact of the atmospheric artifacts that are spatially correlated thus to be confused with deformation signals.

![Figure 7](image)

**Figure 7.** The coherence value of regional area (a), the coherence value of research area (b).

Figure 7a shows the coherence value of 24 data pair. The high coherence presented by bright portions indicated high correlation of the phase signal in data pair. Figure 7b is a subset coherence image for Surabaya city. It shows that the coherence of the study area is high. Therefore, the data pairs are plausible to generate high quality of deformation. Pictured above is the value of coherence of the study area. A high coherence presented by bright portion indicated that the InSAR deformation could be calculated properly. Figure (7a) is the appearance of the value of coherence in regional areas. This figure shows that the study area is located at high coherency. Figure (7b) is detail image the coherence value, the image is an area of research site.

Phase Unwrapping
The Phase Unwrapping (PhU) step, i.e., the problem to retrieve, starting from the computed modulo-2π restricted differential phases, the full phase variation signal, the latter associated to the occurred deformation, is probably the most critical task in SAR interferometry. However, in a multi-temporal DInSAR scenario, where large interferogram data set are involved, exploitation of temporal relations among the different interferometric phases can help Phase Unwrapping procedures.

Figure 8. Unwrapped phase master 1 and slave 7.

- Atmospheric filtering and orbital ramps estimation

Detecting possible atmospheric artifacts is the final step of the SBAS processing. This processing is based on the observation that the atmospheric phase signal is highly correlated in space but poorly in time [12]; [13]. Consequently, the undesired atmospheric phase signal is estimated from the computed time series by a lowpass filtering step in the two-dimensional spatial domain and a temporal highpass filtering operation. The filtering is implemented with spatial extent of approximately 1 km in azimuth and range, consistent with the spatial correlation length of the atmospheric phase signal [14]. The atmospheric artifacts are removed and the generation of the final deformation time series is computed.

- Geocoding and SBAS Inversion

All the SBAS deformation products are obtained onto the SAR reference geometry but they can be represented with respect to an easier output reference grid.

The SBAS inversion steps are performed to obtain the LOS displacement of each time period. The LOS displacement can be converted into vertical and horizontal components. In this case, the GPS measurements indicated that the displacement in east–west direction is very small. In consideration of vertical component is a one dimensional vector, the conversion of the LOS displacement to vertical displacement can be expressed as \( d_{\text{disp}} = d_{\text{LOS}} / \cos \alpha \) where \( d_{\text{disp}} \) is the vertical displacement; \( d_{\text{LOS}} \) is the LOS displacement; \( \alpha \) is the incident angle, which can be obtained from the SAR data. The geocoded vertical displacement mapped in WGS84 coordinate system is shown in Figure 9 in which the colour points are the spread of groundwater wells in the Surabaya city.

3.2. Aquifer potential zone

The 20 points resistivity data were obtained from field measurement at study area. In interpreting subsurface geological conditions, principally the value of resistivity reflects physical condition of layers or lithology. The interpretation of the geological conditions initially was obtained by 1D models. According to the model, we interpreted the depth and thickness of lithological layers (Table 2). The value of the same thickness in the area of research then a contour map created. After the process of making the aquifer contour, unconfined aquifer presented by thickness contour was depicted by figure 10a and confined aquifer by Figure 10b. The blue portion of the contour is an
aquifer with high thickness and green does not have the potential to be aquifer aquifers due to green color does not have a sufficient thickness to keep the water in the pores. The unconfined aquifer seen to have four zones between Northern Surabaya, covering Bulak districts and Asemrowo districts. The Southern Surabaya has potential aquifers in Gununganyar and Karangpilang districts. The confined aquifer seen to have two zones. Major aquifers found in Gubeng-Bubutan districts and minor aquifer foid in Gununganyar districts.

Table 2. The thickness of the aquifer were obtained from measurements of geoelectric

| Drill point | Depth       | Thickness | Lithology          |
|-------------|-------------|-----------|--------------------|
| 1           | 4.6m – 16.5m| 10.97m    | sandy mudstone     |
| 2           | 7.37m – 18.8m| 11.13m   | sandy mudstone     |
|             | 41.7m – 56.7m| 15m      | sandy mudstone     |
| 3           | 9.6m – 15.8m| 6.2m      | sandy mudstone     |
| 4           | 8.45m – 13.3m| 4.85m    | sandy mudstone     |
|             | 22.7m – 41.4m| 18.8m    | sandy mudstone     |
| 5           | 4.59m – 11.3m| 6.71m    | tuffaceous sandstones |
| 6           | 3.99m – 10.6m| 6.61m    | tuffaceous sandstones |
|             | 51.1m – 66.1m| 15m      | sandy mudstone     |
| 7           | 6.05m – 18.5m| 12.45    | tuffaceous sandstones |
| 8           | 4.38m – 7.48m| 3.1m     | sandy mudstone     |
|             | 17.3m – 30.2m| 12.9m    | tuffaceous sandstones |
|             | 65.2m – 80.2m| 15m      | sandy mudstone     |
| 9           | 3.99m – 10.7m| 6.71m    | tuffaceous sandstones |
|             | 23.3m – 38.3m| 15m      | sandy mudstone     |
| 10          | 8.68m – 10.4m| 1.72m    | sandy mudstone     |
|             | 14.2m – 32.2m| 18m      | sandy mudstone     |
| 11          | 6.13m – 10.7m| 4.57m    | tuffaceous sandstones |
| 12          | 6.88m – 9.91m| 3.03m    | sandy mudstone     |
|             | 76.5m – 90.5m| 5.28m    | sandy mudstone     |
| 13          | 9.43m – 16.8m| 7.37m    | conglomerate       |
|             | 39.1m – 54.1m| 15m      | sandy mudstone     |
| 14          | 12.4m – 19.2m| 6.8m     | conglomerate       |
|             | 36.7m – 51.7m| 15m      | sandy mudstone     |
| 15          | 10m – 16.8m  | 6.8m     | sandy mudstone     |
| 16          | 17.2m – 30.8m| 13.6m    | sandy mudstone     |
| 17          | 15.2m – 25.8m| 10.6m    | sandy mudstone     |
| 18          | 6.56m – 11m  | 4.44m    | sandy mudstone     |
| 19          | 6.94m – 16.5m| 9.56m    | sandy mudstone     |
|             | 35.3m – 37.1m| 5.97m    | sandy mudstone     |
| 20          | 49.8m – 64.8m| 15m      | sandy mudstone     |

3.3. Land subsidence and the relationship with the aquifer

Once known of potential unconfined aquifer and confined aquifer in Surabaya city, and known to the subsidence that occurred in the city of Surabaya, further analysis is the correlation between the two of them. Both could have happened any correlation when excessive groundwater extraction, meaning that the fluid (water) previously filling the aquifer zone is reduced. With this reduction, the layer above it
will be down for filling the empty space below, of course, the influence of the load and the compactness of rock above it will take effect.

It can be seen in Figure 9a that the subsidence that occurred in the city of Surabaya, most occurred areas are Wonokromo, Gubeng, Pabeancantikan to Bubutan districts. Even the Subsidence that occurred in the city of Surabaya can reach 40mm per year. The results of InSAR showed some highest in the city of Surabaya, the biggest subsidence zone is indicated by the red color. This area is most common in eastern and surrounding areas. Data from GPS measurements in 3 months (Figure 9b), the east part on the city of Surabaya is also a significant subsidence. Although the data were taken at different times, but the pattern of subsidence in the area of Surabaya can viewed in same.

To determine the cause of the subsidence (surface deformation), should be viewed on a variety of parameters such as geological factors, the loading rate up to mining activities. But in this study, focused on the parameters of existence the aquifer. The results of measurements, obtained contour unconfined aquifer and confined aquifer. unconfined aquifer shown in Figure 10a and confined aquifer shown in Figure 10b. Color contour on both these drawings are the thickness of the rock that has potential as aquifers.

Contur map in Figure 10b is The thickness value of the confined aquifer, in this picture there are two aquifer, which is located in downtown Surabaya. Seeing the results of the processing of InSAR and GPS measurements, confined aquifer is the most match layout of the land subsidence occurred because in confined aquifer, land subsidence caused by the extraction of groundwater, pores or aquifers that should be fills with water will be empty and no water which it replaces [15]. The existence of empty space that can not be filled again, things like this happen when drilling for water too deep, thus bypassing the impermeable zone and aquifer that is called a confined aquifer [16]. So that surface water can not fill this area. Another cause of course due to the extraction of ground water that is too excessive.

In addition to the aquifer contour maps and map decline in the city of Surabaya, there is also a map of drilling locations in the city of Surabaya (Figure 11), this map is a representation of groundwater carried out in the city of Surabaya. The groundwater extraction even up to more than 4000 m³ per month. When looking at this map, we will know where the most extracted groundwater. So with the spread of drilled wells (Figure 11) seen that the distribution of wells drilled numerous in the confined aquifer (the most) in the area Gubeng to district Bubutan and the free aquifers are several wells drilled in the aquifer zone districts of Bulak.

![Figure 9](image_url)

**Figure 9.** (a) Subsidence maps obtained from SBAS InSAR processing, (b) Subsidence maps obtained from GPS measurement. Map shown in Surabaya area with a color scale that indicates the amount of subsidence that occurred.
4. Conclusions
SBAS Insar method has proven effective to estimate the deformation in the city of Surabaya. According to the SBAS InSAR, the general subsidence was occurred in the city of Surabaya. The highest subsided zones about 30-40 mm per year are presented by red portion and located at Wonokromo district, Gubeng district, Bubutan district, and Pabeancantikan district. On the unconfined aquifer zones, there are four zones of potential aquifers at Asemrowo districts, Bulak districts, Karangpilang district, and Gununganyar district. The four potential zones of the aquifer were located at the same position with the land subsidence in Surabaya, Gununganyar district, and Bulak district. On the confined aquifer zones, there are two zones of potential aquifers at Gununganyar, and large aquifers area at Gubeng and Bubutan districts. This large aquifer is the nearest one to the land subsidence in the city of Surabaya.

Figure 10. (a) Thickness contour of unconfined (b) confined aquifer generated from each point geoelectric correlation process. Red portion indicates the thickness of the aquifer is higher than blue portion.

Figure 11. The distribution map of groundwater wells in Surabaya presented by green color.
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