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Using PS-InSAR to detect surface deformation in geothermal areas of West Java in Indonesia

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A R T I C L E I N F O

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A B S T R A C T

In this paper, the Persistent Scatterer InSAR (PS-InSAR) technique is applied in order to investigate the ground deformation in and around two geothermal areas in West Java, Indonesia. Two time-series of ALOS PALSAR and Sentinel-1A acquisitions, covering the period from 2007 to 2009 and 2015–2016, are analysed. The first case study examines the Wayang Windu geothermal zone where the PS-InSAR analysis provides an overview of the surface deformation around a geothermal reservoir. Uplift is observed around the injection wells in the area. The second example involves the use of the PS-InSAR technique over a more recent geothermal system in Patuha field. Again, a pattern of uplift was observed around the only available injection well in the area. Due to the dense vegetation coverage of the geothermal areas in West Java, the longer wavelength ALOS PALSAR data is provides better results by identifying a larger number of PS points. Additionally, experiments have been carried out to compare the resulting deformation with another example of the fluid migration process i.e. water extraction in Bandung basin. The potential of sentinel-1A and ALOS PALSR data are compared in all the experiments.

1. Introduction

Geothermal energy is a rapidly growing source of power within Indonesia, which has the third highest installed capacity for geothermal energy production in the world and generates more than 1200 MW of electricity on an annual basis (REN21 2010). The production wells are used to withdraw hot water from depths of 0.5–2 km. Following generation of electricity, the water is recycled back into the subsurface via the injection wells.

The use of remote sensing in geothermal activities dates back to the mid-1980s and it quickly diversified to include optical, thermal, hyperspectral and microwave remote sensing. A recent review was given in (van der Meer et al., 2014). They grouped the various contributions of the remote sensing to geothermal research into gaseous emissions (Bateson et al., 2008; Tank et al., 2008), structural analysis (Kuria et al., 2010), mineral mapping (Kratt et al., 2010; Littlefield and Calvin 2014), surface temperature mapping (Coolbaugh et al., 2007; Qin et al., 2011), heat flux mapping, geobotany (Boothroyd 2009) and surface deformation studies (Carnec and Fabriol 1999; Lubitz et al., 2013).

There are several studies investigating the surface deformation caused in geothermal sites. Changes in underground water levels, pressure and temperature caused by production and injection activities can lead to surface deformation occurring over the areas of geothermal fields. Most of the conventional geodetic methods e.g. GPS or levelling approaches rely on essentially point measurements at the Earth surface, which makes it difficult to obtain a complete picture of movement occurring across entire geothermal fields. In contrast, Differential SAR interferometry (D-InSAR) can provide a unique opportunity to obtain the host rock deformation induced by fluid migration at depth over a large spatial coverage ($> 10^4$ km^2) and with a high spatial resolution up to several meters (Rosen et al. 1996; Massonnet 1997). D-InSAR estimates the displacement along the line of sight direction using the phase changes between two overlapping SAR images from similar viewing geometries after subtracting terrain and orbital contributions (Bamler, 1988).

D-InSAR technique has successfully been applied in various fields including tectonic movement (Pathier et al., 2003), tidal loading (Massonnet and Feigl 1998), mining (Wright and Stow, 1999; Donnelly, 2009; Chen et al., 2013), volcanic activity (Massonnet and

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Feigl, 1995), ground water withdrawal (Amelung et al., 1999; Hoffmann et al., 2001; Normand and Heggy 2015), hydrocarbon production (Grasso and Wittlinger, 1990), post-seismic processes (Jonsson et al., 2003) and geothermal activities (Massonnet et al., 1997; Ishitsuka et al., 2016).

Despite the successful use of the D-InSAR technique in many applications, their applicability is limited due to the geometrical and temporal decorrelation, as well as atmospheric disturbances (Ferretti et al., 2001). Temporal decorrelation (Zebker and Villasenor 1992) occurs from the change in scattering properties of the ground surface and objects within the resolution cell. Geometrical decorrelation (Zebker and Villasenor 1992) is the result of increasing the spatial baseline. The atmospheric disturbances (Sabater et al., 2003) superimpose an additional phase on each image, which prevents the accurate interpretation of the ground surface changing information.

Persistent Scatterer InSAR (PS-InSAR) is able to overcome the above-mentioned problems by the analysis of the high quality phase information of coherent targets referred as persistent scatterer (PSs) (Ferretti et al., 2001). PSs are defined as pixels stable phase which are minimally affected by the decorrelation. Moreover, because the phases in PSs are stable, the other nuisance terms including DEM error and atmospheric effects can be estimated and subtracted to estimate a more accurate surface displacement velocity.

In this study, we applied the PS-InSAR technique to two well-known geothermal plants in Indonesia namely Wayang Windu and Patuha. The Wayang Windu geothermal plant is located 40 km south of Bandung in West Java. The zone is located around a cluster of Quaternary volcanic cones termed as Kendang volcanic complex. The Patuha geothermal system is a vapor-dominated reservoir located about 40 km southwest of Bandung on western Java. A great part of the areas in both plants is covered with vegetation, mainly tea plantation, and forest. This makes the application of the conventional DInSAR technique very challenging due to the lack of the temporal coherence.

This paper is the first attempt to measure the surface deformation due to the geothermal activities across the geothermal power plants in West Java. SAR data has been widely used previously in this area for the purpose of surface manifestation at geothermal zones (Dinul and Asep 2016) or identification of linear features at geothermal fields (Haeruddin et al., 2016). However, the InSAR data analysis has not been previously employed in this area for the estimation of deformation caused by geothermal activities. In Bandung city, however, several studies were carried out for the estimation of land subsidence due to the excessive water extraction using InSAR data (Gumilar et al., 2015). To the best of our knowledge, there have been no previous studies in West Java for the analysis of the deformation trend in the geothermally active areas. The study has three main objectives. First, to estimate the land displacement caused by geothermal activities in the study area. For this purpose, the PS-InSAR analysis was performed using a set of ALOS PALSAR images acquired from 2007 to 2009. With the recent launch of Sentinel-1A, SAR data with global coverage, operational reliability and quick data delivery became freely available, thus provide excellent opportunity for developing many InSAR applications. Therefore, the second objective of this research is to evaluate Sentinel-1 SAR data for land deformation monitoring in geothermal fields. For this, we repeated the PS-InSAR analysis with a series of sentinel-1A images from 2015 to 2016 to explore the most recent impacts of the geothermal activities in the study area. We aimed to compare the effectiveness of the C-band sentinel-1 data with L-band ALOS PALSAR data for the deformation analysis of the geothermal activities in Wayang Windu power plant. In order to evaluate the results, we performed the same procedure in the Patuha geothermal field and compare the results with those obtained in Wayang Windu study area. Ground water extraction is another example of the fluid migration which is usually accompanied by surface deformation. Bandung city, located 40 km north of the Wayang Windu plant, is highly suffering from this phenomenon. Therefore, the third objective of the paper is to compare the deformation results obtained in geothermal fields with that of caused by the ground water extraction in the study area.

2. PS processing

The PS-InSAR technique was first introduced by Alessandro Ferretti and his colleagues (Ferretti et al., 2001). The method is based on a stack of SAR data of the same area, typically consisting of a few datasets. From this stack one single master acquisition is selected, considering baselines in time and space in a way to ensure high coherence in all interferograms formed over the stack. The master image is preferably chosen in the middle of the temporal and spatial baseline spaces. Using this single master configuration, a stack of co-registered Single Look Complex (SLC) images is then produced. Using $N + 1$ Single Look Complex (SLC) images, one can make N interferograms. Once, the influence of earth curvature and the topography is removed from the phase information, one can get a series of phases for each pixel. The phases of an interferogram are now influenced by several factors, such as linear phase ramp, inaccuracy of external DEM, atmospheric phase screen, the displacement of scatterer, and speckle and decorrelation noise as follows (Ferretti et al., 2000)

$$\phi^k = \frac{4\pi}{\lambda}\frac{B_\perp^k}{R\sin\theta}h + \frac{4\pi}{\lambda}T^k v + \phi_{atm}^k + \phi_{orb}^k + \phi_{noise}^k \tag{1}$$

in which the first term corresponds to the DEM error (h) which is due to the inaccuracy of the external DEM, the second term corresponds to the linear displacement rate or velocity (v) which comes from the movement of the target scatterers during the data acquisition period. ϕ_{atm}^k is the atmospheric phase delay. As the atmosphere has a certain amount of water vapor content, it delays the propagation of the microwave waves emitted from the SAR antenna. ϕ_{orb}^k is the residual orbital error phase which is caused by inaccurate orbit determination, and ϕ_{noise}^k is the temporal and geometrical decorrelation noise. Temporal decorrelation results from the change of scattering characteristics as a function of time which is commonly found over agricultural or forest areas. Geometrical decorrelation occurs from the change of scattering characteristics as a function of radar geometry. These decorrelation sources are detailed in (Gens and Van Genderen 1996).

In this study, the surface deformation measurements were obtained using the procedures implemented in SARPROZ (Perissin et al., 2010). The PS processing procedure in our study includes the following 3 steps:

1) Initial selection of the PS Candidates (PSC): at each pixel the time series of the amplitude values is extracted to calculate the mean $\bar{a}$ and the standard deviation σ_a. A pixel is considered as a PS candidate if it satisfies the amplitude stability index criteria

$$D_{stab} = 1 - \frac{\sigma_a}{\bar{a}} > 0.8 \tag{2}$$

2) Estimation of the unknown parameters: the estimation of the unknown parameters of DEM error and the velocity is based on relative phase observations between nearby PS, therefore, a robust network (the spatial graph) is considered and the preliminary parameters are estimated along the connections of points. Afterwards, a robust numerical integration is necessary in order to obtain absolute values at all PS positions. For this, a reference point has to be chosen from the reference network as a starting point for the integration procedure. This reference PS has to be selected very carefully, because an undesirable choice may result in biased parameters for all PS. It should be noted that in the integration process, the temporal coherence is used as a weight to see which connection is reliable and which is not.

3) Final estimations: after the removal of Atmospheric Phase Screen (APS), a second estimation of the parameters were performed on a wider set of points selected based on a spatial coherence criterion. Finally, at the end of the PS processing, all PSs with temporal coherence above a reliable threshold were selected. For each PS, the DEM error, the linear displacement rate along the Line of Sight (LOS) and the