ESTIMATION OF HOT MUDFLOW CURRENT USING LONG TERM DINSAR

Josaphat Tetuko Sri Sumantyo[1]
[1]Center for Environmental Remote Sensing, Chiba University
1-33, Yayoi-cho, Inage-ku, Chiba-shi 263-8522 Japan,
Email: jtetukoss@faculty.chiba-u.jp

KEY WORDS: Synthetic Aperture Radar, Consecutive, DInSAR, Law of conservation of material, Multi Sensor

ABSTRACT: Several techniques have proposed to observe long-term land deformation using phase information of synthetic aperture radar (SAR), for example, InSAR, DInSAR, PS-InSAR, SBAS using spaceborne SAR images. But every mission of spaceborne SAR has an orbit duty period less than ten years and other problems of discontinuity or blank period of observation using the similar specification of sensors. Hence land deformation with an observed time of more than ten years is not available to be monitored continuously using a single mission. This research proposed a method called Bridging Consecutive DInSAR (BC-DInSAR) to connect Consecutive DInSAR. These methods were employed to investigate land deformation and the impact caused by hot mudflow accident at Regency of Sidoarjo, Indonesia, where this disaster happened on 29 May 2006 and is flowing until now. The differential GPS data since 2006 was employed to validate the analysis result of BC-DInSAR, which obtained 0.46 m RMS error.

1. INTRODUCTION

Synthetic Aperture Radar (SAR) is well-known as a multi-purpose sensor that can operate in all-weather and day-night time. The SAR system generates images that contain information on intensity, phase, and polarization. Several methods have proposed to observe disaster and environmental change using phase information, especially interferometric SAR (InSAR) and differential InSAR (DInSAR) for single event change by a pair of images, Permanent Scatterer InSAR (PSI) to derive velocity of land deformation.

The author has proposed the Consecutive DInSAR (C-DInSAR) technique to observe long-term land deformation using images of JERS-1 SAR and ALOS-1 PALSAR-1 sensors (Sri Sumantyo, 2012). Satellite mission has limited operating period, i.e., JERS-1 and ALOS-1 were operated by JAXA from 15 April 1992 to 11 October 1998, 15 May 2006 to 13 April 2011; ERS-1, ERS-2, and Envisat were operated by ESA from 17 July 1991 to 10 March 2000, 21 April 1995 to 4 July 2011, and 1 March 2002 to 8 April 2012, respectively. Therefore, the previous C-DInSAR technique remains the issue to derive land deformation between two periods of different satellite missions. Therefore, this research proposed a Bridging C-DInSAR (BC-DInSAR) method to connect two or more C-DInSAR to realize long term continuous observation using spaceborne multi-sensor in multi-mission.

2. PROPOSED METHOD

The author proposed the C-DInSAR method in 2012 using SAR images of two missions of JERS-1 SAR and ALOS-1 PALSAR-1 to observe land deformation (Sri Sumantyo, 2012). This method remained an issue on land deformation estimation derived by C-DInSAR between two missions, e.g., JERS-1 and ALOS-1 or blank satellite mission from 1998 to 2004.

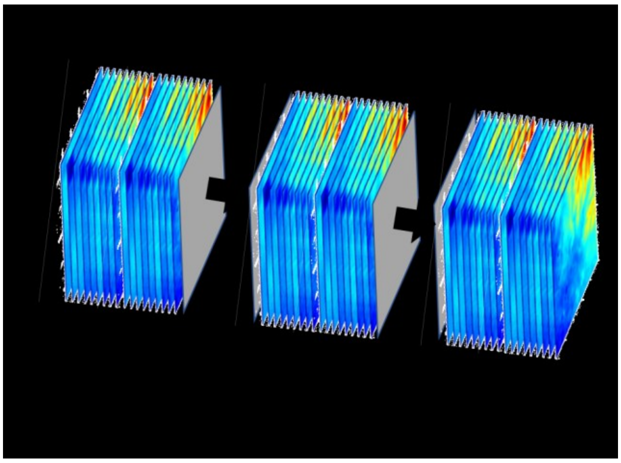

Fig.1. Concept of Bridging Consecutive DInSAR

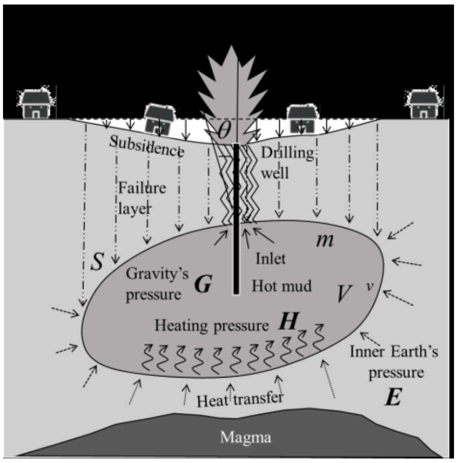

Fig.2. Subsidence and mudflow model

2.1 Bridging Consecutive DInSAR

Fig.1 shows the concept of Bridging Consecutive DInSAR (BC-DInSAR), where this method solves the blank satellite mission by employing a digital elevation model (DEM) at the end of the earlier satellite mission and beginning of later satellite mission. For example, we have three satellite missions (Satellite-1, Satellite-2, and Satellite-3) shown in Fig.1. Each image of C-DInSAR of analyzed mission as C-DInSAR-1, C-DInSAR-2, and C-DInSAR-3. DEM of Satellite-1 (DEMS1-1) is derived using a pair of images observed in closed time at the end period of the satellite-1 mission. The image pair recorded in close time to get high accuracy of DEM. The same manner is done to derive DEM using a pair image at the beginning period of the satellite-2 mission to get accurate DEMS2-1. Then DEMS2-1 was eliminated using DEMS1-1 to get information on land deformation of the study area in blank mission period. The same manner for further analysis of land deformation using later satellite missions, i.e., Satellite-3 and so on.

2.2 The Law of Material Conservation

We propose the model of continuity equation of the law of conservation of material to estimate the volume of released material in the study area as Fig.2. *S* is analyzed subsidence area with a volume of material (mud) inside and material density are *V* (m^3) and *m* (kg/m^3), respectively. The pressure of material outflow is caused by subsidence, gravity's pressure *G*, heating's pressure *H* by magma, and inner Earth's pressure *E* with velocity *v* on surface *S*'s change. We consider a small area ΔS with perpendicular or norm vector $\boldsymbol{n}$, and flow strength or current of spouted material (mudflow) *P* (kg/m^2s) to derive the relationship of the current of spouted material on drilling well's hole and velocity of release material as shown on Fig.2. The current means an outflow of material on surface *S*, where the outflow causes the material volume decreases in this closed surface. In other words, if the total material in this closed surface *S* is *V*, and the material density at the point indicated by the coordinate vector $\boldsymbol{r}$ is *m*, hence this phenomenon could be derived as

$$\oint_S \boldsymbol{n}\cdot\left\{\boldsymbol{P}(\boldsymbol{r},t)-\frac{1}{v}\big(\boldsymbol{G}(\boldsymbol{r},t)+\boldsymbol{H}(\boldsymbol{r},t)+\boldsymbol{E}(\boldsymbol{r},t)\big)\right\}dS=-\frac{\partial}{\partial t}\oint_V m(\boldsymbol{r},t)dV \quad (1)$$

The mud sample collected in ground surveys and the density m is measured as 1,400±200 kg/m^3. In this model, we focus to investigate the contribution of subsidence that caused the current and volume of released material, therefore we simplify Eq.(1) as

$$\oint_S \boldsymbol{n}\cdot\boldsymbol{P}(\boldsymbol{r},t)dS=-\frac{\partial}{\partial t}\oint_V m(\boldsymbol{r},t)dV \quad (2)$$

Then the left side can be derived from Gauss's theorem and since *V* can be of any size, if we consider *V* as a very small volume ΔV around the point $\boldsymbol{r}$, then we obtain

$$\boldsymbol{\nabla}\cdot\boldsymbol{P}(\boldsymbol{r},t)+\frac{\partial}{\partial t}m(\boldsymbol{r},t)=0 \quad (3)$$

Eq.(3) shows a continuity equation and expresses the law of material conservation of material (hot mud). In the case of steady material, the material density does not change over time. In the case of subsidence in this study, we don't consider other potential or pressures. In other words, we only consider the current that generated by the subsidence or volume change on Fig.2 that could be derived by the proposed BC-DInSAR.
As the assessment and demonstration of the BC-DInSAR, we applied it to analyze long-term land deformation of hot mudflow at the regency of Sidoarjo, East Java province, Indonesia, then spouted volume estimation using equations above, as discussed in the further sections.

3. STUDY AREA

The study area locates in the Regency of Sidoarjo, the southern capital city of East Java province, Surabaya as shown in Fig.3. This area is the location of the various industry includes oil and gas industries for domestic and export. This area is a strategic area to connect the Surabaya, and the southern East Java province. This figure shows landuse map of the study area and the position of differential Global Positioning System (DGPS) stations for validation.

Indonesian private gas and oil industry, Lapindo Brantas Inc started to drill the site in February 2006 for the first test drilling with depth well in Banjar Panji 1 (BJP-1) station targeted with 4,000 m depth at Reno Kenongo village of the district of Porong for gas exploration. Hot mud bubble and gas release started to flow at 150 m away from BJP-1 drilling well on 29 May 2006, where this accident is considered by miss procedure in drilling activity. The hot mud flew to settlement and the industrial area surrounding the accident well and destroyed 600 ha and 16 villages in Porong, Jabon, and Tanggulangin districts. About 8,200 people in Reno Kenongo, Siring, Jatirejo, and Kedung Bendo villages evacuated in August 2006.

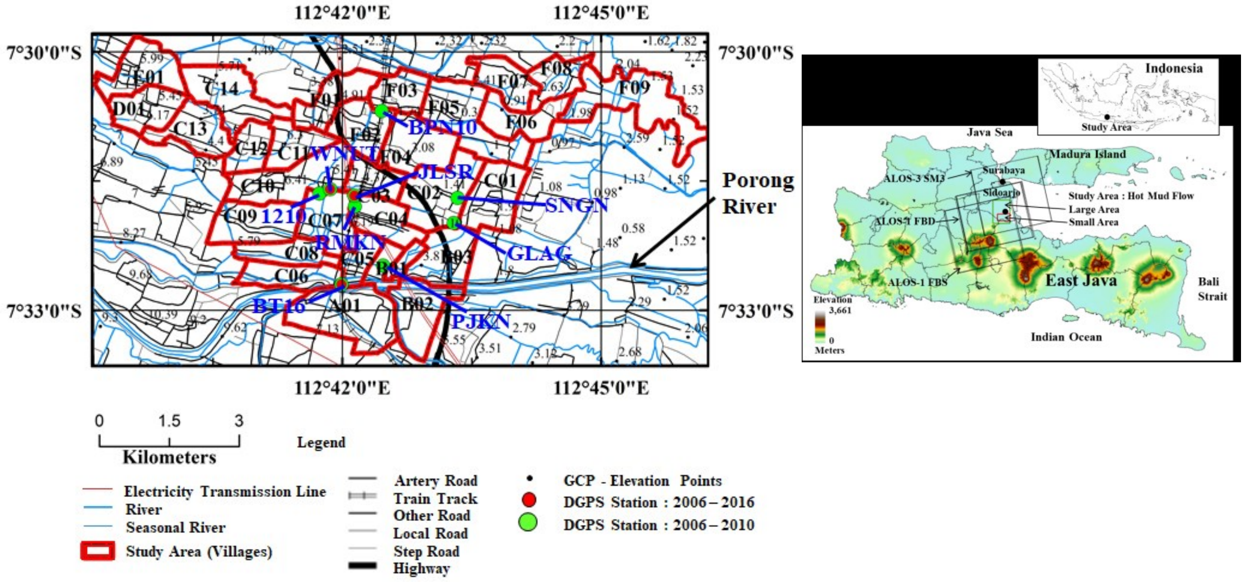

Fig.3. Map of the study area: Hot mudflow at Regency of Sidoarjo, Indonesia

The hot mud and gas spout in the study area since May 2006 generated subsidence and serious damage around the center of the accident area. In this research, the impact of subsidence in the study area was investigated numerically by the proposed BC-DInSAR method using images of Fine Beam Single Polarimetric (FBS) and Fine Beam Dual Polarimetric (FBD) modes of ALOS-1 PALSAR-1 and SM3 mode of ALOS-2 PALSAR-2 between 19 May 2006 and 14 July 2020.

4. SATELLITE IMAGES, ANALYSIS USING BC-DINSAR, AND VALIDATION USING DGPS

Firstly, the C-DInSAR images of ALOS-1 PALSAR-1 generated by using images of FBS mode (ascending) for the period of 19 May 2006 to 24 November 2008. ALOS-1 satellite did not cover the same area with FBS mode after 24 November 2008. Therefore, we continue the C-DInSAR using FBD mode images (ascending) in period 4 October 2008 to 25 August 2010. Then we employed image pair of 25 August 2010 and 10 October 2010 (FBD mode) to generate a digital elevation model (DEM) as DEMS1-1 in Fig.1 to bridging to consecutive images generated by ALOS-2 PALSAR-2 images. We processed the ALOS-1 PALSAR-1 images (FBS and FBD modes, original data: Level 1.0 or raw data, resolution 20 m) using JAXA SIGMA-SAR software (Shimada, 1999) to obtain interferogram for C-DInSAR and DEMS1-1 for bridging to DEMS2-1 generated by ALOS-2 PALSAR-2 images in the next process.

Secondly, DEM of ALOS-2 PALSAR-2 was derived using Stripmap (SM3) mode of 7 July 2015 and 15 September 2015 images with 20 m of output resolution to adjust to the resolution of DEMS1-1. This process did by SARPROZ software (Perrisin, 2006). We substituted the DEMS2-1 by DEMS1-1 to bridging ALOS-1 and ALOS-2 mission to obtain pixel value of land deformation of the study area in period 10 October 2010 and 7 July 2015 (five years). In the same manner, the C-DInSAR of ALOS-2 PALSAR-2 images processed by using SM3 mode (ascending) for the period of 15 July 2015 to 14 July 2020.

Fig. 4 shows the analysis result of BC-DInSAR with an observation period of 19 May 2006 to 14 July 2020 using ALOS-1 and ALOS-2 satellites with the coverage in Fig.3. Pair of FBS-1 observed in the preliminary period from 29 May 2006 to 19 February 2007. It shows a large subsidence area centered on the hot mudflow area and impacted the northern area about 10 km. Pairs of FBS-2, FBS-3, FBD-4, and FBD-5 show active subsidence in the accident area.

The BRIDGE was derived using DEMS1-1 and DEMS2-1 of ALOS-1 and ALOS-2. The result shows subsidence within five years of observation in period 10 October 2010 to 7 July 2015. The noise appeared in this figure caused by the long-term analysis and different sensor's characteristics used in the method, that needs further investigation.

SM3-1 to SM3-4 shows the decreasing of subsidence in the center of the accident well, but a new subsidence area appeared in the eastern accident area since SM3-2 period. We found three new subsided sites around new mining facilities in the visual analysis of optical satellite images and ground surveys. The western accident center shows subsidence since 2006, as an effect of volume loss in the accident area.

As shown in Fig.3, we measured differential GPS (DGPS) for validation of BC-DInSAR result with nine ground control point (GCP) stations that recorded from 2006 to 2010 (five years), and three GCP stations that observed from 2006 to 2016 (11 years). The DGPS used dual-frequency geodetic receivers with observation session lengths of 5 to

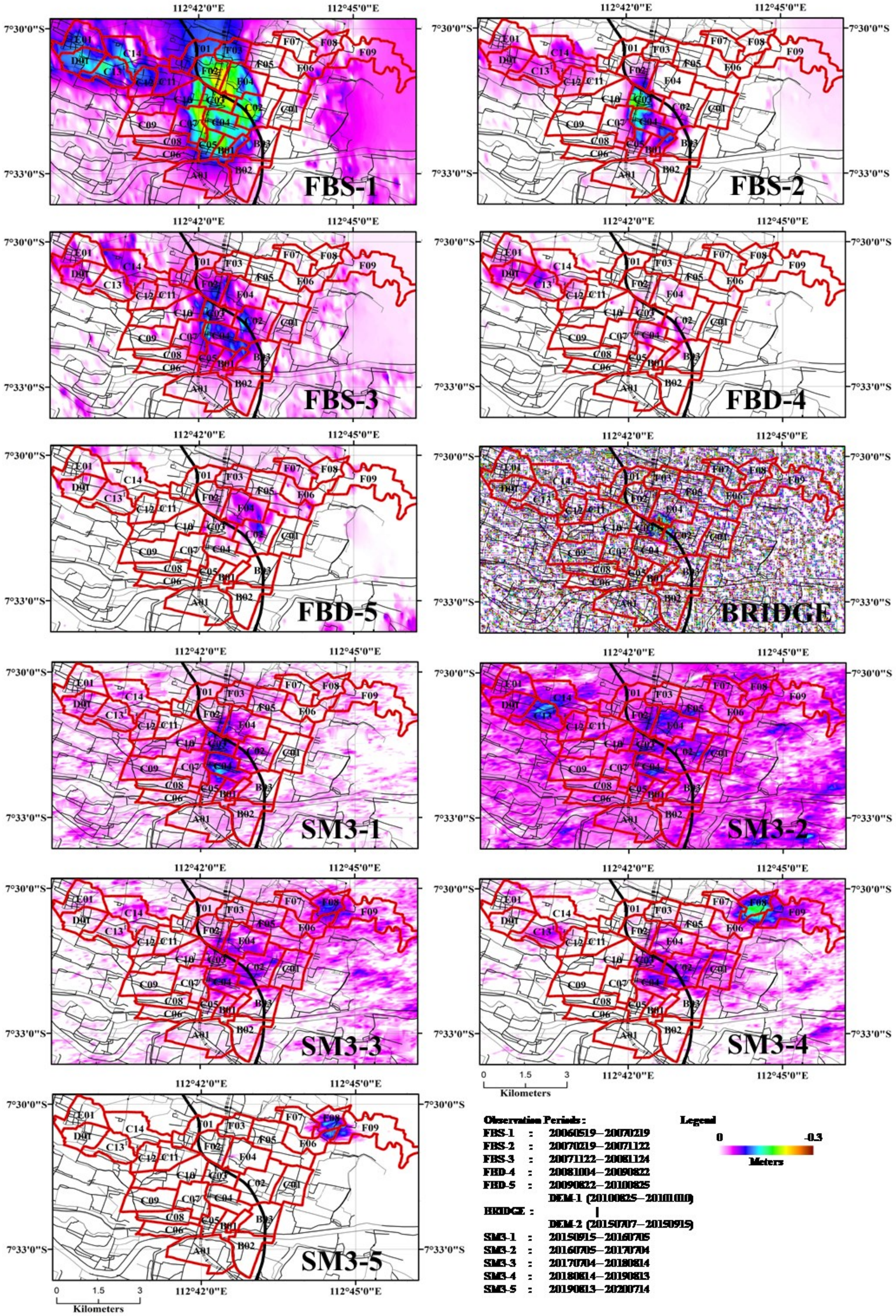

Fig.4. Analysis result of BC-DInSAR with observation period of 19 May 2006 to 14 July 2020 using ALOS-1 and ALOS-2 satellites

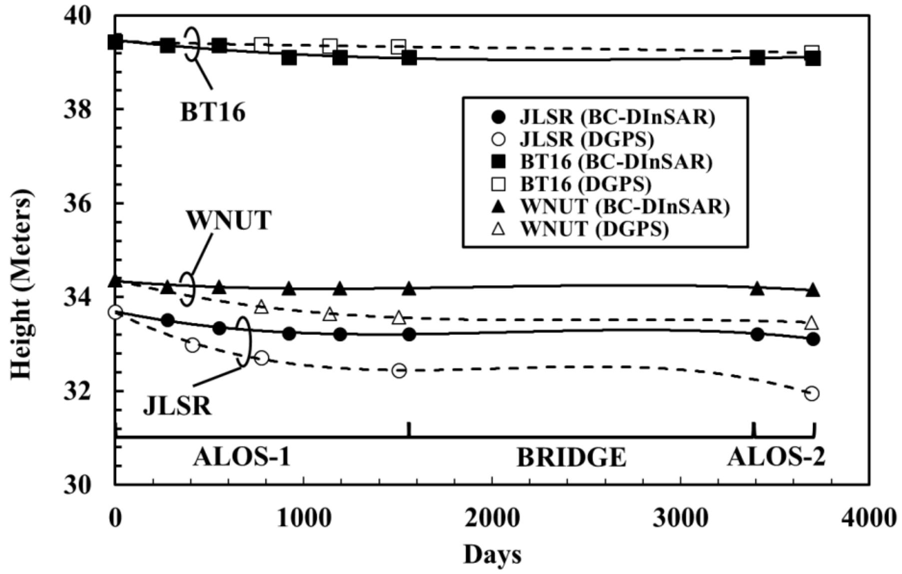

Fig.5. Regression value of BC-DInSAR and DGPS measurement in the period of 2006 to 2016 (Three GCP stations)

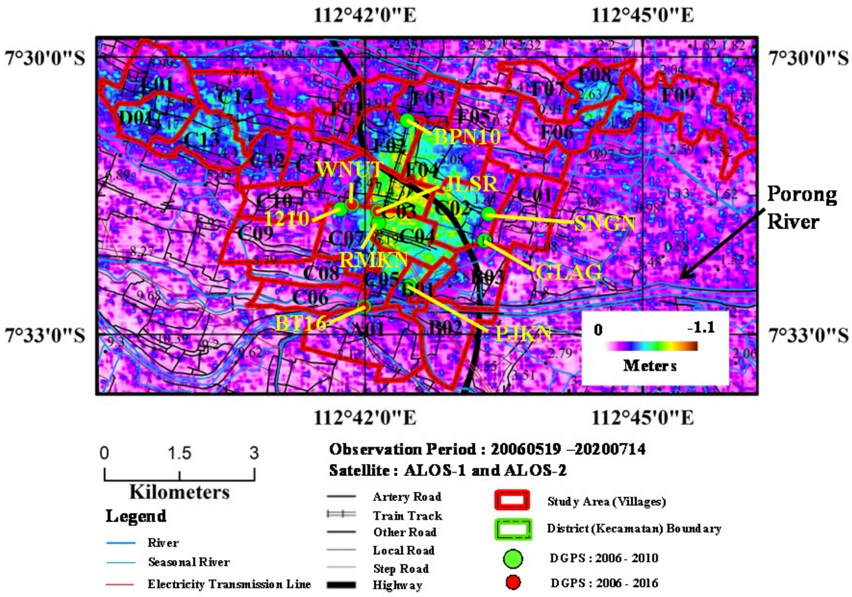

Fig.6. Total subsidence in the study area

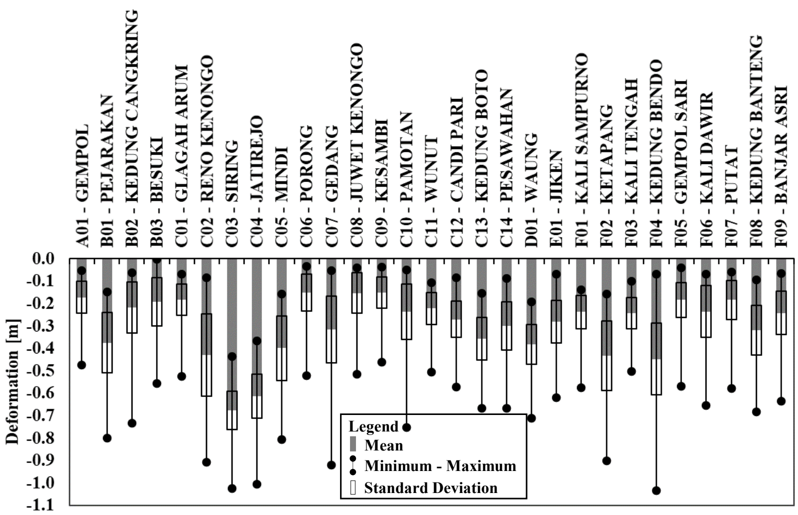

Fig.7. Total subsidence in the study area

10 hours starting on 22 September 2006 to 2016. Some numbers of observed GPS stations measured in different periods shown in Fig.5, due to the change in the mudflow coverage area. Base on Fig.5, BC-DInSAR method has an accuracy of 0.46 m (RMS).

5. RESULT AND DISCUSSION

Fig.6 depicts total subsidence in the study area in the period of 19 May 2006 to 14 July 2020 (15 years). Fig.7 shows total subsidence in the study area derived from Fig.6 observed between 19 May 2006 and 15 July 2020. This result shows mean of subsidence with a value more than 0.3 m occurred at villages of Pejarakan (B01) 0.38 m at the district of Jabon; villages of Reno Kenongo (C02) 0.43 m, Siring (C03) 0.68 m, Jatirejo (C04) 0.61 m, Mindi (C05) 0.4 m, Gedang (C07) 0.32 m, Kedung Boto (C13) 0.36 m, Pesawahan (C14) 0.30 m at the district of Porong; the village of Waung (D01) at the district of Krembung; villages of Ketapang (F02) 0.43 m, Kedung Bendo (F04) 0.45 m, and Kedung Banteng (F08) at the district of Tanggulangin.

The ground survey was held five times on 17 November 2006, 28 March 2013, 13 June 2014, 5 September 2017, and 17 October 2019 to investigate infrastructure conditions in the study area. Base on the ground survey, the subsidence generated a significant impact on the study area, as well as wall cracked in settlement and infrastructures, bent railway track, tilted electricity transmission towers, and poles, broked gas pipe, and explosion on 22 November 2006. This hot mudflow also made sedimentation and change habitat at the Porong river.

6. SUMMARY

This research proposed a Bridging Consecutive DInSAR (BC-DInSAR) method to connect Consecutive DInSAR using images of multi spaceborne SAR missions. This method was assessed to investigate long term of land deformation and the impact caused by hot mudflow accident at regency of Sidoarjo, East Java province, Indonesia, where this disaster happened on 29 May 2006.

In this research, the DGPS data observed in the period of 2006 to 2016 was employed to validate the analysis result of BC-DInSAR, which acquired 0.46 m error (RMS). It could be improved by increasing the resolution of SAR images in the future mission to improve the quality of DEM used in BC-DInSAR.

ACKNOWLEDGEMENT

Thank to Daniele Perissin, Joko Widodo, Heri Andreas, Ketut Wikantika, Mohammad Rohmaneo Darminto, Akbar Kurniawan, Mokhamad Nur Cahyadi, and Teguh Hariyanto to collaborate in this research. This work is supported in part by the Japanese Government National Budget - Ministry of Education and Technology (MEXT) FY2015-FY2017 under Grant 2101; Chiba University Strategic Priority Research Promotion Program FY2016-FY2022, and Japan Society for The Promotion of Science Grants-in-Aid for Scientific Research No. 19K22905 FY2019-FY2021.

REFERENCES

Perissin, D. and Rocca, F., 2006, “High Accuracy Urban DEM Using Permanent Scatterers,” IEEE Trans. Geosci. Rem. Sens., Vol.44, pp.3338-3347.

Shimada, M., 1999, “Verification Processor for SAR Calibration and Interferometry,” Adv. Space. Res., Vol.23, No.8, pp.1477-1486.

Sri Sumantyo, J. T., Shimada, M., Mathieu, P.P., and Abidin, H.Z., 2012, “Long-term Consecutive DInSAR for Volume Change Estimation of Land Deformation,” IEEE Trans. Geosci. Rem. Sens., Vol. 50, No. 1, pp.259-270.