

DETECTION OF 3D LAND DISPLACEMENT AFTER THE GREAT EAST JAPAN EARTHQUAKE IN 2011 FROM MULTI-TEMPORAL SAR IMAGES AND GPS DATA

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ABSTRACT

This paper presents the results of estimating land displacement of the areas after an earthquake by utilizing synthetic aperture radar (SAR) time-series images. We selected the nuclear power station in Fukushima Prefecture, Japan, damaged by the Great East Japan Earthquake in 2011, and the tsunami triggered by the earthquake. The still ongoing displacement of the areas, especially the underground frozen soil wall installed, should be quantitatively estimated. In usual, the displacement estimated by persistent scatterer interferometry (PSI) [1,2] is obtained only in the radar line-of-sight (LOS) direction. We estimated three-dimensional displacement velocities by applying the least-squares method to the results from PSI and Global Positioning System (GPS) data. We used 13 and 17 ALOS-2/PALSAR-2 images acquired on the ascending and descending orbits, respectively in addition to the displacement data measured at 10 GPS stations. The obtained results show that local displacement is estimated, and the displacement along the frozen soil wall is different from the neighboring areas. Consequently, it was shown that combining PSI results and geodetic deformation measurements is effective for monitoring land subsidence.

Index Terms— Synthetic aperture radar (SAR), 3D land displacement monitoring, multi-temporal SAR image analysis, PSInSAR

1. INTRODUCTION

North-eastern part of Japan was severely damaged by the Great East Japan Earthquake in March 11, 2011. The tsunami triggered by the earthquake attacked Fukushima Daiichi Nuclear Power Station, and it became out of control. After the tsunami, decommissioning of the station started. One of the works in parallel with the decommissioning is to prevent the underground water from being contaminated by the station. As the countermeasure, underground frozen soil wall was installed around the nuclear power station, and the

operation of the wall started in March 2016 [3]. The maximum horizontal and vertical subsidence observed in Fukushima Prefecture were 3.25 m and 0.55 m, respectively [4]. The ongoing displacement has been observed whereas the amount of the displacement is getting less and less [5]. However, it was not confirmed that the effect of the frozen soil wall to the land displacement. Therefore, local three-dimensional (3D) displacement should be quantitatively observed.

Multi-temporal SAR analysis provides the long-term land displacement information. Because the information is one-dimensional (1D) displacement along the radar line-of-sight (LOS), we need a technique to estimate the 3D displacement from the 1D displacement. One of the approaches is to combine displacement from ascending orbit images, displacement from descending orbit images, and other observations [6]. Global satellite navigation systems, including the Global Positioning System (GPS), provide 3D displacement with sub-centimeter accuracy, point-based and spatially sparse observations can be merged with estimates from satellite images. We presented a method for estimating 3D displacement velocities by combining PSI data with GPS data. for land subsidence in and around civil infrastructure [7]. In this paper, we present the result obtained by applying the method [7] to the area around Fukushima Daiichi Nuclear Power Station.

2. DATA USED

In this research, we used Advanced Land Observing Satellite-2 (ALOS-2)/Phased Array type L-band SAR-2 (PALSAR-2) level 1.1 (L1.1) data: 13 images acquired on the ascending orbit, and 17 images acquired on the descending orbit. The transmitting–receiving polarization of the radar used to acquire the images was HH. The daily displacement data measured at 10 GPS stations around the nuclear power station were downloaded from the Web site of Geospatial Information Authority of Japan (GSI) [8]. The study area and geolocation of GPS stations are shown in Fig.1, and the observation dates of the SAR images used are

listed in Table 1. For the PSI analysis, we downloaded the 10-m-grid digital elevation model published by the GSI [9] to remove the effect of topography.

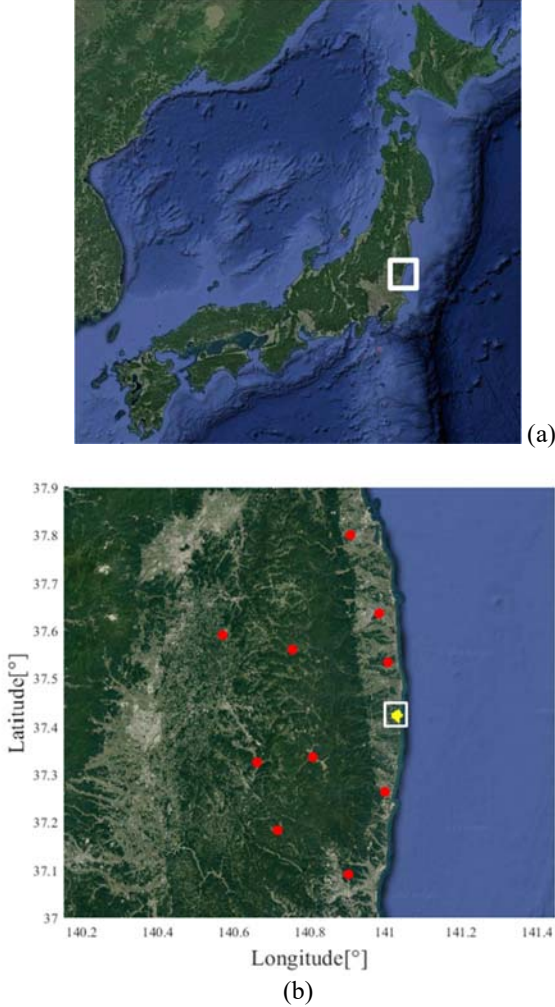


Fig. 1. Study area. (a) Around Japan, and (b) the study area, shown in yellow circle and a white rectangle. The white rectangle in (a) corresponds to the area shown in (b). The red circles in (b) represent GPS stations operated by GSI, Japan. The images are from Google Earth. Map data ©2018 Google, ZENRIN.

3. METHOD

PSI involves selecting PSs as phase-stable pixels and using only them to reduce the main errors (e.g., temporal and geometrical decorrelation, atmospheric artifacts) in conventional processing methods. In the present study, we used PSI software developed by the infrastructure monitoring group in the Earth Observation Research Center (EORC) of the Japan Aerospace Exploration Agency

(JAXA). Once the user has selected the region of interest, the software processes the PSI data from the raw data.

Table 1. Observation dates of PALSAR-2 images used for the experiment (yyyy/mm/d)

Ascending	Descending
2014/10/21	2015/01/01
2014/12/16	2015/11/05
2015/03/10	2016/02/25
2015/06/30	2016/06/02
2015/08/25	2016/08/25
2015/11/17	2016/10/20
2016/06/14	2016/11/03
2016/11/15	2017/02/23
2017/02/21	2017/06/01
2017/05/30	2017/08/10
	2017/11/02
	2018/02/22
	2018/05/31
	2018/08/09

The estimated displacement is a displacement relative to a certain point known as a zero-displacement point. Thus, we convert the relative values to absolute values by adjusting the average PSI to that of the reference points to connect PSI to a reference frame.

The velocity estimated by PSI, V_{PS} , is that in the radar LOS direction and is related to the radar LOS unit vector as follows:

$$V_{ps} = V_{ps}^e \cdot u_e + V_{ps}^n \cdot u_n + V_{ps}^u \cdot u_u \quad (1)$$

where V_{PS} is the estimated velocity of a PS along the radar LOS, V_{ps}^e , V_{ps}^n and V_{ps}^u are the unknown components of the velocity vector, and u_e , u_n , and u_u are the unit vectors pointing from the PS toward the satellite.

The final 3D displacement field is estimated from the PSI and interpolated results by applying the least-squares (LS) method. The observation equations of the LS model are

$$\begin{bmatrix} V_{ps}^a \\ V_{ps}^d \\ V_{GPS}^e \\ V_{GPS}^n \\ V_{GPS}^u \end{bmatrix} = \begin{bmatrix} u_e^a & u_n^a & u_u^a \\ u_e^d & u_n^d & u_u^d \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} V^e \\ V^n \\ V^u \end{bmatrix} \quad (3)$$

where $[V^e, V^n, V^u]^T$ is the vector of displacement velocities, V_{GPS}^e , V_{GPS}^n and V_{GPS}^u are interpolated vectors, V_{ps}^a and V_{ps}^d are the PSI velocities estimated along the ascending and descending orbits, respectively, and $[u_e^a, u_n^a, u_u^a]^T$ and $[u_e^d, u_n^d, u_u^d]^T$ are the unit vectors along the ascending and descending orbits, respectively. We resolve the observation

equations using the LS approach and obtain the 3D displacement velocities.

4. RESULTS AND DISCUSSION

We applied the method described in the previous section to PALSAR-2 images and GPS data. We need a threshold to match identical PSs obtained from ascending orbit images and descending orbit images. We set it to 100 m, but it was confirmed that more than 50% of the match was searched within a radius of 10 m. The 3D displacement results obtained are shown in Fig. 2. The estimated displacement is a displacement relative to a reference point, and in this research, we selected the center pixel of the images used for the analysis. Note that the velocities shown in Fig. 2 are not absolute velocities.

Fig. 3 shows the results of the ordinary kriging in units of mm/year. The horizontal results show that the area is moving to the south-east, and the vertical result shows that the area is uplifting. These results indicate that the local displacement is unable to be observed because they were generated by interpolating 10 points of GPS observations, shown in Fig. 1(b). In Fig. 2, the results reflect both SAR observations and GPS observations, and the local displacement is detected. Especially, it is clearly shown that the displacement along the underground frozen soil wall, whose geolocation is indicated by Fig. 4, is unique, and moved more to north-west and uplifted more than the neighboring areas.

These results indicate that combining PSI results and GPS data is effective for monitoring 3D land subsidence. In case that we interpret 1D PSI results, in most of cases we assume that no horizontal displacement occurred and covert the LOS displacement into vertical displacement. This process may be acceptable for monitoring the ordinary land subsidence. However, it may not be suitable for monitoring land displacement triggered by earthquake because it causes 3D displacement. In this regard, the obtained results are supportive for decommissioning the nuclear power station.

5. CONCLUSIONS

This paper presents the results of estimating land displacement of the areas after an earthquake by utilizing Multi-temporal SAR images and GPS observations. The obtained results show that local displacement is estimated, and the displacement along the frozen soil wall is unique. Consequently, it was shown that combining PSI results and geodetic deformation measurements is effective for monitoring land subsidence. Because the validation data were not available to us, we did not validate the results obtained in this research. In near future, we assess the results obtained with the validation data if available.

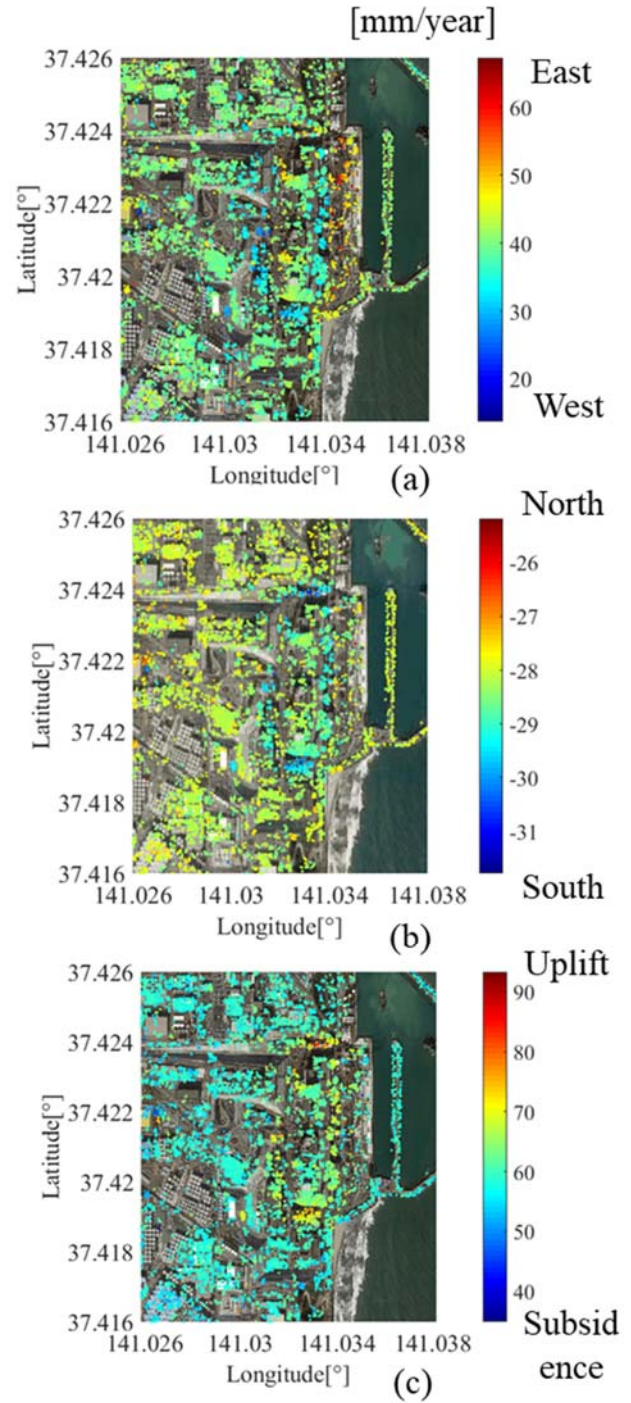


Fig. 2. Land displacement estimated from time-series ALOS2/PALSAR-2 images with GPS data. (a) East-west displacement, (b) north-south displacement and (c) vertical displacement.

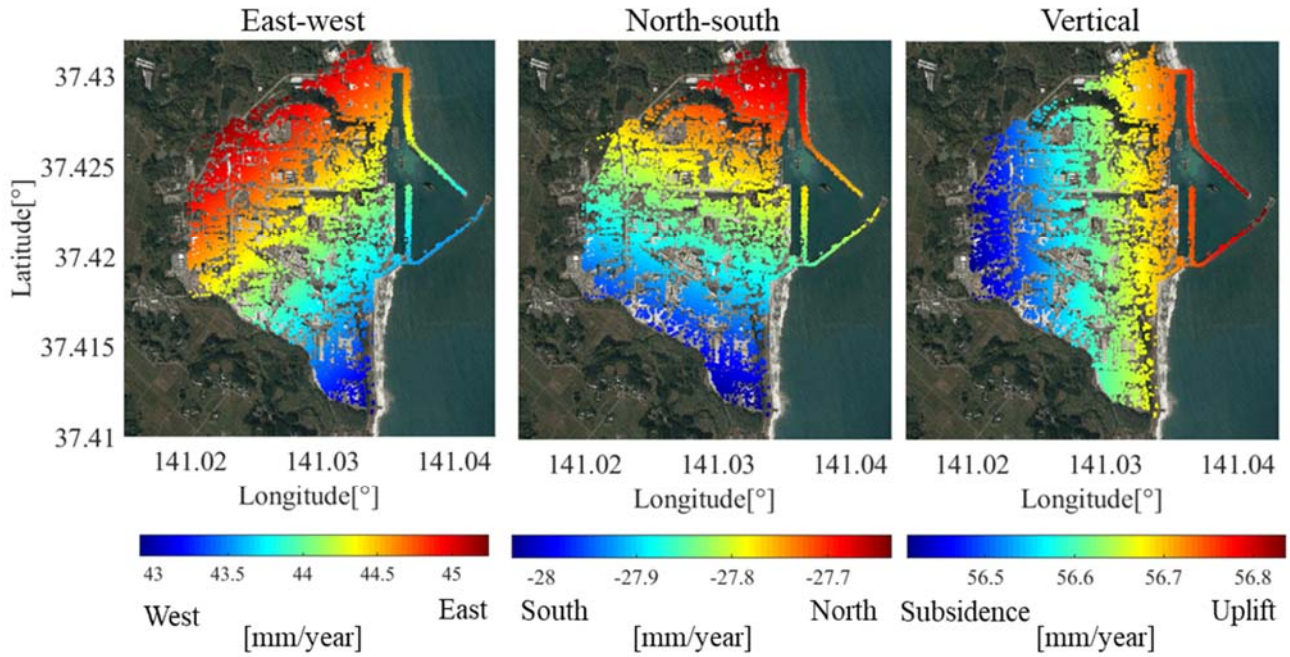


Fig 3. Land displacement generated by interpolation of GPS data with ordinary kriging.

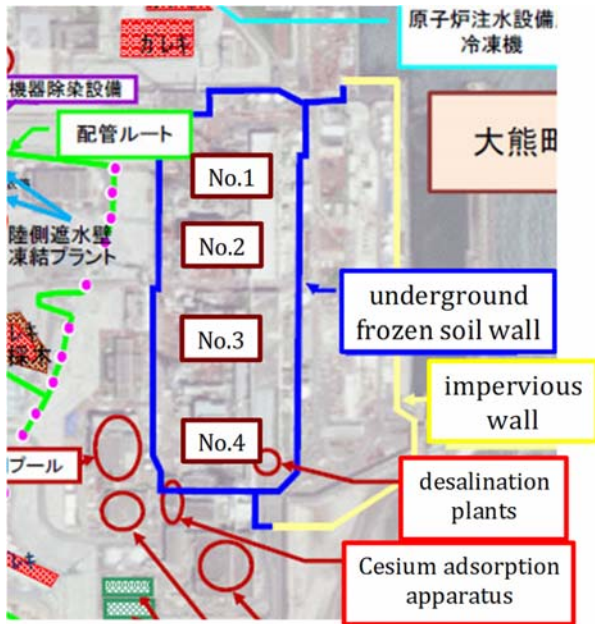


Fig. 4. Underground frozen soil wall installed around Fukushima Nuclear Power Plants No.1 to 4 in Fukushima Prefecture, Japan [10].

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