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SURFACE CHANGE OF THE SOIL LIQUEFACTION CAUSED BY THE 2011 GREAT EAST JAPAN EARTHQUAKE DERIVED FROM SAR DATA

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ABSTRACT: To reveal changes in surface scatters associated with the 2011 Great East Japan Earthquake, we performed Interferometric processing using SAR images in Kanto region. As a result, we detected areas of scatter changes at the waterfront along Tokyo bay and Tone River. Furthermore, spatially-continuous ground subsidence inferred from DInSAR analysis was found in the same area. Since these results are consistent with field studies in liquefaction areas, we concluded that our results demonstrate surface changes due to soil liquefaction caused by the earthquake.

Key Words: soil liquefaction, remote sensing, the 2011 Great East Japan earthquake, DInSAR analysis

INTRODUCTION

On March 11th 2011, the 2011 Great East Japan Earthquake was generated along northeast of the Japan Trench with ruptured fault as large as 500km×250km (Ozawa et al., 2011). Moreover, several large aftershocks continuously struck along the Japan Trench. In Kanto region including Tokyo, it has been reported that wide range of soil liquefaction was occurred mainly at the waterfront along the shore (Yasuda and Harada, 2011; Bhattacharya et al., 2011). Due to the soil liquefaction, residential buildings and infrastructures have suffered a great deal of damages. Soil liquefaction is usually investigated by field reconnaissance and aerial photography. In order to investigate soil liquefaction associated with the 2011 earthquake, several studies have been performed and revealed the areal extent of soil liquefaction areas (e.g., KRDB and JGS, 2011). In this study, however, we tried to investigate the areal extent and its degree of the occurrence of the soil liquefaction using images acquired by Synthetic Aperture Radar (SAR). SAR is active sensor which irradiate electromagnetic microwave to scatters on earth's surface and receive backscatter signal. The main reason we used SAR images in this study is an advantage for providing us broad and dense information on the Earth’s surface without the need of ground-based observation.

First of all, we created initial interferogram from two SAR images. Then, phase-corrected coherence (coherence map) was calculated based on the amplitude (backscatter intensity) of two SAR images. When soil liquefaction is occurred, the ground surface might become more wetting and constructions might be inclined. Hence, we can detect the changes in the relationship of amplitude among adjacent pixels before and after the 2011 earthquake using the loss of phase-corrected coherence. Since the loss of coherence is composed of several effects, coherence difference map was created to extract the effect due to the 2011 earthquake (Figure 1). After that, we compared our results with previous research (KRDB and JGS, 2011) to validate our results. Several studies have tried to detect surface changes due to soil liquefaction as the loss of coherence after previous huge earthquake (Saraf et al., 2002; Ramakrishnan et al., 2006). However, this study has a distinguishing characteristic in the view of validation of the ability of satellite-based liquefaction investigation using such a detail field investigation conducted by KRDB and JGS (2011).

Moreover, to reveal the degree of soil liquefaction, we used phase difference before and after earthquake. This method is usually referred to as Differential Interferometric SAR (DInSAR) (Massonnet and Feigl, 1998; Simons and Rosen, 2007) and provide us from ground displacements of centimeter or sub-centimeter accuracy. Since GPS stations in the liquefaction area are also suffered from damages due to tilted ground, it is important to estimate ground subsidence inferred from DInSAR analysis in the liquefaction area (Figure 1).

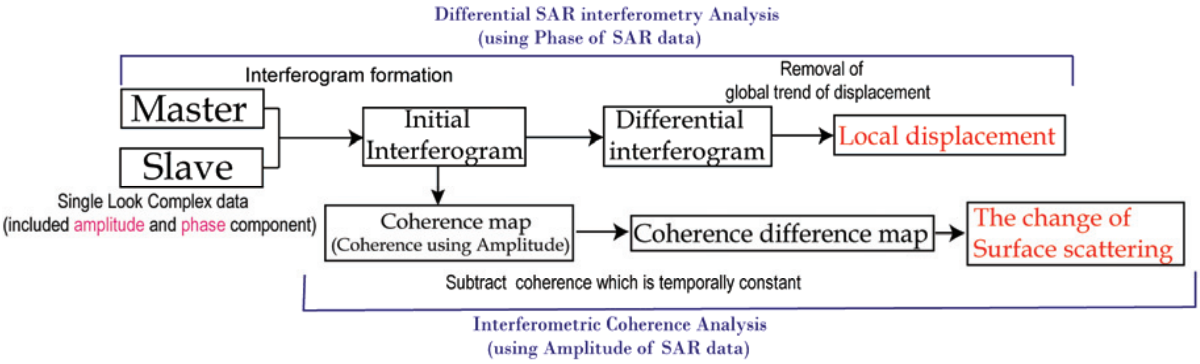

Fig. 1 The flow of this study

METHODS

The SAR images in this study were acquired by the Phased Array Type L-band SAR (PALSAR) instrument on the Japanese Advanced Land Observing Satellite (ALOS). We used interferograms of I1 I3 in Table 1 covered with Tokyo bay and I2 I4 in Table 1 covered with Tone River for estimating the loss of coherence and interferograms of I3 I4 in Table 1 for estimating ground subsidence (Table 1, Figure 2).

Table 1 SAR images used in this study

Type	ID	Master	Slave	Direction	Bperp	Covered area
Preseismic	I1	2011/01/04	2011/02/19	Ascending	709m	Tokyo bay
Preseismic	I2	2010/10/05	2010/11/20	Descending	593m	Tone River
Coseismic	I3	2011/02/19	2011/04/06	Ascending	394m	Tokyo bay
Coseismic	I4	2010/11/20	2011/04/07	Descending	914m	Tone River

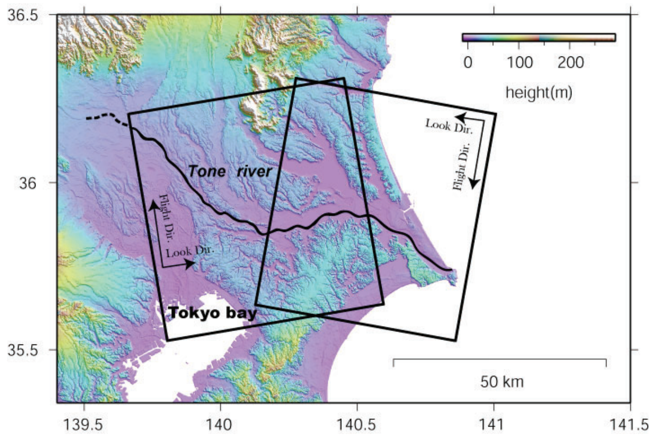

Fig. 2 Kanto region and covered area of SAR image used in this study.

Estimating the loss of coherence

To measure physical change of the earth surface statistically, we used phase-corrected coherence (γ) (Hagberg et al., 1995).

$$\gamma = \frac{\left| \sum_{n=1}^{N} C_1^{(n)} C_2^{*(n)} e^{-i(\phi_1 - \phi_2)} \right|}{\sqrt{\sum_{n=1}^{N} \left| C_1^{(n)} \right|^2 \sum_{n=1}^{N} \left| C_2^{(n)} \right|^2}} \tag{3}$$

where $C = Ae^{i\phi}$ is complex value in Single Look Complex (SLC), which contains amplitude (A) and phase (ϕ), N indicates the number of adjacent pixels to compute coherence as spatial average, referred to as window size. In this study, we chose N =7×7, which indicate adjacent area of 98 m× 112 m is used to estimate coherence. Phase corrected coherence has the characteristics of computing coherence using amplitude. Amplitude represents backscatter intensity on the surface at a each location. It is known that backscatter intensity is affected by the water content and roughness on the surface with the same incidence angle, polarization and electromagnetic microwave length. Hence, sand boiling on the surface or inclined buildings induced by soil liquefaction change the relationship of amplitude among adjacent pixels, which result in decorrelation. Although, these temporal changes on the surface are one of the sources of decorrelation by this earthquake, other effects are included as the source of decorrelation as follows. The coherence (γ) comprises contributions from four effects (i.e., γ_N : thermal noise, γ_V : geometric effect, γ_V : volumetric effect and γ_T : temporal effect) (Zebker and Villasenor, 1992). Since the influence of soil liquefaction appear as the decreasing of γ_T, we need to extract γ_T from total coherence. Therefore, we made coherence difference map which is the result of subtracting coherence of preseismic pair acquired before earthquake (I1 I2 in Table1) from that of coseismic pair acquired before and after earthquake (I3 I4 in Table1).

Estimating ground subsidence

We used DInSAR analysis to estimate ground subsidence associated with soil liquefaction. Phase difference between data acquisitions ($\psi = \phi_1 - \phi_2$) is composed of several effects.

$$\psi = \psi_{disp} + \psi_{orbit} + \psi_{topo} + \psi_{atm} + \psi_{noise} \quad (4)$$

where ψ_{disp} is phase difference induced by surface displacement toward line of sight (LOS) direction. ψ_{orbit}, ψ_{topo}, ψ_{atm} and ψ_{noise} are phase difference due to satellite position difference, topography, atmosphere inhomogeneity and noise. To subtract phase component other than surface displacement, we can estimate phase difference induced by ground displacement. We performed DInSAR analysis using coseismic pair acquired before earthquake and after earthquake (I3 I4 in Table1). Although sand boiling on the surface might have been removed at the acquisition of SAR images after earthquake (2011/04/06 in I3 and 2011/04/07 in I4), we estimated surface displacement without consideration of the effects of removed sand boiling. To eliminate the effect of the difference in the satellite positions for the two acquisitions of a pair, we used 50m mesh digital elevation models provided by geospatial information authority of Japan (GSI). As the strategy for remaining high resolution, we used adaptive filter whose performance magnitude depend on coherence (Baran et al., 2003) which is calculated by only phase in this study. As a result, we obtained differential interferogram which represents surface displacement toward LOS direction caused by the 2011 earthquake. To pick up the local ground subsidence associated with soil liquefaction, we removed the long wave ground displacement caused by the 2011 earthquake by applying a best fit quadratic function.

RESULTS

The loss of coherence

The coherence difference map is calculated to extract temporal decorrelation due to the earthquake. The negative value indicates the areas where coherence decrease due to the earthquake. In the result of coherence difference map, negative value is distributed in the waterfront (artificially filled ground) along Tokyo bay, and waterfront along Tone River. These observations suggest that physical properties of the ground surface such as water contents of soil or surface roughness were changed due to the earthquake in these areas. To confirm whether surface scatter change is associated with soil liquefaction or not, we compared our result with existing survey, which is performed by foot or air photograph soon after earthquake (KRDB and JGS, 2011). As a result of comparison, at the areas along Tokyo bay and the Tone River, 93 and 91 percent of the liquefaction locations detected by the field survey performed by KRDB and JGS (2011) are consistent with the results of this study, respectively (e.g., Figure 3). Because our result is consistent with the result of existing survey, negative coherence corresponds to the surface change due to soil liquefaction caused by the 2011 earthquake.

Ground subsidence

Local surface displacement after removing global surface displacement demonstrates that local surface displacement was mainly occurred at the soil liquefaction area, (i.e., waterfront along Tokyo bay and Tone River). In soil liquefaction areas, there are certainly decorrelation-induced phase discontinuity, however, we obtained spatially continuous displacement. Moreover, local surface displacement inferred from DInSAR analysis was occurred in the opposite to LOS direction in both pair taken on ascending orbit (I3 in Table1) and descending orbit (I4 in Table1), which denote that the local displacement is ground subsidence (e.g., Figure 4). Therefore, we concluded that this local surface displacement was associated with soil liquefaction induced by the 2011 earthquake.

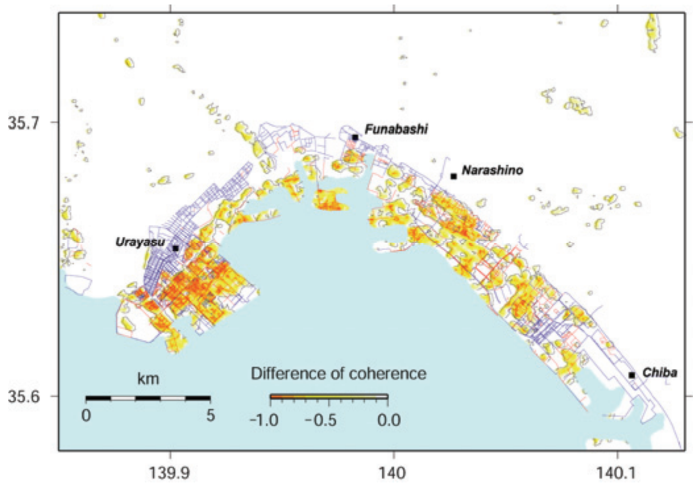

Fig. 3 Comparison the loss of coherence and field survey (KRDB and JGS, 2011). The red lines and blue lines indicate liquefaction and non-liquefaction locations detected by field survey. The yellow and orange area indicate negative value (under -0.1) inferred from phase corrected coherence in our analysis.

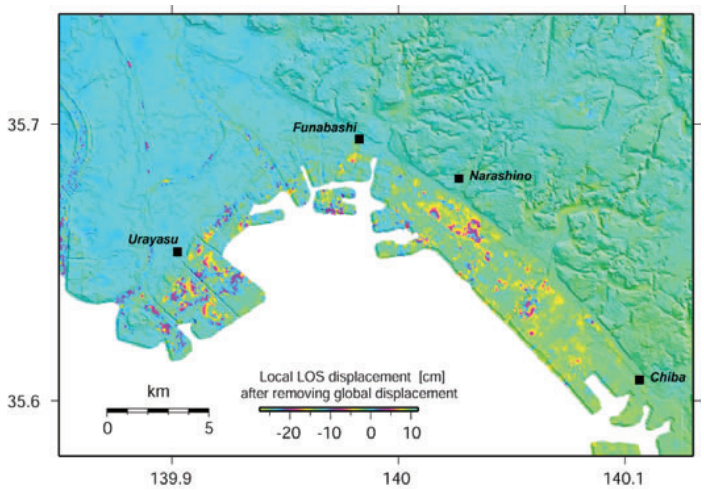

Fig. 4 Local surface displacement at waterfront along Tokyo bay.

CONCLUSIONS

We detected the change in surface scattering property caused by the 2011 earthquake using the difference of phase corrected coherence between preseismic and coseismic SAR data pairs. We further revealed local surface displacement using DInSAR analysis. These results are consistent with existing field survey results. Therefore, these surface changes should be associated with soil liquefaction. This study further detected undiscovered liquefaction area especially in waterfront along midstream and downstream of Tone River. This study proposes the effective use of SAR data to investigate soil liquefaction and clarify that SAR data can provide spatially broad insight to the soil liquefaction. In this study, we performed interferometric processing and then compared the result obtained from SAR data and the result of field survey, but if we apply the proposed methodology in this paper immediately after the occurrence of the earthquake using SAR data, field survey works would be performed more efficiently.

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