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The high accurate monitoring technique of land deformation by using satellite image - PSInSAR -

Toshimi Mizuno[1], Shigeki Kuzuoka[2]
[1] OYO Corporation Technical Center Geotechnical engineering center, [2] ImageONE Co., Ltd.

Abstract: Remote sensing can provide invisible information in addition to acquire wide-view image data from space. Synthetic Aperture Radar (SAR) transmits microwave to the earth from a satellite and collects the reflected echo from the surface. Interferometric processing of SAR data can detect the subtle land deformation. The information of the surface movement by SAR is useful to monitor the volcanic activity, extended subsidence of urbanized area and the prediction of the earthquake caused by crustal deformation, and it complements the conventional levelling and GPS technique. PSInSAR (Permanent Scatterers Interferometric SAR) is one of interferometric techniques to be applied to practical projects in Japan.
In this paper, the projects of land deformation monitoring are shown after the explanations of the PSInSAR principle. Tokai earthquake risk assessment is the first example. PSInSAR detects the subduction of crustal deformation of the adjacent area of new assumed epicenter region of the Tokai Earthquake. The extended subsidence of the urbanized area was implemented by using Japanese satellite data i.e. JERS that has so much data the surrounding of Japan as the archive. We examine the relationship between the geological structure and settlement at Nohbi basin including Nagoya city.

1. Introduction

In recent years, the development of remote sensing technology is remarkable and applications of remote sensing in geo-technical field are increasing rapidly. Especially, InSAR technology is useful comprehending the distribution of the land deformation before and after big earthquakes since SAR acquisition is not influenced by the weather, and the exact distance measurement can be analyzed by interferometric technology.

Above all, PSInSAR could assure the mill metric accuracy, and could analyze the subsidence distribution and time series of the extended urbanized area using by PS (permanent scatterer) on the SAR image (for example PS density of urbanized area; 500 points/km^2). PSInSAR has developed by Politecnico di Milano (Alessandro Ferretti, Claudio pratli, and Fabio Rocca) and aided by ESA (European Space Agency).

We did implement the applications to geo-technical engineering of PSInSAR positively, i.e., land deformation of urbanized area, the active fault behaviour at the time of earthquake, and the subduciton zone of Tokai earthquake in Japan. For example, Technology Center of Tokyo Gas Co., Ltd. has carried out the risk assessment of pipeline by using the historical subsidence of PSInSAR result.

Moreover, the capability to carry out PSInSAR has expanded absolutely, since PSInSAR by using Japanese satellite JRS that there are enough acquisitions to use for PSInSAR in Far East area from 1992 to 1998, has developed (Prof. Fabio Rocca, Dr. Kenji Daito, L-band PS analysis: the potential of the JERS-1 archive, Fringe2003, esa Frascati, December 2 – 5, 2003 submitted).

2. The principle of PSInSAR

For land deformation monitoring, Differential Interferometer Synthetic Aperture Radar (Denser) technique has been applied by researchers. Denser technique calculates the difference of phase information from two SAR scenes over a target area and measures the target movement between the two SAR acquisitions at mill metric order. As Denser monitors the land deformation accurately over two-dimensional area, it has been used to monitor the land deformation caused by an earthquake or a volcano eruption.

Though this conventional Denser has been used for academic projects, it has two limitations for the practical monitoring projects. The first limitation is the difficulty of SAR scenes' selection. Denser needs a specific orbit condition between two scenes. The distance between the two orbits should be within a certain distance. Two SAR scenes should be selected to meet this orbit criterion. This limitation decreases the monitoring chances. The second limitation is the unexpected phase change caused by the vegetated surface and the atmospheric effect. It is difficult to know these effects until DInSAR analysis starts. DInSAR sometimes does not succeed to provide any meaningful results at all. In brief, DInSAR can not provide the results all times, although it can provide the really accurate results if it succeeds.

PSInSAR is one of DInSAR technology for the practical use. It was developed by TeleRilevamento Europa (T.R.E.) at Milano (Ferretti et al, 2000). European Space Agency (ESA) has supported this technique for the commercialization. Because it almost works well at an urban area, it has been mainly used to monitor land subsidence at an urban area for the practical purpose. PSInSAR uses ERS-1/2 satellites, which was launched by ESA, and RADARSAT, which was launched by Canadian Space Agency.

PSInSAR has two advantages to monitor the land deformation. It can measure two-dimensional land deformation accurately at first. Conventional levelling or GPS can measure the land deformation only at a specific point. On the other hand, PSInSAR can provide the measurement results over the area as an image. This feature can give the outline land deformation over the area and it can also detect the local land deformation where the levelling or GPS measurement has not been deployed. This feature provides the local subsidence caused by a subway construction, for example.

As the second advantage, PSInSAR can provide the time history of land deformation. Using the archived SAR images, we can monitor the land deformation as a function of time over the period of the data acquisition. This gives us historical land deformation information from the time before levelling or GPS measurement starts.

PSInSAR watches only stable points over 30 scenes and constructs models that show land deformation well. PSInSAR needs over 30 SAR scenes acquired at different times over a target area. It takes three years to acquire 30 images by ERS-1/2 as minimum, but it takes about 10 years for the usual case in Japan because of the number of archived SAR scenes. The technique selects PS points automatically if the phase of the reflected microwave is stable over the period at the point. This kind of PS can be a building or an artificial object that return echo very strongly and is stable over 30 scenes. The density of PS reaches 500 points per square kilometers at an urban area at least.

PSInSAR measures the wave phase at each PS to develop two models. The first model is the two-dimensional model for atmospheric effect at each scene. Because the atmospheric effect depends on the location, PSInSAR models the effect as two-dimensional function for each image. Then it generates more than 30 sets of two-dimensional atmospheric models. PSInSAR also models the time series of the PS movement over 30 scenes. This is the one-dimensional time function as the distance between the satellite and the target PS. These time functions can be modelled linearly or non-linearly depending on the target PS features. Then it generates the one-dimensional model as the number of PSs. As results, PSInSAR generates over 30 sets of two-dimensional models as many as the number of scenes and the one-dimensional models as many as the number of PS points. These models contain a huge number of unknown parameters. PSInSAR solves the unknown parameters using the phase information on each PS points over 30 scenes as an inverse problem.

PSInSAR measures the changing rate of the distance between the satellite and the PS as mill metric level per a year, if the PS density is more than 100 points per square kilometers and the numbers of scenes are over 30. The first condition can be achieved easily at an urban area and the density of PS candidates can be estimated before PSInSAR full analysis. The second condition can be checked easily if ESA archive is searched. Then the feasibility and the expected accuracy can be known before the full analysis. This is the advantage of this technology for practical use.

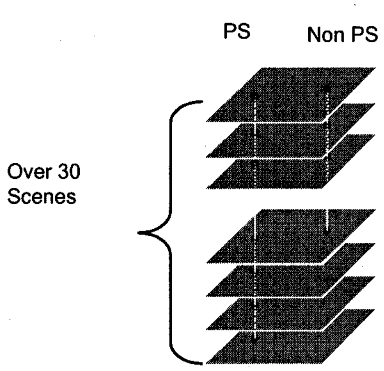


Fig. 1. Concept of PSInSAR.

Ferretti indicated the principle of PSInSAR using numeric equations as follows. Assume there are N+1 scenes of SAR images that were acquired at the same area by the same mode. The N scenes are registered to a master scene accurately, then N sets of interferogram are generated. The phase residuals ϕ_i can be described as follows after the orbit correction and the DEM correction.

$$\phi_i = \frac{4\pi}{\lambda} rT_i + \alpha_i + n_i + \varepsilon_{topo\_i} \quad (1)$$

where

λ : wave length

α_i : phase effect caused by atmosphere

n_i : de-correlation noise

ε_{topo_i} : phase residuals caused by DEM error (It is proportional to the base line length B_{n_i} at each image.)

rT_i : land surface movement along the line of sight (LOS).

The first term of (1) can be described as follows.

$$\frac{4\pi}{\lambda} rT_i = \frac{4\pi}{\lambda} \cdot v_r \cdot T_i + \mu_{NL_i} = C_{vi} \cdot v + \mu_{NL_i} \quad (2)$$

where

v : the average speed of the land surface along LOS direction

μ_{NL} : the phase error effect cased by the non-linearity of the land surface movement

T_i : the acquisition time difference between the master scene and the i-th scene.

Then the following N sets of linear equation were derived for each pixel using two unknown parameters (ε_z, v_r) because there are N sets of differential interferogram at the same point.

$$\phi_i = C_{zi} \cdot \varepsilon_z + C_{vi} \cdot v \qquad i = 1 \cdots N \quad (3)$$

where:

ε_z : DEM error

C_{zi} : coefficient that is proportional to the base line length B_{n_i}

This equation shows that the average land surface movement along LOS direction and the DEM error can be calculated if the unwrapped phase values are available in case that the S/N level is enough high.

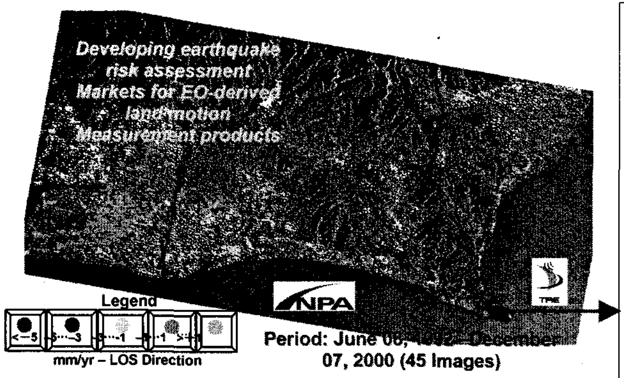
3. The applications of PSInSAR for geotechnical engineering

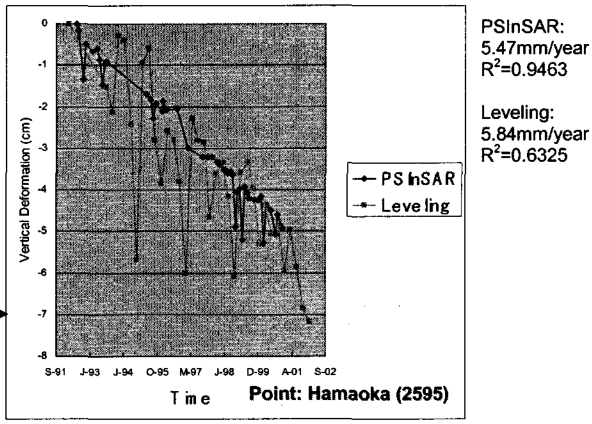
Above mentioned, PSInSAR is very useful monitoring technique of land deformation. In Japan, there are so many natural disaster issues that human cost is increased by earthquakes, heavy rain, and volcanoes activities. PSInSAR will be the promising monitoring technology and system for the approaches of extended subsidence, active fault behaviour, prediction of earthquake by monitoring of subduction zone, and changing shape of volcanic mountain.

Subduction zone around the epicentre region of Tokai earthquake

First PSInSAR analysis was carried out on Tokai earthquake epicenter region by TRE (Fig. 2). At the bottom of the sea in Suruga Bay, the trench called Sagami trough is distributed. This trench is thought to be a boundary of plates "Philippine Sea plate", coming from the southern part of Japan Islands, squeezes Izu peninsula, it slips beneath "Eurasian plate" located at the west side of Japan Islands (Fig. 3). PSInSAR result well explains the subduction rate of the Philippine Sea Plate, about 5mm/year that is almost same the conventional levelling.

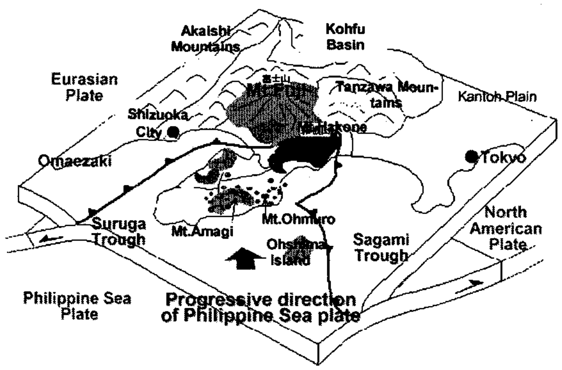
It is assumed that this plate boundary is the epicenter region, and a large earthquake (Magnitude about 8) will occur in the near future. This is called "Tokai earthquake". The Result of PSInSAR, which caught crustal deformation in Tokai earthquake epicenter area, is very useful to estimate the behaviour of the subduction zone with GPS. It will be able to provide the basic material for the prediction of earthquakes.





a) The distributions of land deformation of PSInSAR result (assumed linear model) b) Time series by non-linear model

Fig. 2. PSInSAR analysis on the Tokai earthquake epicenter region.



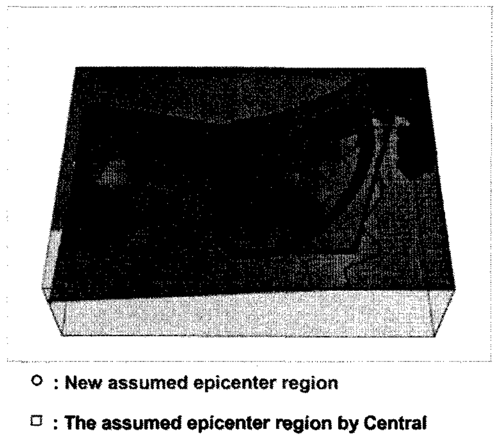


Fig. 3. The conditions of Omaezaki, left; Present's physical geography situation in Izu peninsula and adjacent areas (Masato Koyama (1994)), right; New assumed epicenter region of the Tokai Earthquake (Central Disaster Prevention Council, 2001).

The active fault behaviour

In Mt. Iwate, earthquakes may be related to the volcanic activity increased from the middle of March 1998 around Mt. Iwate and the activity was continued for few months. The earthquake frequency was 1000 or more from the beginning of volcanic activity as of April 6, 1998. And earthquakes that the maximum magnitude is M 2.7 occurred on April 29, 1998. In a continuous observation using GPS, crustal deformation that was thought to be related to the volcanic activity in the radical line length of GPS Earth Observation Network arranged around Mt. Iwate, has been detected. The radical line across Mt. Iwate expanded over 2cm was observed since beginning of February 1998.

When confirming the PS distribution by the image of Landsat-7, the feature of the area where PS cannot be acquired is similar to the area where vegetation is shown around the top of the Mt. Iwate (Fig. 4). It is very important feature and condition in order to implement PSInSAR. In Japan, the PS acquisition is feasible to judge roughly by vegetation.

Permanent Scatters could be acquired in the crustal deformation area near by active fault that generated earthquake in September 3, 1998. As the result of the analysis, crustal deformation of the active fault west side's was clarified. Fig.5 is shown that earthquake occurred before and after in September 3, 1998. PS1, PS4, PS5 and PS6 was deformed up when earthquake occurred and this distribution of PS was identified the feature of land deformation area by earthquake.

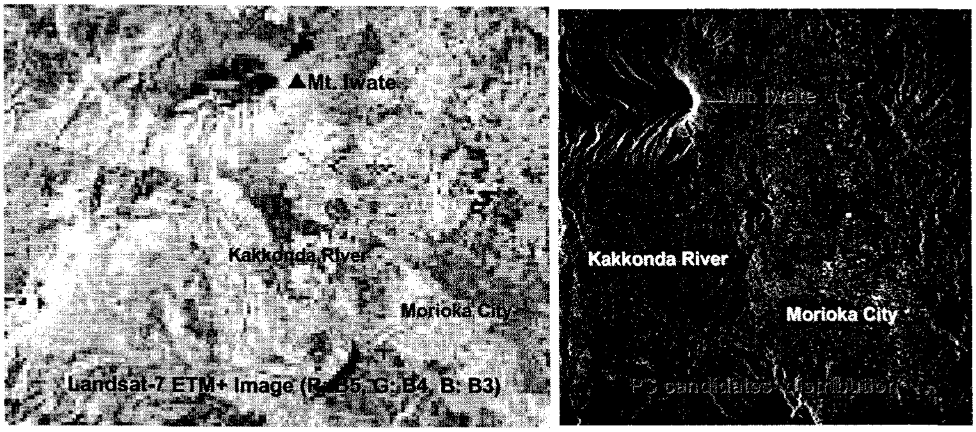


Fig. 4. The feature of PS aquisiton around Mt. Iwate.

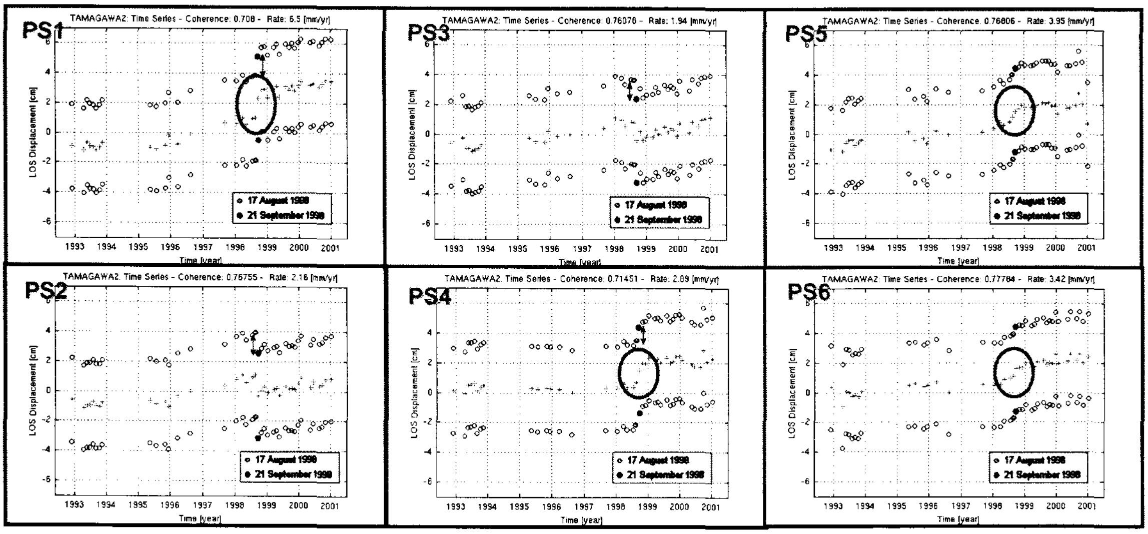


Fig. 5. Time series of Nishine fault group when earthquake occurred.

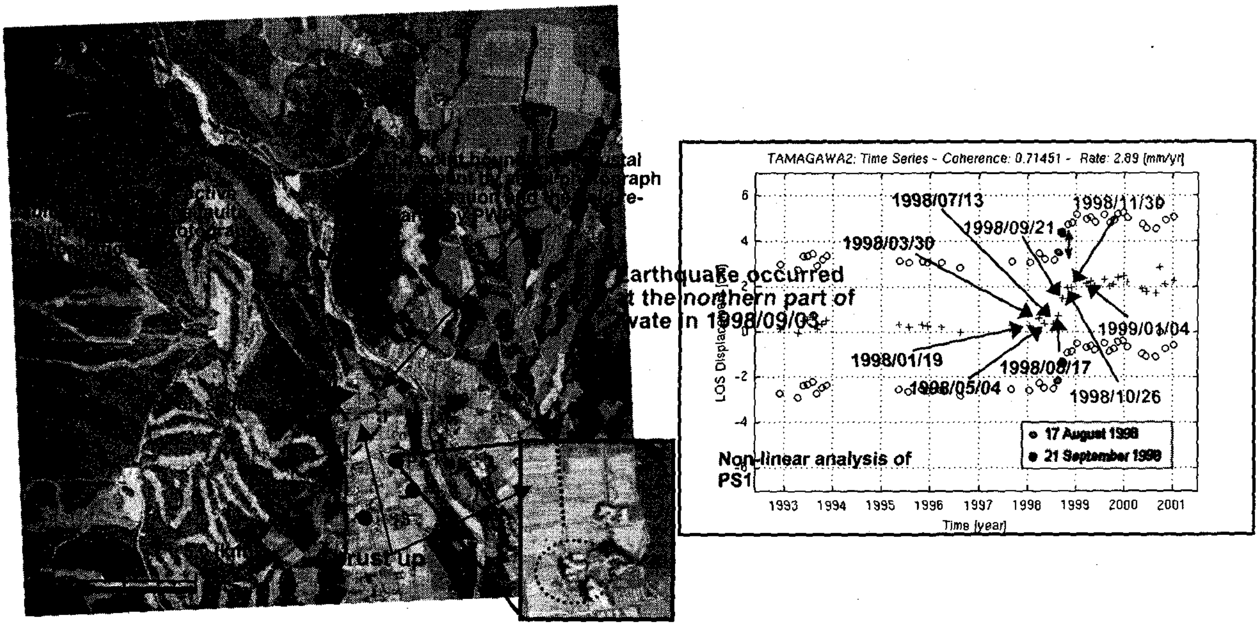
At the PWRI (Public Works Research Institute) report and aerial photograph interpretation, deformed by earthquake area was detected. The respective non-linear analysis of PS1 to PS6 is good corresponding with the shape of active fault and deformed area. PS1and PS4 to PS6 supposed to distribute on the deformed area. And PS2 and PS3 are distributed outside of deformed area.

PSInSAR, especially non-linear analysis, excels at monitoring before and after events and identifying the historical deformation using SAR archive.

The extended subsidence of Kanto and Nohbi basin

The extended subsidence is severe issue of urbanized area because Tokyo metropolitan and Nagoya cities have so many facilities and properties in high density. In Tokyo metropolitan city, the underground water level is increasing since pumping up underground water has stopped in 1960's. But, local subsidence is identified all of Tokyo city. It is supposed effects of underground excavations, underground water condition and etc.

PSInSAR was carried out around Tokyo metropolitan area for last 5 years. At result of PSInSAR analysis, high density PS was acquired and local subsidence was extracted (Fig.7). PS density is 1,000/km^2 because term of analysis was short. And non-linear analysis of 5,000 points or more has carried out. It is fast experience that PSInSAR and non-linear analysis was implemented in high density absolutely in Japan. The analysis in order to clarify causes and effects is approaching now. PSInSAR analysis as archive will be very useful material to detect and examine mechanism of extended subsidence in Tokyo metropolitan city.



a) The distribution of PS, active fault and deformed area b) The expectation of non-linear analysis of active fault

Fig. 6. Active fault and deformed area analysis by PSInSAR.

In Nohbi basin including Nagoya city, pumping up underground water is controlled by underground water level by monitoring of wells. Therefore, the extended subsidence will be spread quickly in dry season. Prof. Daito in Daido Institute of Technology studies this phenomenon in Kanie city mainly. But, conventional levelling points are too small to approach the mechanism of extended subsidence, and to control underground water level.

PSInSAR using JERS images is doing implement as the collaboration with Daido Institute of Technology, TRE, ImageONE and OYO Corporation because there are not enough ERS images to analyze in Nohbi basin area. The identification of PSInSAR using JERS has three merits as follow, first, the capability of PSInSAR in Far East is expanded, second, JERS archive will be used effectively, third, L Band SAR for next Japanese satellite ALOS (SAR sensor is PULSAR) will be very useful for Japanese disaster prevention because L Band PSInSAR was developed by collaboration.

Comparing with C-band data, like ERS-1/2 or Radarsat, JERS-1 L-band data have several features for PSInSAR application. The first, the orbit data of JERS-1 is less accurate than ERS-1/2 data. This less accuracy makes the registration and phase error correction difficult. The difference of L-band and the C-band is also the point to be considered at the second. Because L-band data can locate much PS points at vegetation area than C-band data, PS from JERS-1 could be detected much more than PS from ERS data. However the measurement accuracy of a PS could be higher at C-band than L-band because of the wave length. Then the total measurement accuracy could be considered. At last, because of the difference of the polarization, PS from JERS-1 data could be different from PS from ERS data. The difference depends on the difference of the target structure. Considering these three points, JERS-1 PSInSAR technique needs to be developed.

Prof. Daito and his collaborators will clarify the extended of Nohbi basin i.e. the cause of subsidence and the effect of extended subsidence by pumping up underground water in the near future.

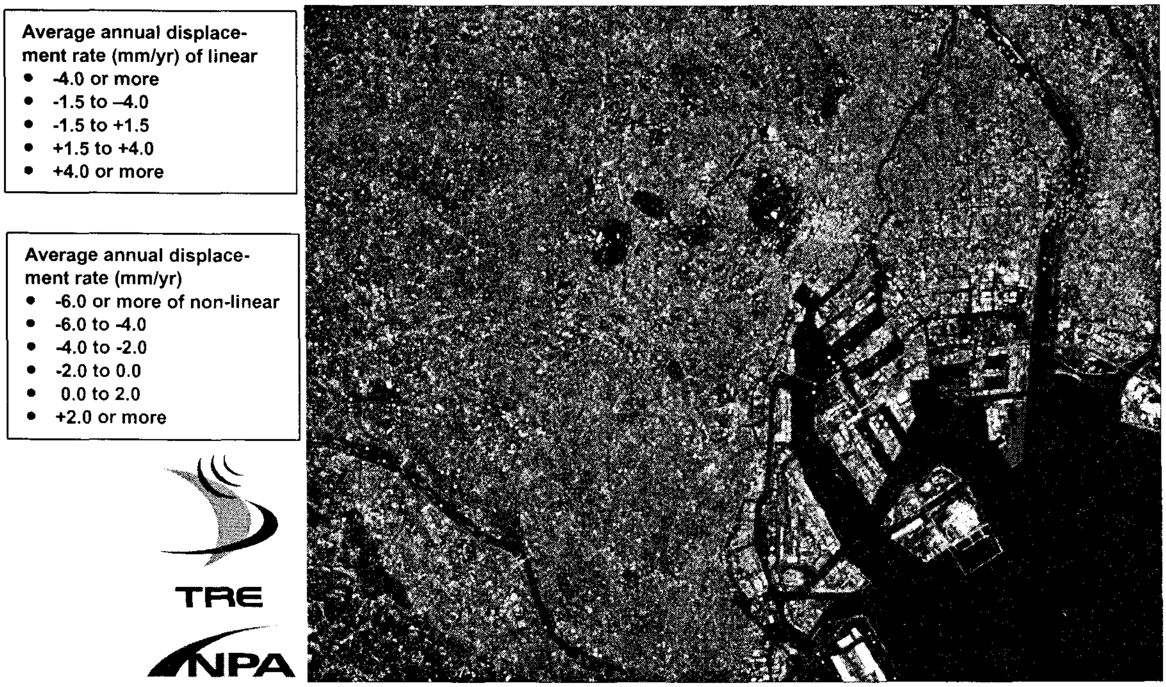


Fig. 7. PSInSAR result in Tokyo (small ●; linear analysis distribution about 70,000 points, big ●; non-linear analysis distri bution about 5,000 points or more).

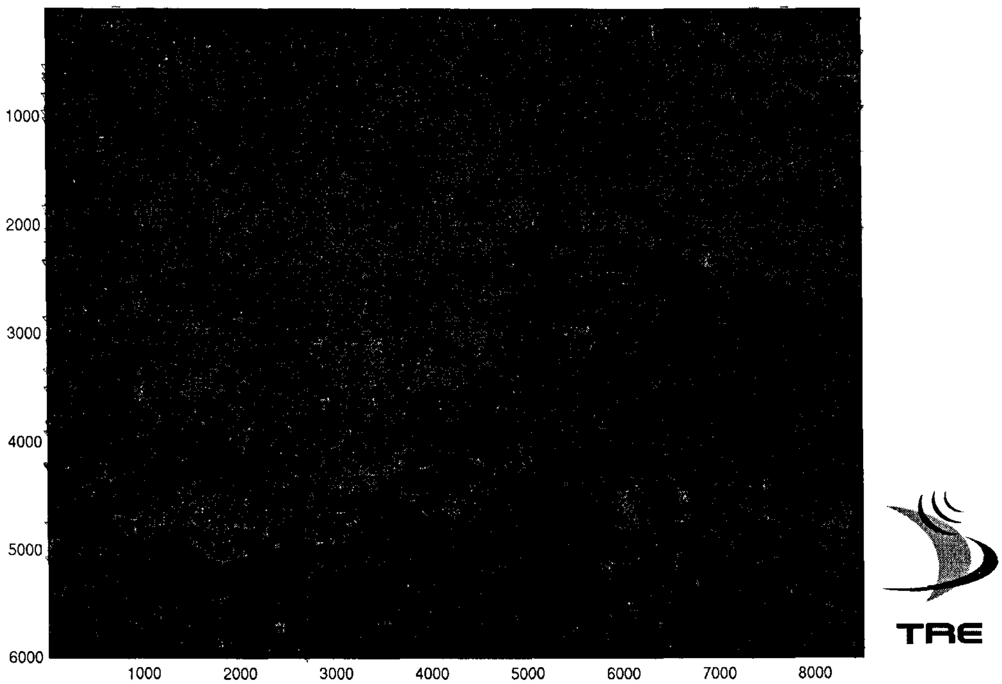


Fig. 8. PS candidates of Nohbi basin.

4. Conclusions

At the beginning, PSInSAR for geo-technical engineering did implement positively in order to make sure the accuracy and condition to apply. There are so many cases to apply PSInSAR for natural disaster issue for example earthquake, active fault, and active volcano in Japan. Especially, non-linear analysis of Nishine fault group was clarified the activity and geophysical feature of active fault at the time of earthquake. It is breakthrough that conventional method by using instruments installed can not identify absolutely. Moreover, extended result of PSInSAR in urbanized area is very useful to administrate facilities and life lines.

ON contrary accepted wisdom of InSAR, PSInSAR will be able to detect the extended historical deformation and non-linear analysis by the high accuracy. And the expectation of land deformation caused by pumping up underground water, earthquakes, volcanic activity and etc. will be clarified exactly. In Japan, natural disaster is severe issue for life and safety of people. PSInSAR will contribute to solve issue of natural disaster and environment preventions for Japanese people.

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