Mapping land uplift and subsidence in the industrial parks in northern Taiwan by radar interferometry

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The prevailing complex geological and ecological conditions of Taiwan have drawn considerable attention from various geo-ecological communities because of their vulnerability to produce various natural hazards at different scales. Located in the tropical/subtropical zone of the Pacific Rim, its ecological and rugged mountainous properties are environmentally sensitive making monitoring and observation especially difficult because of the high population density. In this article, we have investigated the land deformation in two adjacent industrial parks, Jhong-Li and GuEI-Shan, in northern Taiwan using radar interferometry. The Interferometric Synthetic Aperture Radar technique for processing a series of data sets was first validated by comparison with ground levelling measurements over a test site. Excellent agreement was obtained in both deformation pattern and magnitude of subsidence rate. The period of observation dated from 1993 to 2000 with Synthetic Aperture Radar images from ERS-1 and ERS-2. The results, after least-squares adjustment, revealed that the maximum subsidence reached 10 cm and the subsidence rates were about 1.8 cm year−1 (at epicentres) since 1993 at both parks. It was also found that the subsidence rate slowed down after 1998 at Jhong-Li park while continuing at GuEI-Shan park. This was strongly associated with local groundwater extraction activities.

1. Introduction

The complex geological and ecological settings in Taiwan have drawn substantial attention from various communities because of their vulnerability to produce viable natural hazards at different scales (Dadson et al. 2003). Located in the tropical/subtropical zone, its ecological system in such rugged mountainous terrain is environmentally sensitive because of its high population density, making its monitoring and observation especially difficult. In terms of natural hazard mitigation, those tectonically active regions can be used for correlation with the causes of abundant risk events such as coastal erosion, landslides, land subsidence and earthquakes, hazards

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occurring frequently on the island of Taiwan, which thus may serve as an example for assessing those geologically disastrous processes on a global scale.

To monitor deformation of the earth’s surface, geotechnical instrumentation, GPS-based systems and many other geodetic techniques are currently available (Segall and Davis 1997). However, most of them are point-based measurement techniques and are too costly if a very large area needs to be monitored. Interferometric Synthetic Aperture Radar (InSAR) (Gabriel et al. 1989, Massonnet et al. 1993) can be used to detect terrain variation (Zebker and Goldstein 1986) and/or deformation (Dixon 1994, Lundgren et al. 2001). Under favourable conditions, accuracy at a sub-centimetre level can be reached for deformation measurement, which is good enough for many monitoring purposes. However, some problems associated with the key processing procedures must be tackled before it can become a practically viable measurement technique for deformation monitoring, especially when the gradient of change is significant. Land surface deformations have been observed to occur in the Taiwan area from assessing different geodetic and geological indicators (Chang et al. 2004, Huang et al. 2006). A considerable effort has been paid to understanding the nature of these deformations and their corresponding factors. In terms of natural hazard mitigation, those tectonically active regions are suited for assessing the causes of abundant risk events, such as landslides, land subsidence and earthquakes. As a consequence, the island of Taiwan is ideally predestined to be an example for studying those geologically disastrous processes expected to be reappearing for many more centuries. This article examines some issues on the monitoring of earth-surface deformation with InSAR over industrial parks in northern Taiwan.

2. Geological settings and data processing

2.1 Background

The complex tectonic environment in Taiwan is the result of the collision of the Eurasian plate (EU) and the Philippine Sea plate (PSP) at the rate of about 8.2 mm year$^{-1}$ towards the north-west relative to the Penghu Islands (Yu et al. 1999) and the change of the polarity of subduction between the EU and PSP (figure 1). In contrast with south-central Taiwan, north-east Taiwan has undergone post-collisional processes, and the transpressional and transtensional deformation regimes dominated, based on geodetic measurements and numerical modelling (Hu et al. 2002).

2.2 Data processing and validation of the method

It is now a more common practice to perform InSAR processing. A multi-scale matching technique for fast and accurate co-registration from bi-temporal satellite Synthetic Aperture Radar (SAR) images on various viewing geometries and terrain relief was applied. The procedure involved two major steps: coarse registration and refined registration. The first step started with the estimation of initial offset between the object and reference images via automatically selected tie points. The wavelet transformation was employed to estimate the initial offset. In the refined registration step, a pyramidal approach was adopted for spatial feature extraction so that reliable tie points could be picked out. Another procedure was needed to reduce the phase noise. In this article, we adopted a newly developed, improved sigma filter by Lee et al. (2009). It was based on a minimum mean-square error (MMSE) algorithm by simultaneously taking the coherence and phase noise level (or standard deviation) into account. Results show that filtering performance is superior to commonly used filters. The necessary
Digital Terrain Model (DEM) is a 20 m × 20 m grid size derived from aerial photographs supplied by the Aerial Survey Office of Taiwan. To validate the procedures, we compared the InSAR-derived deformation due to subsidence with a precise levelling survey by the Water Resource Agency (2007). The test site, Changhua county, located in the western plain of Taiwan, is an important agricultural production region.
where the irrigated area is up to 109,500 hectares, and agricultural water consumption reaches approximately 90% of all available water resources in the Choshui river basin. Moreover, since there is no sufficient surface water supply, groundwater becomes a vital resource for every water-consumption target. For InSAR processing, ENVISAT ASAR data pairs between 19 April 2007 and 8 February 2007 were selected to match the ground survey time period. Figure 2(a) and (b) display the amplitude image of 19 April 2007 and coherence map, respectively. The deformation rate (cm year\(^{-1}\)) was plotted for both InSAR (figure 2(c)) and precise levelling (figure 2(d)) results. For the purpose of comparison, the contour lines (in black) of the levelling measurements were also overlaid onto the InSAR results in figure 2(c). It can be clearly seen that excellent agreement was obtained in both deformation pattern and magnitude. The epicentres were well co-located to each other.

### 2.3 Study areas and data sets

The major geomorphic unit in the study area was the Taoyuan-Hukou tableland, which is the youngest broad terrace in the Taoyuan-Chungli area (figure 3). This terrace is created as an alluvial fan by the paleo-Tahan River (Lin et al. 2005). The
major composition of the Taoyuan-Hukou tableland is of Quaternary deposits with cobbles overlain by finer alluvial materials. The Taoyuan-Hukou tableland is located close to the transitional regimes mentioned above (Hu et al. 2002). The rate of horizontal displacement revealed by global positioning system (GPS) measurements is about 2–6 mm year\(^{-1}\) north-westward (Yu et al. 1997). Several active tectonic structures have been identified (Lin et al. 2007), such as the Nankan fault (NKF) found at the western boundary of the terrace and the Hukou fault (HKF) located in the southern part of the terrace (figure 3). The two study sites of the Jhong-Li (JL) and Guei-Shan (GS) industrial parks are located rather close to these two fault systems. Red and yellow-brown soil predominates in the north-central plain and hilly areas, the dominating characteristic of the sloping regions. The mountainous sector in the south-east is rocky, while in the river valleys an alluvial layer has accumulated. The region lining the coast to the north-west is mainly made up of hills formed by centuries of wind action. According to a recent study (Lin et al. 2005), the groundwater table profile estimated from borehole data indicates that lateral groundwater recharge and discharge have accounted for major morphological variations of soils. This study has also discovered the secondary soil morphological variations along the banks of the Tahan River resulted from differences in their relative positions in a paleo-fluvial landscape. Although soils on the terrace edge are generally developed in a well-drained condition favourable for lateritization and can be regarded as an indicator of terrace

![Figure 3. Satellite image of the study sites (Jhong-Li and Guei-Shan Industrial parks). The solid red lines are faults (data: Central Geological Survey, MOEA). A high-speed railway, indicated by a solid yellow line, runs through the outskirt.](image-url)
correlation, a detailed soil-drainage history should be reconstructed before applying soil morphology to terrace correlation. A high-speed railway, indicated by a solid yellow line, runs through the outskirt.

In repeat-pass SAR interferometry, the interferograms were formed from repeated observations acquired on the same platform. With respect to the Earth, the ERS-1 and ERS-2 satellites go through a 35-day cycle of orbit, which means that the satellite returns to the same local region every 35 days. After this period of time, one or more orbital repeat cycles, the same area may be imaged again to acquire additional SAR images. In this study, 21 ERS-1/2 SAR images spanning the period from 1993 to 2000 were processed into 20 pairs of interferograms. Figure 4 shows the time span and corresponding perpendicular baselines for the image pairs covering the study site as indicated in figure 3. The master image was selected to be 19 August 2000. The shortest and longest time spans were 105 and 2747 days, respectively. The shortest baseline was 16 metres.

Before the interferogram processing, we examined the coherence quality of all the interferometric data pairs under consideration, in order to quantify the accuracy of the deformation derived from the interferograms. In figure 5(a) we plotted a false-colour map by temporally averaging the coherence (red), mean amplitude (green) and temporal variance of radar returns (blue) over all the 20 interferometric pairs as given in figure 4, spanned from 1993 to 2000. It is noted that the study sites reveal reasonably high coherence and hence good quality of interferograms. Larger returns from city or urban areas are visible (figure 5(b)). Stronger fluctuations outside the urban areas and very low coherence and returns from scatter ponds (water bodies) are also visible (figure 5(c)). On the other hand, high variance appears in vegetated surfaces, while urban areas have more stable radar returns and thus present lower variance (figure 5(d)).
The next procedure was the processing of InSAR to obtain the interferograms. Before unwrapping, to remove possible system or process errors, the least squares fit method (Lundgren et al. 2001) was used. A second-order non-linear function along the range and azimuthal directions was adopted to represent the interferograms. Over the study areas, some constant phase and phase gradient points were picked out as reference or calibrated points. By minimizing the cost function based on MMSE, the unknown coefficients were then estimated. Then a refined interferogram could be obtained. Figure 6 displays a sequence of 20 interferograms with time span referenced to 11 August 2000. From the first two pairs, the deformation does not seem so visible. Starting from 1995, slight deformation was observed at both sites, in which a clear quasi-circular pattern was standing out at JL site. The quasi-circular deformation patterns appeared at both parks, and were visible during the period 1996–1997. During
Figure 6. Interferograms with dates indicated below referenced to 11 August 2000. The quasi-circular deformational patterns appearing at both parks were visible during the period from 1996 to 1997. After 1998, this kind of pattern faded away at JL but remained clear at GS, particularly during 1999.

this period, the duplet of the deformation between JL and GS was clearly revealed. After 1998, this kind of pattern started to fade away at JL but remained clear at GS, particularly in 1999. The time series of the deformation patterns given in this figure
allows us to calculate the subsidence or uplift and their rate within a certain period of interest. Quantitative analysis will be discussed in the following section.

3. **Data analysis and interpretation**

To obtain the quantitative deformation, we performed phase unwrapping of all the interferograms using the NAPHU algorithm and software developed by Chen and Zebker (2002). Before unwrapping, to remove possible system errors, the least-squares fit method was used. Note that one phase cycle corresponds to 28 mm change at C-band (5.6 cm). We may determine whether it is subsidence or uplift. Figure 7 shows the estimated deformation along line of sight (LOS) between 1993 and 2000 at JL and GS parks. The values were derived at the epicentres revealed in figure 6. Generally, the temporal patterns were quite similar at both sites, with GS site showing a larger swing. Under the geological setting and tectonic structure, the mechanisms that induce the deformation are likely the same. According to the Industrial Development Bureau of Taiwan (2007), the average daily water supply for JL and GS are 45 000 and 14 600 tons, respectively. A large-scale subsidence occurred between 1995 and 1996 and rebounded afterwards. In figure 8 we plotted the land deformation rate along LOS between 1993 and 2000 at JL and GS parks. The threshold setting was chosen such that the standard deviation was greater than two fringes. Roughly 1740 days after 1993, we see that the deformation rate at JL had decreased and turned to uplift (positive rate), while at GS the subsidence continued at an even higher rate although the deformation scale was smaller (see figure 8).

Comparing with the observed fringes given in figure 6, we can see very clearly that the two patterns at respective dates are very similar, thus confirming the uplift and

![Figure 7. The land displacement along LOS between 1993 and 2000 at JL and GS parks. A large subsidence occurred between 1995 and 1996 and rebounded afterward.](image-url)
4. Conclusion

In this study, we applied the InSAR technique to a series of data sets in order to map the deformation in two environmentally sensitive areas: JL and GS industrial parks. With the historical archive and updated data sets, long-term and short-term subsidence patterns can be effectively and efficiently obtained. The maximum observed subsidence reached 10 cm, which occurred between 1995 and 1996, with an average subsidence rate of 1.8 cm year$^{-1}$ at both parks. Further investigation of the causes of these land surface deformations, related to tectonic activities or water pumping, is being undertaken. Frequent revisits of space-borne SAR from various satellites provides images which can be rapidly processed to combat the noise and loss of coherence due to the atmospheric phase screen, thus offering a powerful tool for environmental alert.
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Figure 9. The subsidence along LOS between 19 August 2000 and 10 August 1996, showing a duplet deformation pattern at JL and GS parks (the solid red line regions). The black cross marks indicate the two epicentres.

References


