MONITORING THE STABILITY OF LEVEES WITH TIME-SERIES ENVISAT ASAR IMAGES

Yuanyuan Pei(1), Mingsheng Liao(1), Teng Wang(1),(2), Lu Zhang(1)

(1) State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, P.R. China
(2) Division of Physical Sciences and Engineering Department, King Abdullah University of Science and Technology, Kingdom of Saudi Arabia

ABSTRACT

Levees are constructed to protect coastal cities from typhoon, flood, and sea tide. Since the stability of levees is important, it is necessary to monitor their deformation regularly. Repeat-track space-borne SAR images are useful for environment monitoring, especially for ground deformation monitoring. Shanghai resides on the Yangtze River Delta on China's eastern coast. Each year, the city is hit by typhoons from the Pacific Ocean and threatened by the flood of the Yangtze River. We used Persistent Scatterer Interferometry to monitor the deformation of the levees. Our experiments show that the levees around Pudong airport and Lingang town suffer from serious deformation.

1. INTRODUCTION

Typhoons and floods have been, particularly in recent years, a top threat to coastal regions. When coastal cities are attacked by natural disasters, levees are very important for flood-prevention and wave-protection. The destruction of a levee will cause substantial loss of lives and properties. For example, on July 25, 1947, a strong typhoon hit Shanghai and one levee at the east beach of Nanhui was destroyed on a length of 25 km, which resulted in a huge number of casualties and economic loss. Thus, it is necessary to monitor the levee regularly to ensure safety and to detect possible weak zones before it is too late.

With increasing economical investments in coastal areas, the creation of new land from sea is a hot topic in many countries. Notable example of reclamation is the Netherlands, in which 20% of the area is reclaimed land. In the Netherlands, which are sometimes referred to as the 'sink' of Europe, the primary levees have a total length of around 700 km. Many cities where land is in short supply are also famous for their efforts on land reclamation, for example Tokyo, New Orleans, Hong Kong, and Shanghai.

Over time, during the course of repeated tidal flooding, the sedimentation process forms mudflats. Then levees are built to enclose the mudflat, and filled with concrete and sediment. So the geological foundation of the reclamation land is unstable because of the short amount of time and the lack of consolidation. The soil of the reclamation land has some bad characteristics, such as high moisture content, high pore ratio, and low intensity. These conditions can cause subsidence on the reclamation land. Levee stability can be negatively affected by ground subsidence adjacent to the levee. Therefore, levees build on these subsiding areas should be monitored more regularly. High subsidence rates adjacent to levees require more immediate attention than areas where there are lower subsidence rates.

Monitoring levees is crucial for the safety of the lower-lying areas. It allows for coastal zone management, flood risk assessment, levee mapping, and stability monitoring. Deformation is an important monitoring item for levee. Traditional subsidence monitoring methods focus on ground-based monitoring, such as leveling measurement and GPS technique, which can offer high precision, but are manpower intensive, time consuming, and costly. The density of leveling points and GPS points is limited and subsidence in a single small section may stay undetected. Remote sensing techniques were introduced in recent years, such as Laser Intensity Direction and Ranging (LIDAR) and Synthetic Aperture Radar (SAR). The advantages of radar remote sensing are frequent revisits, wide area coverage, and high precision displacement monitoring.

Permanent Scatterer Interferometry (PS-InSAR) is one of the latest developments in radar interferometry processing. This technique can bypass the problem of geometrical and temporal decorrelation. By using a large amount of data, the atmospheric error is estimated and corrected for. The advantages of PS-InSAR include frequent revisits, wide area coverage, and high precision. Therefore, PS-InSAR technique extends the concept of standard interferometry and has boosted the application of active microwave remote sensing in many areas.

PS-InSAR was developed at Politecnico di Milano, Italy, in 2000 [1, 2]. In the PS-InSAR technique stable point-like targets, the so called permanent scatterers (PS), are identified. PSs are image pixels coherent over a long time series. The coherent values on PSs may be quite high even for interferograms with low overall coherence. In our application, it is our aim to find as many PS as

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possible because the subsidence pattern has to be sampled as dense as possible. On the other hand, we want to avoid unreliable points causing incorrect estimations.
Modified techniques are developed to further improve the time series InSAR technique, such as Coherent Target Monitoring (CTM), Interferometric Point Target Analysis (IPTA) [3], or Spatial Temporal Unwrapping Algorithm (STUN) [4]. At present, the PS-InSAR technique has been successfully applied in urban subsidence monitoring [5-7].

Shanghai's typhoon season is during mid-October and late-May each year. Investigations indicate that soft soil in Shanghai easily leads to ground deformation damage. Shanghai has been suffering from subsidence since the 1920s [8]. The city has invested around 580 million RMB in a large project to rebuild and strengthen the key parts of the 521-kilometer long coastline. Most sections of the levee, along Pudong, Nanhui, and Fengxian districts, have been built up and reinforced.

In the frame of Dragon II program, we collected 24 scenes of Envisat ASAR images, acquired from October 2007 to February 2010. In this paper we present our results using differential interferogrammetry and the PS-InSAR technology to monitor the deformation of levee.

2. METHODS

2.1. InSAR processing

First, a master scene is selected in order to start the InSAR processing. Parameters for the selection criteria are: the effective baseline, the acquisition date, and the Doppler centroid frequency.

The processing begins by assembling a stack of co-registrated single look complex images. In practise, we choose those pairs where the spatial baseline is less than 100 meters. The mapping function of the master image to each other images is then estimated by a weighted least-squares inversion.

The Shanghai test area is rather flat. According to the Shuttle Radar Topography Mission (SRTM) data, the maximum topographic is less than 20m. The interferometric phase is used as data input for PS-InSAR processing.

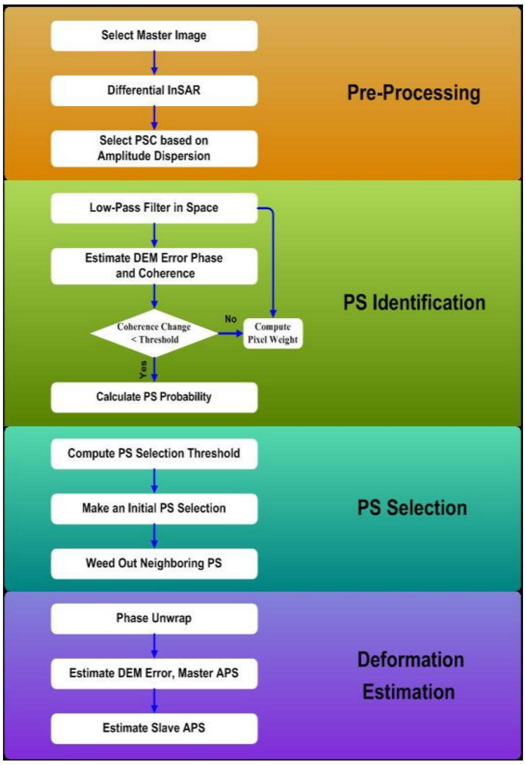
2.2. PS-InSAR processing flow

The wrapped phase of a point in a differential interferogram can be decomposed into uncompensated topography, target motion in the time between the acquisitions, object scattering phase related to the path length traveled in the resolution cell, the atmospheric phase accounting for signal delays, the phase caused by imprecise orbit data, and an additive noise term.

Important in the context of the phase model are spatial and temporal characteristics of the different terms. For example atmospheric phase can be considered low-pass in the spatial domain and high-pass (random) in the temporal domain.

Identification of PS is one of the key procedures in both SAR image interpretation and analysis for monitoring surface deformation. The temporal coherence was introduced to identify PS. In order to exclude sidelobes we assume that adjacent selected pixels are dominated by the same scatterer, and discard all but the pixel with the highest temporal coherence.

The time series phases are unwrapped in a three-dimensional (3-D) way. The unwrapped phases were divided into DEM error phase, deformation phase, APS distribution of master and slave images, and noisy parts. The whole PS-InSAR processing flow is shown in Fig. 1.



Figue 1. The PS-InSAR processing flow chart

3. EXPERIMENTAL RESULT

3.1. Experimental data

In the frame of Dragon II program, we collected 24 scenes of Envisat ASAR images (Ascending, Stripmap Mode, Track 497), acquired from October 2007 to

February 2010. The area coverage of the Envisat ASAR images is shown in Fig. 2. The basic information of 23 interferograms is shown in Tab. 1. The master image was obtained on August 2008. The maximum of spatial baseline is no more than 600 meters. All these interferograms are used to estimate the deformation velocity of the levee of Shanghai.

Table. 1 The basic description of interferogram

No.	Data	Bn	Bt	Fdc	ρ_{total}
1	29-Oct-07	-33.11	-280	4.74	0.82
2	3-Dec-07	-96.64	-245	1.79	0.79
3	7-Jan-08	33.05	-210	2.72	0.86
4	11-Feb-08	-288.62	-175	-7.00	0.66
5	17-Mar-08	-69.62	-140	3.80	0.86
6	21-Apr-08	-272.83	-105	-5.21	0.71
7	26-May-08	17.50	-70	4.58	0.94
8	30-Jun-08	142.65	-35	-1.32	0.85
9	4-Aug-08	0.00	0	0.00	0.00
10	8-Sep-08	-330.72	35	-4.55	0.68
11	13-Oct-08	255.49	70	-3.61	0.74
12	17-Nov-08	-172.14	105	-2.54	0.79
13	22-Dec-08	185.80	140	-0.91	0.77
14	26-Jan-09	-214.39	175	-1.01	0.73
15	2-Mar-09	130.33	210	-5.74	0.78
16	6-Apr-09	-166.99	245	-4.47	0.73
17	11-May-09	295.92	280	-13.83	0.61
18	20-Jul-09	123.15	350	-2.71	0.72
19	24-Aug-09	-137.64	385	-11.30	0.68
20	28-Sep-09	-146.21	420	-5.02	0.67
21	2-Nov-09	117.62	455	-1.44	0.67
22	7-Dec-09	-217.21	490	-0.61	0.59
23	11-Jan-10	224.86	525	-100.45	0.53
24	15-Feb-10	-198.83	560	-7.39	0.56

Figure 2. Area coverage of Envisat ASAR image

3.2. Resolution of subsidence velocity

The levees of Shanghai are built on beaches and soft soil. In our experiments we focus on the highlighted rectangular areas shown in Fig. 3.

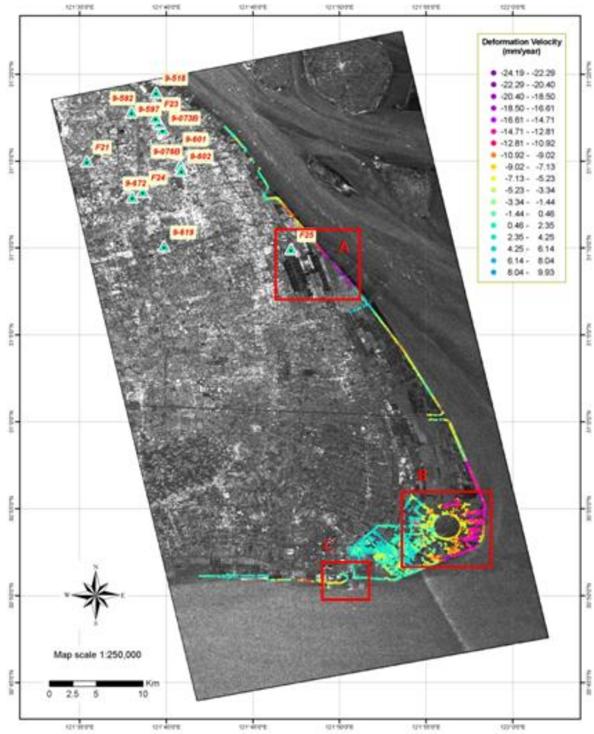


Figure 3. The deformation velocity map of the levees

（1） Section A: Levee in Pudong

The construction of a large levee to protect the Pudong International Airport began in October 1998. The levee at the Pudong International Airport has to fulfill the highest standards in resisting a strong storm. Fig. 4 shows the deformation at Pudong airport and the levee, with a Google Earth image as background. The deformation of the levees is more serious than the deformation at the airport. The levees are built on soft soil and the ocean tide causes serious sediment deposition outside of the levee.

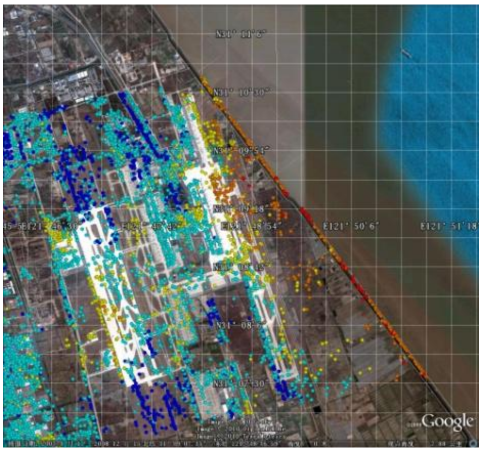
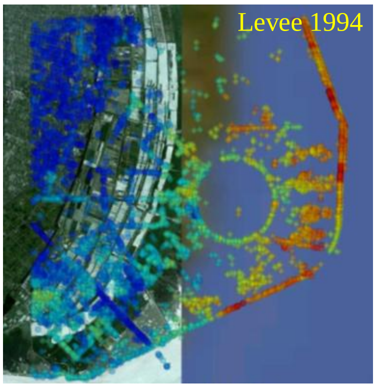


Figure 4. The deformation velocity map of Pudong International Airport

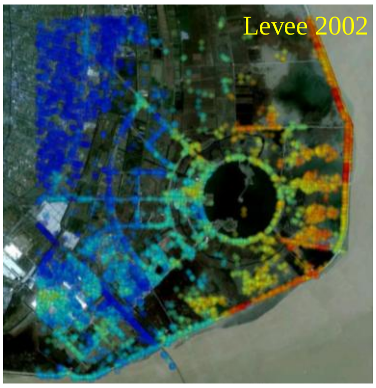
（2） Section 2: Lingang Town

Lingang town lies at the junction of the Yangtze River and Hangzhou bay, covering an area of about 296 km^2. Lingang Town was built from November 2003 and up to now the cost for reclamation are approximately 400 billion RMB. The Lingang Industrial Zone is strategically positioned to become the most modern logistic facilities for Northeast Asia. There is a man-made lake named Dishui Lake in the center of Lingang town, which covers 5.56 km^2.

The deformation showed in Fig. 4 demonstrates that the subsidence in the west side is higher than that of the east side. The most serious areas are detected at the region near the levees. According to the geologic structure, the engineering geology condition in the whole eastern part were surpassed the west.



(a)



(b)

Figure 5. The deformation velocity map of Lingang Town

(a)The background is an optical image from 07/11/2002

(b)The background is an optical image from 02/23/2007

In the western part, the follow-up weight consolidation settlement is relatively small, because the area was consolidated for a longer period of time. The filling soil has been formed for more than 10 years. In the east, the soil is filled recently. The compactness and uniformity of the soil is poor. Because of its high moisture content, large void ratio and low strength, this kind of less consolidation soil may result in considerable unevenly distributed ground subsidence when it consolidates [11]. Therefore, different ages of filling soil have a great impact on its engineering geological properties.

（3） Section 3: Luchao harbor

Luchao harbor is located on Nanhui at the Hangzhou bay. The fishing port is gradually becoming an important harbor for loading and unloading cargo ships. Our experiments indicate that the levee in the southern of the Luchao harbor have experienced a serious subsidence because of the soil compaction, while the eastern slope of Luchao Harbor is generally stable. There are large areas of less filling soil consolidation in the southern slope, especially at the steep slopes along the shore.

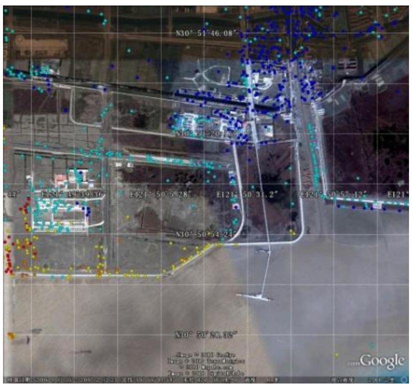


Figure 6. The deformation velocity map of Luchao Harbor

4. CONCLUSION

PS-InSAR technique is feasible to monitor the deformation of levees. According to the monitoring results, levees built on reclamation areas show a higher deformation velocity. Special attention should be paid to those areas which are most seriously subsiding.

The subsidence is quite serious in Lingang Town. The leveling measurements in Lingang town should be added into the land subsidence monitoring network system of the whole city. Using high-resolution SAR satellites like for example TerraSAR-X and RADARSAT-2, will improve the environmental change detection drastically and enhance the ability of examining the deformation of levees. Compared with conventional survey methods, the advantages of using repeat-track space-borne SAR images are:

1. Less field work is needed in non-urban area.
2. The density of the detected points is significantly higher.
3. It is suitable for areas not covered by a benchmark network.

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