Contraction of a newly reclaimed mudflat detected by Differential SAR Interferometry

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Abstract: This paper reports the observation of the interferometric synthetic aperture radar (InSAR) phase anomaly on a newly reclaimed mudflat, Hwaong, in west coast of Korea, detected by a series of Radarsat-1 SAR data obtained mostly during 2003. The observed phase anomaly could be from subsidence of mud land caused by volumetric contraction of mud in dry season. This process must have been initiated from March 2002 when tidal water supply to this region was permanently blocked by the newly constructed embankment. The maximum subsidence rate measured from InSAR signal is about 3 cm per month. The local heterogeneity of the subsidence rate over the reclaimed mudflat may indicate various mud composition, surface-subsurface hydrological processes, or subsurface information of the mud and basement rock structure. In-situ measurement must follow to support this observation from space.

Keywords: InSAR, subsidence, reclaimed, mudflat, contraction, embankment, synthetic aperture radar.

1. Introduction

Satellite-based, multi-temporal differential interferometric synthetic aperture radar (DInSAR) technique has been widely used to monitor the centimeter or millimeter-scale movement of land surface over several months or years of period caused by natural or anthropogenic origin such as movement of volcano and glacier, subsidence by over extraction of ground water, surface displacement from earthquake. These successful applications of DInSAR technique are based on the condition that the surface movement should occur in wide area relative to SAR resolution in reversible way (not in irreversible, ruptured way) while the individual surface scatterers remain stable in centimeter scale. Only under this condition can multi-temporal DInSAR data maintain high coherence between observations enough to interpret the signal as surface deformation. This is the main hindrance of DInSAR technique, especially with C-band microwave, available only in arid, semi-arid area or frozen-stable ice land. There is virtually limited applicability of DInSAR technique in tropical or semi-tropical region.

This is the case in Korea where the annual precipitation is more than 1300mm and most terrain surface is covered by thick vegetation or anthropogenic activities which change very rapidly with respect to microwave sensing. It is very rare to find, especially, a natural place where surface scatterers are stable over months or years of time with reversible block movement. One such exceptional case is the observation we are reporting here.

We present an observation of very stable and strong interferometric SAR signals on a newly reclaimed mudflat in west coast of Korea. We also try to understand the origin of the interferometric phase anomaly and analyze these features using a series of Radarsat-1 SAR amplitude and phase observations in conjunction with other circumstantial data such as precipitation and tidal data.

2. Observations

1) Study Area and Precipitation Data

The mudflat is a flat, mud-covered estuary made by constant water supply from tide. There are many such places in the western part of Korea, where the reclamation works have provoked prolonged social debate on the values between preservation of natural mudflat and development by reclamation.

In the natural mudflat, water supply from tide, river and precipitation is balanced by the seasonal change of evaporation rate. When this balance is breached by the artificial embankment blocking the supply of water from 12-hour period tide, then the mudflat may begin to dry and shows volumetric contraction causing land surface subsidence.

Located in west coast of Korea peninsula, Hwaong reclaimed mudflat was blocked permanently from the tidal water supply by the embankment in March 2002. The main source of water supply has been changed from tidal

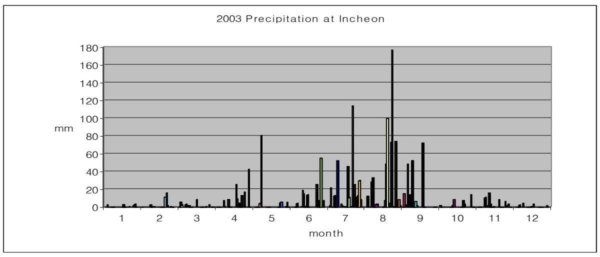

Fig. 1. Precipitation record of the year 2003 at Incheon.

water to precipitation which has longer period or even poorly periodic compared to the 12 hour tidal period. The effect of evaporation becomes more dominant factor on the mudflat so that there are sudden environmental changes until a new equilibrium state establishes between evaporation and water supply.

The precipitation records in Fig. 1 shows there were much rain from April to mid-September, then it turns into a relatively dry season from mid-September to the following March. Therefore, it is plausible that the volume contraction may have occurred more severely from the beginning of the dry season. The following SAR and InSAR observations support this theorem.

2) SAR Dataset and Data Processing

There are 8 InSAR-oriented Radarsat-1 observations covering the study area obtained one scene at July 2001, before the complete closure of the embankment, and 7 scenes taken from March to October 2003, after the blockage with 24-day period successively as seen in Table 1. All images, named from hw1 to hw8, respectively, are in right-looking ascending mode with incidence angle of 39° approximately.

The amplitude images were detected from the single look complex (SLC) data. The SLCs are then interferometrically processed by using 'einsar' in-house software[1]. The images are co-registered up to 1/16 pixel accuracy. The baseline estimation and the successive earth-flattening were done by extracting the irrotational component from the dominant InSAR phase.

Three InSAR pairs have shown interpretable phase signal on the study area. SRTM-3 DEM [reference] is then used to remove topographic phase from the InSAR phase only to recover the differential InSAR (DInSAR) signal possibly from surface displacement or atmospheric effect.

3) SAR Observations of Mud Land Moisture Change

As the reclaimed mudflat on the study are is very flat and already hardened so that even a car can access most study area up to tens of meters near to the water channel. There is no vegetation or artificial structure that can contribute to the radar backscattering significantly. Therefore, the overall amplitude of the mudflat is very low compared to the surrounding land or natural mudflat.

Compared to natural mudflat nearby and the hw1 image taken before blockage, the radar backscattering of the blocked mudflat was very small no matter what the precipitation rates were. This proves that the mudflat follows the general moisture-backscattering rule: the higher the surface moisture is, the stronger the radar backscattering is. It also implies that the annual precipitation can not account for the previous tidal water supply and the environmental change is in due course.

The development of gully structure along the river system is evident in the SAR amplitude image along the drainage that appears as high backscattering coefficient due to radar-facing gully wall. It indicates that the drainage system for the precipitation is developing in the mudflat by erosion, just as the case in a desert area[2]. These gully features are only found after reclamation of natural mudflat.

No meaningful correlation between precipitation data and SAR amplitude on the blocked mudflat was found within the dataset used in this study. The data time-spacing seems to be too large to show subtle change of surface moisture from seasonal precipitation/evaporation cycle.

Table 1. List of Radarsat-1 SAR data used.

ID	Acquisition Date	B_p and ΔT
hw1	20010703	
hw2	20030506	
hw3	20030530	147m, 48days
hw4	20030623	72m, 48 days
hw5	20030717	
hw6	20030810	
hw7	20030927	81m, 24days
hw8	20031021	

4) DInSAR Measurement of Mudflat Subsidence

We have three InSAR pairs, hw24 (hw2 and hw4 image pair), hw35, and hw78, that meet critical baseline criterion to obtain interpretable interferogram.

The coherence image of hw78 shows very high coherence value in the reclaimed mudflat, which indicates there was little random surface change such as erosion from precipitation or vegetation growth during the period between hw7 and hw8 image acquisitions. The other two pairs show relatively low coherence possibly from cm-scale random surface change from heavy rain between image acquisitions.

Fig. 2 shows DInSAR image of hw78 that shows local variation of phase over the reclaimed mudflat. There can be several candidates for the cause of this DInSAR anomaly: 1) change of radar penetration depth due to surface moisture change; 2) atmospheric effect; 3) land subsidence by volume contraction of mud in dry season.

The density of mud is so high (~1.5 g/cm^3) that we can not imagine the change of penetration depth from surface moisture variation caused the phase anomaly observed. This effect could be accounted for only in sand desert or freshly cultivated soil.

The atmospheric phase is not a plausible cause of this phase anomaly because of the following two reasons. Firstly, the DInSAR phase shows some correlation between surface morphology such as the existence of nearby water, which indicates the observed phase anomaly is of ground-origin. Secondly, the study area is virtually flat surface that there is no elevation-driven atmospheric effects.

Therefore, the cause of hw78 phase anomaly is considered as land subsidence in the reclaimed mudflat caused by volume contraction of drying mud surface or body in relatively dry season. If this is confirmed, the maximum subsidence rate can be read as 3cm per month. There was no such anomaly in hw24 and hw35, which indicates the occasional rainfall during wet season kept the mud surface from drying out or volume contraction.

The subsidence rate tends to be higher at regions where there is no adjacent water. The subsidence rate along the water channel is particularly low probably due to constant water supply. This is shown as reddish color (less subsidence rate) along the river and the gully channels in Fig. 2.

There are also some regional variations in the subsidence rate. The upper part of the mudflat shows relatively low subsidence rate of 0-1 cm/month while the lower part shows 2-3cm/month. This regional difference may come from the difference of the physical properties and compositions of the mud between two regions due to gradational sedimentation in the estuary. Measurements of physical composition of mud at various locations are necessary, which remains as future research.

5) Laboratory Experiment on Mudflat Subsidence

We conducted a simple but very illustrative laboratory experiment on the volume contraction of drying mud. A pack of dried mud sampled from the study area was dissolved in a 500ml beaker with water. It was then precipitated and dried in a 90°C oven to accelerate evaporation. The volume, mass, and subsidence were recorded. The data shows up to 50% volumetric contraction from fully saturate to fully dehydrated states, while the density of mud remained almost constant (1.3 ~ 1.5 g/cm^3). Only the vertical subsidence occurred until 35% contraction and then the contraction happened in all directions due to boundary effect. From this experiment, it is considered that up to 35% volume contraction may happen before mud crack occurs.

In the reclaimed mudflat where there is no boundary effect, the actual subsidence and volume contraction would occur within limited depth and thus would be much less than the experiment conducted in extreme condition, but cumulative subsidence rate of several centimeters per month could be common enough to explain the observed DInSAR signal.

The actual subsidence rate would also be dependent on the depth of the mud, or subsurface bedrock structure in such a flat surface as well as the mud composition, water supply from both surface and ground. More delicate laboratory simulations can be designed to accommodate these factors such as larger mud volume to reduce boundary effect, undulating subsurface bedrock structure, locally differentiated surface and ground water supply.

6) Field Measurement Recommendation

There can be various ways of field survey and in situ measurements to support the subsidence rate observed from space. These can be 1) field survey and laboratory measurement of composition, surface moisture, and other physical properties of mud, 2) subsurface bedrock structure from seismic reflection survey, 3) seasonal and long-term measurement of actual subsidence rate using GPS or embedded sensors.

3. Conclusions

From the DInSAR observation, we conclude that the newly reclaimed mudflat at Hwaong suffers land subsidence of up to 3 cm/month due to volumetric contraction of mud body. The subsidence mainly occurs in relative dry season, from mid-September to March. Local heterogeneity of DInSAR-derived subsidence rate may indicate heterogeneous mud composition, hydrological supply, or even subsurface bedrock structure. In situ measurements of subsidence and other geophysical survey are essential to support the observation from space.

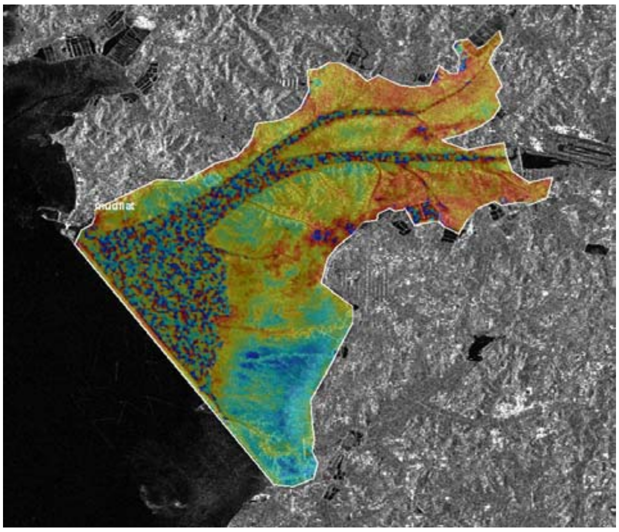

Fig. 2. DInSAR measurement of subsidence rate from zero (red) to 3cm per month (blue) obtained from Radarsat-1 InSAR pair acquired at September 27 and October 21, 2003, overlying time-averaged SAR amplitude image (16km × 15km). Maximum subsidence rate occurs at lower part of mudflat possibly due to lower supply of surface or ground water, finer mud composition, or thicker mud volume (equivalently, deeper subsurface bedrock). Note the lower subsidence rate along the river or drainage system due to constant surface water supply preventing volume contraction of mud.

Acknowledgement

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