Plover Cove Dam Monitoring with Spaceborne InSAR Technique in Hong Kong

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Abstract—**From the Tai Mei Tuk Peninsula, the 2 km long Plover Cove dam was built in 1960s across the strait to connect it with the small Harbour Island. The marine dam was formed by dumping earth and rockfill under water after removal of the marine deposits in the dam foundation. The whole scheme was completed with the capacity of Plover Cove Reservoir to 186,244 acre-ft. Monitoring deformation of dams and reservoirs is important to ensure the safety of adjacent and surrounding areas. Traditional geodetic measurements require frequent field trips which cost lots of human and money resources. In this paper, we apply the remote sensing spaceborne Synthetic Aperture Radar Interferometry (InSAR) technique to monitor the deformation at Plover Cove dam in Hong Kong.**

Spaceborne InSAR has become nowadays a very powerful technique to monitor ground motions and terrain height. The advanced permanent scatterers (PS) technique, which exploits a long series of SAR data, could monitor ground deformations with millimeter accuracy on a high spatial density grid of pointwise targets. With the development of high resolution SAR sensors like TerraSAR-X and Cosmo-Skymed, many permanent scatterers can be found in one individual man-made construction like building or dam. Therefore PS-InSAR technique starts to play an important role in civil surveillance like ground motion and structure stability monitoring.

For monitoring Plover Cove Dam, we apply PS-InSAR technique to 73 scenes of data including 62 TerraSAR-X and 11 TanDEM-X images acquired between October 2008 and June 2012 in Hong Kong. Hundreds of permanent scatterers were successfully found and millimetric non-linear time series movements were detected on the road of the dam and embankments of reservoir. We correlated the PS-InSAR results with water level data of the reservoir provided by Water Supplies Department (WSD) of Hong Kong government. The results show good agreement with each other.

Keywords-InSAR; PS-InSAR; deformation monitoring; TerraSAR-X

I. Introduction

In recent years, Synthetic Aperture Radar interferometry (InSAR) technology has proved its capability in deriving high accuracy ground deformation information from Synthetic Aperture Radar (SAR) images [1]. Comparing with traditional leveling method and GPS method, InSAR technology is favored for its unique characteristics of all-time, all-weather and especially, wide-area monitoring capability. Moreover, for the purpose of overcoming the major limiting factors of InSAR technique, namely geometric and temporal decorrelation plus atmospheric phase screen (APS) disturbance, the Persistent Scatterer Interferometry (PSI) technique was proposed and has since became the core concept in precisely measuring earth deformation from a time series of SAR images [2]. Reliable deformation information with millimetric accuracy can thus be obtained and extracted from searching persistent scatterers from long temporal series of interferometric pairs.

In addition, thanks to the development of new X-Band high resolution SAR satellite, namely TerraSAR-X (TSX) launched by Germany and COSMO-SkyMed (CSK) by the Italian Space Agency, the possibilities of monitoring man-made structures of higher accuracy has become true. The new CSK and TSX sensors provide spatial resolutions on order of magnitude better than previously available satellite SAR sensors adding to their shorter revisit time (11 days for TSX and up to 4 days for CSK), thus appears to be more promising in monitoring dense linear-feature structures and rigid structures and providing more detailed ground features.

II. Plover Cove dam

Construction work of Plover Cove dam in Hong Kong commenced in 1960 and was completed in 1968, providing a capacity of reservoir for 170 million m^3 of water. Soon after introducing water from Plover Cove reservoir into supply in October 1967 the demand for water increased, thus further works began to increase the reservoir capacity to nearly 230 million m^3 - works increasing the height of the dam finished in 1973 [5].

Plover Cove was the first in the world to construct a lake from an arm of the ocean. One main dam and three service dams were built to shut the original cove off from the sea. The cove was then drained and was converted into a fresh-water lake by seawater pumping. In late 1970s the mean daily consumption of water from Plover Cove Reservoir exceeded 1 million m^3 per 24 h. Nowadays, however, a higher quality water from Dongjiang is preferred for water supply and water from Plover Cove Reservoir is used only for rural purposes and as a natural fish pond.

The main Plover Cove dam is the object for monitoring of deformations. It is 28 m tall and approximately 2 km long and it was built by layers of sand and gravel. Fig. 1 represents its cross section [4].

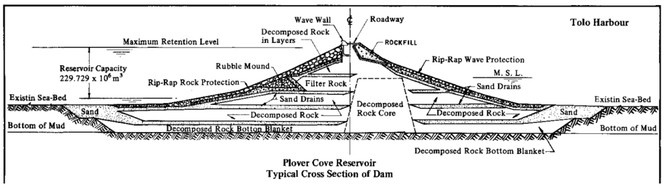

Figure 1. Cross Section of Plover Cove Dam [4]

III. DATASET

For monitoring of deformations of the dam, 62 acquisitions from TerraSAR-X and 11 TanDEM-X stripmap ascending acquisitions of line of sight from nadir (LOS) angle 37.3° covering dates between October 2008 and June 2012 have been processed together by SARPROZ software [3] using PSI technique. In total, 73 high resolution SAR images in ~3.5 years time range (see Fig. 2) suppose an optimal configuration, with a high probability of proper modeling of APS and estimation of height changes. The area around the object of interest, Plover Cove dam, is lacking stable scattering objects – either the area is filled by water or it is vegetated island. This is the main barrier for proper APS estimation which cannot be neglected for a 2 km long structure.

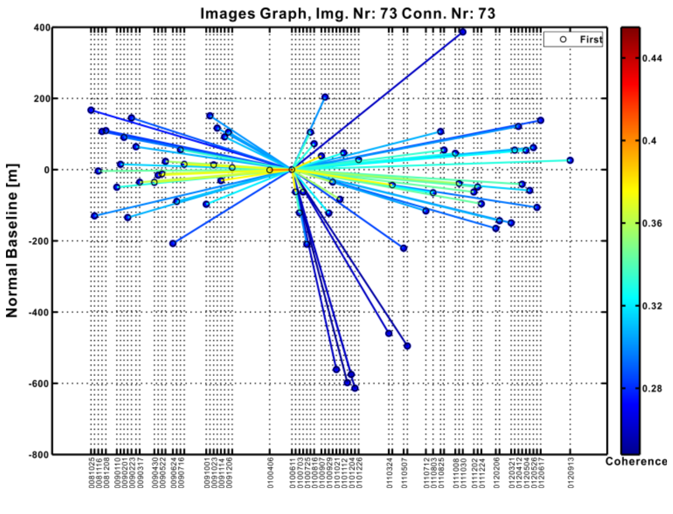

Figure 2. Dataset of TerraSAR-X and TanDEM-X used in the processing: x-axis indicates the temporal baseline and y-axis indicates the normal baseline.

IV. PSI PROCESSING APPROACH

A. Selection of reference point

In order to neglect possible atmospheric effects and to choose appropriate reference point for PS processing, a small area covering land surface and small part of the dam has been selected. Five reference point candidates with a very high amplitude stability index have been selected and analyzed. After PS processing of test area using different reference points, results of using two reference point candidates showed much lower dispersion of phase residuals of PS points than in the case of other reference point candidates. After field overview, a reference point corresponding to a concrete rooftop (see Fig. 3) has been preferred over aluminum roofing of the second candidate (where a higher relation to temperature changes was expected). Their relations to other PS points, however, showed very similar phase differences. Both of them can be regarded as relatively stable, with only small fluctuations in amplitude.

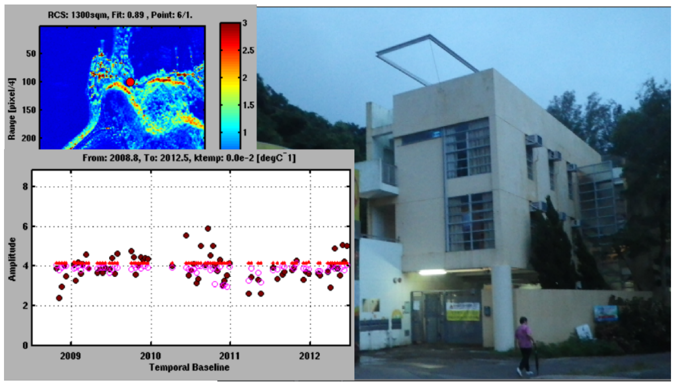

Figure 3. Selected ref.point corresponding to reflection probably from roof construction of the building situated less then 150 m from the dam

B. Estimation of dam deformations

In order to evaluate rate of continuous deformations of the dam in time, it is necessary to correctly estimate other causes of phase changes. Generally, the differences of phase values between two temporally separated SAR acquisitions, as readable in interferogram, can be decomposed as:

$$\Delta\varphi = \Delta\varphi_{displacement} + \Delta\varphi_{height} + \Delta\varphi_{atmosphere} + \Delta\varphi_{noise} \quad (1)$$

, where

$\Delta\varphi_{displacement}$ ... phase difference caused by physical displacement in the satellite line of sight,

$\Delta\varphi_{height}$ ... phase difference induced by topography/elevation of scatterers due to different position of satellite during acquisitions,

$\Delta\varphi_{atmosphere}$ ... phase difference caused by different delay of radar signal in penetration through atmosphere,

$\Delta\varphi_{noise}$ ... any other contribution, including inaccuracies of satellite orbit data, data processing errors, instrument noise etc.

Using appropriately large dataset in the case of dam structure, it is possible to estimate using PSI method at least contributions of $\Delta\varphi_{height}$ and continuous trend of $\Delta\varphi_{displacement}$. Unfortunately, due to low density of PS points in the surroundings of the dam, it is more complicated task to properly estimate influence of $\Delta\varphi_{atmosphere}$. In PSI algorithms, the estimation of $\Delta\varphi_{atmosphere}$ is based on an assumption that contribution of $\Delta\varphi_{atmosphere}$ is correlated spatially but not temporally, corresponding to behaviour of such atmospheric artifacts as clouds are. However in case of non-linear deformations caused for example by variable water pressure, such deformations have small or no temporal correlation and would be estimated wrongly as part of $\Delta\varphi_{atmosphere}$ in a model of APS. Such attempt is useful enough in case where only temporally continuous deformation trend is searched for – as presented in Fig. 4.

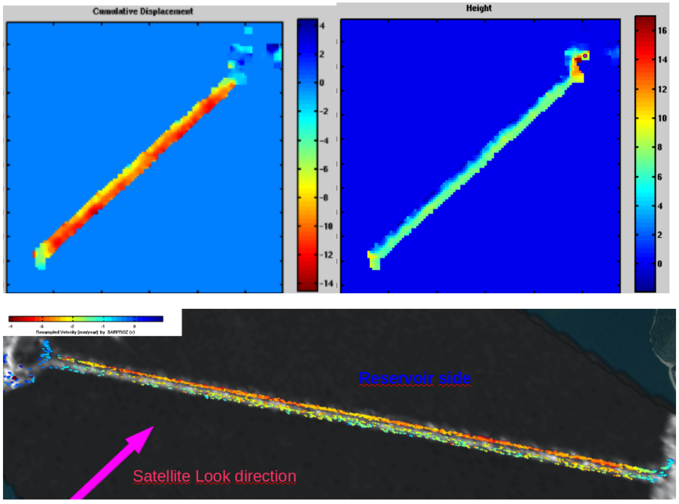

Figure 4. PSI processing result; left: Estimated cummulative deformation of dam (2008-2012 in the satellite LOS), right: estimated height, lower: average rate of displacement geocoded and superimposed over amplitude image.

From the processing results it can be concluded that the whole dam body is linearly deforming in the rate of up to ~4 mm/year in LOS – maximal deformations are on the side of water reservoir.

C. *Effect of water level of reservoir, temperature and tide changes of surrounding sea*

Fig. 5 represents difference in temporal coherence before estimation and removal of APS (left) and after APS removal (right). The coherence of points at the dam is very low in the former case where $\Delta\varphi_{atmosphere}$ together with other non-linear deformations are present as a source for estimation of deformation trend, while it approaches high values once all temporally non-coherent contributions are removed as APS.

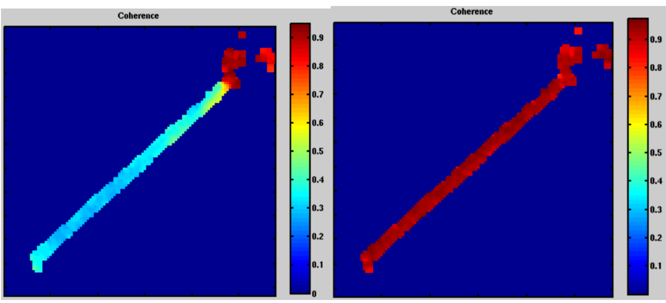

Figure 5. Temporal coherence before removal of APS (left) and after removal of APS model (right)

Fig. 6 presents graph of residual phase (i.e. without the continuous deformation) recomputed into mm deformation of a selected point on the dam surface, w.r.t. reference point, together with a graph of water level changes. Their correlation seems obvious from this figure.

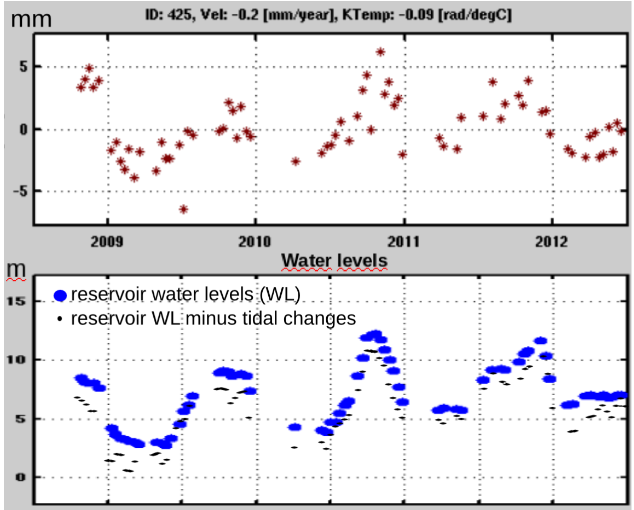

Figure 6. Phase residuals recomputed as deformation in LOS [mm] of selected point on the dam surface (upper figure) and water level of the reservoir [m] during acquisitions (lower figure).

Water level data has been applied into the original PSI dataset, in order to estimate its influence on dam deformation. Majority of PS points over the dam shows strong correlation with water levels, with a correlation coefficient of up to k_{max}=~0.65 rad/m.

According to

$$D_{max} = k_{max} \cdot E \cdot \lambda / 4\pi \qquad (2)$$

, where

D_{max} ... maximal deformation in LOS [mm],

λ ... SAR carrier wavelength in [mm] (= 31.1 mm),

k_{max} ... maximal estimated coefficient of linear correlation [rad/m] or [rad/°C],

E ... range of values of investigated parameter [m] or [°C],

it can be computed that if difference between minimal and maximal water level is E=9.8 m, maximal deformations caused by water pressure can reach D_{max}=16 mm in LOS. Obviously this linear model of correlation with water level data seems simplified - a non-linear characteristics has to be searched for.

Plover Cove dam is surrounded by water from both sides (it forms an interface between sea and fresh-water reservoir). Therefore also changes of pressure due to tidal fluctuations of sea level should cause observable dam deformations from the opposite side of the dam. A processing attempt has been performed using information about tidal fluctuations, removing their values from water level values of the reservoir. Such attempt showed better fit for several tested points and was used for further processing. However, its effect seems small and neglectable.

Finally, a thermal dillation can be regarded as a third factor influencing interferometric phases. Fig. 7 represents estimated linear correlation between PSI phases and values of water level and temperature, without using information about tides.

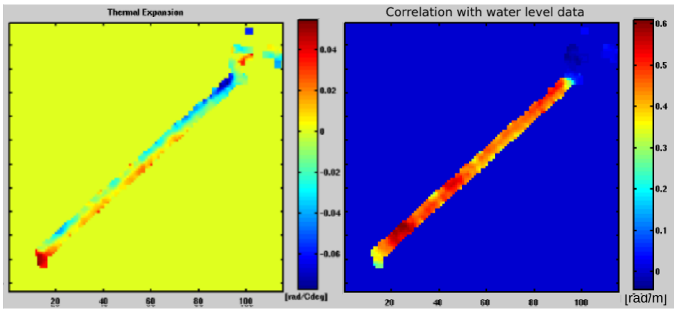

Figure 7. Estimated linear correlation between PSI phase values and temperature (left) and reservoir water level data (right).

It can be noted that, as estimated and recomputed simply using relation (2), the effect of temperature is much lower than effect of water level changes – with a range of temperature extremes of E=~22°C, the points on the dam can be affected by movement in the range of up to D_{max}=4 mm in LOS for maximal value of k_{max}=0.07.

D. APS Residuals

After removal of all estimated parameters – correlation with temperature, water levels (+tidal information), heights and linear deformation trend, the residual phase values can be used to estimate contribution due to atmospheric influence.

However a brief look on estimated APS can lead to suspection of unmodelled residual deformations that are often present in the middle of dam. These residuals are not correlated temporally neither correlated with values of water levels and they conform with conditions of atmospheric effect. An example of three selected APS is shown in Fig. 8.

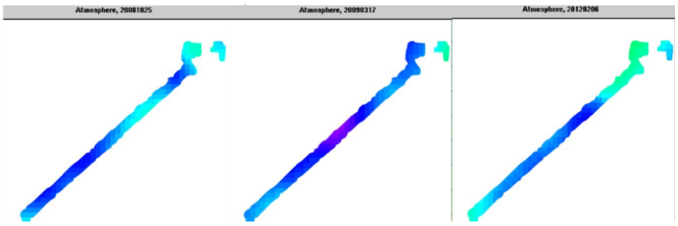
Figure 8. Estimated APS screens of three selected dates showing possibility of unmodelled residual deformations.

V. Conclusions and Further Work

Thanks to large dataset of frequently acquired high resolution SAR data, it was possible to properly discover various types of deformation movements over Plover Cove dam using PSI technique and related algorithms. The satellite LOS is inclined 37.3° from nadir. Such relatively high inclination means good sensitivity not only for deformations in LOS or vertical direction, but also horizontal. Yet it is not possible to distinguish from current results whether pressure of water in the reservoir causes variations of the observed top part of the dam in the direction back and forth from the reservoir (horizontal movements) or if the water pressure changes cause swelling of rock filling or other vertical effects depending on lithological character of applied material.

General dam deformations, either horizontal due to bending of dam crossbeam or vertical due to subsidence, have usually maximal rate in the middle of the dam [6]. Such behaviour wasn't detected in the processing. Instead, it seems that the dam is affected by very shallow but continuous subsidence almost homogeneously throughout its body (with higher rate on the side to the reservoir – Fig. 4) and by higher rate of movements corresponding to water level changes, at the sides of the dam (Fig. 7).

After estimation of linear correlation with water level and temperature, the APS has been computed from phase residuals. In majority of APS models, very similar spatial artifacts could be observed. It is supposed that some of the sources of phase influence have non-linear correlation character, since these spatial artifacts have no correlation in time neither correlation with normal baseline nor correlation with water levels. They conform with conditions of atmospheric effect. More investigation is planned for this issue.

Local air temperature seems to have also significant impact on the deformations throughout the dam, especially in the parts with direct contact with water (lower parts of dam – Fig. 7). However a correlation between temperature and tidal fluctuations of surrounding sea has been found – a further analysis may separate these parts and should lead to better understanding of deformation mechanism of the dam.

An analysis of correlation between water level data and LOS deformations will be performed, in order to find better fitting (polynomial) model of such correlation. The same will be performed to describe correlation with temperature and/or tidal fluctuations of the sea. It can be expected that after using more appropriate fitting model, APS would contain only effects due to atmospheric disturbance.

Finally, several deformation phenomenons have been found over the Plover Cove dam body. In further work, a geological-structural explanation of these deformations will be searched for.

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