

Structural Health Monitoring of Dams by Advanced Satellite SAR Interferometry: Investigation of Past Processes and Future Monitoring Perspectives

P. Mazzanti^{1,2}, D. Perissin³, A. Rocca¹

(1) NHAZCA S.r.l., Spin-off of Sapienza University of Rome – Italy

(2) Earth Sciences Department, Sapienza University of Rome – Italy

(3) Civil Engineering Department, Purdue University, IN – USA

Abstract

Satellite Synthetic Aperture Radar Interferometry (InSAR) techniques and, specifically, Advanced Differential InSAR techniques (A-DInSAR) are becoming, in last years, a powerful tool for the investigation of ground and structure deformations, also thanks to new space missions with last generation sensors able to provide high spatial resolution (about 3x3 m), high displacement accuracy and high sampling rate (up to 4 days) data. This paper describes three successful case histories where such techniques have been applied for the structural health monitoring of dams; specifically, the Three Gorges Dam (China), the Plover Cove Dam (Hong Kong) and the San Liberato Dam (Italy) have been investigated. Both recent high-resolution SAR images and past low-resolution images have been used, depending on specific aims of each case study.

In various geographical context, type of structure, kind of satellite sensor used, A-DInSAR technique showed its great potential for reaching specific purposes for every case-study: monitoring the stability of the structure and surroundings areas (Three Gorges Dam), monitoring of the structure response to cyclic stresses investigated by means of recent SAR images (Plover Cove Dam) and analyses of past stability conditions for the health assessment of the dam (San Liberato Dam).

The lesson learned by the described case studies is that Advanced Satellite InSAR techniques can be a reliable diagnostic tool in the SHM of dams, especially for long-term investigations or for historical analyses where other monitoring data are lacking.

1. Introduction

Structural health assessment is a well-established practice for managers and responsible of civil structures. Over the last decades several monitoring approaches have been adopted ranging from visual inspection to instrumental continuous monitoring (Fuhr & Huston, 1993; Kronenberg et al., 1997; Alonso Pérez de Agreda & Gens Solé, 2006; Alba et al., 2006), but very often an engineer's challenge is to infer what happened in the past. Without this historical information the assessment of the present condition is likely to be incomplete, and any planned countermeasures may be not enough accurate. As a matter of fact, monitoring the key parameters of an engineering structure from its construction, is the best way to know its history and understand its present behaviour. However, especially for older structures, this is almost impossible.

At this regard, A-DInSAR can be an effective tool in hands of engineers in charge of SHM (Wang et al., 2011; Tomás et al., 2013). Such a technique is characterized by several features that make it a unique tool in monitoring of structures, such as the capability to provide information about past deformations with millimetre accuracy. Furthermore, data spread over the territory (structure and

surroundings) are an additional source of information, not always achievable by standard field monitoring equipment.

Thanks to archive radar images available from the early 1990s, in fact, past conditions can be investigated with quantitative data over wide areas.

In this article we present three case-studies related to three dams with very different characteristics monitored by A-DInSAR methodology in different structural and environmental contexts and with different kind of data.

2. A-DInSAR methodology

In recent years, Synthetic Aperture Radar interferometry (InSAR) technology has proved its capability in deriving high accuracy ground and structure deformation information from Synthetic Aperture Radar (SAR) images (Curlander & McDonough, 1991). Comparing with other traditional methods, InSAR technology is favoured for its capability to provide monitoring data all-time, with all-weather conditions and especially for wide-areas. The other aforementioned relevant key-factor of InSAR-based monitoring is the possibility to perform past-oriented deformation measurements thanks to archive SAR data made available by National and International Space Agencies.

The first satellite missions with SAR sensors were launched in the early 1990s and since then images have been collected in several parts of the world and revisited over same area several times each year. For example, the minimum time interval between images collected by the Envisat-ASAR sensor is 35 days even if some temporal gaps, due to problems in the satellite acquisition, can be present.

In addition, thanks to the development of new X-Band high-resolution SAR satellites, namely TerraSAR-X (TSX) launched by German Space Agency (DLR) and COSMO-SkyMed (CSK) by the Italian Space Agency (ASI), the potential for monitoring man-made structures with high accuracy is more achievable. The new sensors provide one order of magnitude higher spatial resolution than previously available satellite SAR sensors, in addition to their shorter revisit time (11 days for TSX and up to 4 days for CSK).

The basic elements to perform InSAR analyses are the SAR images acquired by satellites. SAR images consist of a matrix made of resolution cells (i.e. pixels) whose size depends on the satellite sensor (usually ranges between few meters up to few tenths of meter) that contains information about the satellite-target distances. Ground and structures deformation can be investigated thanks to the Differential InSAR (DInSAR) methodology and is based on the difference of electromagnetic phase between two SAR images acquired at different time. The computed phase difference (interferogram) is then put in relation with the displacement occurred between the acquisition of the first and second image.

In order to overcome the major limits of InSAR technique, whose most important is the presence of the atmospheric phase screen (APS) disturbance, the Advanced Differential InSAR (A-DInSAR) methods were proposed to successfully perform ground and structure deformation measurement thanks to long time series of SAR images (Ferretti *et al.*, 2001, Berardino *et al.*, 2002).

By analysing several SAR images acquired in the same area over time, A-DInSAR methodology allows derivation of displacement-time information of natural targets on the ground that are visible from the satellite (Figure 1).

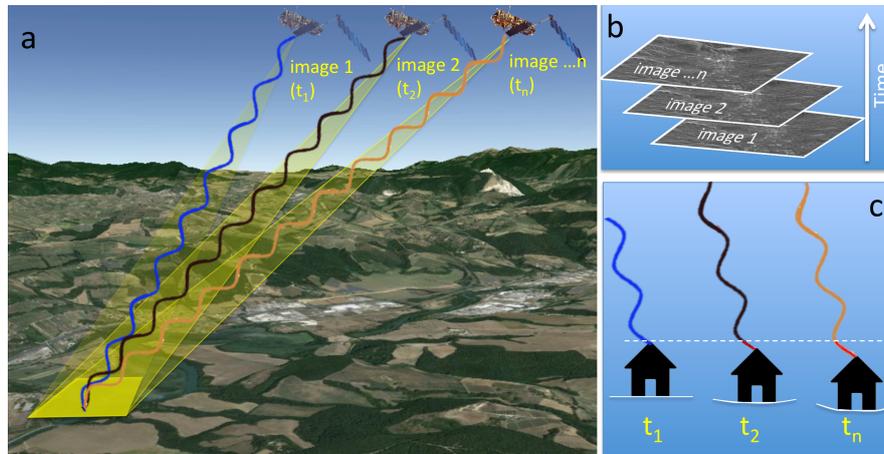


Figure 1 Sketch of A-DInSAR principles: (a) multi-pass satellite acquisitions, (b) image stacking, (c) phase difference of the multi-temporal SAR signal used to infer displacement related to good radar targets

Since only displacements along the satellite Line of Sight (LOS) can be measured, combinations of data acquired from different points of view allows improvement of displacement orientation information. In fact SAR images can be acquired in two different orbital geometries: during the passage of the satellite from North to South (descending geometry), and from South to North (ascending geometry). Hence, the same area can be observed by two angles of view almost symmetrical.

Among the characteristics of A-DInSAR, one of the most effective is based on the analysis of measurement points characterized by a high and stable radar reflectivity over time. This is the basic principle of the A-DInSAR method known as “Persistent Scatterers Interferometry” (PSI) (Ferretti *et al.*, 2001; Kampes, 2006). Usually, such good targets are buildings, roads, railways, pylons and structures such as dams, bridges as well as exposed rocks and portions of homogeneous soil. Once the measurement points have been detected, the electromagnetic phase signals reflected by targets on the surface of the earth can be used to infer several data, such as: i) the trend of deformation during the whole time period covered by the images; ii) the time series of displacement, starting from the first available data, with an accuracy up to some millimetres; iii) the height of the target w.r.t. the ground; iv) cyclic (non-linear) deformation due to several factors (e.g. temperature variations).

3 The Three Gorges Dam Case Study

The Three Gorges Dam along the Yangtze River in China is the largest hydroelectric project in the world. 2.3 km long, the dam is 185m high and it created a water reservoir 660 km long. Its power generator is the largest in the world, having a huge impact on economy, environment, civil protection, with both positive and negative consequences (Gleick, 2009).

The stability of the Dam is clearly a key and extremely sensitive factor for the Hubei region and for the whole Chinese country. Several instruments are installed on the dam structure and new technologies are continuously investigated to provide new and complementary measurements (Z. Li *et al.*, 1996; Shen *et al.*, 2004; Fourniadis *et al.*, 2007; Q. Li *et al.*, 2009). A-DInSAR has been proved to be an economic and convenient way for this task.

The analysed area is about 50 km² centred around the Three Gorges Dam. It includes the dam itself and surrounding buildings, the towns of Zigui and Sandoupingzhen and a couple of topographic

relieves.

3.1 A-DInSAR analysis of the Three Gorges Dam

The dataset is formed by two COSMO-SkyMed images stacks, one ascending and the other one descending, 29 images each. The data have been acquired in the period from February to August 2011. All acquisitions are Stripmap in interferometric mode.

To retrieve the terrain deformation, PSI A-DInSAR analyses, were performed in both datasets. Figure 2 shows the main outcome of the analysis, namely the displacement rate observed in the analysed time span. The colour-scale of the two pictures ranges values from -60 (red) to 20 (dark blue) mm/year. Negative values indicate movements away from the satellite, while positive values are for movements toward the satellite.

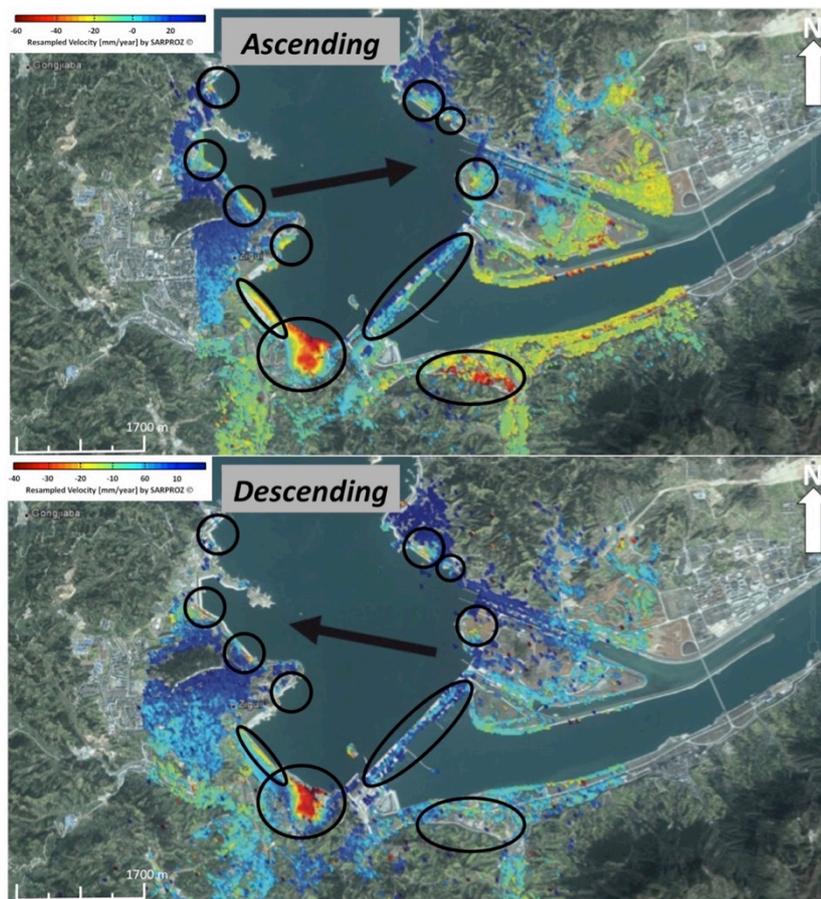


Figure 2 Results of the Three Gorges Dam A-DInSAR analyses: displacement rate (mm/year) during the period covered by the images. The black arrows show the orientation of the LOS. Black circles identify the areas affected by significant displacements

Figure 2 (top) shows the linear deformation map obtained from the ascending dataset. It is very interesting to notice a series of areas affected by deformation away from the satellite (subsidence-like) along the riverbanks. The moving areas have been surrounded by circles to drive the reader's attention. In particular, we notice a strong deformation on the south west of the dam body. Figure 2 (down) is the corresponding map for the descending dataset. The first macroscopic detail we notice

is the identification of the same macro-subsiding area on the south west of the dam body, in good agreement with the ascending case. Several details are then less visible, due to the different acquisition geometry. Also the motion intensity is slightly different, as a consequence of the different viewing angles. The preliminary results show important movements of the river banks and a relative stretch between up and down river sides. The main challenge of the study has been the impossibility of separating seasonal movements from linear displacement due to the very short observed time (less than 1 year). Works are still ongoing to merge ascending and descending results, interpret them and retrieve the high resolution 3D model of the Dam structure.

4. Plover Cove Dam case study

The construction of Plover Cove dam in Hong Kong has been completed in 1973, providing a capacity of reservoir for 230 million m³ of water (Chen, 2001). 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.

The Plover Cove main dam (Figure 3) has been subject to the analyses discussed herein. It is 28 m tall and approximately 2 km long and it was built by layers of sand and gravel.



Figure 3 The Plover Cove main dam. Source: Google Earth.

4.1 A-DInSAR analysis of the Plover Cove Dam

In order to evaluate the dam deformations, 62 TerraSAR-X and 11 TanDEM-X (German Space Agency - DLR) Stripmap images acquired in ascending orbital geometry with an angle of the line of sight from nadir equal to 37.3° have been used. Such data cover the period between October 2008 and June 2012 and have been processed by SARPROZ software (Perissin, 2009) by using PSI technique. In total, 73 high resolution SAR images in ~3.5 years time range suppose an optimal configuration, with a high probability of proper estimation and removal of atmosphere disturbance. A-DInSAR investigation allows to derive several outcomes, however, for the aims of this paper, we want to point out the good correlation of temporally non-linear movements of the dam body with

variations of the water level. Figure 4 presents graph of residual displacement in millimetres 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.

Finally, another contribution derived from interferometric phase signal is related to deformation modelled with the temperature data acquired in the study area simultaneously with the satellite images acquisition. Even if the correlation seemed clear, the influence appeared very small if compared with other factors discussed above.

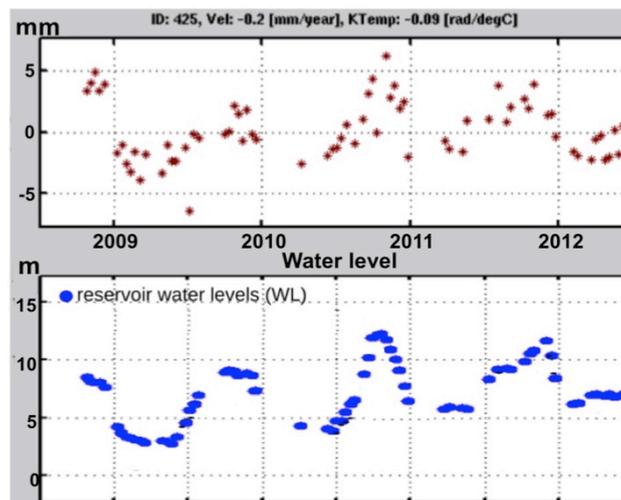


Figure 4 Main result of the Plover Cove Dam: cyclic deformation of a measurement point over the dam in relation with the water level variation of the reservoir.

5 The San Liberato Dam Case Study

The last case study we present herein is related to an investigations performed for the San Liberato dam (Umbria region, Central Italy) (Figure 5). The related reservoir, the main purpose of which is hydroelectric power generation, is the result of the damming the Nera River, with an earth dam about 360 m long.

The National Dam Authority required verification of whether deformation affected the dam in the 2002 – 2010 period. Since we were interested in the analysis of past displacements, archived SAR images were used. It is worth noticing that today A-DInSAR is the only approach to get past deformation information with millimetre accuracy.

5.1 A-DInSAR analysis of the San Liberato Dam

We measured and analysed past deformations of natural and man-made targets present in the San Liberato dam and its surrounding area using SAR images acquired by the Envisat satellite (European Space Agency - ESA). The analysis of San Liberato dam was performed using ascending and descending orbital geometries. 93 Envisat satellite images were used in data processing: i) 42 images in descending acquisition geometry, for the period from January 3rd, 2003 until October 8th, 2010; ii) 51 images in ascending acquisition geometry, for the period from November 16th 2002 to 25th September 2010.

The analysis was carried out using two main approaches: a full-site processing, allowing us to derive deformation trends of the entire area (about 113 km²) and local-scale processing on the dam

body, to identify non-linear deformation behaviour over time, related to the pressure of the upriver water or by cyclic variations (e.g. seasonal variation of the temperature).



Figure 5 Upstream view of the San Liberato dam

In the full site analysis, about 3,000 measurement points were identified and processed for inferring displacement and elevation information.

The local A-DInSAR analyses were performed to achieve a stronger control of displacement-time information for every single measurement point. Final results have been selected by applying a high temporal coherence threshold (Ferretti et al., 2001), selecting only pixels characterized by a very high quality parameter to achieve reliable data.

Figure 6 shows the average LOS displacement velocity for each measurement point obtained for ascending (a) and descending (b) geometry. Negative velocities (from yellow to red) represent movement away from the satellite while positive velocities (from light blue to dark blue) represent movement towards the satellite. Green colour represents stable areas. The results show a general absence of movement within the area during the investigated period.

The lower part of Figure 6 shows the detailed results of measurements points identified over the dam that has been analysed by considering specific sectors of the structure, in order to better investigate the behaviour of each part (upstream face, downstream face, crest of the dam, etc.). The reliability of these results can be considered very high (temporal coherence 0.9), also thanks to the substantial agreement for ascending and descending results which derive from independent analyses.

Seasonal deformations of few millimetres related to temperature variations were identified only in correspondence of the crest, characterized by the presence of metallic elements (Figure 7). This result is useful to appreciate the high sensitivity and accuracy of the system in the estimation of the observed processes.

The A-DInSAR analyses on the San Liberato dam confirmed the lack of permanent deformation of the dam during the period 2002-2010. The results are considered reliable thanks to the substantial agreement between ascending and descending data (which are analysed independently). Moreover, also seasonal effects were excluded except for minor movements in the metallic element that anyway, is absolutely in line with expectations and normal for such a type of structure.

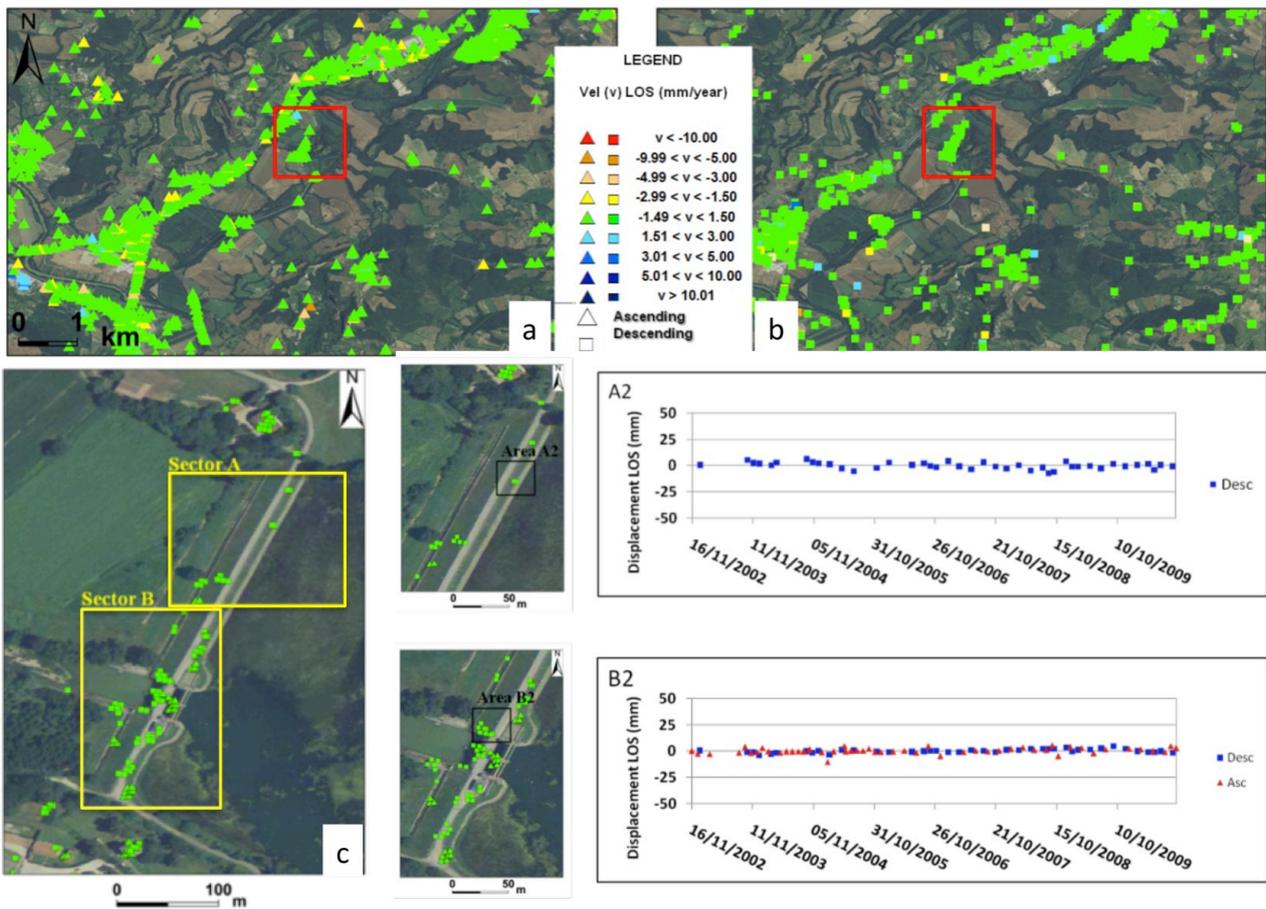


Figure 6 LOS velocity map obtained with full site processing. The red box localizes the San Liberato dam. In (a) measurements points are depicted as triangles for ascending results, while in (b) they are represented by squares for descending results

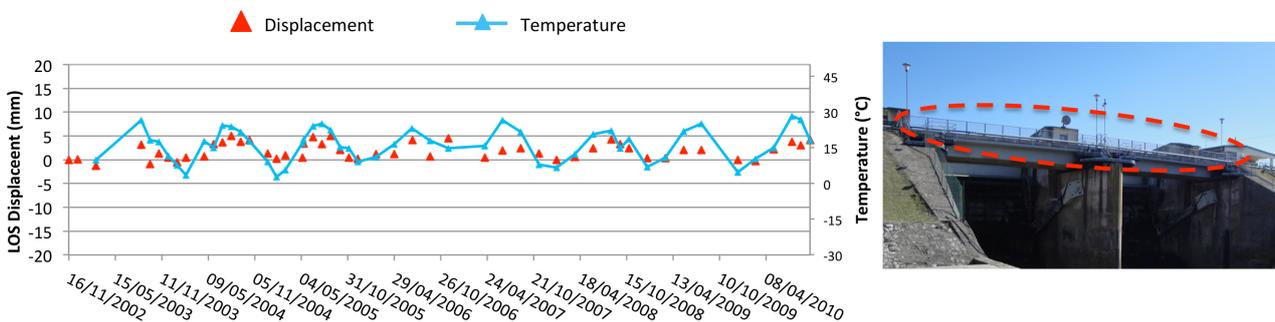


Figure 7 Displacement time series of a measurement point located on the crest of the dam, obtained by thermal analysis (red triangles). In light blue is plotted the time series of local temperature data.

6. Conclusion

A-DInSAR analyses proved to be an effective solution for SHM of dams, especially for the capability of providing data characterized by both wide-spread covering over large territories and



high detail both in spatial resolution, temporal frequency and accuracy in displacement measurement.

The high potential of the methodology is well established by the capability to provide several outcomes, thus allowing the identification and measurement of various factors that contribute to the overall process.

The use of double orbital geometry (ascending and descending) allows to achieve better results in terms of redundancy of data, observation of different portions of the structures and possibility to separate vertical and horizontal displacements.

Finally, the methodology deserves particular interest for its unique capability to provide quantitative information about past deformation processes where no specific monitoring activities have been performed.

Acknowledgments:

The authors would like to thank: Dr. Milan Lazecky for his contribution in data analyses for the Plover Cove Dam case study, the RGC GRF grant 415911 of the Hong Kong SAR, Infoterra Germany for providing The TerraSAR-X and TanDEM-X data through the cooperation with Ralf Duering, Beijing; Agenzia Spaziale Italiana (ASI) for providing CSK data through COSMO-SkyMed AO projects (ID 1280); the CUHK Direct Grant 2021113 (3D reconstruction and stability monitoring of the Three Gorges Dam with COSMO-SkyMed PSInSAR).

Special thanks of the authors also go to Claudio Simonetti and Gennaro Martire for their cooperation in the San Liberato Dam case study.

REFERENCES

- FUHR, P. L., & HUSTON, D. R. (1993). MULTIPLEXED FIBER OPTIC PRESSURE AND VIBRATION SENSORS FOR HYDROELECTRIC DAM MONITORING. *SMART MATERIALS AND STRUCTURES*, 2(4), 260.
- KRONENBERG, P., CASANOVA, N., INAUDI, D., & VURPILLOT, S. (1997, MAY). DAM MONITORING WITH FIBER OPTICS DEFORMATION SENSORS. IN *SMART STRUCTURES AND MATERIALS' 97* (PP. 2-11). INTERNATIONAL SOCIETY FOR OPTICS AND PHOTONICS.
- ALONSO PÉREZ DE AGREDA, E., & GENS SOLÉ, A. (2006). AZNALCOLLAR DAM FAILURE. PART 1: FIELD OBSERVATIONS AND MATERIAL PROPERTIES.
- ALBA, M., FREGONESE, L., PRANDI, F., SCAIONI, M., & VALGOI, P. (2006). STRUCTURAL MONITORING OF A LARGE DAM BY TERRESTRIAL LASER SCANNING. *INTERNATIONAL ARCHIVES OF PHOTOGRAMMETRY, REMOTE SENSING AND SPATIAL INFORMATION SCIENCES*, 36(5), 6.
- WANG, T., PERISSIN, D., ROCCA, F., & LIAO, M. S. (2011). THREE GORGES DAM STABILITY MONITORING WITH TIME-SERIES INSAR IMAGE ANALYSIS. *SCIENCE CHINA EARTH SCIENCES*, 54(5), 720-732.
- TOMÁS, R., CANO, M., GARCÍA-BARBA, J., VICENTE, F., HERRERA, G., LOPEZ-SANCHEZ, J. M., & MALLORQUÍ, J. J. (2013). MONITORING AN EARTHFILL DAM USING DIFFERENTIAL SAR INTERFEROMETRY: LA PEDRERA DAM, ALICANTE, SPAIN. *ENGINEERING GEOLOGY*, 157, 21-32.
- J. C. CURLANDER AND R. N. McDONOUGH, "SYNTHETIC APERTURE RADAR: SYSTEMS AND SIGNAL PROCESSING", JOHN WILEY & SONS, NEW YORK, NY, USA, 1991.
- FERRETTI A. ET AL. PERMANENT SCATTERERS IN SAR INTERFEROMETRY: *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING*, 2001; 39(1), pp. 8–20
- BERARDINO ET AL. A NEW ALGORITHM FOR SURFACE DEFORMATION MONITORING BASED ON SMALL BASELINE DIFFERENTIAL SAR INTERFEROGRAMS: *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING*, 2002; 40(11), pp. 2375–2383
- KAMPES, B. M. (2006). *RADAR INTERFEROMETRY*. SPRINGER.
- GLEICK P. H., THREE GORGES DAM PROJECT, YANGTZE RIVER, CHINA, WATER BRIEF 3, THE WORLD'S WATER 2008-2009, pp:139-150.
- Z. LI, Z. LIU, Z. WANG. "GPS IN DAM DEFORMATION MONITORING (IN CHINESE)," *J WUHAN UNIV HYDRAULIC ELECTRIC ENG*, VOL. 29, p.26– 29, 1996.
- SHEN C. ET AL. DYNAMIC VARIATIONS OF GRAVITY FIELD IN HEAD AREA OF THREE GORGES RESERVOIR IN RECENT YEARS (IN CHINESE): *J GEOD GEODYN*, 2004; VOL. 24, pp. 6–13
- FOURNIADIS I. G. ET AL. REGIONAL ASSESSMENT OF LANDSLIDE IMPACT IN THE THREE GORGES AREA, CHINA, USING ASTER DATA: *WUSHAN-ZIGUI: LANDSLIDES*, 2007; VOL. 4, pp. 267–278
- Q. LI, X. ZHAO, J. A. CAI, ET AL. "P WAVE VELOCITY STRUCTURE OF UPPER AND MIDDLE CRUST BENEATH THE THREE GORGES RESERVOIR DAM AND ADJACENT REGIONS," *SCIENCE CHINA EARTH SCIENCES* 2009, VOL. 52, p.67-578 DOI: 10.1007/s11430-009-0047-6 ISSN: 1674-7313 CN: 11-5843/P
- CHEN, Y. D. (2001). SUSTAINABLE DEVELOPMENT AND MANAGEMENT OF WATER RESOURCES FOR URBAN WATER SUPPLY IN HONG KONG. *WATER INTERNATIONAL*, 26(1), 119-128.
- PERISSIN, D. (2009). SARPROZ MANUAL: [HTTPS://ENGINEERING.PURDUE.EDU/~PERISSIN/MANUAL/MAIN_MASTER.HTML](https://engineering.purdue.edu/~perissin/manual/main_master.html)