Technologies for Dam Deformation Measurement: Recent Trends and Future Challenges

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Abstract. In recent years, some new technologies have been applied to dam deformation measurement, offering unprecedented opportunities to safety management and structural analysis. Among these, Areal Deformation Measurement techniques from terrestrial (Terrestrial Laser Scanning and Ground-Based InSAR) and spaceborne (InSAR) sensors may provide the chance to extend the observed region to a large portion of a structure, instead of merely measuring a set of a few control points. GNSS techniques have reached a consolidated maturity for dam deformation monitoring, either for the periodical measurement of networks, and for the implementation into continuously operating systems. Research in the field of data processing is still ongoing, especially for the robust solution of geodetic networks. Eventually, the development of sensor networks and methodologies for data integration has offered the opportunity to analyze different observations in a spatial and temporal context.

Keywords. Dams, Deformation Measurement, D-InSAR, GNSS, Ground-based InSAR, Sensor Networks, Terrestrial Laser Scanning

1 Introduction

Monitoring of dams has always been playing a key-role owing to the high-impact and high-risk related to this kind of civil infrastructures. The complexity of dams calls for the use of manifold sensors, each of them focusing on a different area of the structure, on structural and non-structural elements, and on different processes (structural deformations, water infiltration, corrosion, weathering, etc.).

Specifically, the problem of measuring structural deformations of dams according to the geodetic meaning (see Lang 1929) is addressed in this paper. Since decades, optical instruments and contact deformation sensors have been widely applied to this purpose (Marazio *et al.* 1989). These sensors can provide precise observations but limited to a relatively small number of points and with variable time acquisition rate (from quasi-continuous observations up to periodical repetition of surveying campaigns at monthly or yearly rate).

In recent years, some new technologies have been tested and introduced for dam deformation measurement. Such new solutions have started to offer unprecedented opportunities for safety management and structural analysis. Among these, *Areal Deformation Measurement* (ADM) techniques provide the chance to extend the observed region to a large portion of a structure, instead of merely measuring a set of a few control points (Capra *et al.* 2015). Such techniques on one side include *terrestrial remote sensors*: *Terrestrial Laser Scanning* (Lindenbergh & Pietrzyk 2015) and *Ground-Based InSAR* (Monserrat *et al.* 2014). On the other side, the *Advanced Differential InSAR* (Interferometric Synthetic Aperture Radar) techniques along with high-resolution satellite SAR data can help monitor displacements of the upper parts of large dams that are illuminated by spaceborne sensors. Anyway, since the first experimental applications of these methods published in the period 1999-2006, many improvements have undergone and the current state-of-the-art features a much greater potential for field operations.

Monitoring methods based on *Global Navigation Satellite Systems* (GNSS) techniques have been widely developed for dam deformation measurement, because of the high precision they can provide and the chance to install sensors for continuous monitoring.

Since traditional and GNSS *geodetic networks* are still largely used for dam deformation measurement, research work on the improvement of data processing and adjustment techniques is still ongoing.

The development of *sensor networks* and methodologies for data integration has offered the opportunity to analyze different observations in a spatial and temporal context. Some deformation processes can be better understood only if multiple observations are merged, compared, and cross-checked.

Eventually, an important trend goes in the direction of integrating monitoring observation and structural modelling.

The paper will try to review the main new innovative applications in the field of dam deformation measurement, according to the classification reported in this introduction.

2 Areal Deformation Measurement

2.1 Terrestrial Laser Scanning

Terrestrial Laser Scanning (TLS) can directly provide high-density 3D data and additional information, such as intensity and RGB colours. Although its single point measurement accuracy is lower than the one of a theodolite, change detection methods can potentially profit from the large data redundancy. Based on these characteristics, TLS technology yields a challenging and interesting approach to model and analyze possible deformations of objects. The challenge is to identify and, if necessary, parameterize sets of points belonging to the same object in multi-epoch point clouds, since the scanning process can neither repeat the measurement of points at the same precise locations. A thorough review of this subject is reported in Lindenbergh & Pietrzyk (2015).

In real applications, different methodologies have been investigated to detect and parametrize the deformation of object surfaces. Plane fitting to a subset of the laser point cloud was explored in order to detect the deformations of a sea lock with TLS technology (Lindenbergh & Pfeifer 2005). Thanks to the adopted interpolation, the measurement noise could be reduced to a few millimeter level. A residual systematic error with magnitude of 2 mm could not be explained, probably because of the unmodelled influence of laser-beam incidence angles and of laser intensity. Further information on monitoring lock gates with TLS have been reported by Kopacik & Wunderlich (2004) and Hesse & Kutterer (2007).

For longer distance measurements, a group of Italian researchers set up a test field on the Cancano Lake dam (Italy) in order to check the real performance of long-range laser scanners for dam monitoring applications (Alba *et al.* 2006). Suggestions for future work were addressed to investigate the effect of the incidence angle and the necessity to take a major care of geo-referencing. In particular, in this study the response of retro-reflecting material used for targets was strongly criticized, as also demonstrated after a successive study (Alba *et al.* 2008b).

Eling (2009) investigated multi-scans by TLS applied in Harz dam monitoring tasks. A uniform framework was used to compare the possible deformation of the dam surface. He also showed the presence of residual systematic errors with a magnitude of approx. 5 mm that should be further investigated. Inspired by this, Wang (2013a) analyzed the various error sources that are likely to influence the point clouds' quality in outdoor environment. External error modelling in a combined model and fine registration were investigated to decrease the size of systematic errors as well as to improve the precision of the final point clouds (Wang 2013b; Wang *et al.* 2015). The proposed extended methodology reduces these systematic errors by approximately 3.2 mm, along with a drop of a posterior variance of approximately three times.

2.2 Ground-Based InSAR

Ground-Based InSAR (GBSAR) sensors (see Monserrat *et al.* 2014 for a review of the current state-of-the-art) have been applied since the beginning of their history to measure horizontal displacements of dams' downstream face. In Tarchi *et al.* (1999) and Alba *et al.* (2008a) two pioneeristic experimental applications in discontinuous and continuous acquisition modes are reported. The advantages offered by GBSAR sensors are the dense spatial distribution of observations (sub-metre point resolution) and the high precision (at millimetre level). These results have been demonstrated in both the above-mentioned studies by comparing GBSAR observations with the ones recorded by means of traditional sensors inside the dam body. GBSAR monitoring may provide high temporal resolution (a few minutes when working in continuous node, but with a tendency to shorten such a time in the up-to-date instruments) at operating ranges up to few miles.

Despite of this great potential for dam deformation measurement, the regular application of GBSAR in the practice of dam monitoring is not documented in the literature. Successive works (see, e.g., Crosetto *et al.* 2014) still describe applications for study the dam behaviour within short time periods, but not permanent installations can be found. This is also motivated by the cost of the current technology and the complexity of instrument management. However, the same problems can be found in applications for landslide monitoring (Casagli *et al.* 2010; Bozzano *et al.* 2011).

The influence of the environmental conditions may result with easy in errors on some observed points, as reported in Alba *et al.* (2008a). For this reason, recent studies focused on the application of corrective models (Xing *et al.* 2014), while processing techniques that are normally used with satellite InSAR data, such as *Persistent Scatterer Interferometry* (PSI – see Crosetto *et al.* 2015), started to be applied to GBSAR data as well (IDS company, personal communication).

It's worth to mention that Real Aperture Radar (Luzi *et al.* 2010) sensors could also find some interesting applications in static deformation measurement of dams, although these sensors are more powerful for the observation of high-dynamic processes.

2.3 Digital Photogrammetry

In the case of digital photogrammetry (Luhmann *et al.* 2014), the application to measure dam deformation is strongly limited by the image scale, see Scaioni *et al*. (2015). Some applications of image-based techniques would be possible for inspection of the conservation state of surface materials, or to measure 2D surface displacements in specific points. In such a case, images captured with long focal lens cameras and automatic processing techniques would be required (see, e.g., Barazzetti & Scaioni 2008).

2.4 Spaceborne InSAR

At the beginning, spaceborne InSAR could be correctly applied for measurement of ground subsidence over large areas or for detecting earthquake-related deformations. Then it has been extended to the analysis of smaller sites like unstable slopes. Recently, thanks to the developments in ground resolution, repeat pass time, and the processing methods, Differential InSAR (DInSAR) techniques extended their applicability for measuring deformations of civil structures. Several applications to dams have been reported in the literature. As in the case of GBSAR, the use of DInSAR cannot be finalized to set up continuous monitoring and early-warning. This is mainly motivated by the still too long time needed for covering the data downstream and processing pipeline. Further reasons that currently prevents its application have to be sought in the continuity of data quality and in the possible lack of *coherence* (Osmanoglu *et al.* 2015), i.e., the fact that the same points on the structure can be tracked over a long time. Anyway, D-InSAR has been widely used to measure the deformations of dams over limited time periods, to ascertain the presence of instability problems, or to reconstruct the past failures of some reservoir on the basis of archive SAR data (see, for example, Grenerczy & Wegmueller 2011). In addition, the same SAR images adopted for measuring deformations of the dam structure and the hydraulic infrastructures could be also exploited for assessing the stability of the slopes at the border of the water basin (Wang *et al.* 2011; Wang & Perissin 2012; Tomás *et al.* 2013; Anghel *et al.* 2016). Since SAR images generally cover wide areas, their use is recommended when the infrastructures to analyze span over several kilometers. This is the case of large basins bordering communication corridors, like is reported in Michaud *et al.* (2015). Also thanks to the wide-range potential, DInSAR can be used for detecting subsidence problems in areas where dams are located, since such problems might have influence on the stability of dams themselves (see, e.g., Ferguson *et al.* 2014).

Among the Advanced DInSAR techniques (Crosetto *et al.* 2011), PSI has gained great popularity for the measurement of man-made structures' deformation. In Crosetto *et al*. (2015) a review of PSI and a presentation of existing implementations can be found. Lazecky *et al.* (2015) report three examples of PSI application to monitor deformation of three different types of dams, using different SAR data: Charvak Dam in Uzbekistan based on ENVISAT-ASAR data, Three Gorges Dam in China based on Cosmo-SkyMed data, and Plover Cove Dam in Hong Kong based on TerraSAR-X data (see also Lazecky *et al.* 2013).

The application of DInSAR techniques was used to detect surface displacements of an earthfilled dam at La Pedrera reservoir (Spain). The open geometry of such kind of barrages, facilitating the illumination from SAR sensors, allowed the detection of a displacement of about 13 cm along the satellite line-of-sight between Aug. 1995 and May 2010. A data set composed of medium resolution ERS-1, ERS-2 and Envisat-ASAR images was mainly used, whilst a small test with high-resolution TerraSAR-X data was operated over a couple of years. The joint analysis of historical instrument surveys and DInSAR-derived data has allowed the identification of a long-term deformation process. This study demonstrates the integration of DInSAR with in-situ techniques, which helps provide a complete spatial vision of the displacements in the dam thereby helping to differentiate the causal mechanisms. Earthfilled dams were also investigated in Honda *et al.* (2012) using ALOS PALSAR data, and in Di Martire *et al.* (2014) using a series of 51 Envisat-ASAR images. In the latest study, the comparison with independent in situ measurement showed an agreement below 1 cm level. In Vöge *et al.* (2011), the dependency of the quality of results obtained from DInSAR techniques and the geometry of the slopes is also confirmed.

Anghel *et at.* (2016) applied TLS, GNSS and theodolites for precise 3D modelling of the Puylaurent concrete dam infrastructure (France). The model was then use for the projection of deformation component from SAR processing to obtain a more realistic interpretation and analysis of vector point displacements. The analysis, carried out over a time span of approximately eight months, demonstrated a good agreement between results from DInSAR and in situ measurements. In Anghel et al. (2015) the authors had previously presented the algorithm for refocusing SAR Tandem-X and TerraSAR-X images adopted for this study.

Results obtained so far are quite encouraging for promoting future efforts in the application of spaceborne SAR data for dam deformation measurements. Indeed, the availability of last-generation very high-resolution images acquired by TerraSAR-X, COSMO-SkyMed and SENTINEL constellations will hopefully allow us to obtain better results in terms of ground resolution and shorter revisiting-time by means of algorithms that produce increasingly reliable results.

3 Global Navigation Satellite Systems

GNSS-based techniques can be considered now a consolidated approach for measuring geodetic networks to obtain precise point displacements in key-locations on and around dams (Van Cranenbroeck 2011). Unfortunately, in some countries GNSS techniques are not yet recognized to provide official measurements for dam deformation control, e.g., in Italy (Dardanelli *et al.* 2014). Measurements can be periodically repeated on a monthly or a yearly basis. Different authors have proved the application of GNSS networks to take over 2D traditional networks based on optical instruments (see Liu 2010; Li & Wang 2011; Lan 2014; Wang 2015), while they cannot reach the higher precision level granted by spirit and hydrostatic levelling. As specifically addressed in next Sect. 4, also some aspects related to the theory of GNSS data processing for deformation analysis have been afforded in recently published research, see Fan *et al.* 2010.

Yang *et al.* (2010) proposed the application of pseudolite-augmented GPS technique that could help overcome some limitations of GPS-only surveys in unfavourable environments, like urban areas, deep open-pit mines and valleys. However, several problems need to be overcome before pseudolites can be employed in precise surveys for dam monitoring.

On the other hand, the main innovative contribution of GNSS to deformation monitoring of dams and infrastructures in general is represented by continuous measurement systems that are becoming more and more popular for automatic auscultation and also early-warning (see He *et al.* 2012; Jiang 2012a; Dardanelli *et al.* 2014). The basic architecture of GNSS monitoring systems is based on a few receivers positioned in key-locations on the top of the main and ancillary structures, whose displacements are elaborated with respect to one (or more) external master station(s). The increasing diffusion of continuously operating reference systems (CORS) can be also exploited for establishing the external reference, as in Jiang *et al.* (2012b).

Control points can be also instantiated to monitor the stability of the slopes around the upper water basin, e.g., because of the presence of landslides. In general, however, the length of baselines is kept quite short (from a few hundred metres to 1-2 km) in order to improve the quality of the observations. In addition, the availability of long time-series can be exploited in data processing to compensate for errors and to correlate observed displacements to different causative reasons (thermal expansion, water level, others).

As a leading-edge application, Galan-Martin *et al.* (2013) implemented Differential GPS (DGPS) for real-time monitoring of structures with millimetre accuracy after an appropriate mathematical treatment. Real-time DGPS positions were filtered to reach millimetric accuracy through Kalman filter. Such results were positively validated against reliable pendulum and angular collimation measurements. In addition, the 15 months field experimentation showed that thorough attention should be paid to the adopted communication system.

4 Data Processing

The analysis of data coming from sensors adopted in dam deformation measurement is also an important field that still require future research. Nevertheless, this is a very wide domain, which overlaps and intersects with other research fields and then it would call for specific study. Here we limit to address the main research topics about data processing and to mention a few recent studies specifically focused on dams.

Topics related to data processing can be organized in four main research lines:

1. Analysis of errors in time series and geodetic networks;
2. Separating noise, systematic errors and deformation components that are caused by different agents such as water pressure and temperature;
3. Statistical analysis of deformations, especially when ADM techniques are used; and
4. Interpolation of deformation fields.

Just to mention a few examples of recent research work, Dai *et al.* (2015) proposed an Independent Component Analysis (ICA) as a method for modelling different signal components, which are assumed to be mutually independent. The topic of robust estimate of geodetic networks based on traditional and GNSS observations is still quite investigated, since the high demand in term of required precision that is usually very close to the measurement noise (see Nowel 2015; Tasci 2010). Also the implementation of new sensors results in the integration of multiple observations requiring a reformulation of the functional model of network adjustment. In the case described in Casaca *et al.* (2015), the combined adjustment of angle and range is discussed.

5 Sensor/data integration

The observation of dams' deformations is a typical field of Engineering where multiple sensors have always been implied (Giussani 1981). This is due to the presence of several phenomena and processes that should be monitored, but also to the size that big barrages may have, requiring ubiquitous instruments. Thus, dam deformation measurement is intrinsically connected to the adoption of *sensor networks*. In the recent year, this concept of network has evolved into the one of *geospatial sensor network*, where the knowledge of relative locations among sensors become an important aspect (Nittel *et al.* 2008). In such networks, communication among sensors is also largely emphasized under a twofold point of view. On one side, the technological infrastructures for data transfer have been largely investigated and many solutions proposed. The wireless technology has been largely exploited (Khichar & Shivanandan Upadhyay 2010), even though in the case of hydropower plants, where data safety and reliability have a primary relevance, these solutions may have some limitations from technical and/or legacy point of views. On the other side, several protocols for smart sensor communication and interoperability, also through Web-services, have been developed (Chen *et al.* 2009).

Examples of sensor networks applied to dam monitoring are difficult to find in the literature. This is mainly motivated by the fact these applications are not given too much attention by the scientific community, but they are really important in the daily practice of those organizations dealing with hydropower plants administration, management and regulation. An interesting example is the system GOCA (www.goca.info) developed at Hochschule Karlsruhe (Germany), which integrates GNSS, theodolites and other sensors on the hardware side, along with models for data analysis and prediction.

Indeed, GOCA system can be used for online control and early-warning.

Another interesting aspect of sensor/data integration consists in the corroborative use of more sensors to improve their potential and efficiency. As a clear example of this category, Anghel *et al.* (2016) combined spaceborne SAR image processing with the 3D model of the dam obtained from TLS surveying. The availability of such a detailed model is exploited to better define the spatial geometry of radar signals. In this way, an augmented interpretation of 3D displacements can be achieved.

In Mascolo *et al.* (2014) and Nico *et al.* (2015) the integration of GBSAR and spaceborne D-InSAR analysis of CosmoSkymed data was exploited for studying horizontal and vertical displacements of old embankment dams. The former instrument was exploited for measuring horizontal displacement vectors, the latter for vertical displacement vectors.

Last but not least, the integration between the sensor network and the structural modelling of barrages is also important. So far, this task has been mainly operated offline for the purpose of study the structural behavior of a dam over a limited time span. The chance to carry out the analysis online by using observations from the geospatial sensor network would allow timely forecasting of forthcoming critical conditions. In addition, data modeling techniques such as *data assimilation* could be exploited for the mutual cooperation between observations and numerical modeling. Such techniques, which have been successfully applied to other domains characterized by highly dynamic phenomena (e.g., in meteorology) seem to be really promising for dam monitoring as well.

6 Conclusions

This paper has reported a review of modern techniques that have been recently applied for dam deformation measurement. Mainly they consist in the Areal Based Deformation measurement techniques, including ground-based (Laser Scanning and Ground-Based InSAR) and spaceborne (InSAR) sensors; in the GNSS-based methods, which can be generally organized in GNSS-based periodical networks and in continuous monitoring systems; in the data processing techniques, especially for geodetic network robust adjustment; and in sensor and sensor/modelling integration.

The general frame offered by these new technologies is absolutely promising, even though future efforts should be put to understand which techniques have the potential to follow-up in the regular practice of dam surveillance and which may only offer a contribution to scientific investigations. Attention should be also given to other emerging technologies, such as Fibre Optic Sensors (Inaudi 2014) and Synthetic Aperture LADAR (Turbide *et al.* 2014).

The increasing use of satellite observations is an important point to discuss. On one side, such data can be used for the remote monitoring of dams and the nearby environment, whose influence on the safety of the barrage itself may be really relevant. On the other side, the future availability of new improved data sets (for example, Sentinel data) is supposed to foster even more the application of satellite data.

Attention should be also paid to data integration, which may create added value and an increased data redundancy to be used for cross-checking observations.

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