Satellite Technologies for Dam Motion Monitoring

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Abstract. In our information era, the current trend of adoption of new technologies for automation of dam monitoring presents a challenge when it comes to accurately monitor absolute 3D movements of a dam.
In many cases, dam movement is measured by means of plumb lines and manual surveying techniques. In the first case, automation can be done by optical or electronic means but, instead of an absolute motion which is only restricted to inverted plumb lines anchored deep under the foundation, we obtain tilt and, from it we can estimate the motion. In the second case, being surveying campaigns, automation is rarely possible and hence, the number of readings over time is scarce.

There are many emerging technologies trying to fill the gap like robotised total stations, ground based radar, etc. which rely on very expensive and delicate equipment to be installed on site and subject to vandalism.
The problem is even worse when it comes to monitoring slopes, abutments and landslides. The inaccessibility of some sites makes the task a huge challenge.
Satellite technologies can provide tools to accurately monitor movements without the need of expensive equipment on the ground. GNSS and InSAR are two different approaches to the problem that can complement each other to get a robust and complete solution.
GNSS can provide fully automated motion monitoring in 3D and real-time to a millimetre-level accuracy for a discrete number of points by means of affordable GNSS receivers on the ground.
InSAR, on the contrary, provides infrequent, near-vertical movements of a large number of points over a wide area also to millimetre-level accuracy without any equipment on the ground.
Together, a comprehensive reservoir motion monitoring can be achieved, and the radically different approach provides robustness to the system to better comprehend the behaviour of the dam-reservoir system.

Keywords. Global Navigation Satellite Systems (GNSS), Interferometric Synthetic Aperture Radar (InSAR), Structural Health Monitoring (SHM)

1 Needs and Specific Constraints in Dam Displacement Monitoring

The GNSS technique offers advantages in more and more fields of application. However, tn the field of fixed infrastructure, it is taking longer to deliver practical results due to the required accuracy.
The routine monitoring of the surrounding terrain and the structures themselves (bridges, dams, singular buildings…) is not often a priority, more often than not it is the identification of abnormal or unexpected behaviour in these that is important. The mechanisms of these anomalies are not always identified or understood a priori, therefore the interpretation of the whole monitoring system is needed at different levels of knowledge [1].
With respect to dams, at a conceptual level, the necessary monitoring can be classified into the (1) kinematic, (2) hydraulic and (3) thermal fields. Into the first group, kinematic, the monitoring of displacements, settlements and accelerations would fall, which are the subject of this paper.
Equally important is the hydraulic monitoring, including the impounding loads, seepage, uplifts and interstitial water pressure in the affected terrain and

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JISDM 2016 Vienna

even the wash out of materials due to the gradients of the water flows as a hint of internal erosion.

The thermal aspect is important in the construction phase of concrete dams and plays a less critical role during operation.

Regarding kinematic monitoring methods, and particularly motion, we find that frequently, the GNSS monitoring proposals are compared with classical systems. The monitoring of tilt through direct pendulums or clinometers, foundation movements through borehole rod extensometers, external surveying and geodesy monitoring, differential displacement in joints, collimation, etc… deliver partial information about the total movement of the dam. Each technique has its caveats but also its qualities and advantages that should not be undervalued.

GNSS systems have been regarded as lacking in accuracy, a topic that we will deal with later. Besides, they will provide, in most cases, a complement rather than an alternative to the conventional methods, but delivering an added value that we want to highlight.

This added value is based on two key lines:

- Operational conditions
- Data interpretation

Operational Conditions

The expected movements of a dam during the operational phases are a consequence of the load variations, mainly the water level of the reservoir, and the temperature in normal conditions, and more exceptionally, of foundation settlements or deformation of the constitutive materials of the dam body, like concrete expansion, micro-collapse[4] of loose materials, etc.

The dam motion monitoring during the behaviour confirmation phase as well as for anomaly identification requires a certain level of accuracy (millimetre-level) in order to detect positional variation between points in time. Moreover, it demands rapid response, in many cases with difficult access constraints (remote or mountainous locations) and with adverse weather conditions. For this reason there is a great desire to automate the monitoring systems, but that should never lead to an absence of direct visual inspection. In most cases, the first hints of malfunctioning come from the hydraulic component, with rising interstitial pressures and uplift, seepages or even suspended materials in the leaks. It is however essential to confront these parameters with their effect in the structure through its kinematics.

Therefore, the inclusion of GNSS or InSAR systems for the detection and tracking of movements, demand a high grade of accuracy and reliability, apart from availability in adverse conditions, which is determinant for the other mentioned techniques.

The capacity to provide early warning, even with lower levels of accuracy represents a qualitative leap for the dam safety monitoring.

Data Interpretation

Often there is partially redundant information that can lead to apparent contradictions. The data reliability and accuracy plays an important role for those responsible of its interpretation.

For this reason the capability of a monitoring system to deliver, not only the data, but the degree of uncertainty in the measurements, offers an added value that is key for the interpretation and validation, and even hints about mechanisms of unexpected behaviour. Indeed information about the uncertainty of the data greatly increases the value of the data itself.

Returning to the necessity for a kinematic monitoring of the dam structure (its movements), it is necessary to recognise that the movement, fluency, settlement or acceleration are seldom known "a priori" and hence, the predicted behavioural models of the project phase, need to be redefined, completed or even built in the operational phase. The fact that a significant proportion of failures take place in the first impounding confirms this difficulty in the prediction.

Too frequently, the information is compared to historical data in similar circumstances like time of the year or water level. The analysis of the repeatability or the trend is usually the main criterion for the data interpretation, at least in a first instance.

The introduction of predictive mathematical models for dam bodies and foundations' movements is slow and costly in the operation phase and complex in the interpretation of anomalous behaviour differing to that expected in the initial design.

From the data, we need to get the information and from the information, the diagnosis. Therefore, the data has to become information through its reliability and uncertainty. The information joins the engineering knowledge, both generic and project specific, in order to generate a diagnosis. This

[4] Volume reduction

methodology needs to know the uncertainty of both the data and the behavioural model. Both are sources in order to obtain a reliable diagnosis.

2 Solutions Provided by Satellite Technologies

2.1 GNSS

GNSS systems are used worldwide for position determination in a wide range of applications from vehicle navigation to asset tracking, the American GPS system being the most common.
These systems are not known, however, for their great accuracy so it might appear surprising that they are suitable for precise motion monitoring. Nevertheless this accuracy limitation can be overcome as explained below.
GNSS use the range measurement between the receiver antenna and, at least, four satellites to compute the position of the receiver on the earth at a point in time. These range measurements are subject to a number of errors that degrade the accuracy. The error sources include accuracy in the satellite orbit determination, delays of the GNSS signal through the atmosphere, satellite and receiver clock errors, multipath, etc. When a single receiver is used, all the aforementioned factors play their role and hence, measurements no better than a few decimetres are obtained. Obviously this accuracy is not good enough for structural motion monitoring.
In order to improve the accuracy of the measurement, different techniques can be used. Let us consider relative positioning using phase ranges. Most of the error sources mentioned above are common to two receivers located in the vicinity of each other. Therefore, if we have a static receiver with known coordinates, the relative position of the other received can be calculated with much higher level of accuracy as most of the errors are common to both receivers and, thus, can be taken out of the equation [2]. With this technique, called DGPS, centimetre-level accuracy can be achieved.
So as to further improve precision, mathematical methods to remove measurement noise can be applied. One of the most common methods used is Kalman filtering to obtain a weighted average between the predicted and the measured position. As we will show later, it has been demonstrated empirically that for quasi-static points, a millimetre-level precision can be obtained. This level of accuracy is enough for dam motion monitoring in most of the cases.

2.2 System Description

A proven configuration to obtain the best results consists on a fixed network of GNSS receivers with at least one of them acting as reference as depicted below.

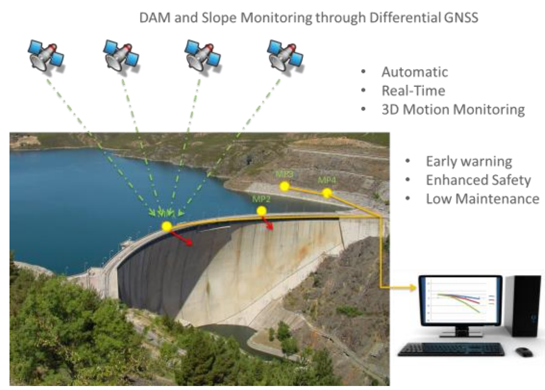

Figure 1: Typical physical system schematics

The main elements of the systems are:

- Reference station (at least one)
- Monitoring Station (as needed)
- Communications Infrastructure
- Processing Computer

After a warm-up period of about 24 hours, the system is able to deliver real-time data to a rate of one measurement per second and can run unattended for years.
Additionally, an internet connection can be added to replicate the data in the cloud and to allow global access.

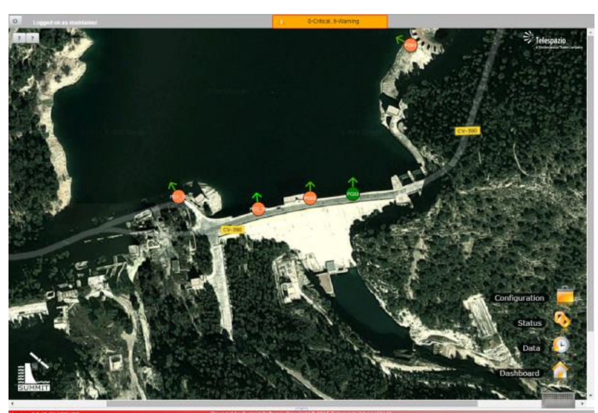

Figure 2: Example of real-time representation of motion vectors. SUMMIT-SHM

2.3 Advantages of GNSS

A system like the one described above has characteristics that make it really valuable for SHM applications. The main characteristics are:

- Near real-time
- Three-dimensional
- Millimetre-level accuracy
- Unattended (no human intervention)
- Cost-effective
- Suitable for retrofitting old dams

This solution eliminates the need of surveying methods that are expensive and human error-prone, achieving the same level of accuracy.

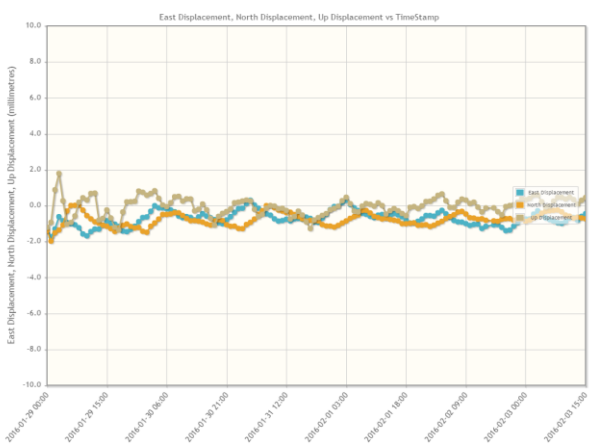

Figure 3 - Measurement noise at millimetre-level. SUMMIT-SHM

2.4 Space-borne InSAR

The InSAR technique developed by Telespazio Group (e-Geos) is called PSP-IFSAR [3][4][5] and provides measurements of displacements – typically due to landslides and other slope failures, hydrogeological changes, tunnelling, oil/gas or mineral extraction, earthquakes and volcanic phenomena – of objects on the ground or the ground itself exhibiting radar backscattering properties stable over time, called Persistent Scatterers (PS). Typically, several PS are found in non-cultivated and scarcely vegetated areas, and in particular in man-made or natural structures like buildings, rocks, etc. The group capability for high volume processing has been exploited to allow a nationwide InSAR survey of Italy [6].

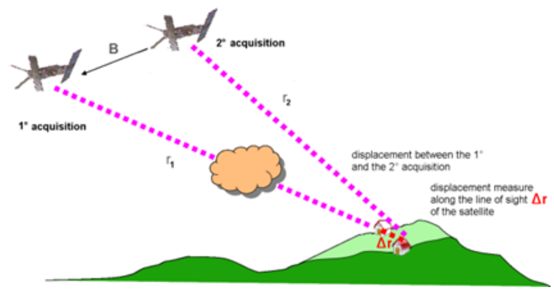

Figure 4: Principles of InSAR technology.

In the context of its application to reservoir and dam monitoring, several use cases exist:

1) Monitoring of the reservoirs surroundings for landslide and other ground displacements.

This use case is particularly effective in exploiting the unique benefits of InSAR as it can provide a detailed survey of motion in areas which are often not surveyed at all or can only be very sparsely surveyed with other methods due to the large surface area. The example below shows such an application where a four-year survey of ground motion depicts the extents of two large landslide bodies. The density of measurements made (with no in-situ installation) varies due to vegetation cover but the availability of useful displacement measurements is remarkable and gives and excellent indication of areas of concern where ongoing monitoring via InSAR or real-time in-situ monitoring systems could be continued.

2) Measurement of ground displacements on the dam structure

Most dam types also lend themselves well to InSAR motion measurement. In the same example the motion on the dam itself is seen. In-situ and real-time systems are best used for dam safety monitoring however InSAR can add significantly to the knowledge since historical archives of applicable SAR satellite data exist from 1992-present allowing a retro-analysis of past ground motion to be carried out. This allows dam owners to understand the past motion on their dam if no pre-existing system existed. This is particularly useful in the cases of a mine tailings dams and other dams which may pass from one owner to another, and where the past knowledge of the dam might be scarce.

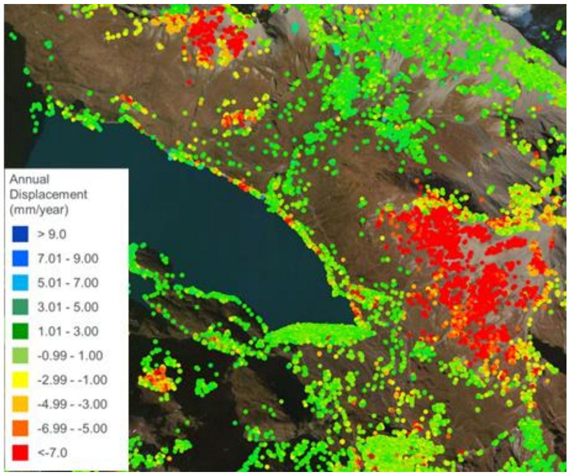

Figure 5: Landslide motion measured by PSP-IFSAR (2011-2014) on the slopes above Mont Cenis Lake, France.

2.5 Satellite Communications

In many cases dams are located in remote areas, far from where the interpretation of data is required. Up to date information is important to evaluate risk and get early warning against possible failure, however, the remoteness of the asset makes communication often difficult.

In areas without conventional means of communications, Satellite Communications can solve the problem, providing a reliable and cost-effective method of delivering the data wherever it is needed from anywhere in the world.

3 Case Studies in Spain

Some experiences in Spain using DGPS during the last 15 years led the authors to improve little by little the knowledge and the performance of this measurement methodology by means of real implementations.

The potential landslides of the Arenos reservoir [7,8] required an extensive way to monitor a large area of slope by the reservoir. Manually operated DGPS over some dozens of control points was the kick-off of a new way to conceive the measurement of slope motion around reservoirs.

At that time, some experiences such as Pacoima Dam [9] and Libby Dam [10] in the USA or Kops dam in Austria [11] showed promising advances also in dam bodies themselves.

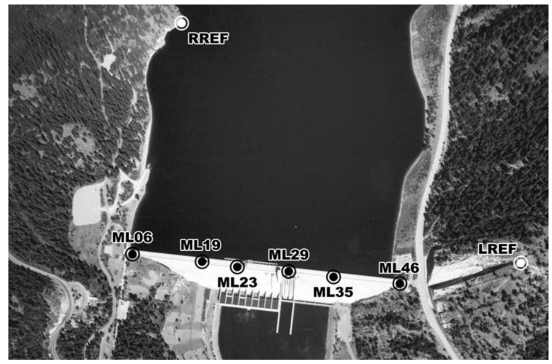

Figure 6: Libby Dam (USA) taken from Rutledge [10]

Automation of the data acquisition in Arenos reservoir was the next step and the success in this led to the first experiences measuring dam crest motion in La Aceña dam in central Spain [12].

Figure 7: Aceña dam (Spain).

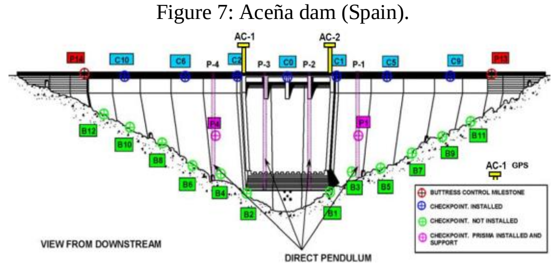

Figure 8: Downstream view with instrumentation: direct pendulums, angular collimation and DGPS at crest in la Aceña dam (Spain).

An intensive comparison was possible thanks to the triple redundancy in the dam, considered as a prototype at the time.

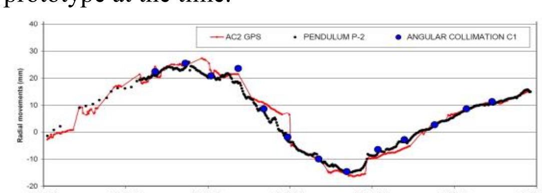

Figure 9: Comparison between three redundant measurements of crest displacement.

Results of this comparison were extensively analysed under different conditions and the accuracy level, which will be discussed later, was assessed to be between 1-3 mm.
The dam owner decided to install DGPS systems in two more dams, Riosequillo and El Atazar dam in central Spain [13].

Figure 10: Monitoring station in El Atazar Dam . Intercontrol Levante SA [13]

Figure 11: Receiver antenna installation at El Atazar Dam. Intercontrol Levante SA [13]

Some Results

A thorough analysis of measured and filtered DGPS data in La Aceña, but also later in Riosequillo and El Atazar dams, has shown that some levels of uncertainty were reduced to very few millimeters if appropriate Kalman filter and predictive models are adequately implemented. Differential processes must be coupled to reduce noise but also systematic errors induced by environmental conditions.
At La Aceña dam, data from two antennas and one static reference were processed by 3DTracker software supplied and implemented by Intercontrol Levante [14].
Two strategies [Galan, 6] for predictive modelling were implemented in order to address follow up of medium term behaviour or short time unpredicted anomalies, taking advantages for both hypotheses.
Root mean square (RMS) errors of the reail-time GNSS measurements were evaluated, in comparison to pendulum data, for different periods and under different impounding cases.
Once the system was fully operational, RMSs were estimated resulting the following [15]:

Comparison Pendulums vs processed GNSS	RMS difference (radial motion)
Pendulum 2 vs Antenna 2	1.44 mm
Pendulum 3 vs Antenna 1	1.88 mm

4 Final Remarks

New developments in GNSS technologies, differential processing algorithms and Kalman filtering under different predictive models enable satellite position technologies to provide accurate enough and reliable information to be implemented confidently in dam safety monitoring schemes.
Nowadays the main concerns about precision can be seen as old prejudices as many systems are currently operating successfully all over the world. Data processing is able to provide information with errors about some few millimetres, as proven (amongst others), on several cases in Spanish dams. These errors are similar or even lower than those provided by classical angular collimation.
Kalman filtering of differential processed GNSS data allowed the measurement noise to be reduced and provided an assessment of the involved uncertainty.
Complementarity with conventional systems is still necessary while confidence from safety managers consolidates. The combined design of conventional systems with GNSS can lead to savings by using the latter for early warning while the former, with higher operational costs, can be useful for the definitive diagnostic of anomalous behaviour.
Dams located in areas with difficult access or seasonal constraints can be properly monitored in real-time, triggering detailed inspections based on alerts. The operational costs of the combined use are reduced so that the savings can be used to improve safety control.
When dams are located in canyons careful planning is required in order to ensure a good geometry and reception of the satellite signals. Likeliness of lightning events must also be considered as they can affect power and communication systems.
Some instrumentation systems for precise geotechnical monitoring, like rod extensometers are not substitutable with GNSS and are easily

automatable. Regardless of the high cost, they will still be needed due to their important role.

Different predictive behavioural models allow the use of raw data to derive different behavioural hypothesis, leading to improvements in the displacement forecast while delivering additional information about statistical confidence in the proposed models. This feature of certain processing systems like SUMMIT-SHM [16] enables the validation of behavioural hypothesis, delivering great benefits for the experts in charge of the safety assessment of the dam.

The combination of GNSS and InSAR provides a comprehensive solution, not only for the dam body, but also of the surrounding area so that the dam-terrain system can be monitored as a whole and movements in unpredicted areas can be spotted.

ACKNOWLEDGMENTS

Authors wish to thank the Exploitation Division of Jucar River Basin Authority and the Dam Safety Department of Canal Isabel II for their confidence since the beginning of this long journey from R&D to real and operational installations. Special recognition must be given to Fernando Solanes, Juan Pablo de Francico and Francisco Blázquez, and especially to David Galán who put his trust in the technology and a great effort in its validation, as well as to the experts from Intercontrol Levante S.A.

Special thanks to Gary Holzhausen for sharing his knowledge and experience and for his continuous support.

References

[1] Enrique Cifres. “Dam Safety reflexions”. Risk Analysis as Applied to Dam Safety and Security, UPV-SPANCOLD Valencia, February 2008

[2] B. Hoffmann-Wellenhoff, H. Lichtenegger, E. Wasle. Global Navigation Satellite Systems: GPS, GLONASS, Galileo & more. Springer-Verlag Wien, 2008

[3] M. Costantini, S. Falco, F. Malvarosa, and F. Minati, “A new method for identification and analysis of persistent scatterers in series of SAR images,” in Proc. Int. Geosci. Remote Sensing Symp. (IGARSS), Boston MA, USA, vol. 2, pp. 449–452, July 2008.

[4] M. Costantini, F. Malvarosa, and F. Minati, “A General Formulation for Redundant Integration of Finite Differences and Phase Unwrapping on a Sparse Multidimensional Domain,” IEEE Trans. on Geosci. Remote Sensing, vol. 50, no. 3, pp. 758–768, Mar. 2012.

[5] M. Costantini, S. Falco, F. Malvarosa, F. Minati, F. Trillo, F. Vecchioli, “Persistent scatterer pair interferometry: approach and application to COSMO-SkyMed SAR data,” IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 7, no. 7, July 2014.

[6] M. Costantini, F. Minati, M. G. Ciminelli, A. Ferretti, and S. Costabile, “Nationwide Ground Deformation Monitoring by Persistent Scatterer Interferometry,” in Proceedings of IEEE IGARSS, Québec, Canada, July 2014

[7] Kofoed-Hansen, H., Cifres, E. and Kronborg, P. (2001) "Modelling of landslide-generated waves in MIKE 21", 4th DHI Software Conference, Elsinore, Denmark, 6-8 June 2001.

[8] Fernando Solanes. “Laderas del Embalse de Arenós”. Jornadas técnicas sobre estabilidad de laderas en embalses. CHE-Spancold, Zaragoza (Spain), junio 2007

[9] Behr, J. et al. “Monitoring Structural Deformation at Pacoima Dam, California, using continuous GPS”. USGS, Southern California Earthquake Center, Los Angeles, USA, SCIGN-USGS 2000.

[10] D. Rutledge, S. Meyerholz. Performance monitoring of Libby Dam with a Differential Global Positioning System. United States Society of Dams, June 2005

[11] R. Jäger et al. “GNSS/GPS/LPS based Online Control and Alarm System - Mathematical Models and Technical Realisation of a System for Natural and Geotechnical Deformation Monitoring and Hazard Prevention”. GOCA 2002.

[12] D. Galán-Martín et al. “Control de movimientos en presas mediante DGPS. Aplicación a la presa de La Aceña, España”. Ciencias del Agua, vol. II, núm. 3, julio-septiembre de 2011. México.

[13] Canal Isabel II. “Suministro de un sistema de auscultación de presas mediante GPS diferencial (DGPS) en las presas de El Atazar y Riosequillo”, Intercontrol Levante SA, BOCM/2011/10/03. Madrid, 2011.

[14] Intercontrol Levante SA. On line. www.intercontrol.es. R&D projects.

[15] David Galán. “DGPS Real Time Monitoring: Design and Validation”. ICOLD Annual Meeting, Seattle (USA), 2013.

[16] Ricardo Cifres. TELESPAZIO VEGA UK. On line. www.summit-shm.com