

## FIRST EXPERIENCES WITH THE DEFORMATION ANALYSIS OF A LARGE DAM COMBINING LASERSCANNING AND HIGH-ACCURACY SURVEYING

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### ABSTRACT:

Monitoring the static and dynamic behaviour of large dams has always been a topic of great importance, due to the impact these structures have on the whole landscape where they are built. Many instruments and surveying methods have been applied so far in order to continuously access to the safety of this kind of huge structures. However, the common approach in a lot of developments has been focused towards the possibility of measuring, with high accuracy and reliability, displacements of a singular number of points.

This paper presents preliminary ideas and first results of a project in progress for monitoring displacements of big structures such as large dams using new technology, terrestrial laser scanner. Particularly, this paper proposes the development and testing of a methodology that allows us to perform the recording and structural monitoring of large concrete dams combining laserscanning and high-accuracy surveying. For this purpose, a test field has been established on the dam of 'Las Cogotas' (Avila, Spain). First results and analyses have been focused on two main aspects: the network design; and the network adjustment that incorporates statistic tests in order to provide more accuracy and reliability. Finally, some future proposals for the deformation analysis of the large dam exploiting the power of laserscanning technology are outlined.

### 1. INTRODUCTION

The theory about deformation analysis has been well-known since the eighties (Caspary, 1987). The main reasons that contribute to its development were its own necessity, as well as its technological advance, especially supported by accurate instruments and powerful computers. Nowadays, the deformation analysis is applied to a wide spectrum of fields: control of movements and deformations applied to engineering works, glide surfaces, cortical movements, glaciers evolution and last but not least as phenomenons of subsidence. The basic goal is focused on analyzing the geometric variation of an object or surface with the passage of time. In this sense, there are several elements that take part during the process.

- i) Geometric evolution of the theoretical model with the passage of time.
- ii) Characterization about the geometric variation based on relative position of control points.
- iii) Necessity of measuring the geometric variation through two basic methods: direct measurements (inclinometer, pendulum or extensometers) or indirect measurement based on the classical surveying methods and observables (angles, distances, height variations, etc.). Both approaches need to be contrasted through different epochs.

Particularly, regarding structural monitoring of large dams by high-accuracy surveying, several approaches can be founded. Starting with the use of pseudolites which can be traced back to the late 1970s (Harrington and Dolloff, 1976), where the

pseudolites in fact were used to validate the GPS concept before launch of the first GPS satellites. The concept of inverted pseudolite positioning was first introduced by (Raquet et. al., 1995). In their experiment, a ground-based test was conducted to investigate the feasibility of using the mobile pseudolites for precise positioning of military aircraft; (O'Keefe et. al., 1999) also discussed the pseudolite-based inverted GPS concept for local area positioning and presented their experimental results. In this system, more flexibility was obtained and cost was reduced because all the hardware equipment and software were configured on the ground, where the power, size and computational load constraints could be easily resolved. Regarding deformation analysis based on GPS technology, a lot of approaches have been developed. Particularly, in the context of large dams, (Jeffrey and Kenneth, 1999) presented a monitoring structural deformation applied to a large dam using GPS technology. Nearly three years of data were analyzed from this sub-array to provide quarter-daily estimates of station-to-station baseline lengths. Quantitative methods were assessed to allow the identification of a number of outlying data points that could be misinterpreted as GPS station motion in a real-time system. The experiment successfully demonstrated the applicability of continuous GPS to the field of structural monitoring.

More recently, with the emergence of laser scanner technology new approaches and computer methods have been applied for deformation monitoring of large structures. (Stathas et. al., 2003) presented a new monitoring technique combining total station and ground-based laser scanner through plane fitting. Nevertheless, their approach to test laser scanners' ability in determining deformations has not been tested on more complex

surfaces; (Gordon et. al., 2003) outlined an investigation designed to explore the sensitivity of terrestrial laser scanner systems for structural deformation monitoring tasks. Two experiments over wooden and concrete beams were performed involving controlled load testing of structures. A negative and critical aspect was focused on the selection of the most appropriate surface modelling technique. They used a grid for modeling beams, but no interpolation was considered in order to getting an optimal and adaptative grid spacing; (Schäfer et. al., 2004) introduced first operational experiences in the usage of Leica Geosystems DS1 2500 laser scanning system for the determination of surface deformations of several centimetres which can be observed at the lock gates of a hydropower station during the filling and emptying process; more recently, (Tsakiri et. al., 2006) presented and developed new algorithms and methods that assessed and exploited the metric accuracy of a commercial laser scanner, especially accurate algorithms for the detection of the centre of retroreflective targets. Several experiments were tested in order to assess the reliability and accuracy of the algorithms. However, the experiments were only focused on small objects, so there was nothing that involved experiments of larger scales and applications such as large dams; (Guarnieri et. al., 2006) showed a multi-sensor approach for structural analysis applications in Cultural Heritage. To this aim a medieval wall was surveyed with combined surveying techniques: reflectorless total station, GPS for establishing a local network and terrestrial laser scanner for the generation of a 3D model of the walls. Several cross-sections and profiles were extracted and compared with the passage of time in order to perform the structural analysis. Particularly, the structural analysis was based on finite element methods which were more suitable for complex structures. The study is current under development and it is aimed to detect the areas of the wall requiring most important consolidation works.

To sum up, structural monitoring approaches based on the laser scanner and remarked upon above, outline that laser scanners constitute a real and effective solution. Laser scanners are capable of acquiring a very large number of points, so that the structural control could be extended to the whole structure instead of being limited to a few points. However, although long range laser scanners allow us to measure 3D points also at a distance of 800-1000 m, greater ranges are not considered because the data quality sharply decreases and in structural monitoring accuracies around a few millimeters are always required.

The paper presents the following structure and organization: after this introduction, Section 2 develops the network design. Section 3 explains in detail the data acquisition process. Section 4 describes an accurate and reliable approach for the network adjustment. A final section is devoted to outline some future proposals for the deformation analysis of the large dam exploiting the power of laserscanning technology.

## 2. NETWORK DESIGN

A fundamental step in the structural monitoring of large dams is the network design. Conceptually, the purpose of the network design is to plan an optimal network configuration and an optimal observation plan that satisfy the preset quality with minimum effort. In other words, after the definition of the network quality requirements (accuracy and reliability) the technique of network optimization allows us for finding such an

optimal network configuration and an optimal set of observations that satisfy the following goals:

- Reach a determined global accuracy.
- Establish a real stochastic model that can be tested.
- Design an observation campaign suitable under practical and economical considerations.

The first goal is conditioned directly by the observables accuracy, the network configuration, the observation campaign, as well as the reference system definition also known as the datum problem. Under no circumstances the reference system should be constrained, due to lack of accuracy. The second goal is directly related with the reliability of the model. Finally, to fulfil the third goal, it is very useful to dispose of digital cartography about the emplacement which allows us to get a first approximation to observation campaign.

In the past, it was very difficult, if not impossible, to solve all aspects of the network optimization in a single mathematical step. Instead, the problem of network design was divided into subproblems in each of which some progress could be made. The accepted classification proposed by (Grafarend, 1974) was:

- Zero-Order Design (ZOD): the datum problem (reference coordinate system)
- First-Order Design (FOD): the configuration problem.
- Second-Order Design (SOD): the weight problem.
- Third-Order Design (TOD): the densification problem.

Nowadays, the development of computer methods enables us to design, compute and control the complex network design problem with more accuracy and reliability. Moreover, if the requirements of network design have not been overtaken, an optimization of the network can be performed modifying or introducing new network's parameters.

Particularly in our case, a high-accuracy network was designed composed by two different blocks (Figure 1):

- A *reference block* which was situated out of the dam structure, consisting of 4 main vertices materialized by special targets fixed in concrete elements on the ground. The reference block provided an external and fixed structural support, as well as the reference system definition.
- An *object block* which was composed by 44 natural control points placed on the dam front and 6 artificial control points situated at the crest. Natural control points were perfectly measured thanks to some circular marks present in the concrete structure. Artificial targets were perfectly measured as well, because a special support was designed to place these targets in the same position in each epoch.

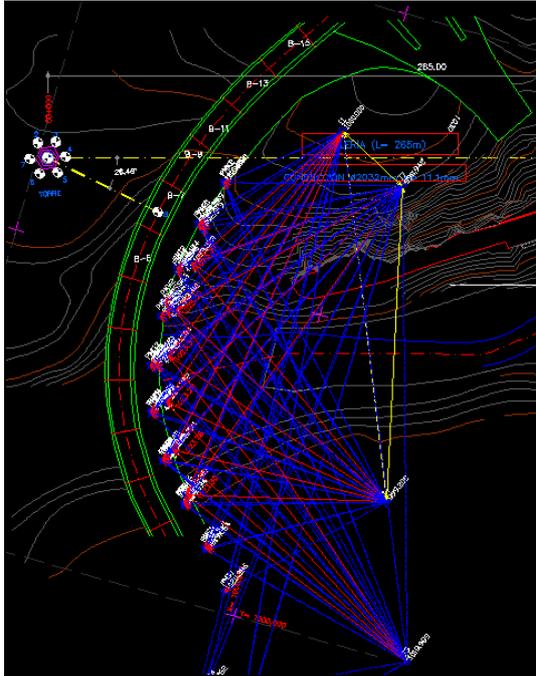


Figure 1. Network design.

### 3. DATA ACQUISITION

Data acquisition was accomplished by combining two different sensors, laser scanner and total station. In May 2006 (spring), when the dam was completely full, the first campaign was performed.

#### 3.1 The test field

The dam of ‘Las Cogotas’ (Figure 2) was built in 1994 on the Adaja river, generating a basin of about 58.6 Hm<sup>3</sup> of water. The dam presents an arc structure featuring 66 m of height and 300 of length at the crest with a maximum water level height of 1050.50 m. The conservation of the structure is good, thanks to the monitoring which is carried out by traditional sensors (strain gauges, inclinometers, etc.) and by periodical geodetic measurements (levelling and geodetic control networks, optical collimators). Moreover, the availability of other deformation measurements is very important to access the results obtained from laser scanning.

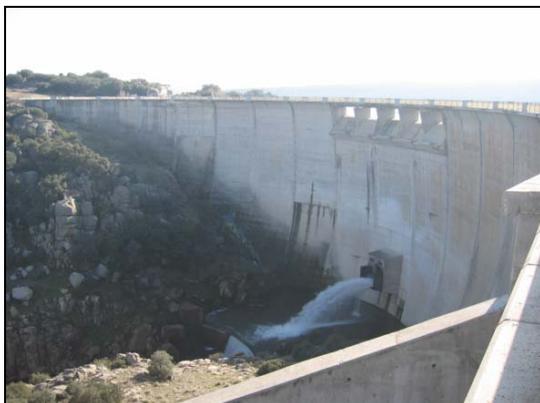


Figure 2. Downstream face of the dam of ‘Las Cogotas’.

#### 3.2 Range data acquisition

Regarding range measurements, a time of flight laser scanner, a medium range Trimble GS200 (URL1), was used in each epoch. This instrument is motorized and allows angular and distance accuracies about of 2.5 mgon and 1.5 mm at distances below 100 m respectively. In order to avoid alignment errors, laser scanner was always stationed in a fixed position (Figure 3) at mean distance of 100 m from the dam surface. The dam was scanned with a different resolution. The central portion of dam, which is the part subject to major deformations, was scanned with 2 mm resolution; while the rest of dam was scanned with 2 cm. Moreover, control points belonging to the reference and object block and represented by special targets were scanned automatically with the highest resolution.

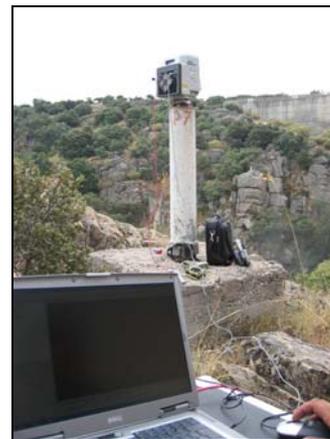


Figure 3. Laser scanner.

This process was put in practise in each epoch maintain the same criterions strictly.

#### 3.3 Surveying data acquisition

Regarding high-accuracy surveying, the designed network (Figure 4) was observed in each epoch with a total station, Leica TCA 2003 (URL2). This instrument is motorized and allows angular and distance accuracies of 0.15 mgon and 0.5 mm at distances below 120 m respectively. Particularly, reference and object blocks were measured from the 4 fixed vertices using angular measurements based on multiple intersections techniques. Moreover, control points belonging to the reference block and those placed at the dam crest were measured using distances as well.



Figure 4. Total station.

#### 4. NETWORK ADJUSTMENT

In the structural monitoring context, the network adjustment problem is understood as the estimation of several parameters that describe the structural and geometric support beginning with the observation of different measurements. In this way, two aspects have to be taken into account: on one hand the relationships between observables and parameters, *functional model*, have to be established, and on the other hand the stochastic performance of random variables, *statistic model*, has to be described. Both models constitute the mathematical model.

Particularly, the mathematical model considered in this network adjustment was the Gauss Markov Model. The functional model was expressed as (1):

$$\bar{L} = F(\bar{X}) \quad (1)$$

The equations system was obtained from the linearization through Taylor's method (2) restricting its development to the first order:

$$\bar{L} = F(\bar{X}_0) + \left( \frac{\partial F}{\partial \bar{X}} \right)_{\bar{X}_0} \bar{x} \quad (2)$$

The statistic model was expressed as (3):

$$A\bar{x} = \bar{b} + \bar{r} \quad (3)$$

where the **b** and **r** vectors are random magnitudes which follow statistic properties.

Therefore, the Gauss Markov Model established by the functional and statistic models remarked above was expressed as (4):

$$GMM \equiv (\bar{b}, A\bar{x}, \sigma^2_0 Q_{ll}) \equiv \begin{cases} A\bar{x} = \bar{b} + \bar{r} \\ \bar{r} \approx N(0, \sigma^2_0 Q_{ll}) \end{cases} \quad (4)$$

In our case, two different adjustments were performed sequentially. At first, the reference block was adjusted based on least squares adjustment and a free network solution. As a result, a reference coordinate system (datum) was materialized through the reference block. Secondly, both blocks (reference and object) were adjusted considering the reference block fixed and the object block free.

Finally, once the adjustment was solved in its first iteration, both blocks were checked for possible outliers using several statistic tests. Particularly, Baarda (Baarda, 1968) and Pope (Pope, 1976) tests were applied iteratively, allowing us to detect wrong observations corresponding to the object block.

The next table (Table 1) shows some of the results related with the standard deviations of control points belonging to the reference block. The final average standard deviation in the reference block was 2 mm in XY and 3 mm in Z.

Reference Block (4 <sup>th</sup> iteration)				
Epoch	Control Points	Standard Deviation (mm)		
		$\sigma_x$	$\sigma_y$	$\sigma_z$
May 2006	17	1.3	1.4	2.8
	11	0.7	0.5	1.2
	14	2.4	1.8	3.1
	13	2.6	1.5	2.4

Table 1. Reference block: standard deviations.

Regarding the object block, the final average standard deviation was 4 mm in XY and 5 mm in Z. The next table (Table 2) shows some of the results related with the standard deviations of control points belonging to the object block.

Object Block (6 <sup>th</sup> iteration)				
Epoch	Control Points	Standard Deviation (mm)		
		$\sigma_x$	$\sigma_y$	$\sigma_z$
May 2006	PM1	4.5	3.4	5.1
	PM15	3.2	4.5	6.1
	PM21	4.1	3.1	3.0
	PM37	4.3	3.7	5.8

Table 2. Object block: standard deviations.

#### 5. TOWARDS A DEFORMATION ANALYSIS

Once the network adjustment has been computed and checked for possible outliers, a structural monitoring could be performed based on the analysis between epochs. A unification of each epoch should be performed taking the same reference system, reference block, for each epoch. Currently, this stage is work-in-project and only the guidelines established are outlined here.

In our case, the idea will be to apply a structural monitoring following a twofold criterion. Firstly, in terms of the classical deformation analysis applied in Geodesy (Casparly, 1987) extracting the deformation vectors and the variance-covariance matrix. Secondly, applying a more rigorous analysis exploiting laser scanner dataset and making a comparison between epochs by considering mathematical surfaces fitted to measured points.

Regarding classical deformation analysis, from the combined adjustment of two epochs we will arrange of deformation vectors and its variance-covariance matrix of observables. The deformation model will be established by the equation (5)

$$Bp = \Delta + \varepsilon \quad E[\varepsilon] = 0; \quad E[\varepsilon\varepsilon^T] = \Sigma_\Delta = \sigma^2_0 Q_\Delta \longrightarrow \varepsilon \approx N(0, \sigma^2_0 Q_\Delta) \quad (5)$$

where,

- $\Delta = \hat{x}_{oi} - \hat{x}_{oj}$  is the deformation vector
- $Q_\Delta = Q_{\hat{x}_{oi}\hat{x}_{oi}} + Q_{\hat{x}_{oj}\hat{x}_{oj}} - Q_{\hat{x}_{oi}\hat{x}_{oj}} - Q_{\hat{x}_{oj}\hat{x}_{oi}}$  is its cofactor matrix
- $\sigma^2_0$  is the posteriori variance
- B** is the design matrix
- p** is the parametevector

The analysis from two observation epochs will be fundamental, because it will constitute the best way to analyze the movement produced in two different periods. The main objectives of this analysis will be:

- Confirm the stability of the points belonging to the reference block and detect singular movements.
- Contrast a movement model from the deformation vectors.
- Detect critical deformations not predicted and which could have serious consequences.

Regarding laserscanning structural monitoring, the idea will be to apply for deformation analysis an area-based method (Schneider, 2006), i.e. to make a comparison between data acquired from different epochs by considering mathematical surfaces fitted to measured points. Since different point clouds were already georeferenced into the same reference system, the comparison between interpolated surfaces will allow us to evaluate displacements applied to the whole dam structure. The next figure (Figure 5) illustrates a global laser scan model obtained from dam recording.



Figure 5. Global laser scan model applied to the whole dam structure.

Particularly, in order to get a structural monitoring of the dam supported by a comparison of surfaces, a double-step approach will be performed. At the first step, we will pass from point cloud to surface (Figure 6) based on incremental Delaunay triangulation algorithm (Bourke, 1989). In the second step, we will perform a deformation analysis based on orthogonal sections applied over both surfaces belonging to different epochs. The resulting sections will allow us to extract automatically displacements vectors not only applied to a limited number of points, but also to the whole dam structure, especially in the frontal part of the dam.

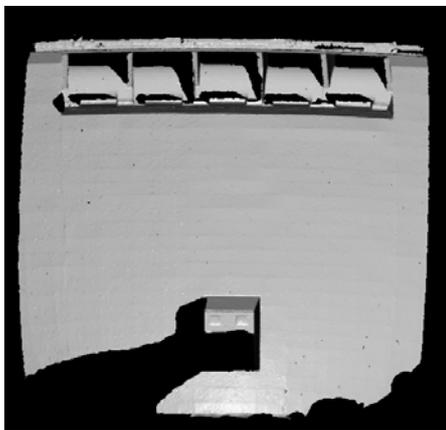


Figure 6. Triangular surface model of the dam.

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