Undisputable, Objective and Reliable Geodetic Dam Monitoring with FRM Standardization

Stelios Mertikas[1], Xenofon Frantzis[1], Achilles Tripolitsiotis[2]

[1] Technical University of Crete, Geodesy & Geomatics Engineering Laboratory, GR-73100, Chania, Greece, (metrikas@mred.tuc.gr)
[2] Space Geomatica P.C., Xanthoudidou 10A, Chania, Crete, Greece, (admin@spacegeomatica.com)

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ABSTRACT

Deformation monitoring of the "VALSAMIOTIS" dam in Chania, Crete, Greece is carried out by GNSS geodetic surveying in combination with total geodetic station monitoring. A central monitoring site, near the dam, has been established with absolute and permanent GNSS site coordinates, as well as with a number of selected reference geodetic control points around the dam. Geodetic coordinates for these reference markers have been determined in an absolute way, with respect to the center of mass of the earth and thus not influenced by local effects.

To establish a continuous, homogeneous and reliable system for this dam deformation monitoring and to ensure dam stability and safety, uncertainties arising from each essential geodetic constituent in observations, instruments and processing have to be identified and carefully dissected. The main steps involved in this standardization process are presented along with the overall uncertainty of the monitoring system. This work will provide a roadmap following internationally agreed standards to (1) support accuracy in scientific and monitoring data we produce and evaluate, (2) to provide accurate information presented to the public when critical values have been reached, and finally (3) to help make the right decisions, and put into action the right policies for large project deformation monitoring. Ways to express uncertainty will be given to meet the guidelines of the Bureau International des Poids et Measures.

I. INTRODUCTION

For more than 5,000 years, dams have been constructed primarily to store water, maintain water table on islands, and change flow of rivers, among others. According to the International Commission on Large Dams, there are more than 59,000 dams at present that support irrigation, hydropower, water supply and flood control (World Register of Dams, 2018). Besides the benefits dam bring along to society, a few drawbacks might come out as well. These could include, for example, impact on biodiversity and the environment, relocation of local population and risk of dam failure. (Boye & de Vivo, 2016). The most frequent causes of dam failures are water spilling over its top, foundation defects with settlement and slope instabilities, cracking, piping (internal erosion caused by seepage) and inadequate maintenance and upkeep (Association of State Dam Safety Officials, 2019). For example, instability of reservoir slopes caused a 125m high wave over the Vaiont dam in Italy resulting in the death of 2600 people in 1963.

Dam failures may cause human fatalities, infrastructure damage, land loss, permanent or temporary evacuations and extreme economic losses at local and national levels. Historic dam failures around the world have, on the other hand, contributed to the development of several dam safety programs. In this vein, surface movements and deformations in dam's body, but also in its surrounding slopes are regularly and continuously monitored in any dam safety program (Williamson, 2015).

To keep up safety and evaluate performance of any type of dams (i.e., embankment, concrete, masonry, etc.), several fundamental physical parameters need to be reliably and continuously monitored. These could be pore and uplift pressures, water level and flow, seepage flow, seismic activity, stress and strain, weather and precipitation, displacements and deformations (Texas Commission on Environmental Quality, 2006).

In dam safety, deformation is divided into surface, internal and joint and crack monitoring. Surface deformation is the horizontal or vertical change in position of a point on a dam's body with respect to reference and fixed points. When deformation is detected in relation to some point on the structure or in the foundation of it, then internal movement may have occurred. Finally, joint and crack monitoring refers to relative horizontal or vertical displacement between two parts of a dam structure (Central Dam Safety Organization, 2018).

Geodetic and surveying monitoring has been extensively applied at large dams to provide warnings on surface deformations. Yet, there has not been an internationally agreed strategy for dam deformation monitoring which is based upon undisputable and reliable metrology standards. Alternatively, there exist guidelines and recommendations published by regional and national entities in charge of design, operation and maintenance of large dams, such as those provided by the US Army Corps of Engineers (2018).

This work provides at first a description of geodetic techniques and instruments for dam deformation monitoring (Section 2). Then, it presents the "VALSAMIOTIS" dam in Crete, Greece along with its current deformation monitoring. Finally, it addresses and promotes a roadmap for the establishment of a continuous, homogeneous and reliable surface deformation monitoring for dam safety and stability based upon SI-traceable (Système International d'Unités) results, along with uncertainty budgets.

II. GEODETIC MONITORING OF DAMS

Large structures such as dams are subject to short (daily/weekly/monthly) or long-term (annual/decadal) horizontal and vertical displacements in a relative but also in an absolute sense. Horizontal surface deformations are usually observed as baseline offsets, as a function of time, between reference points and several control points established on the dam. The same control points are commonly used also to monitor vertical surface movements through precise leveling. Nowadays, modern geodetic techniques with terrestrial laser scanners, ground-based radar interferometry, close-range photogrammetry, and others enable accurate monitoring of the entire area and the body of a dam without using a limited number of control points. A review of geodetic techniques and associated sensors can be found in Scaioni et al.(2018) and Mertikas (2016). The type of dam, the level of potential movement and the desired accuracy regulate and lead to the method and instrumentation which is to be employed for surface movement monitoring.

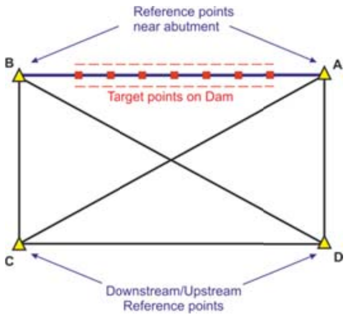

Figure 1: Example of good distribution of reference and target points for geodetic deformation monitoring of concrete dams.

The distribution of control and reference points also affects the accuracy of the employed geodetic survey and depends upon the type of the structure to be monitored. For example, in embankment and concrete dams, control points are often placed in one or more lines along the crest of the dam, while reference points are established at the ends of these lines (Fig. 1). However, this layout cannot be implemented in arch dams, where the reference points must be placed in a stable area outside the dam crest.

Trigonometric principles of triangles formulated by the reference and control points are employed to solve for the coordinates of points on a dam using either triangulation or trilateration. In both methods, the distance and height difference between reference points has to be known with millimeter accuracy. In triangulation, the angle between a control point and two reference points is determined. In trilateration, the distance between reference points and the unknown control point is measured. Distance measurements are regularly more precise than angles. Thus, trilateration is more accurate than triangulation. Distances are usually measured with total stations (robotic or not; with automated target recognition functionality or not, etc.) which carry electronic distance measuring equipment.

Global Navigation Satellite Systems (GNSS) antennas placed on top of a dam have been also used to provide three-dimensional positioning of control points (Barzaghi, Cazzaniga, De Gaetani, Pinto, & Tornatore, 2018). The selection of the GNSS data processing technique (i.e., Precise Point Positioning, Differential Positioning, etc.) regulates and controls the produced accuracy of the GNSS-derived surface movement.

The frequency on which measurements are made for deformation monitoring constitute another key parameter for the selection of the geodetic technique to be employed. This parameter is defined at each monitoring program adhering to respective regulations for dam safety. Current practices include periodic measurements by specialized personnel on, for example, monthly basis and that becomes more frequent (i.e., daily) when displacements are observed to exceed predefined safety thresholds. Automated systems may also be engaged to provide continuous measurements for surface deformation.

There is no single solution for dam geodetic monitoring that fits all cases. The most appropriate method or combination of methods has to be determined for each specific dam taking into account requirements for its safety that accompanies its design and its construction.

But how is the "most appropriate" method selected? A detailed error budget analysis must be carried out to define objectively the overall uncertainty of each candidate method selected for monitoring. In the following Section, such a qualitative analysis is provided.

III. UNCERTAINTY ANALYSIS FOR DEFORMATION MONITORING

In order to establish a continuous, homogeneous and reliable system for dam deformation monitoring and to ensure dam stability and safety, uncertainties arising from each essential geodetic constituent in instrumentation, observations and processing have to be identified and carefully scrutinized and evaluated. In the following sections the major components for this standardization are given (US Army Corps of Engineers, 2018).

A. *Definition of benchmark monitoring parameter*

Surface movement is monitored by measuring changes in distance between control points on the dam surface and reference points in its vicinity. This is true when using either total stations, EDM, or GNSS instruments. In the latter, the baseline length between the reference GNSS station and the control stations operating on the dam is actually what is determined and evaluated.

The selection of the appropriate instrument to measure surface deformation must be based on the rate at which a failure is expected to develop, the vulnerability of equipment on site conditions (outdoors exposure, weather, etc.), and the available resources. Besides the cost, the simplicity in operation, reliability, durability, longevity, precision, accuracy and performance history of each instrument type and make should be also taken into consideration.

B. *Define number, location of reference points*

The points on the structure where maximum deformations are expected shall guide the monitoring strategy. The spatial distribution of these points should cover the entire structure but they should also be extended to stable regions and outside of the monitoring area. The reference network must consist of stations located at both ends of a dam, along its longitudinal axis and either upstream or downstream from it. At least 4 to 6 reference points must be established for horizontal and vertical control.

C. *Instrumentation Characterization and Calibration*

Instruments selected for monitoring need to be characterized and calibrated in specialized labs and in the field, before their final deployment. Instruments are accompanied with certificates by their manufacturers for their measuring accuracy. These should be considered in the characterization process, along with reference books and values, previous experience, standards, etc.

Uncertainty in distance measurements for total stations is commonly expressed as an absolute value plus a variable (scale error) that depends on the length of the measuring distance. Reference points out of which instruments and prisms measure to determine distance may change with time. Also, GNSS observations produce uncertainties associated with the baseline length and satellite geometry. These should be inspected and checked regularly.

Offsets between the measurement point and the true reflection point on the prism, or the electronic phase center of a GNSS antenna are provided by manufacturers. These offsets are usually determined for a large number of prisms and GNSS antennas. Thus, they are not exact offsets for the instruments employed for monitoring. This implies that the actual distance and or baseline observations may slightly differ from the true value. Offsets are to be calibrated again before deployment.

Traceability on the exact configuration of these pairs and the distance/baseline measurements has to be secured. In such case, the introduction of a correction coefficient in measurements obtained with a different configuration will be possible.

The ISO 17123 standard defines field procedures for testing geodetic and surveying instruments, like EDM measurements to reflectors (Part 4), total stations (Part 5), GNSS field measurement systems in real-time kinematic (Part 8) and terrestrial laser scanners (Part 9). The measurement procedures prescribed in ISO 17123 aim at qualifying the precision and performance of the geodetic instrument and whether they are in agreement with their proper operating condition (Martin, 2008).

D. *Error Constituents in Deformation Monitoring*

Geodetic observations conducted by either total stations or GNSS are subject to errors. These errors may be divided to systematic and random.

Let us take the distance measurement using a light wave carrier EDM instrument. The systematic errors involve the EDM/prism zero error, the scale error, the signal refraction error and the EDM cyclic error. Random errors sources are pointing, centering, levelling and reading.

The uncertainty (σ) for distance (*S*) measurements made with EDM instruments may be expressed as an independent sum of individual error contributions:

$$\sigma_S^2 = \sigma_{res}^2 + \sigma_{cen}^2 + \sigma_{cal}^2 + \sigma_{ref}^2 \quad (1)$$

where: σ_{res} is the instrument resolution provided by the manufacturer, σ_{cen} is the centering error caused when the vertical axis of the instrument and the target is not coincident with the reference mark on the control point monument, σ_{cal} is the residual error after instrument calibration and σ_{ref} is the refraction correction error.

The atmospheric refraction error influences both the EDM and GNSS distance measurements. Changes in temperature, humidity and barometric pressure that have not been appropriately modeled may cause additional errors due to varying velocity of propagation of electromagnetic waves.

By the same token, the overall uncertainty in GNSS deformation monitoring may be expressed as (all terms as distance error):

$$\sigma_S^2 = \sigma_{sat}^2 + \sigma_{atm}^2 + \sigma_{site}^2 + \sigma_{rec}^2 + \sigma_{pro}^2$$

where σ_{sat} is the GNSS satellite induced uncertainties (clock bias, orbital errors, etc.), σ_{atm} corresponds to the atmospheric delay uncertainties, σ_{atm} refers to site dependent uncertainties, such as multipath reflections, satellite visibility, etc., σ_{rec} are the GNSS receiver uncertainties (clock bias, thermal noise, antenna phase center offsets, etc.) and σ_{pro} are the uncertainties associated with GNSS processing.

E. *Uncertainty budget estimation*

To evaluate uncertainty for the SI-traceable geodetic measurements in dam deformation monitoring, we have no means to revert each measuring generation mechanism to the absolute reference for the SI units [i.e., the speed of light, atomic time] for establishing all subsequent monitoring observations and their uncertainty.

We have to rely on a collection of information for calibrating instruments, such as: (1) previous measurement data, (2) experience with or general knowledge of the behavior and properties of relevant instruments, (3) manufacturer's specifications, (4) previous calibration or other certificates, and (5) uncertainties assigned to reference data taken from external sources, handbooks, etc.

In the sequel, we would conduct an exhaustive statistical investigation of every conceivable cause of uncertainty in the process of dam deformation monitoring, for example, by using different makes and kinds of instruments, diverse methods of measurements, various measuring procedures, and differing approximations and environmental conditions. The uncertainties associated with all of these contributions to distance measurement, for example, could be evaluated by a statistical investigation of series of observations and the uncertainty of each cause could be characterized by its measure of location (mean, median, etc.) and its measure of scale (i.e., standard deviation, range, bi-weight, quartile range, etc.).

The observations and measuring procedures followed to estimate the uncertainty in, for example, distance measurement in the field must be tied with fundamental metrology standards as far as possible.

The procedures described in the "ISO 17123 Standard" assess uncertainty of the final result but not of the each and independent contributions (components) of uncertainty. This may be sufficient for the dam monitoring operators. Nevertheless, other approaches may be followed to evaluate uncertainty for each uncertainty constituent. For example, a field procedure for assessing centering errors is proposed by Garcia-Balboa et al. (2018). Along these lines, best practices tailored for efficient dam monitoring with geodetic instruments along with uncertainty budget estimation are given in (US Army Corps of Engineers, 2018).

F. *Data Management, Archival and Documentation*

The collection of reliable data is crucial in any monitoring program for dam safety. These data have to be collected, archived, analyzed and evaluated in a secure and timely manner. Each measuring parameter shall be reported and stored in a database following a consistent format that will permit, preferably, automatic processing and determination of surface deformation results. Coefficients, calibration and characterization offsets, environmental conditions, and weights applied to estimate monitoring, as well as the way how these are to be traced shall be retained in the database.

Also, equipment observations and measurements shall be time-tagged using the same time reference (e.g., UTC time). The GNSS system time is proposed to be used for time tagging all observations in a uniform manner. The following Section presents a working example for uncertainty estimation for the "VALSAMIOTIS" Dam in Chania, Crete, Greece.

IV. THE VALSAMIOTIS DAM

The "Valsamiotis" dam is located [Lat: 35°26'30.12"N, Lon: 23°53'13.01"E] in the mainland of Crete, about 15km south-west of the city of Chania. Construction works for it were completed in 2014. It stores water as of 2014 primarily for irrigation. Table 1 presents technical and engineering characteristics of it. This is a gravity dam built with Roller-compacted concrete (RCC). The RCC is a composite construction material with no-slump consistency in its unhardened state, meaning that this RCC concrete is very dry. The main advantages of RCC type dams versus conventional gravity dams is speed of construction, better workability, and low price per unit of RCC material (MEKA, 2019).

Table 1. "Valsamiotis" Dam characteristics

Characteristic	Value
Owner	Organization for the Development of Crete S.A.
Purpose	Irrigation
Height [m]	67.5 m
Length [m]	335 m
Crest height above mean sea level	+190.20 m
Reservoir Capacity	6 ×10^6 [m^3]

The dam operator is obliged by the Greek National Law to design and implement a monitoring program for dam safety. This program defines the type, procedures and observation timeliness for efficient monitoring with specific instrumental observations. Deformation monitoring of the "Valsamiotis" dam is accomplished by a series of multi-disciplinary instruments, such as direct and inverted pendulums, settlement gauges, three-dimensional crack meters, joint meters, borehole extensometers, etc.

Geodetic monitoring is also carried out for horizontal and vertical deformation monitoring. Thirty permanent control benchmarks exist on the dam's crest to support spirit leveling to monitor vertical displacement. The fundamental benchmark of each such levelling survey is a secure point with known height above mean sea level, placed on stable bedrock.

Horizontal deformation has been monitored with a robotic total station (Leica TS15A) that supports automatic prism recognition. The manufacturer's specifications claim for an uncertainty in angle measurement of ±0.3mgon, display resolution 0.1mgon, and a standard uncertainty (68% probability) in distance measurement 1mm ± 1.5ppm with prism (Leica Geosystems AG, 2015). Four permanent geodetic pillars have been installed around the dam: Two reference ones (REF_1 & REF2) in the abutment, one upstream (REF3), and one (REF4) downstream (Fig. 2).

Figure 2: Location of reference pillars for monitoring in "Valsamiotis" dam.

Six permanent marking bolts have been installed on the crest of the dam to host monitoring prisms during a geodetic survey (Fig. 3).

Figure 3: Two of the permanent geodetice bolts installed on the crest that serve as target points for geodetic deformation monitoring.

Every month, an operational procedure is followed for monitoring deformation of this dam using all these control and reference points and ties.

Observations are then archived and evaluated by engineers responsible for this dam safety. According to their evaluation procedures, a suspicious incident is declared when two successive distance measurements of the same pair of total station and prism exceeds a specific threshold. The same holds true for any departure above a certain value for the orientation of a geodetic baseline. A combined evaluation of these geodetic results along with geotechnical instrument data records is carried out to conclude whether surface deformation has happened. In that case, and depending on the magnitude and nature of the observed movement, densification of measurements is carried out both in time and in space (more control points are observed).

A drawback of this procedure is that each monitoring instrument (geodetic, geotechnical, etc.) realizes its own reference system. This implies that it is not easy to directly and quantitatively compare displacements monitored by diverse instruments if they do not refer to the same reference system. However, as demonstrated in Barzaghi et. al., (2018), each pendulum on a dam realizes its own local reference system. Dedicated analysis is needed to define rotation angles and scale factors to permit cross-comparison of the pendulum and GNSS-derived deformation results.

Table 2. Uncertainty Budget Analysis for the "Valsamiotis" Dam

Constituent	Variance	Source
Slope distance	±1.75 mm	(Leica, 2015), Dist = 500m
Horizontal angle	±0.24 mm	(Leica, 2015), Dist = 500m
Centering error	±0.50 mm	Garcia et al., (2018)
Automatic Target Recognition	±0.68 mm	Wang et. al, (2015)
Monument Stability	±0.15 mm	Haas et. al., (2012)
Atmospheric correction	±0.15 mm	(Leica, 2015), Dist = 500m, RH=60%
Unaccounted effects (repeatability, scale error, index error, survey method, processing, etc.)	±10.00 mm	
Standard Uncertainty	13.47 mm	Assuming normal distribution
Combined Uncertainty	10.19 mm	Square root of sum of standard uncertainties

Table 2 presents a working example of the surface deformation uncertainty as carried out at the "Valsamiotis" dam. The guidelines followed are those given by the Bureau International des Poids et Measures (BIPM, 2008). This analysis cannot be considered complete as yet but it is presented here purely for demonstration. Further work must be performed to conclude on the overall uncertainty in geodetic deformation monitoring for this dam based on the strategy of Fiducial Reference Measurements (FRM) (Mertikas et al., 2019).

As a first step towards this FRM effort, absolute coordinates of the reference pillar have been calculated with respect to the center of the mass of the Earth. Because of security, power supply and environmental protection issues, it has not been possible to establish a continuously operating GNSS reference station at this dam. As a consequence, periodic GNSS campaigns are scheduled on a semi-annual basis in collaboration with the dam operator.

Absolute coordinates for the position of the fundamental reference pillar of the dam have been determined by GNSS static relative positioning and with respect to the "TUC2" permanent GNSS station installed inside the campus of the Technical University of Crete, Greece. This GNSS site has been part of the European Reference Frame (EUREF) network since 2004. Geodetic benchmarks and control points established by the Hellenic Military Geographical Agency (GYS) in the vicinity of the dam have been used in this investigation as well. All in all, the pillar's coordinates of the fundamental reference point for monitoring the "Valsamiotis" dam have been detrmined to be: Lat: 35°26'22.42884"N, Lon: 23°53'13.74520"E, Ellipsoidal Height: 228.408 m (WGS-84 Reference System).

Additionally, kinematic GNSS positioning has been performed for 3 days and on the reference pillar of the dam. Results indicated that the pillar's displacement lie within the limits of this GNSS processing for such short-term campaigns. Uncertainties have been determined to be ± 9 mm for horizontal coordinates and ±27 mm for heights (Fig. 4).

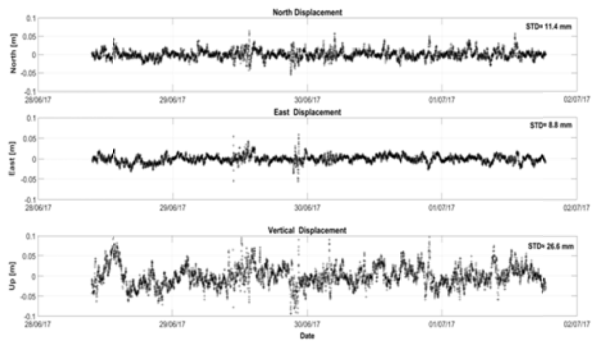

Figure 4: Two of the permanent control points installed on the Valsamiotis dam crest that serve as target points for geodetic deformation monitoring.

V. CONCLUSIONS

Structural deformation when monitoring dams involve precise observations with delicate geodetic and geotechnical instrumentation. The former measures the external deformation and away from the structure of the dam, whereas the latter instruments are commonly installed inside the structure and thus estimate its inner deformation.

In this work, various sources of uncertainty in geodetic monitoring techniques for dam deformation have been identified. The need to estimate the associated uncertainty for each constituent contributing uncertainty to the final monitoring results has been stressed and also recommended that the produced uncertainties and observations have to be connected to internationally agreed metrological standards (i.e., speed of light, atomic time). Also, geodetic and geotechnical observations must be tied to a common reference system and time to permit their integrated evaluation.

The following approach is recommended for efficient geodetic structural deformation monitoring:

Step 1: Define the measurand (i.e., monitoring distance) to be observed; its maximum expected displacement and the associated requirement for its uncertainty. This monitoring uncertainty is recommended, for example, to be one fourth of the maximum expected displacement (95% probability level) (US Army Corps of Engineers, 2018).

Step 2: Select instrumentation based on performance, reliability, accuracy, precision, cost, etc. Plan and design the observational scheme (quantity and location of instruments, geodetic technique, formatting and reporting, threshold to issue alert, etc.). Prefer using instruments employing diverse measuring principles (i.e., total station & GNSS) to reduce uncertainty and improve redundancy and reliability of observations. Benefit from global best-practices for the specific dam type and adapt them accordingly in your design.

Step 3: Define sources of uncertainty per instrument, method, processing, observational strategy and estimate (theoretically) the respective overall uncertainty (Type B uncertainty). Connect each component of uncertainty and its contribution to the final uncertainty for monitoring. If the uncertainty exceeds requirements (Step 1), then modify the design and/or instrumentation (Step 2) and re-estimate overall uncertainty.

Step 4: Characterize and calibrate all instruments before their deployment in the field. Confirm their performance based on, for example, ISO 17123 field procedures or adapt them to site's particularities.

Step 5: Estimate Type A uncertainty (real-life observations) and Type B (theoretical or previous knowledge) uncertainty and the respective combined uncertainty.

Step 6: Archive measurement and report uncertainties based on Step 2.

Step 7: Geodetic-derived displacements must be combined, connected and evaluated with other displacement sensors. Uncertainty of each sensor must be reported.

Step 8: Modify the geodetic monitoring scheme (Step 2) if needed to locate and investigate any source of displacement. Update uncertainty budget analysis accordingly.

This proposed roadmap (1) supports trustworthiness in scientific and monitoring data we produce and evaluate by expressing uncertainties following BIPM and FRM guidelines, (2) provides reliable information to dam operators and the Public for safety, and (3) helps us make the right decisions, and put into action the right policies for structural deformation monitoring of large structures.

A working example has been given on how uncertainty for each error contributors is estimated. A case has been presented for the "Valsamiotis" dam in west Crete, Greece.

Redesign of current practices in geodetic monitoring of the "Valsamiotis" dam is highly recommended. This is because this preliminary analysis demonstrated that the overall uncertainty may be significantly reduced if an improved monitoring scheme is selected.

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