

The Monitoring of Gravity Dams: Two Tests in Sardinia, Italy

Riccardo BARZAGHI, Livio PINTO and Riccardo MONACI
DIAR-Politecnico di Milano, Italy

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SUMMARY

Dams are important civil engineering structures which require careful monitoring. It is therefore essential that these structures are controlled by means of monitoring networks. In this paper, it was first characterized the deformation behavior of a dam on the basis of pendulum observations. This analysis has been done for two dams located in Sardinia, the Genna Is Abis and the Cantoniera dams. These two structures have crests of relevant linear dimensions (1295 m and 582 m respectively). The characterization of the deformations has been made through the estimation of appropriate analytical models that depend on time, on the reservoir water level and/or other physical variables, such as air and water temperatures. All models were able to reproduce the pendulums data with residuals having a standard deviations less than one millimeter. The second aim of this study was to test the GNSS technology for controlling the dam deformations. To this end, the reference deformation model deduced from pendulum observations was compared with the estimated displacements derived from GNSS observations. This was done in two points of the Genna Is Abis dam that are in correspondence to two pendulums set up into the structure. The comparison gave very positive results because the standard deviations of the residuals between model derived and GNSS deformations is less than one millimeter. These encouraging outcomes open new perspectives in the study of deformations of structures. As a matter of facts, to complement the monitoring instrumentation used to date, it will be possible to consider the GNSS technology that has operational properties (high data acquisition rate, automatic data processing) that can be profitably used for optimizing the estimation of the ongoing deformations.

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1. INTRODUCTION

As any other important civil infrastructure, large dams need monitoring systems in order to control the structure and prevent critical situations that can occur (Cazzaniga et al., 2006; Kaloop et al., 2009). Key factors for a high quality and reliable control network are adequate spatial density and correct position of observation instruments, as well as high level of accuracy (Carosio and Dupraz, 1993; Gikas and Sakellariou, 2008). As a matter of fact, the amount of most significant dam safety indicators (i.e. crest displacement, joints opening and ashlar lining) is small, of the order of magnitude of few millimeters. Pendulums and extensometers are suitable control instruments since they can provide such measurement precision, provided that they are periodically adjusted and maintained. Also, their installation has to be planned in the original project of the structure: adding one or more pendulum chambers to an existing dam is in fact a very difficult operation that involves complex technical problems and also relevant costs.

Optical collimation systems are often used in combination with pendulums. However, they have heavy shortcomings when used on barrages having a remarkable length. Like any other optic instrument, on long distances, they are strongly affected by refraction biases.

GNSS systems can be an interesting option since they can be easily installed on the dam crest and can attain the required precision if daily solutions are estimated.

Another crucial aspect in deformation monitoring is data analysis and modeling. Since small displacements are expected over a long time span, a careful data handling must be performed. This implies procedures for outliers detection and filtering and proper modeling of the observed data.

This is a critical step, because all the relevant information must be properly extracted from the recorded data in order to check for the dam stability.

In this context, modeling is a powerful tool because it provides the analytical description of the collected data. The best fit model can be profitably used for describing the dam deformation pattern to be considered as a benchmark for identifying anomalous behaviors.

In this paper, the data analysis and modeling on two gravity dams located in Sardinia is presented. They are the Genna Is Abis dam (Fig. 1) and Cantoniera dam (Fig. 2).

The first considered structure is Genna Is Abis, a gravity dam 26 m high and 1295 m long on Rio Cixerri, a torrential river whose waters are collected in a basin of 32 Mm³ for drinking water supply, irrigation and flood lamination.

The structure was built close to Cagliari. It is composed by 85 ashlar, 6 m wide each, and has a complex monitoring network with 161 extensometers, a collimation system and two pendulum chambers (located in ashlar 5 and 43/9). In this work, only pendulum data have been considered because of their high accuracy and reliability. Each chamber contains two optical pendulums (a direct instrument and an inverted one) that measure upstream –

downstream crest displacements with respect to the foundation and whose accuracy is 0.02 mm.

The second analyzed dam, the Eleonora D' Arborea or Cantoniera dam, is larger than Genna Is Abis. It is 100 m high and 582 m long, and impounds waters from the Tirso river creating the Omodeo Lake, one of the largest artificial basin of Europe (at full capacity it will contain 792.84 Mm³ of water). This huge storage will be used for irrigation, drinking water supply and hydroelectric energy generation.

Cantoniera is a hollow gravity dam composed of 38 ashlars, 15 m long and 4 m wide each, and controlled by 90 extensometers, 122 mono-axial and 4 tri-axial joint-meters.

14 critical points of the structure are also equipped with pendulum chambers, inside which two optical instruments (accuracy of 0.01 mm) are installed.

Both Genna Is Abis and Cantoniera have sensors for air and water temperature, and hydrometers for water level detection.



Fig. 1. Aerial view of the Genna Is Abis dam.

Fig. 2. View of the Eleonora d'Arborea dam.



2. MODELING THE PENDULUM TIME SERIES

Analytical models are fitted to observed data in order to properly describe them. They contain parameters that are usually estimated applying the least squares principle. Proper models must be proposed that can describe the actual data. In investigating dam deformations, we are interested in understanding how the barrage reacts to external stress and which phenomena mostly influence the crest displacement. To this aim, pendulum observations are very important but, in order to get reliable results, data time series must be long enough to allow estimating long term periodicity deformations.

Genna Is Abis pendulum data satisfy this condition, since they extend over 20 years with monthly recorded crest displacements. Eleonora D'Arborea data series are good too because, even if shorter (observations cover a period of 6 years, from 2005 to 2011), they have a daily time resolution.

A wide literature can be found on dam modeling, providing also effective models adjusted on experimental data.

De Sortis and Paoliani (2007) proposed a successful formulation for hollow buttress gravity dams. According to their model, upstream – downstream crest displacement S is composed of three terms:

$$S = S^T + S^Q + S^A \quad (1)$$

Specific expressions for each component are:

$$S^T = c \cdot \cos\left(\frac{2\pi t}{365}\right) + d \cdot \sin\left(\frac{2\pi t}{365}\right)$$

$$S^Q = e \cdot H + f \cdot H^2$$

$$S^A = a \cdot t + b$$

where t is the time in days, and H is water level above foundations. S^Q represents the influence of hydrostatic pressure on dam upstream face and S^A a linear trend produced by non reversible strain process and other unexpected behavior.

The harmonic components S^T are related to periodic displacements of the dam crest which are mainly due to thermal expansion. They are caused by the differences between air and water temperature throughout the year. In summer, the reservoir temperature is lower than that of the air causing the dam to expand opposite to downstream direction. In winter, the opposite deformation happens due to the higher temperature of the reservoir with respect to the air temperature.

Resulting displacement is expressed in millimeters and coefficients a, b, c, d, e, f are estimated using the least squares minimum principle.

This analytical expression has been applied to describe Genna Is Abis and Cantoniera pendulum data. As an example, Fig. 3 compares recorded data of ashlar 5 in Rio Cixerri dam with fitted De Sortis - Paoliani model. In the plot, positive values are crest displacement to downstream direction. This chart shows the remarkable agreement between the fitted model (orange line) and the pendulum data (blue dots). The *a posteriori* estimated standard deviation is 0.54 mm. A similar precision level is reached also in the Rio Cixerri dam ashlar 43/9 where the *a posteriori* estimated standard deviation is 0.68 mm.

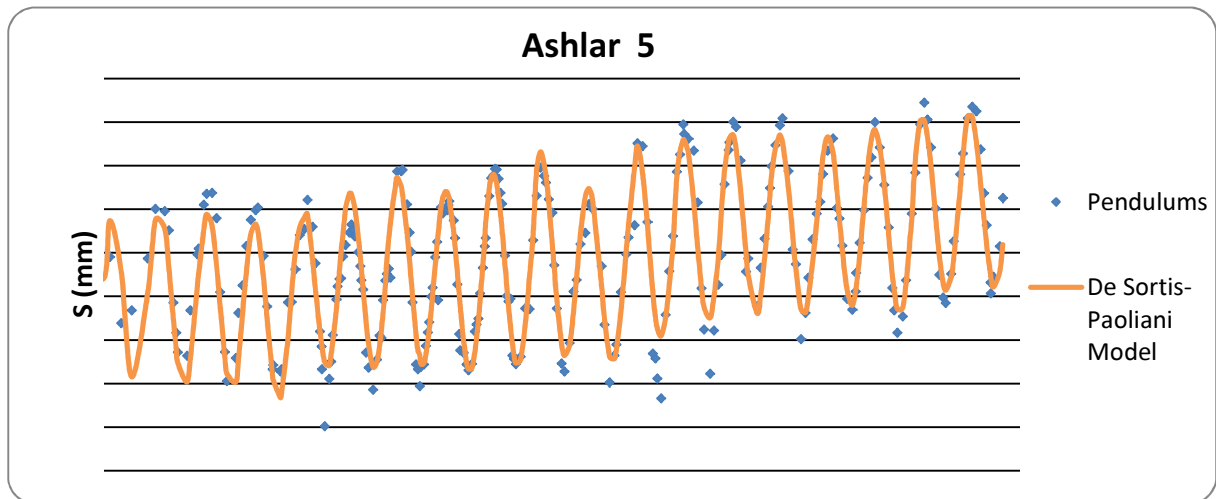


Fig. 3. Upstream - downstream crest displacement for Genna Is Abis dam ashlar 5 - De Sortis - Paoliani Model.

De Sortis-Paoliani model is hence a proper model for the two examined dams. To get a deeper insight in the time behavior of the Genna Is Abis dam, we proposed a model where the period T is not necessarily fixed to 365 days as in the De Sortis-Paoliani model and a suitable number of harmonic components are included. Also, since no relevant water level variations H were present in our data, we simplified the model by removing the S^Q term (Gaetani, 2008). The new proposed model is then

$$S = a \cdot t + b + \sum_{k=1}^n A_k \cos\left(\frac{k\pi t}{T}\right) + B_k \sin\left(\frac{k\pi t}{T}\right) \quad (2)$$

where period T is estimated from the data.

This can be done via Fast Fourier Transform (FFT) analysis on the data. In Fig. 4 the FFT spectrum of ashlar 5 pendulum data of Genna Is Abis dam is presented.

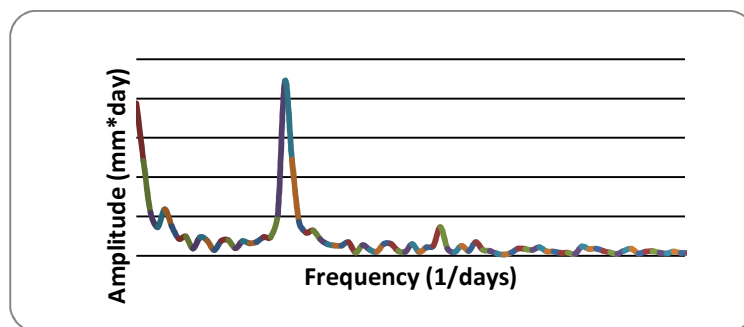


Fig.4. Fourier Spectra for ashlar 5 in Genna Is Abis dam, upstream - downstream direction.

The Fourier spectrum of the data contains two main peaks, one in the origin and the second at $f = 0.00273 \text{ days}^{-1}$. The maximum in the origin is due the spectral response of the mean of the

data. The second maximum corresponds to a period $T_1=366$ days, nearly the 365 days period that is used in the De Sortis-Paoliani equation. Another feature of the spectrum is the third peak, much smaller than the previous two, which occurs at $f = 0.00555 \text{ days}^{-1}$ and accounts for a periodic signal having a period $T_2=180$ days. This behavior is basically the same in all the time series that we analyzed. Thus the selected model was

$$S = a \cdot t + b + A \cdot \cos\left(\frac{2\pi t}{T}\right) + B \cdot \sin\left(\frac{2\pi t}{T}\right) + C \cdot \cos\left(\frac{4\pi t}{T}\right) + D \cdot \sin\left(\frac{4\pi t}{T}\right) \quad (3)$$

with $T=365$ days.

The model was least square fitted with the data and proved to be in good agreement with all the considered pendulum time series. As an example, we plotted in Fig. 5 the model and the data for the Cantoniera 19 ashlar.

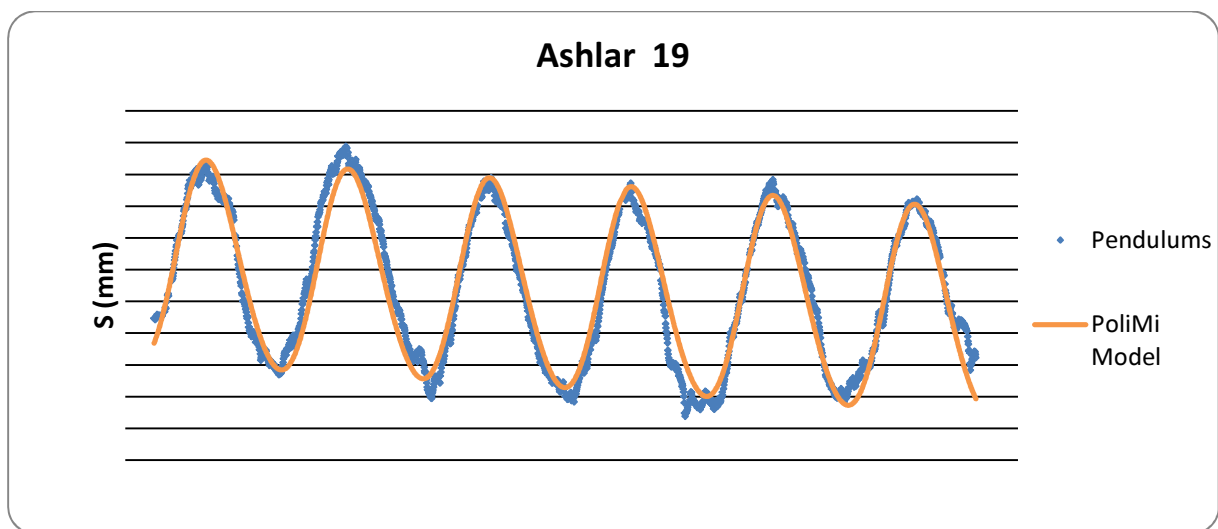


Fig. 5. Upstream - downstream crest displacement for Cantoniera dam, ashlar 19

The *a posteriori* estimated standard deviations from least squares adjustment over the analyzed set of Cantoniera dam ashlar are listed in Tab.1

Ashlar	7	13	19	31
$\sigma(\text{mm})$	0,29	0,38	0,54	0,37

Tab. 1. The estimated *a posteriori* standard deviations of the Cantoniera ashlar

Same statistics were also found in Genna Is Abis ashlar: 0.53 mm and 0.73 mm in ashlar 5 and 43/9 respectively.

Thus, it can be stated that the De Sortis-Paoliani model and the one tuned by FTT analysis gave the same results as the differences in the *a posteriori* estimated standard deviations are not significant. This proves also that the $T_2=180$ days period is not so relevant in the model. Nevertheless, in general, it seems advisable to perform the FFT analysis to solve for any existing harmonic component present in the data.

Another model was further tested which takes into account the explicit relationship with the physical observed variables affecting the dam deformation. In the previous models the basic variables are the water level H and the time t which accounts for the temperature variability. The observed physical quantities usually available that can be considered are the water and the air temperatures and the water level H . In order to prove that these quantities have an impact on the dam crest displacements, correlations between them and observed crest displacements can be computed. In Tab. 2 and Tab. 3 these correlations are evaluated for the Genna Is Abis and Cantoniera dam respectively.

	Ashlar 5	Ashlar 43/9
Air temperature	-0,64	-0,74
Water temperature	-0,78	-0,85
ΔTemp (Air-Water)	0,22	0,15
$T_{ave-water}$	-0,82	-0,88
Water level H	0,32	0,30

Tab. 2. Genna Is Abis dam: estimated correlation coefficient between crest displacement, temperature and water level.

	Ashlar	Ashlar	Ashlar	Ashlar
Air temperature	-0,59	-0,53	-0,48	-0,60
Water temperature	-0,84	-0,81	-0,77	-0,86
ΔTemp (Air-Water)	0,31	0,32	0,34	0,27
$T_{ave-water}$	-0,89	-0,88	-0,83	-0,91
Water level H	0,77	0,75	0,81	0,73

Tab. 3. Cantoniera dam: estimated correlation coefficient between crest displacement, temperature and water level.

The estimated correlations show that dam crest displacements depend highly on water temperature or on the water temperature average computed on a moving average of 15 days (see also Fig. 6).

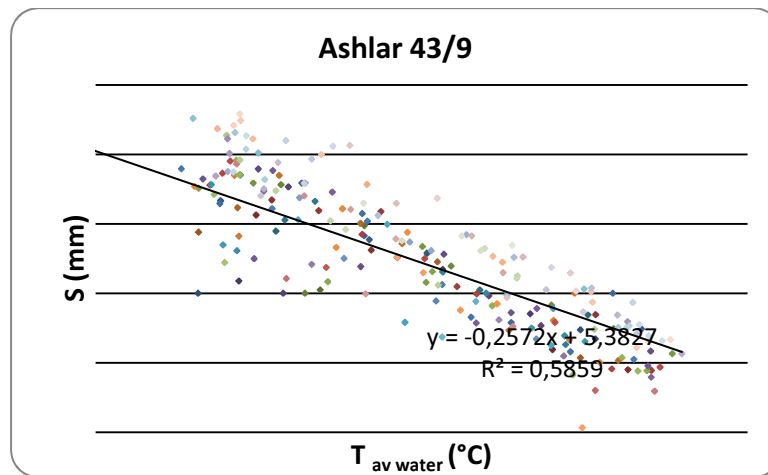


Fig. 6. Linear regression between crest displacement S and $T_{av\ water}$

Furthermore, a significant correlation exists with respect to air temperature. On the contrary, crest displacements are only slightly correlated with the difference between air and water temperatures. Finally, as it holds also for the two models previously presented, the water level H has a relevant impact on crest displacements (this is not the case of the Genna Is Abis dam since no H variations occurred during the considered period). This analysis led to the definition of the following model

$$S = aT_{av\ year\ air} + bT_{av\ water} + cH + dH^2 + e \quad (4)$$

The model depends directly from the two basic physical observed quantities that have an impact on the crest displacement S . $T_{av\ year\ air}$ is annual average of the daily air temperature, $T_{av\ water}$ is the two weeks moving average of the water temperatures and H is, as always, the water level. The model has been set as a function of averaged temperatures in order to regularize these observed values and define a smooth model behavior.

This model has been least squares fitted on both dams data with satisfactory results. As an example of the model fit, we plotted in Fig. 7 the pendulum upstream – downstream observations of Cantoniera 31 ashlar and the fitted model. Also in this case, we got a reasonable agreement with the observed data even though the model is less regular than those previously considered. This is basically due to its structure which depends on data too that can have irregular behaviors even if they have been averaged.

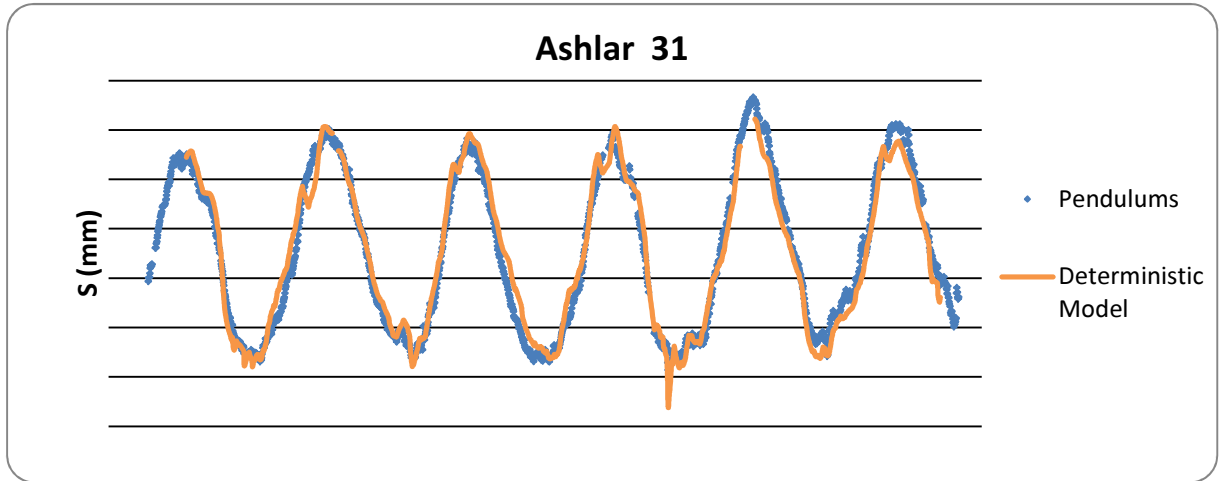


Fig. 7. Upstream - downstream crest displacement for Cantoniera dam, ashlar 31

Statistics of the *a posteriori* estimated standard deviation for the available data are listed in Tab. 4 and Tab. 5.

Ashlar	7	13	19	31
$\sigma(\text{mm})$	0,27	0,33	0,50	0,30

Tab. 4. The estimated *a posteriori* standard deviations of the Cantoniera ashlar

Ashlar	5	43/9
$\sigma(\text{mm})$	0,66	0,73

Tab. 5. The estimated *a posteriori* standard deviations of the Genna Is Abis ashlar

As a final remark on the presented analyses, we can say that the different tested models have the same degree of accuracy in fitting pendulum data. However, the De Sortis-Paoliani model does not depend directly on temperature data T (or on some kind of average of T itself). The dependence on temperature is through time t and thus this model, once tuned on a set of data, can be extrapolated in the future in an easier way (provided that H is given). In the next paragraph, we use this model (or its simplified version (3)) as a benchmark for testing a possible application of GNSS methodologies in dam deformation analysis.

3. ESTIMATING DAM CREST DIPLACEMENTS USING GNSS

The previous analysis based on pendulum observations showed that points along the dam crest have maximum displacements in the upstream-downstream direction that amount to few millimeters. Furthermore, the recorded displacements are periodic in time with main period which is around one year.

As a matter of fact, monitoring instruments need to be of great accuracy and precision, like pendulums and extensometers that are currently used in detecting dam deformations. (collimators that are also used can't give enough precise observations on long distances and their use must be carefully planned). However, pendulums are difficult to install on existing dams. In order to install them one has to dig in concrete and ground foundation (often rock) to create chambers, access galleries and anchoring holes for the instrument wires. These operations must be carefully designed not to compromise dam safety and stability conditions. GNSS technology could represent an interesting alternative because satellite receivers could be installed on dam crest easily (Ehiorobo and Irughe-Ehigiator, 2011). No modifications of the internal dam structures is required and the GNSS antenna mount pillar can be set up in a fast a cheap way. Furthermore, GNSS data collection and analysis can be performed automatically and reliable 3D daily coordinates can be estimated (Rutledge et al., 2006). In order to use GNSS technology in dam control, a key issue is the evaluation of the attainable precision. To prove the feasibility of this method, we designed and devised a GNSS network on the Genna Is Abis dam. This network was established in 2007 and it is based on six double frequency GNSS Leica GMX902 receivers, equipped with AX1202GG antennas. Four of them are located on the dam crest at A, B, C and D points, as it is shown in Fig. 8. REF1 and REF2 are master stations that were monumented, in the dam neighborhood, on an existing reinforced concrete structure and on bedrock respectively.

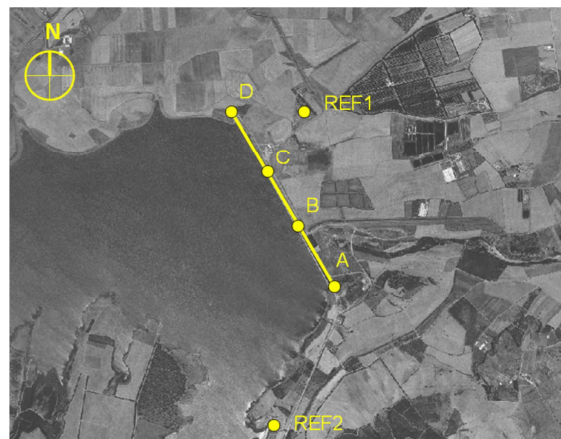


Fig. 8. Genna Is Abis dam: the GNSS monitoring network

B and C points have been placed on ashlar 5 and 43/9 respectively, in order to compare GNSS recorded displacements with pendulum observations.

GNSS data were collected over one year at a sampling rate of 15" and cut-off angles of 15°. They have been processed with LEICA Geo Office software on a daily basis, considering REF1 and REF2 as fixed points. In this way the daily coordinate time series of points A, B, C

and D were estimated. After reference system transformation, these coordinates were given in the upstream-downstream direction and then compared with the model displacement derived from pendulum observations, namely that of equation (3). In Figures 9 and 10 the GNSS estimated crest displacements of ashlar 5 and 43/9 in the upstream-downstream direction are plotted together with the model coming from pendulum observations.

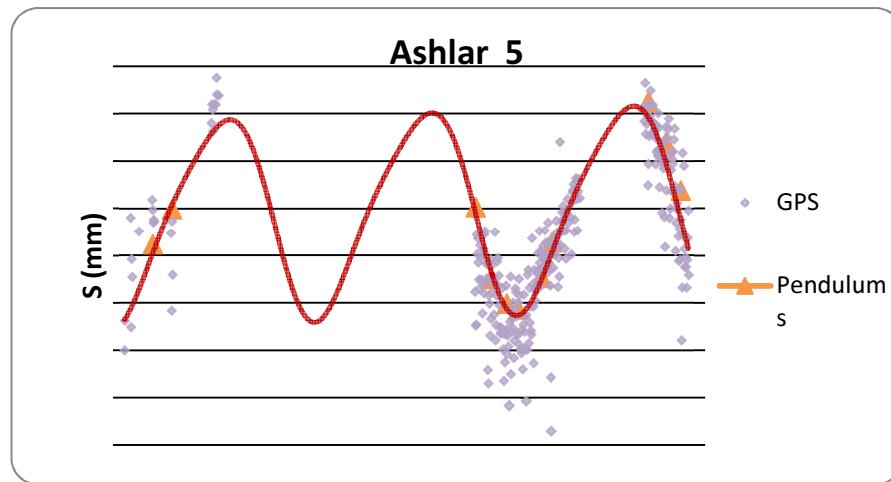


Fig. 9. Genna Is Abis dam: GNSS estimated and pendulum model displacements on ashlar 5

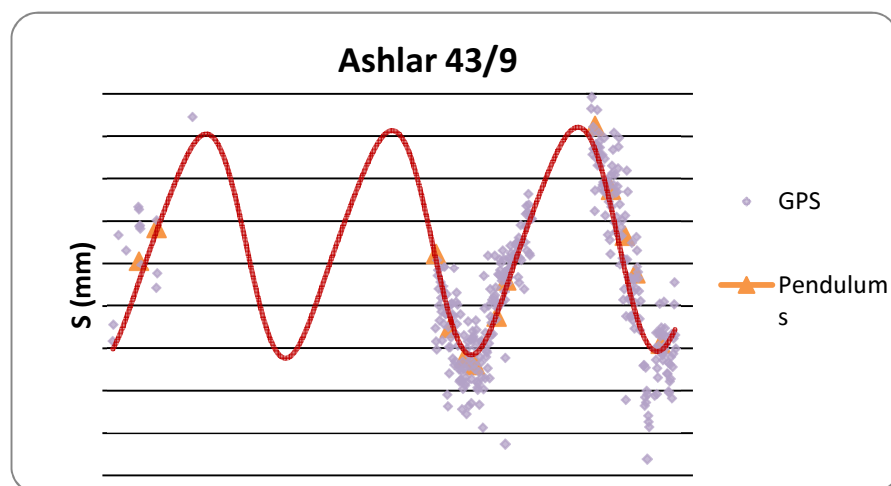


Fig. 10. Genna Is Abis dam: GNSS estimated and pendulum model displacements on ashlar 43/9

The standard deviation of the differences between the pendulum model and the GNSS estimated displacements are collected in Table 6.

Ashlar	5	43/9
$\sigma(\text{mm})$	0,80	0,87

Tab. 6. The standard deviations of the difference between pendulum model and GNSS estimated displacements for the Genna Is Abis 5 and 43/9 ashlar.

The obtained results are surprisingly good and proves that GNSS coordinate time series on short baselines (around two kilometers) can attain a precision of the order of 1 mm (in the horizontal components). It can be thus concluded that GNSS technology can be profitably applied in dam monitoring.

These encouraging results could be reasonably obtained also on the Cantoniera dam where GNSS are going to be monumented. In order to optimize the network design, we evaluated the crest displacement pattern of this dam by inspecting the pendulum observations collected since this dam was built. In the analysis, all the existing pendulums were considered and for each pendulum the model (3) was estimated. In Figure 11, the estimated A and B parameters contained in the model are plotted as a function of the ashlar/pendulum numbers (starting from one side of the dam to the opposite, see also Figure 12). Their distribution can be fitted by the following parabolic model

$$X = R \cdot N^2 + S \cdot N + T \quad (5)$$

where N is the progressive ashlar number (from side to center to opposite side) and X are either the estimated A or B parameters (see Figure 11).

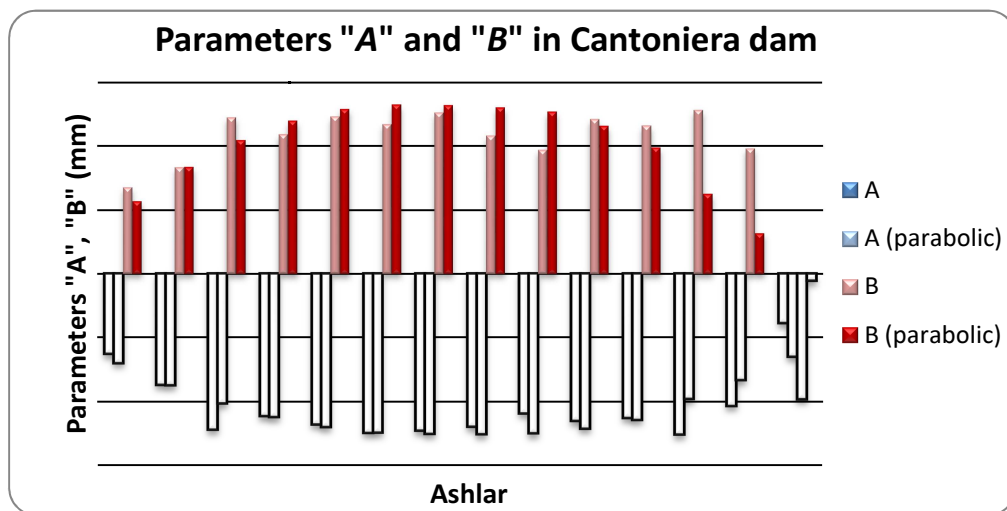


Fig. 11. Observed and modelled A and B coefficients in the Cantoniera dam

The largest displacements are, as expected, in the central part of the dam crest while close to the sides small deformations are observed. According to this analysis and to the experience acquired in the Genna Is Abis dam, GNSS network for Cantoniera dam has been designed. Five receivers are planned on the dam crest and two master stations (REF1 and REF2) are set

on bedrock at a distance of the order of 2 km (see Figure 12). The number of receivers on the dam crest allows a detailed description of the crest deformation according to the deformation structure as derived from pendulum observations. While GNSS in the central part of the crest allow monitoring the maximum crest displacements, GNSS on sides are important for detecting relative movements between the dam and the sides of the basin. Furthermore, all GNSS receivers are placed in correspondence of pendulum devices so that a cross-check will be possible.



Fig. 12. Cantoniera dam: the planned monitoring GNSS network

4. CONCLUSIONS

The analysis of the pendulum observations coming from the installed devices at Genna Is Abis and Cantonier dams (Sardinia Island) led to the definition of possible analytical models able to describe the crest point displacements. As expected, the main displacements occur at central crest points while points close to the sides of the dam have smaller position variations. Different models have been set up which depend on time t and/or physically observed quantities, such as water and air temperatures. Model parameters have been estimated via least squares using all the available data (in some cases for a time span of nearly two decades). The proposed models fit properly the data having *a posteriori* estimated standard deviations which are, for all the tested model, smaller than 1 mm. The main feature of the estimated deformation is given by a periodic term having a maximum amplitude of 3-4 mm and a period of nearly one year. Smaller components are related to semi-annual terms and linear drifts that are however negligible. These investigations were then used to prove the feasibility of GNSS technology in monitoring the dam crest deformations. GNSS coordinate time series were estimated in two Genna Is Abis dam crest points which are set in correspondence of two pendulum devices. The agreement between GNSS estimated and pendulum derived displacements is extremely good being the standard deviations of the residuals less than 1 mm. This proves that, having fixed reference points in a short distance (less than two kilometers), one can get baseline precisions in the daily baseline estimates

that are suitable for monitoring deformations of the order of some millimeters. This opens new interesting perspectives in designing control networks for detecting slow deformations of civil engineering structures (dams, bridges and so on). The GNSS technology can be used together with other techniques to improve monitoring and alarm systems of these structures. The integration of different sensors having the same level of precision and the proper modeling of the observed data is a key issue for designing effective control networks able to detect in due time possible existing critical deformations.

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BIOGRAPHICAL NOTES

Riccardo Barzaghi

Full Professor of Surveying at Politecnico di Milano. His main research interests are in Physical Geodesy, Satellite Geodesy and GPS networks for positioning and deformation analysis.

Livio Pinto

Associate Professor of Surveying at Politecnico di Milano. His main research interest are in Aerial and Close range Photogrammetry, GPS networks for positioning and structural monitoring.

Riccardo Monaci

Engineer, graduated at the Politecnico di Milano discussing his thesis on geodetic monitoring of civil engineering structures.

CONTACTS

Prof. Livio Pinto
DIIAR-Politecnico di Milano
Piazza Leonardo da Vinci 32
20133 Milano
ITALY
Tel. +3902239965
Fax + 390223996530
Email: livio.pinto@polimi.it
Web site: www.diiar.polim.it