GNSS methods in dam monitoring: case studies and future perspectives

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Abstract. GNSS receivers are nowadays commonly used in monitoring applications, e.g. in estimating crustal and infrastructure deformations. This is basically due to the recent improvements in GNSS instruments and methodologies that allow high precision positioning, 24h availability, semi-automatic data processing.
In this paper, we use GNSS technique to monitor dam deformation behavior comparing results with outcomes from pendulum observations that thanks to their reliability and high accuracy can be considered as reference. The study has been carried out for two dams in Sardinia: the Genna Is Abis on Rio Cixerri, and the Eleonora D'Arborea called also Cantoniera dam. Appropriate analytical models of dam deformation depending on time, reservoir water level, air and water temperature have been estimated using pendulum data (for Genna Is Abis dam) and GNSS data (for Cantoniera dam). Both reference models were able to properly fit respectively pendulum data and GNSS data, with standard deviation of residuals lower than one millimeter. Furthermore the Genna Is Abis reference deformation model deduced by pendulum was compared with estimated displacement from GNSS observations and standard deviation of the residuals was still lower than one millimeter. For the send model estimated at Cantoniera dam the comparison with pendulum data gave residual with mean around zero and standard deviation of lower than two millimiter.
These encouraging outcomes open new perspectives in the study of deformations of structures that foresee the GNSS technique as complementary monitoring instrumentation especially for medium-long time intervals.

Keywords. Dam, monitoring, GNSS, pendulum. modelling

1 Introduction

Accurate monitoring of dam deformations is an important task, allowing an effective warning system. It's used to carry out dam monitoring by different kind of instruments, like spirit leveling, collimators, clinometers, extensometers, pendulums etc. However, in most of the cases these surveys can be performed infrequently and just in very few points of the dam itself, being time-consuming and/or expensive. A rather cheap continuous deformation monitoring can be carried out installing some GNSS (Global Navigation Satellite System) devices on the structure. It was proposed to apply this method for dams monitoring already by DeLoach (1989), when GPS (Global Positiong System) was not completed yet. Nowadays there are few examples on real dams. Behr et al. (1998) analysed the time series (covering almost 3 years) obtained from two recording GPS stations respectively located on the left abutment and on the arc centre of the Pacoima Dam (California). They demonstrated the applicability of continuous GPS to the field of structural monitoring. Rutledge et al. (2006) analysed the measurements of six GPS monitoring stations installed on the crest of the Libby Dam (Montana). Four of them were installed coincident with existing gravity-based plumb lines and then their horizontal results were directly compared. The correlation analysis demonstrated a high level of agreement between the two systems, providing evidence that GPS is suited for long-term performance monitoring of dams. Barzaghi et al. (2012) studied the time series of data collected by four GNSS devices located on the crest of the Genna Is Abis Dam (Italy) demonstrating that coordinate time series on short baselines can attain a precision on the order of 1 mm along the horizontal components. Lastly, Dardanelli et al. (2014) considered the GNSS time series collected during few months on the Castello Dam (Italy), achieving an accuracy of few mm and highlighting the relation with the water surface level derived from remote sensing.
The objective of this paper is on one side to characterize deformations with an appropriate analytical model (depending on time, on the

reservoir water level and/or other physical variables, such as air and water temperatures) and on the other side to strengthen the GNSS technique for dam controlling deformation with high accuracy.

In the next section we describe the two dams and used instrumentations that are the object of this study. In Section 3 we describe the case of Genna Is Abis dam where the reference deformation model was deduced from pendulum observations and it was compared with the estimated displacements derived from GNSS observation. The results 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)

As second test case we describe the study carried out at Eleonora D'Arborea dam where, on the opposite, the predictive model has been estimated using GNSS data and this was compared with deformation estimated by pendulum. Residuals had a mean of -0.13 mm and a standard deviation of 1.7 mm. It is also outlined that the linear model used to bring the pendulum height on the crest of the dam needs further investigations that could require a non-linear model.

2 Study cases: Genna Is Abis and Cantoniera dams

This paper concerns deformation study of two dams located in Sardinia (Italy). The management of the dams is carried out by ENte Acque Sardegna (ENAS) who provided the monitoring data, and ancillary information on the dam structures. One of the dams is named Genna Is Abis, it is a gravity dam 26 m high and 1295 m long on Rio Cixerri. Waters of this torrential river are gathered in a basin of 32 Mm^3 to provide drinking water, to irrigate agricultural fields and as a basin lamination in case of flood. The dam structure is shown in Figure 1, it was built close to Cagliari and is composed of 85 ashlars (each one 6 m wide). It is provided by a monitoring network of 161 extensometers, a collimation system and two pendulum chambers (located in ashlars 5 and 43/9).

Among all the non GNSS monitoring systems installed on the two dams we consider only pendulum data due to their high accuracy and reliability. At Genna Is Abis dam there are two optical pendulums (one direct and one inverted) measuring upstream and downstream crest displacements with respect to the foundation, with an accuracy of 0.02 mm. Six GNSS Leica GMX902 (double frequency receivers) equipped with AX1202GG antennas were installed to establish a monitoring system in 2007. The system was designed locating four GNSS receivers on the points A, B, C and D along the dam crest. Master stations REF1 and REF2 were positioned in the dam neighbourhood, one on a reinforced concrete structure and one on bedrock (see Figure 1). In order to compare displacements obtained by GNSS and by pendulum the two points B and C were placed on ashlars 5 and 43/9 respectively.

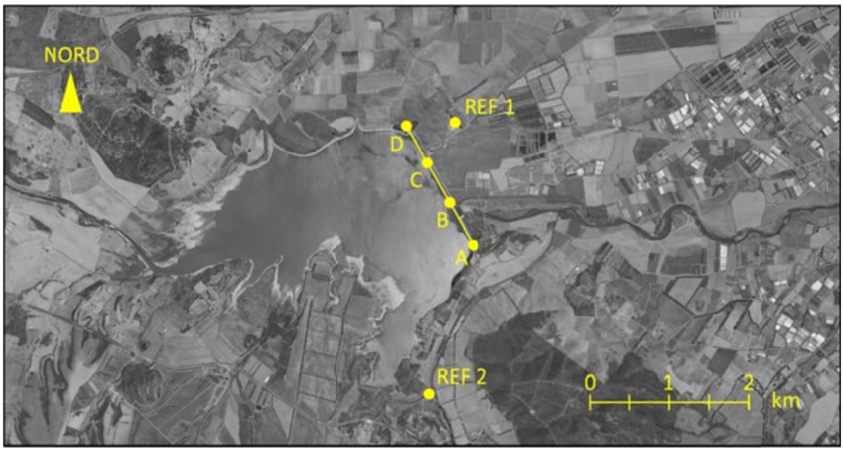

Fig. 1 Genna Is Abis dam (Cixerri Rio) with the GNSS monitoring network (credit by ENAS).

Daily coordinate time series of points A, B, C and D were estimated by GNSS data collected over one year (sampling rate 15" and cut-off angles 15°). Raw data were processed using LEICA Geo Office software using REF1 and REF2 as reference points (coordinates were kept fixed) and the baselines to the A, B,C and D points were estimate (single-base). With adjustment of all baselines daily coordinates of the points A, B, C and D. were estimated. These coordinates, after a reference system transformation, were calculated in the upstream-downstream direction. This allowed to compare estimated GNSS displacements with derived pendulum displacements that we considered as reference model due to their high accuracy.

The second dam, called Eleonora D'Arborea or Cantoniera dam, is larger than Genna Is Abis dam (100 m high and 582 m long). It collects waters from Tirso river forming the Omodeo Lake. This is one of the largest artificial basin of Europe (full capacity is 792.84 Mm^3 of water). This huge storage is used for irrigation, drinking water supply and hydroelectric energy generation. Cantoniera is an hollow gravity dam composed of 38 ashlars (each 15 m long and 4 m wide). It is monitored by 90 extensometers, 122 mono-axial and 4 tri-axial joint-meters. Points in a number of 14 are considered critical points of the structure. They are equipped with pendulum chambers, having installed two optical instruments (0.01 mm accuracy).

The monitoring GNSS network is composed of three permanent stations located on benchmarks outside the dam. In correspondence of ashlars number 6, 14, 24, 29, 31 and 35 there are six rover stations. They are placed on the crest, on significant points of the dam structure. For the ashlars number 14, 24 and 35 GNSS receivers (Leica GMX902 with AX1202GG antenna) were installed. First data became available from the August 5, 2013. The remaining three ashlars were equipped with GNSS receivers during the subsequent year; observations were provided starting on November 5, 2014.

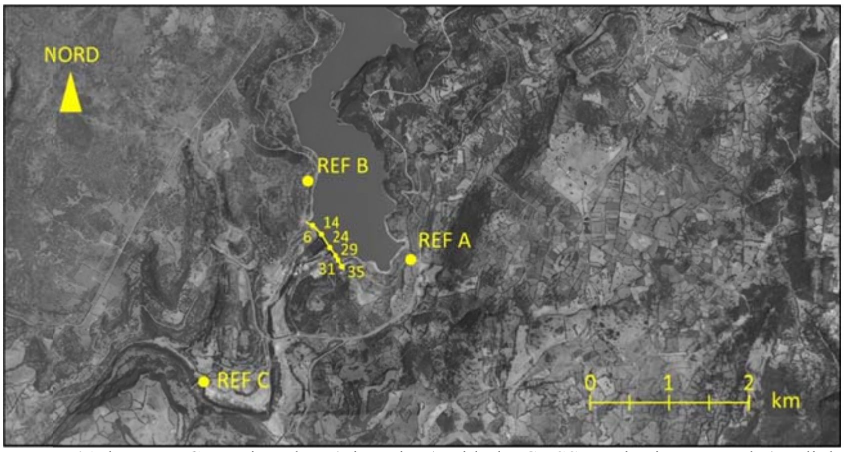

Fig. 2 Eleonora D'Arborea or Cantoniera dam (Tirso river) with the GNSS monitoring network (credit by ENAS).

Daily coordinates time series were estimated in the upstream-downstream direction the model displacements was derived from the GNSS observations and it was compared to pendulum observations.

Genna Is Abis and Cantoniera are also equipped with meteorological sensors monitoring air and water temperature, and with hydrometers for water.

3 Test Description

Main objective of dam deformation investigations concerns how the barrage reacts to external stress and which phenomena mostly influence the crest displacement. In the following comparison GNSS and pendulum data are analysed

3.1 Pendulum time series modelling and comparison with GNSS

Proper models must be proposed that can describe the actual data. Time series must be long enough to allow estimating long term periodicity deformations. Since Genna Is Abis dam disposes of over 20 years with monthly recorded crest displacements, we choose such dam to model time series pendulum and compare the model with GNSS point estimates.

Effective models adjusted on experimental data are also very important. For our analysis we have used a formulation proposed by De Sortis and Paoliani (2007). We modified the model by performing a FTT analysis to solve for any existing harmonic component present in the data. The model was least square fitted with the data and proved to be in good agreement with all the considered pendulum time series.

The *a posteriori* estimated standard deviations from least squares adjustment over the analysed set of Genna Is Abis ashlars are 0.53 mm and 0.73 mm in ashlars 5 and 43/9 respectively. Therefore the model reproduced the pendulums data with residuals having a standard deviations less than one millimetre.

Comparing this model with GNSS estimates we obtained (see Table 1) that the standard deviation of the differences between the pendulum model and the GNSS estimated displacements are also below one millimetre.

Table 1. The standard deviations of the difference between pendulum model and GNSS estimated displacements for the Genna Is Abis 5 and 43/9 ashlars

Ashlar	σ[mm]
5	0.80
43/9	0.87

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

3.2 GNSS time series modelling and comparison with pendulum

These encouraging results have motivated to estimate a predictive model using GNSS time series data to model the movement upstream-downstream of the dam to be used as term of comparison for future observations. This study was performed for the Cantoniera dam. The functional model is the same used for Genna Is Abis dam (having one linear plus one periodic component). To assess the quality of the deformation model, deduced from GNSS time series data, this has been compared with pendulum displacements.

Eleonora d'Arborea dam has optical pendulums (one direct and one inverted) for each ashlar.

Direct pendulums are anchored at about 95 m s.l.m. inside the structure, while inverted pendulums are bounded to the foundation, at an height of only few meters s.l.m. Data of both pendulums are recorded in a common place at the bottom of the dam.

The whole displacement of the structure is therefore obtained by summing results obtained by direct and inverse (with opposite sign) pendulum. It's worth to note that this displacement does not represent the crest movement, at the hight of 120 m s.l.m., but the movement of the suspension point of the direct pendulum that is about 25 m lower.

Being GNSS receivers placed on the crest their displacements measure deformation of the top of the structure. Under the assumption that the movement is linear along the height of the dam the displacement by pendulum can be easily calculated at the crest dam.

Pendulum measurement were carried out during the same interval of the GNSS measurement (from September 2013 to February 2015).

As an example, displacements obtained by pendulum located in ashlar number 24 (disposing of longer time series data) have been compared to the model estimated from GNSS data.

Statistics of the residuals between GNSS model and displacements obtained by pendulum are shown in Table 2.

Table 2. Statistics of the difference between GNSS model and pendulum estimated displacements for the Cantoniera dam ashlar number 24

	GNSS-Pendulum[mm]
mean	-0.131
σ	1.7
rms	1.7
max	2.6
min	-3.5

The differences have a mean close to zero mm and a standard deviation of 1.7 mm. It looks like the pendulums underestimate displacements of the examined ashlars. To prevent displacement underestimation, the linear model (used to bring pendulum measurement to the crest of the dam) should be further investigated. Also longer GNSS time series are needed to better estimate the periodic term of the reference model.

4 Conclusions

The analysis of the pendulum observations coming from the installed devices at Genna Is Abis dam led to the definition of possible analytical models able to describe the crest point displacements. Same analysis carried out on Cantoniera dam using GNSS data time series was successful in defining a reliable model. The two analytics models, fitted respectively to GNSS and pendulum observations, have standard deviations of residuals below one mm. This good agreement in both study cases encourages the use of GNSS technology in dam monitoring. GNSS on short baselines (around two kilometres) 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, especially on medium-long period.

In this way the best fit deformation models can be assessed and profitably used for describing the dam deformation pattern to be considered as a benchmark for identifying possible anomalous behaviours.

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