Measuring Inclinations in Cabril Dam with an Optoelectronic Sensor

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Key words: dam, inclinometer, sensor, monitoring

SUMMARY

A high precision inclinometer was placed at the top gallery of Cabril dam, the highest dam in Portugal (132 m). Cabril dam has been presenting, since the first filling of the reservoir (1953), some horizontal cracks in the central upper zone. The dual axis inclinometer, with a recording measuring rate of 1 Hz, was installed for two days; during the same period a digital thermometer, for recording air temperatures, was placed next to the downstream face of the dam. The dam remained under normal operating conditions: the power generation groups were on or off for periods of variable duration each day. The presented analysis of collected data (inclination measured at a point near the dam crest, in two directions, and air temperature and reservoir level) shows a good correlation between the variations in the inclination with the daily thermal wave and with the changes in the reservoir level. The analysis also shows the reliability of the optoelectronic sensor since it was able to detect the vibration induced by the power groups. The inclination measurements were taken in connection with a test on a fully automated geodetic system for continuous monitoring of displacements in Cabril dam.

Measurement of Inclinations of a Dam: Results of a Test Using an Optoelectronic Sensor

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1. INTRODUCTION

In order to improve the monitoring system of Cabril dam, in 2008, a set of tests (Figures 1 and 2) was performed for two days, to verify the response of the geodetic observation equipment (tacheometers and GNSS) and of software for the continuous monitoring of dam displacements (Henriques et al., 2009). During the test, an inclinometer was also used to measure inclinations at the top of the central cantilever, so as to evaluate some possible variations in the measured inclination throughout the day. The measurement of both displacements and inclinations at the upper zone is proposed because Cabril dam (132 m high concrete arch dam) presents significant horizontal cracking in that zone, between 10 m and 20 m below the crest, which highly influences the deformation of the dam. The deformation monitoring of that cracked zone has been performed only by the control of displacements, measured in geodetic campaigns carried out on an annual basis.

This paper includes the description of the inclinometer and the analysis of collected data (variations in the angle of inclination) using statistical models based on the hypothesis that the inclination is a function of both the temperature and the reservoir level.

Figure 1 – Tacheometer set on a pillar during the continuous monitoring test

Figure 2 – GNSS antenna (reference point) during the continuous monitoring test

2. DESCRIPTION OF THE INCLINOMETER

The inclinometer used was the Nivel 210 one (Figure 3), a drift free dual axis model (see measurement uncertainty in Table 1) manufactured by Leica Geosystems, which measures simultaneously the inclination, the direction of inclination and temperature (Leica, 2005 and 2009).

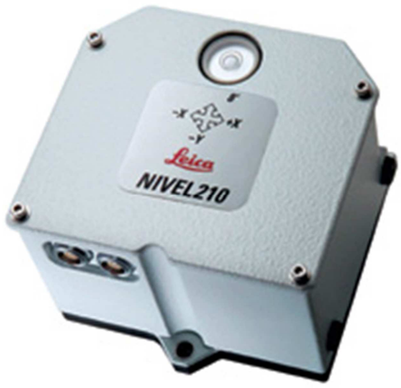

Figure 3 – Inclinometer Leica Nivel 210

Measurement range (“, sexagesimal seconds)	Uncertainty (“)
[-310, 310]	1
[-520, -310 [ ] 310, 520]	3
[-610, -520 [ ] 520,610]	10

Table 1 – Uncertainty of measurements

The main elements of this optoelectronic sensor are: a light source, an optical system (comprising a prism, lens and reflective surfaces), an oil deposit and a sensor (Figure 4). A ray of light, issued by a LED source (1), is reflected in the direction of a prism (2). On one of its sides a line pattern is engraved, which is formed by multiple line segments (Figure 5). The light is refracted towards a small tank (4) containing silicone oil, oil that is chemically and thermally stable, and which transmits efficiently light in the visible band. The surface of this oil, as any liquid in balance, is horizontal. A mirror, located at the base of the liquid and the oil surface cause the light to be twice reflected, so the line pattern is projected in the direction of a vector of coupled sensors (5), which convert light into energy by transforming photons in electric charge (CCD array – charged coupled device array). A reading system, associated with photoelectric cells, determines the position of the images of the line pattern (6) by detecting non lighted cells.

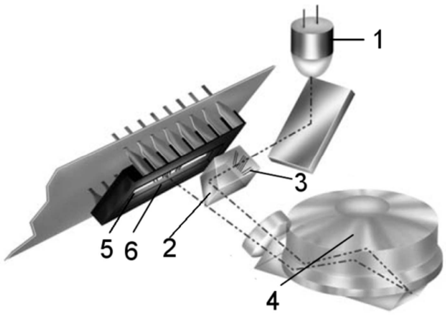

Figure 4 – Nivel scheme

Figure 5 – Detail of the prism: line pattern

To determine the inclination, the image recognition system must establish the position of the line pattern, position that is compared with the reference position. The latter, which is established by the location of the line pattern when the inclinometer is horizontal, is done by the manufacturer. The inclination is measured along two orthogonal components. The value in one of these components is determined by the distance between the centroid of the line pattern and the reference value (component longitudinal, L – Figure 6); the inclination in the orthogonal direction is determined by the distance between the lines inclined (component transversal, computed from the difference between distances T_1 and T_0 – Figure 7). A single sensor measures, at the same time, the two components of the inclination. In Figure 8, the schema above represents the reference position of segments, while the lower schema represents their position when the inclinometer is not horizontal; the horizontal bar represents the CCD array; the small yellow circles represent the points of intersection between the lines and the CCD array; the larger circles (red or green) represent the centroids of each set of lines.

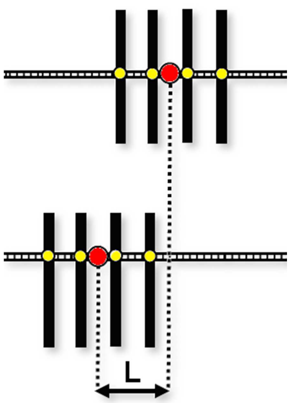

Figure 6 – Measurement of the longitudinal component

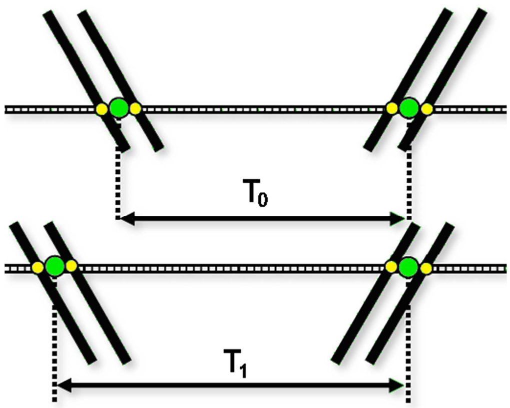

Figure 7 – Measurement of the transversal component

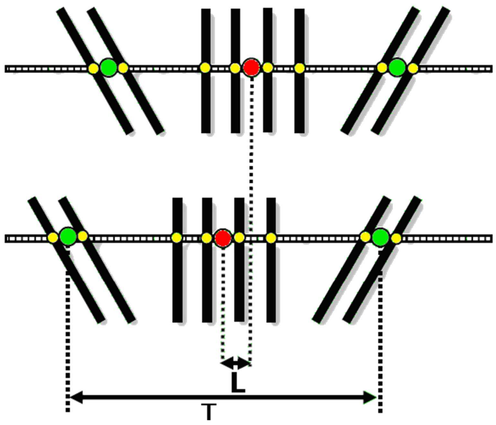

Figure 8 – Join measurement of the two components

According to Chrzanowski et al. (1999), the system that measures Nivel inclination is the same as the one included in Leica's theodolites and tacheometers, and is an upgrade of the inclination sensor developed by Kern Instruments in the 1980s. These measuring instruments include a compensator of the inclination of the vertical axis, the optoelectronic sensor of the inclination being its key element. According to Chrzanowski et al., in some applications, theodolites or tacheometers can be used to measure variations in inclinations.

3 TEST: LOCATION AND DESCRIPTION

The measurements took place at the upper gallery of Cabril dam (Figure 9), a double curvature arch dam founded on a granitic rock mass, located in the centre of Portugal. Cabril dam was built in 1953 and is an arch dam approximately symmetrical, with a maximum height of 132 m. At the crest, there is a unusually greater thickness (Figures 10 and 11): at the central cantilever, the thickness varies between a maximum of 20.2 m, at the basis, to 4.5 m, a little below the crest, and at the top it extends up to a thickness of 8.3 m.

Figure 9 – Cabril dam

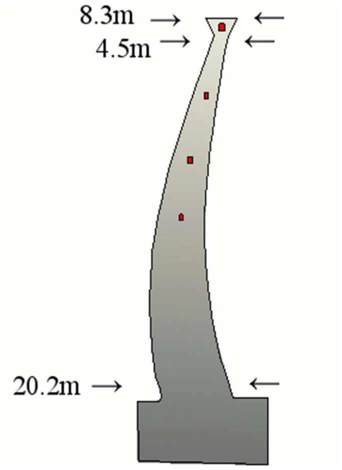

Figure 10 – Cross-section by the central cantilever

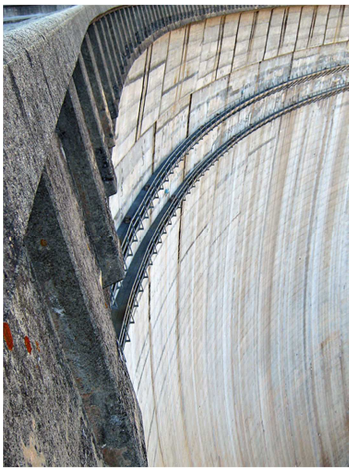

Figure 11 – Top of the dam

The enlargement of the top derived from the need to construct a road linking two villages, *Pedrógão Grande* and *Pedrógão Pequeno*. In the initial design, the crest had a different shape. The change, in the initial project, started already during the construction phase, when it was no longer possible to modify the shape and dimensions of the middle and bottom zones of the structure. Due to the greater thickness, the crest is more rigid, which led to the emergence of cracks in the downstream face of upper arches (Figure 12), situation that was detected early, in the beginning of the dam exploration and has persisted, even after the major rehabilitation works carried out in the 80s.

Early in the first filling of the reservoir, a significant horizontal cracking was detected on the downstream face, located between 10 m and 20 m below the crest. In 1981, after analyzing the structural behaviour, a decision was made to carry out repairs for treating the cracks (Mora Ramos, 2008) with injections of resin after characterization of their openings and depths (Figure 12). With the refilling of the reservoir, it was observed that cracks would occur again in the same area. Figure 13 presents the cracking in 1996, and Figure 14 presents the deformation in the central cantilever (full reservoir) – observation data and numerical results, computed using a 3D finite element model, software DTDIN developed at LNEC (Oliveira, 2000) –, which shows the cracking influence on the structural dam behaviour (that can be simulated using a viscoelastic model with damage). A swelling process has been recently detected.

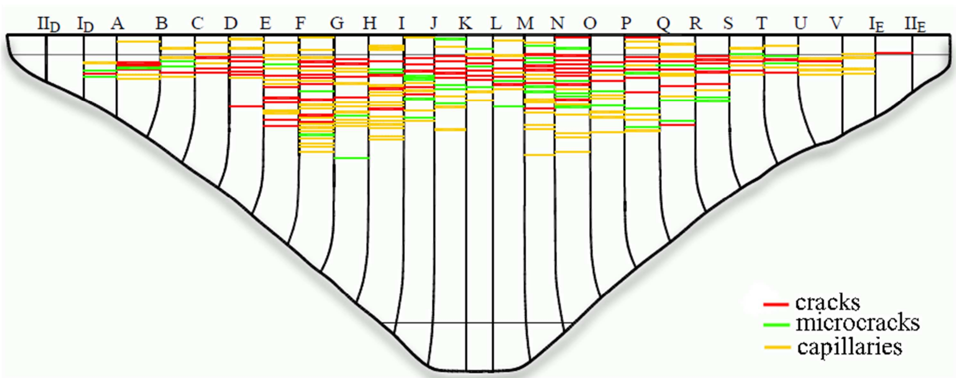

Figure 12 – Cracking at the downstream face of the dam in 1996

Figure 13 – Repair works in Cabril dam

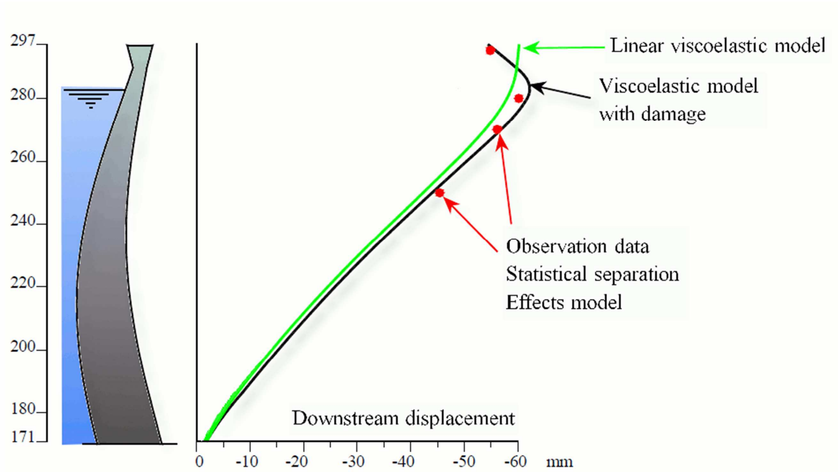

Figure 14 – Displacements at the central cantilever

The inclination measurement was done with the inclinometer placed on a base with levelling bolts, mounted on the top of a small pillar located at the centre of the gallery (Figure 15), in the central cantilever. During the tests, the data was registered on a laptop, with software Leica GNSS QC. The two components of inclination and temperature (Nivel includes a temperature sensor) were registered with a sampling frequency of 1 Hz, during approximately two days (between 2 and 4 of July, 2008). The inclinometer was oriented in such a way that the axes were coincident with the radial and tangential directions (Figure 16). Also during that period, a digital thermo-hydro-barometer Comet D4130 was installed on the upper walkway of the downstream face (Figure 17). The data was recorded automatically every 10 minutes. Throughout those two days, one of the two electricity generators worked during four periods (see Table 2). The other generator was off due to conduit maintenance.

Figure 15 – Inclinometer setting up: computer

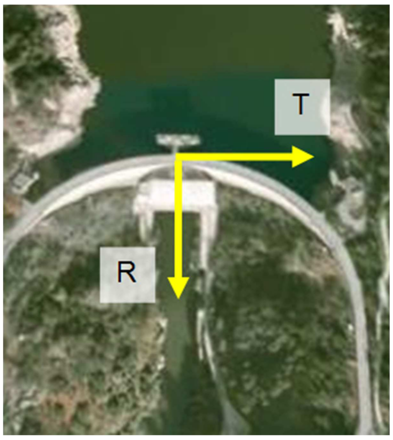

Figure 16 – Orientation of the referential "Radial-Tangential" used

Figure 17 – Digital thermo-hydro-barometer on the walkway

Date	Hour	
	Beginning	End
July, 2	8h40	19h00
July, 3	7h49	20h00
July, 3	21h06	23h00
July, 4	8h53	11h30

Table 2 – Electricity production periods

4 RESULTS

The values recorded – inclination components, temperatures both inside and outside the gallery, the reservoir level, and the average turbinated flow – are presented in Figures 18, 19 and 20. Figure 18 shows the variations in the two components (radial and tangential) of the inclination. In this chart, positive variations in inclination correspond, in radial direction, to an ascent in the upstream side, and in the tangential direction, to an ascent in the left margin. Figure 19 presents the values of the temperatures measured both inside and outside the gallery, at the walkway on the downstream face. Figure 20 presents the reservoir level and flow turbinated. The charts also include the periods in which the generator worked (background shading), and the instants of sunrise and sunset (symbols ☀ and ☾, respectively).

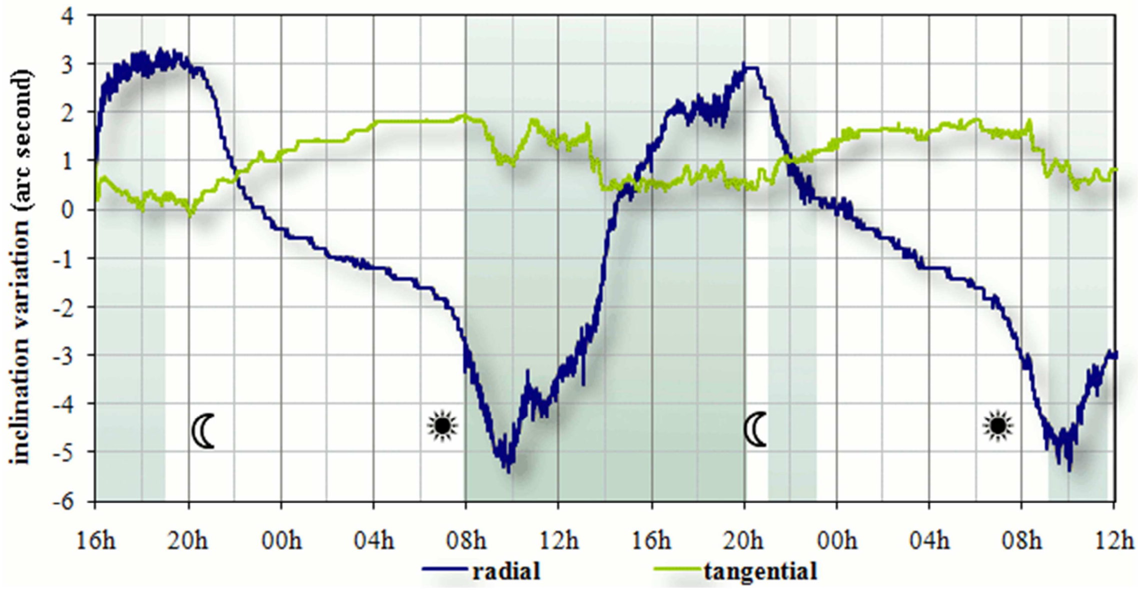

Figure 18 – Variation in the inclination in two directions

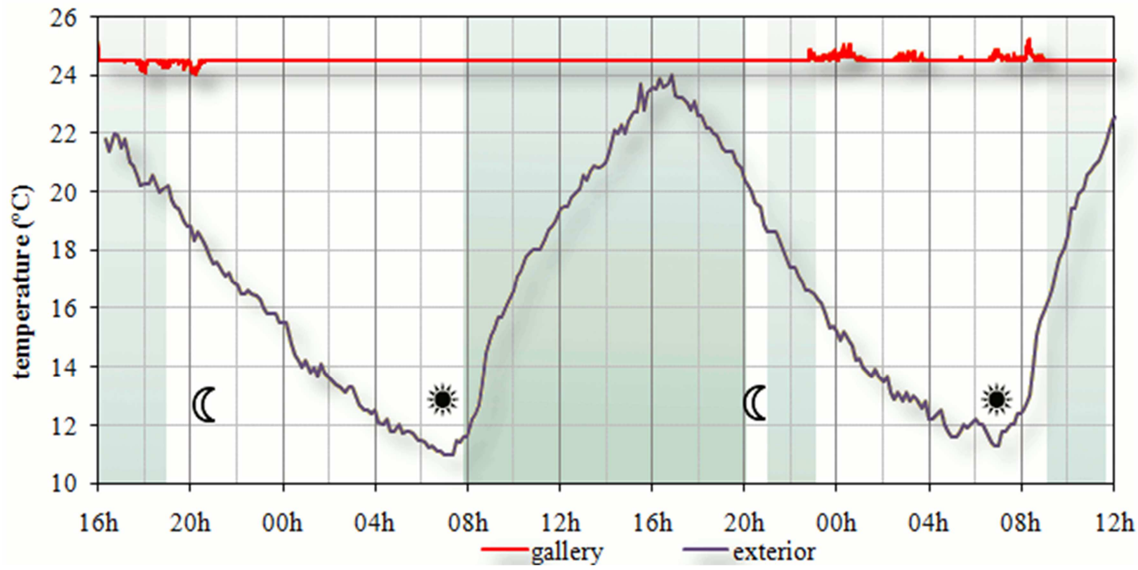

Figure 19 – Inside and outside air temperatures

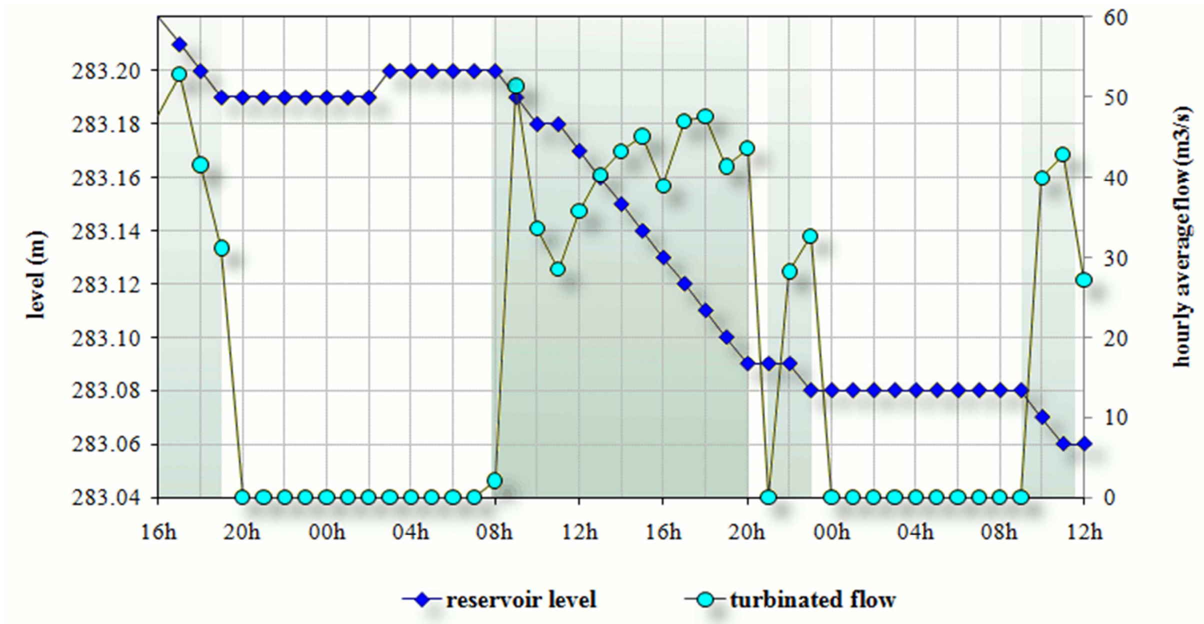

Figure 20 – Evolution in the actions "reservoir level" and "turbinated flow"

In a simple analysis of the charts, it is possible to observe a strong correlation in the radial direction between the variation in the outside temperature, the variation in the inclination and the effect of the generator, because there is a greater dispersion in the values of the inclination when the generator is working.

An analysis of the dispersion in the values recorded was also performed; analysis that was focused on the standard deviation of sets of 60 records, i.e., sets of one minute of observations recorded by the inclinometer. Over the exploitation periods, some changes have occurred in the operation of the generating group, which were dictated by the variable needs in power production. The graphic containing the values of the standard deviation is presented in Figure 21. It is possible to observe that during the periods of greater production, there is less dispersion in values, which seems to indicate that the structure had minor vibrations (this phenomenon is related with resonance effects like the ones we can experience in our cars when, sometimes, more acceleration induces a decrease in vibration).

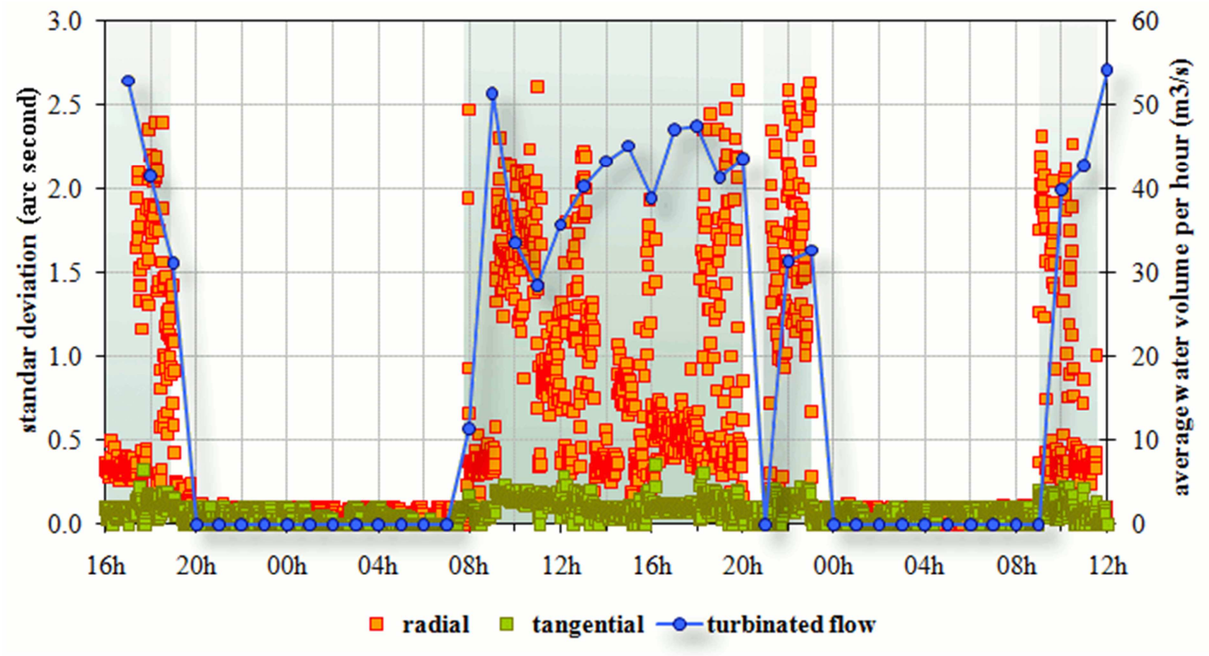

Figure 21 – Standard deviation of the inclination measured in the radial and tangential directions

5 STRUCTURAL BEHAVIOUR

Over the two days, the daily behaviour of the dam was very uniform, the influence of the daily variations on the outside air temperature being especially remarkable. By processing the temperature with the variation in the inclination (radial direction), and when examining a cross-correlation diagram, the occurrence of a time lag of approximately 4 h 40min was detected.

In this study, the radial and tangential components were analyzed separately. To model the variations in each component, a regression model (eq. (1)) was considered. The latter includes a term for simulating the effect of the reservoir level (linear dependence), two terms (cosine and sine), which reflect a harmonic temporal variation within a 24-hour period and also two terms, which represent an identical variation but within a 12-hour period. These two periods, of 12 and 24 hours respectively, were identified as relevant through a Fourier analysis. The variations in the inclinations measured for a day are mainly correlated with the temperature variations measured near the downstream face of the dam. The behaviour of the temperature variation corresponds to a quasi-sinusoidal wave – the warming branch is not symmetric to the cooling branch (see Fig. 19) – which is described as a superposition of two waves in periods of 24 and 12 hours.

The regression model adopted has the following generic expression

$$i(h,t) = a\,h + b_1 \cos\frac{2\pi t}{24} + b_2 \sin\frac{2\pi t}{24} + b_3 \cos\frac{2\pi t}{12} + b_4 \sin\frac{2\pi t}{12} + c \qquad (1)$$

where i represents the inclination component, h the reservoir level and t the time of day. The term ah (first term at (1)) is considered in order to take into account the water level variation over a day (if no significant water level variations occur, the coefficient may be negligible).

Coefficients a, b1, ..., b4 and c were estimated by solving a system of 264 equations, each equation corresponding to the values recorded every 10 minutes. As the inclination values were recorded with a sampling frequency of 1 Hz, an average of 10 minutes of records was used in each equation.

5.1 Radial Component

An analysis of the recorded data revealed that the variations in the inclination of the structure are mainly influenced by the variation in daily temperature; there is a high correlation between these two quantities (correlation coefficient equal to -0.94). For the period addressed, a correlation with the reservoir level is very small (correlation coefficient equal to -0.11) certainly because, during this period, the variation in the water level was negligible. Figure 22 shows the regression curve chart together with the data referring to the variation in the inclination and the outside temperature.

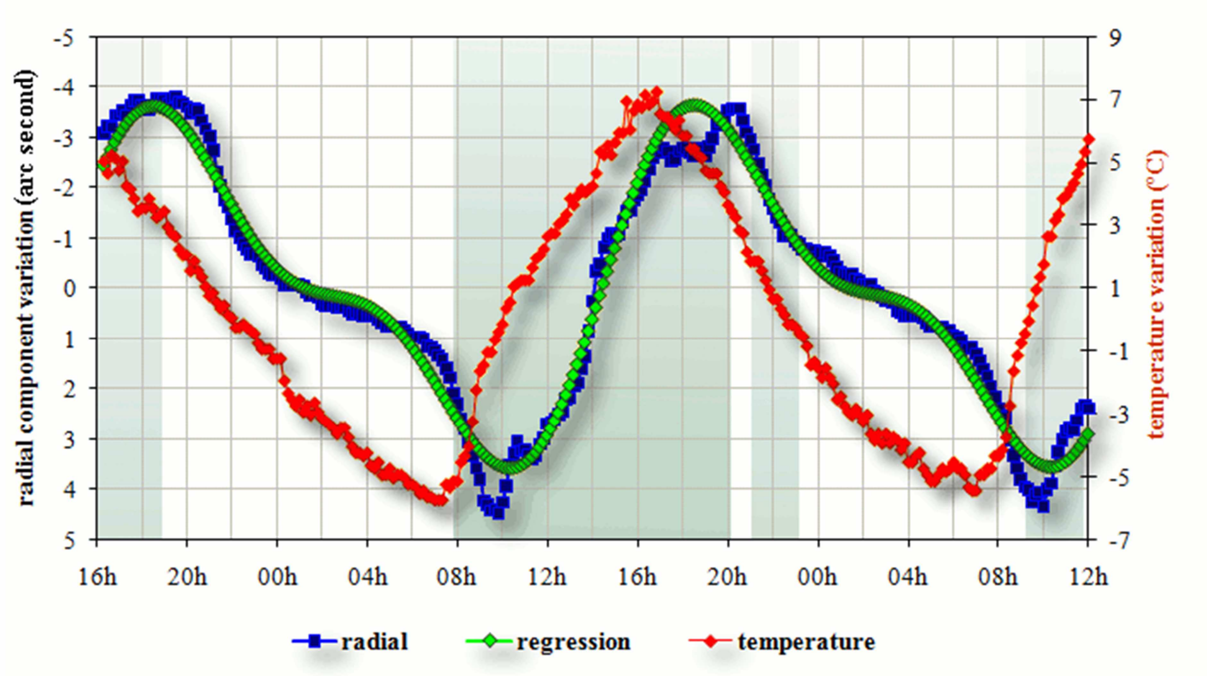

Figure 22 – Variation in the radial component and regression curve

5.2 Tangential Component

Unlike the radial component, the tangential component has a more obvious correlation with the variation in water than with the outside temperature (correlation coefficient equal to -0.70 and -0.50, respectively). Figure 23 shows the regression curve chart along with the variation in the inclination, the outside temperature and the reservoir level.

The variation in the tangential direction has, in these two days, a progressive component, which translates into a correlation with decreasing reservoir level.

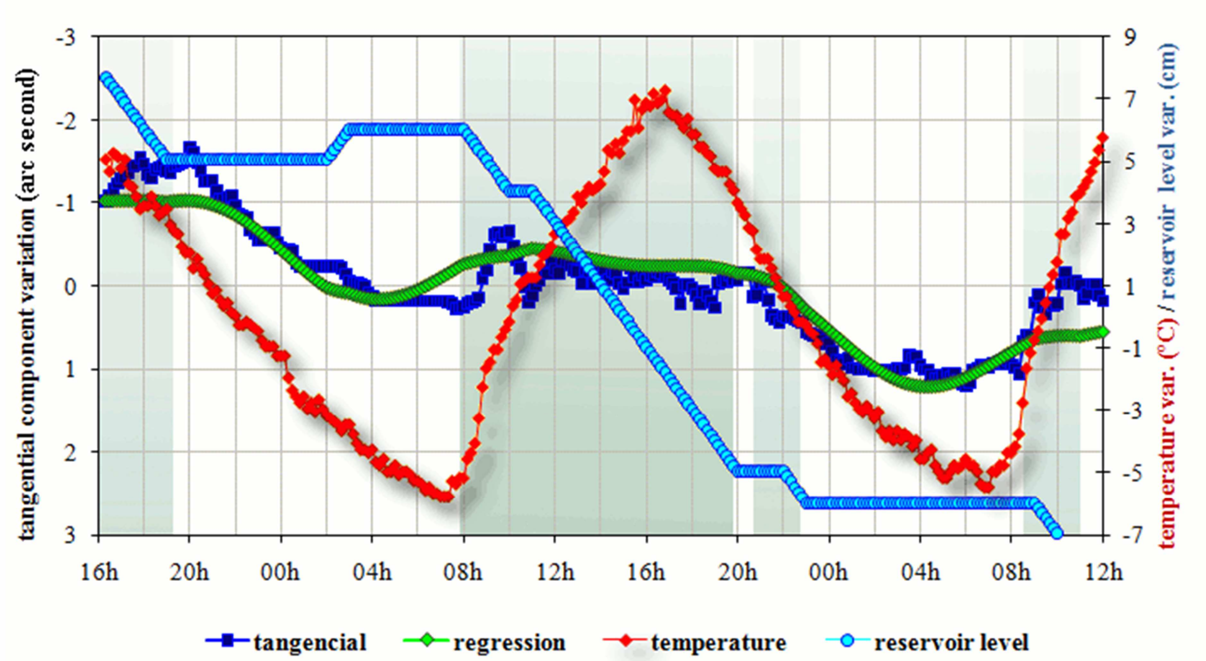

Figure 23 – Variation in the tangential component and regression curve

5.3 Regression model: 3D Visualisation

As presented in (1), the regression model adopted establishes a relation between the variation in inclination ***i*** with the reservoir level (h) and the day hour (t) : ***i*** = f (h, t). Two 3D graphs were drawn (Fig. 24), through MATLAB plotting tools, showing the inclination as a function of the hour of the day (from 0h to 24h) and of the reservoir level variation (from 0 cm to 20 cm). The measured variations in inclination (10 minute average) were also plotted.

6 CONCLUSIONS

Leica Nivel 210 inclinometer was able to detect the influence of temperature and reservoir level on Cabril dam behaviour. It was also capable of recording the vibration of the structure induced by the operation of the electricity generator group. It was noticed, however, that there are some variations in the components of the inclination, which cannot be explained by the regression models used.

In the future, it would be desirable to install this equipment during a longer period of time, if possible for several years, in order to detect the influence of other quantities on the behaviour, including annual variations in temperature, significant variations in reservoir level and possible long term effects.

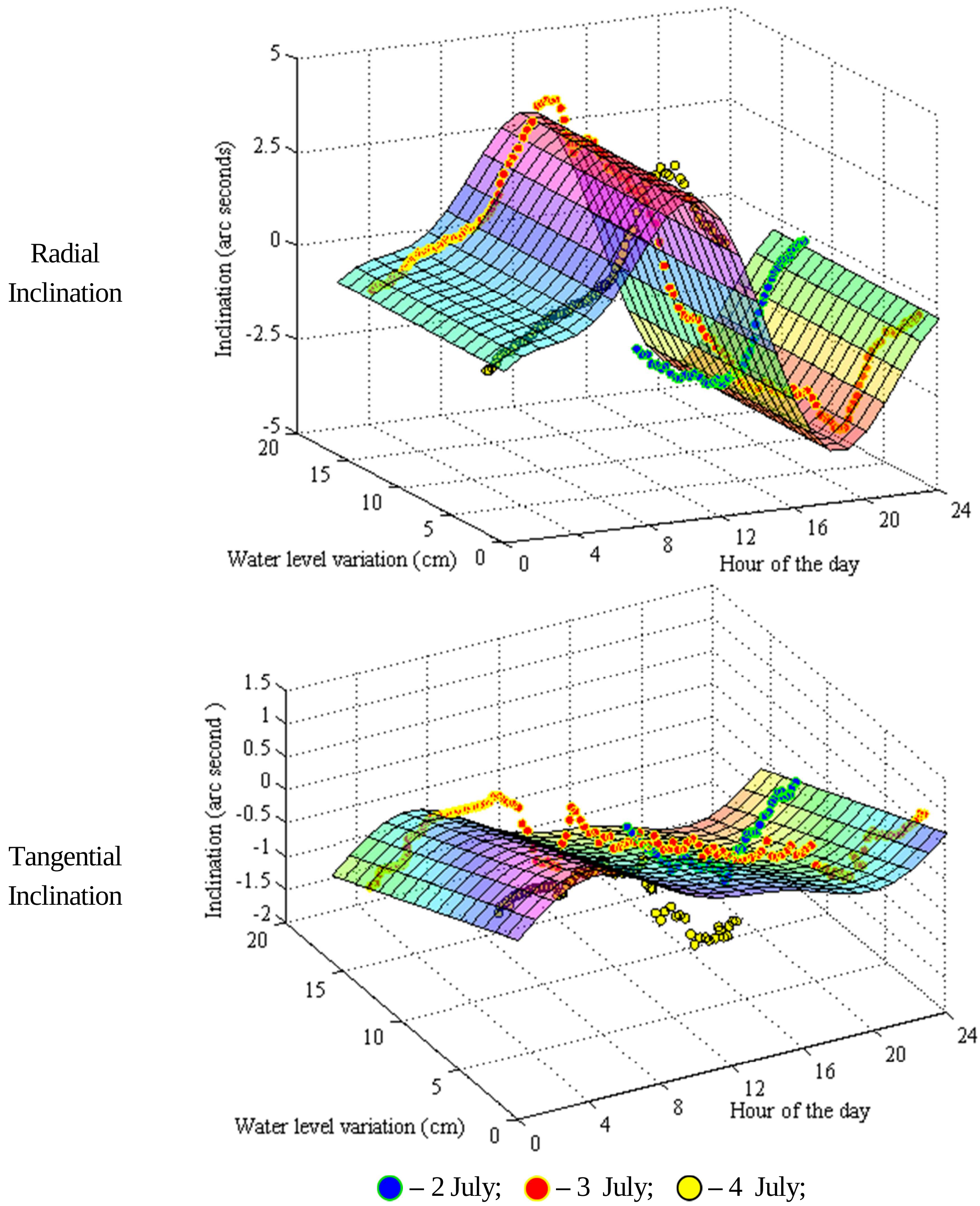

Figure 24 – 3D plot of the inclination (radial and tangential) as a function of the hour of the day and of the water level variation. Multiple linear regression

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BIOGRAPHICAL NOTES

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