Measuring inclinations in the Cabril Dam with an optoelectronic sensor

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Monitoring Cabril Dam, a double curvature arch dam founded on a granitic rock mass in the centre of Portugal

CABRIL DAM is the highest concrete arch dam in Portugal at a height of 132m. However, since the first filling of the reservoir in 1953, horizontal cracks started to appear in the central upper zone. In order to monitor the severity of the cracks and the potential disasterous consequences that could result, a high precision inclinometer was placed at the top gallery.

The dual axis inclinometer, with a recording measuring rate of 1Hz, 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 the dam.

Monitoring

In order to improve the monitoring system of the dam, in 2008, a set of tests 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. 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 was proposed because the dam presents significant horizontal cracking in that zone, between 10m and 20m below

Monitoring the dam in 2008:
Tacheometer set on a pillar during the continuous test.

the crest, which highly influences the deformation of the dam. The deformation monitoring of the 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.

The inclinometer

The inclinometer used was a Leica Nivel 210, a drift free dual axis model (see Table 1), which measures simultaneously the inclination, the direction of inclination and temperature.

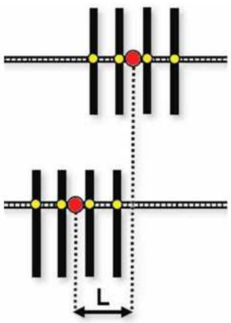
GNSS antenna (reference point) during
the continuous monitoring test in 2008.

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

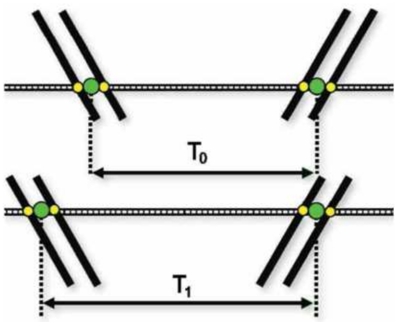
Table 1: Uncertainty of measurements.

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. A ray of light, issued by an LED source, is reflected in the direction of a prism. On one of its sides a line pattern is engraved, which is formed by multiple line segments. The light is refracted towards a small tank containing silicone oil (oil that is chemically and thermally stable), which transmits efficiently light in the visible band.

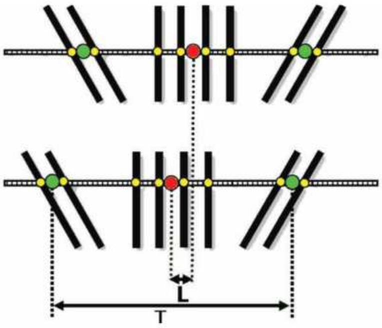
The surface of this oil, as any liquid in balance, is horizontal. A mirror, located at the base of the liquid and the oil surface causes the light to be twice reflected, so the line pattern is projected in the direction of a vector of coupled sensors, which convert light into energy by transforming photons in electric charge (charged coupled device (CCD) array). A reading system, associated with photoelectric cells, determines the position of the images of the line pattern by detecting non lighted cells.



Measurement of the longitudinal component.



Measurement of the transversal component.



Measurement of the two components. 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.

To determine the inclination, the image recognition system must establish the position of the line pattern; a 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); the inclination in the orthogonal direction is determined by the distance between the lines inclined (component transversal, computed from the difference between distances T1 and T0). A single sensor measures, at the same time, the two components of the inclination.

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. In some applications, theodolites or tacheometers can be used to measure variations in inclinations.

Location and description

Cabril Dam was built in 1953 and is an arch dam approximately symmetrical, with a maximum height of 132m. At the crest, there is a unusually greater thickness, at the central cantilever, the thickness varies between a maximum of 20.2m at the base, to 4.5m a little below the crest, and at the top it extends up to a thickness of 8.3m.

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 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 its greater thickness, the crest is more rigid, which led to the emergence of cracks in the downstream face of the upper arches. The situation was detected early, in the beginning of the dam exploration, and has persisted even after major rehabilitation works carried out in the 1980s.

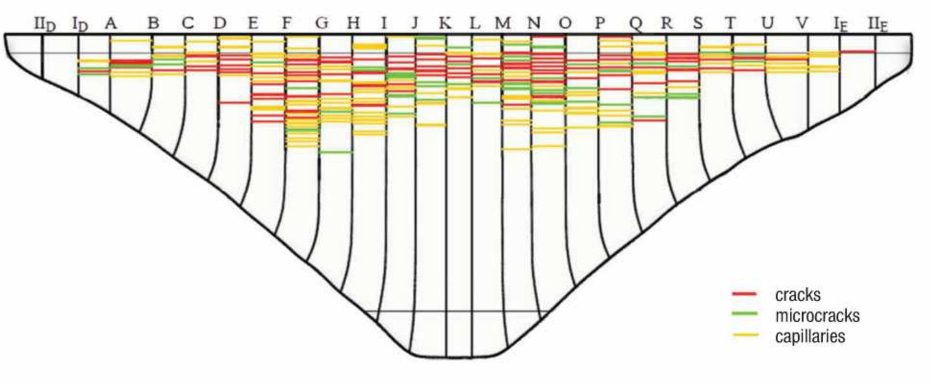
Early in the first filling of the reservoir, a significant horizontal cracking was detected on the downstream face, located between 10m and 20m below the crest. In 1981, after analysing the structural behaviour, a decision was made to carry out repairs for treating the cracks with injections of resin after characterisation of their openings and depths. With the refilling of the reservoir, it

Cabril Dam ©Jorge Manuel.

Due to the greater thickness, the crest is more rigid, which led to the emergence of cracks in the downstream face of the upper arches.

Top of the dam ©Pedro Henriques.

A swelling process has been recently detected.



Cracking at the downstream face of the dam in 1996.

was observed that cracks would occur again in the same area. A swelling process has been recently detected.

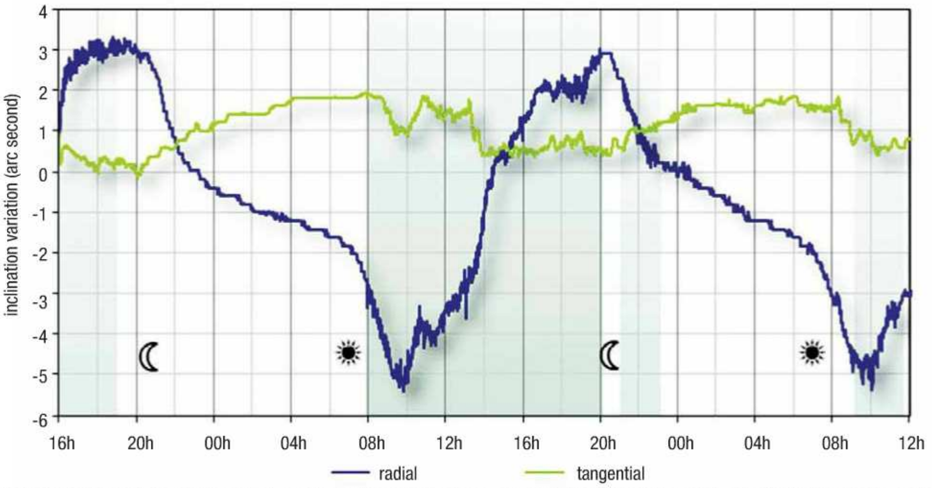
The inclination measurement was done with the inclinometer placed on a base with levelling bolts mounted on the top of a small pillar located at the centre of the gallery in the central cantilever. During the tests, the data was registered on a laptop, with Leica GNSS QC software. The two components of inclination and temperature (Nivel includes a temperature sensor) were registered with a sampling frequency of 1Hz, during approximately two days (between 2-4 July 2008). The inclinometer was oriented in such a way that the axes were coincident with the radial and tangential directions. Also during that period, a digital thermo-hydro-barometer Comet D4130 was installed on the upper walkway of the downstream face. 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.

Results

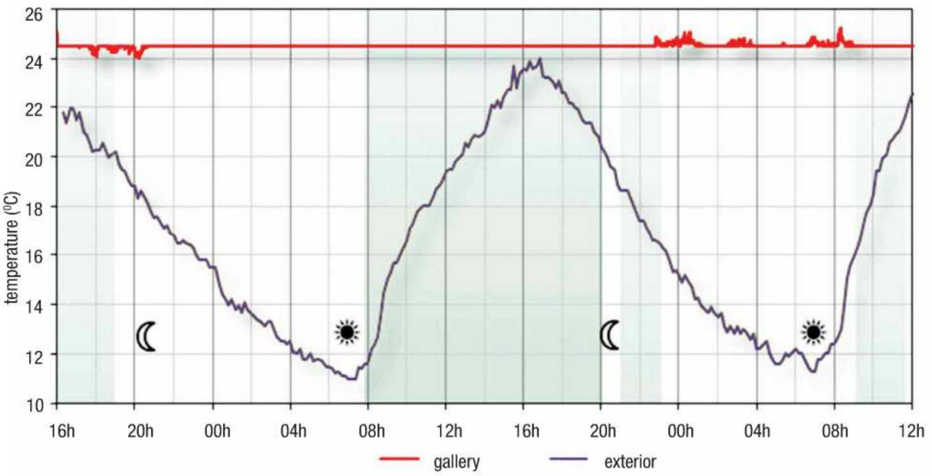
In a simple analysis of the charts overleaf, it is possible to observe a strong correlation in the radial direction between the variation in the outside temperature, the variation in the inclination and the effect of the generator, because there is a greater dispersion in the values of the inclination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

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

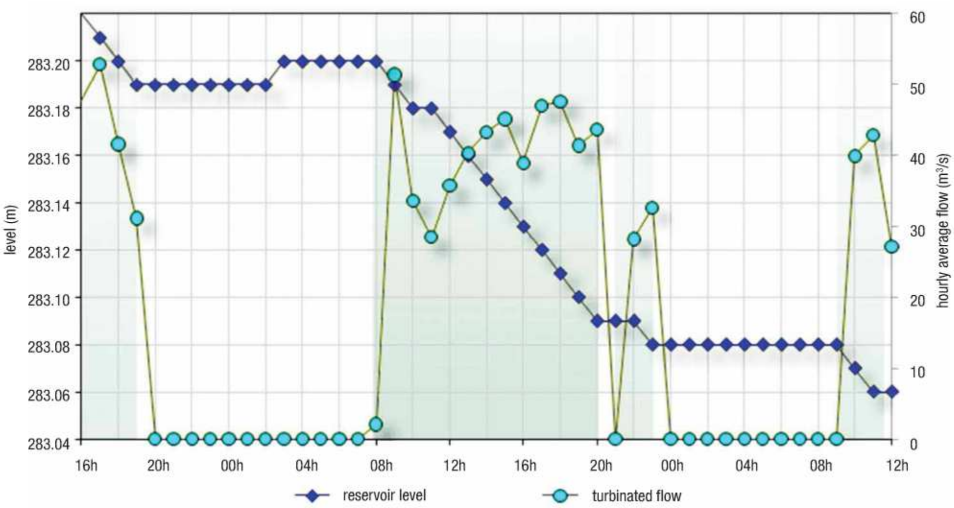
Table 2: Electricity production periods.



Variation in the inclination in two directions: 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.



Inside and outside air temperatures: The values of the temperatures measured both inside and outside the gallery at the walkway on the downstream face.



Evolution in the actions reservoir level and turbinated flow.

The variations in the inclinations measured for a day are mainly correlated with the temperature variations measured near the downstream face of the dam.

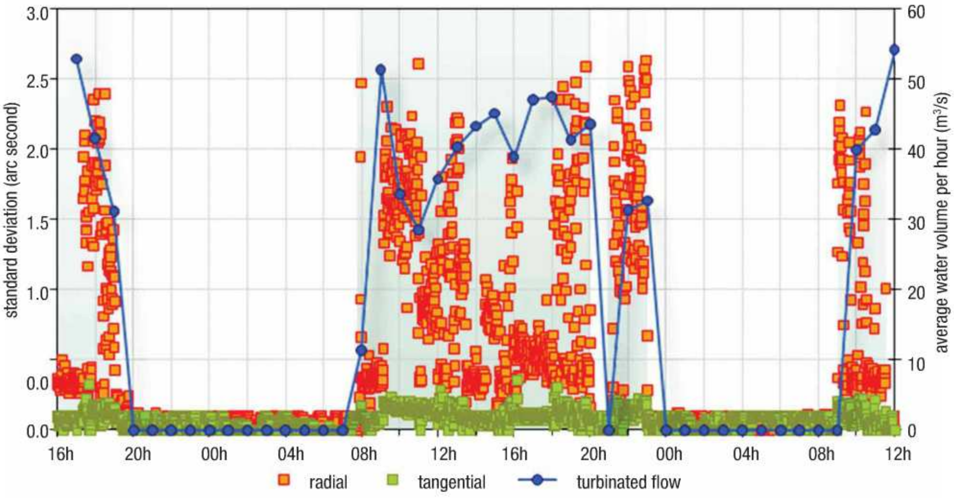
include the instants of sunrise and sunset. The values recorded included inclination components, temperatures both inside and outside the gallery, the reservoir level, and the average turbinated flow.

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 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. 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).

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 hours 40 minutes was detected.

In this study, the radial and tangential components were analysed separately. To model the variations in each component, a regression model (Equation 1) was considered. The latter includes a term for simulating the effect of the reservoir level



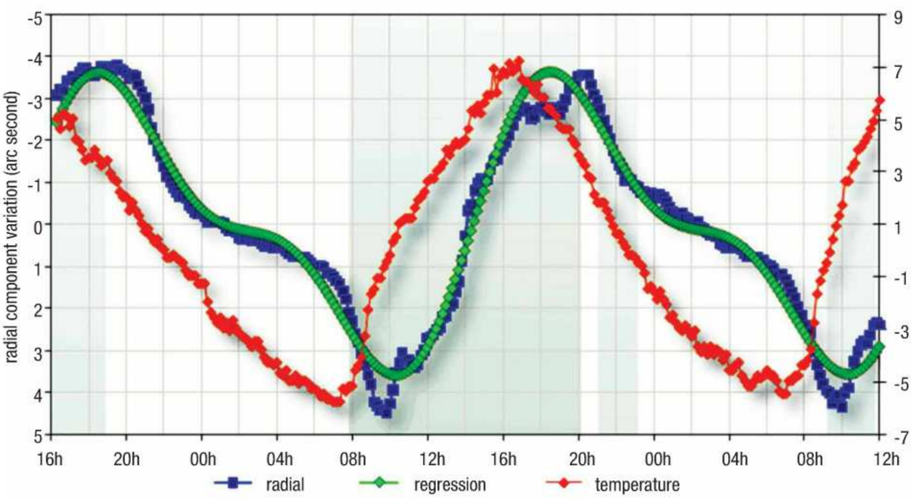
Standard deviation of the inclination measured in the radial and tangential directions.

The regression model adopted has the following generic expression:

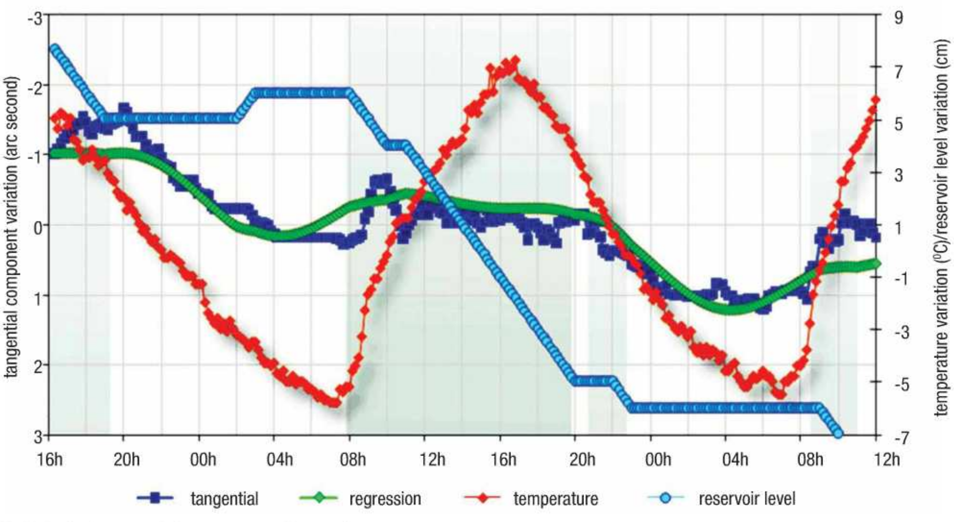
$$i(h,t) = a\,h + b_1 \cos\frac{2\pi t}{24} + b_2 \sin\frac{2\pi t}{24} + b_3 \cos\frac{2\pi t}{12} + b_4 \sin\frac{2\pi t}{12} + c$$

Equation 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 1Hz, an average of 10 minutes of records was used in each equation.



The regression curve chart together with the data referring to the variation in the inclination and the outside temperature.



Variation in the tangential component and regression curve.

It was noticed, however, that there are some variations in the components of the inclination, which cannot be explained by the regression models used.

(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 – which is described as a superposition of two waves in periods of 24 and 12 hours.

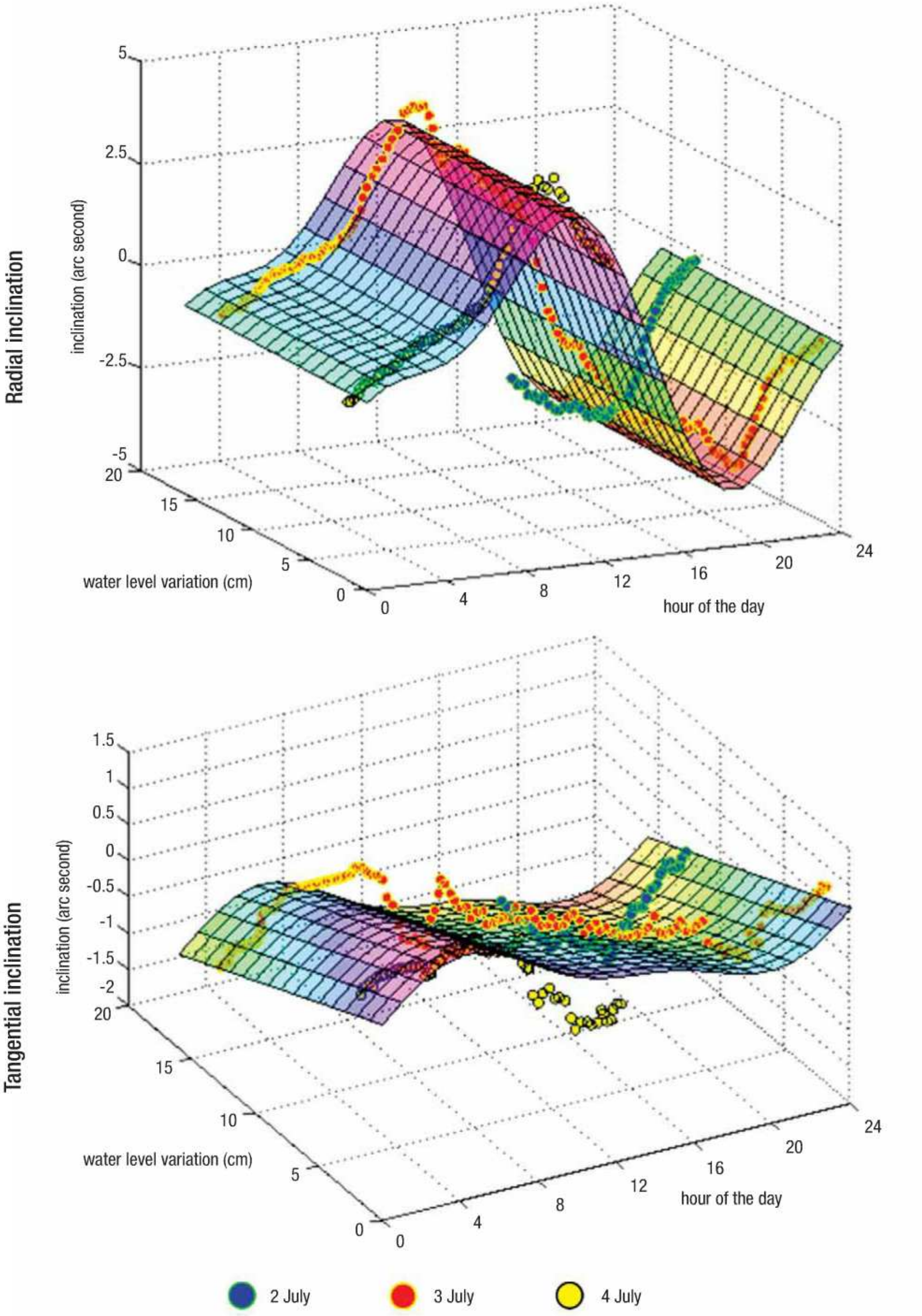
Radial component

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 (with a correlation coefficient equal to -0.94). For the period addressed, a correlation with the reservoir level is very small (with a correlation coefficient equal to -0.11) certainly because during this period the variation in the water level was negligible.

Tangential component

Unlike the radial component, the tangential component has a more obvious correlation with the variation in water than with the outside temperature (with a correlation coefficient equal to -0.70 and -0.50 respectively).

The chart shows the regression curve along with the variation in the inclination,



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.

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.

Regression model: 3D visualisation

As presented in Equation 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, 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 0cm to 20cm). The measured variations in inclination (10 minute average) were also plotted.

Conclusions

The Leica Nivel 210 inclinometer was able to detect the influence of temperature and reservoir level on Cabril Dam's 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.

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