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USING SPECTRAL ANALYSIS OF CABRIL DAM GNSS MONITORING SYSTEM TIME SERIES FOR DETECTING PERIODIC DISPLACEMENTS

José Nuno Lima[1]
LNEC

ABSTRACT

A measurement system based on GNSS (Global Navigation Satellite System) was installed at Cabril dam in order to monitor displacements at the top of the central section. The GNSS system consists of two receivers (stations), one located on the crest of the dam, in central section, and the second located on the left bank, on the top of a medium voltage pole of a line deactivated and cut to be about 6 m high, to work as reference station. Unfortunately, this GNSS monument is exposed to solar radiation and wind effects. Consequently, it is expected that these environmental factors could cause sub-daily noise in the estimation of the dam displacements due to the thermal tilts of the monument. This paper is concerned with the assessment of the impact of this GNSS monument on the noise in the continuous GNSS time series.

In GNSS time series analysis, frequency-domain signature is obtained by converting time-domain data into its unique frequency components using a Fast Fourier Transform (FFT). Through the analysis of frequency-domain signal signatures, the dam displacement seasonal can be detected and isolated from the noise eventually caused by the GNSS monument instability.

Keywords: Arch dam, monitoring, GNSS, time series.

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[1] jnplima@lnec.pt; josenunolima@gmail.com

1. INTRODUCTION

The Cabril dam is located in Centre region of Portugal, in the Zêzere River that belongs to the basin of the Tagus River. The Cabril dam is a double curvature arch dam founded on a granitic rock mass. With a maximum height above the foundation of 132 m and a total crest length of 290 m it presents an approximately symmetric geometry in plan and has the particularity of having a higher thickness zone at the crest level between abutments (Figure 1). The central cross-section has a 20 m thickness at the base, and 4.5 m minimum thickness at the level 290 m, at the transition with the crest zone, from which the thickness increases linearly until 8 m at maximum level (297 m), as shows Figure 1.

Between September 1952 and December 1953 the dam was built. The first filling began early 1954, and lasted about two years.

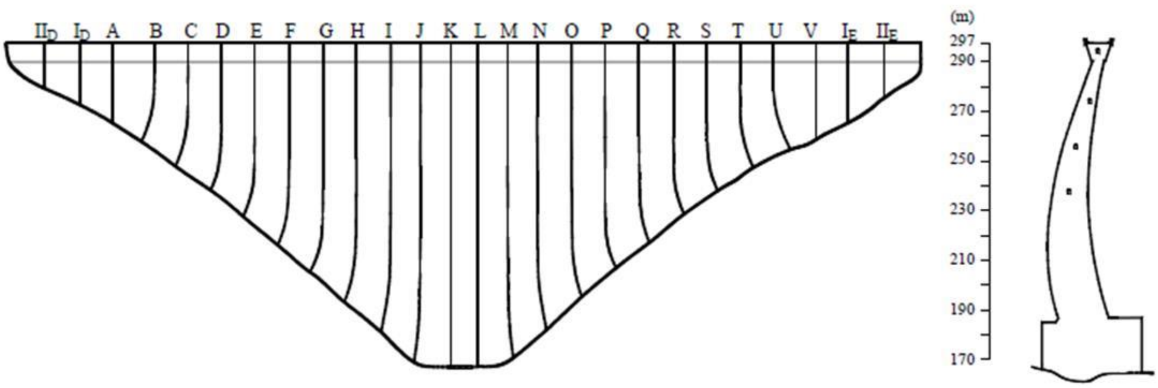

Fig. 1 – Cabril Dam downstream elevation and cross-section of the central cantilever

In the initial stage of operation, a significant horizontal crack was detected in the downstream face (mainly close to the construction joints), in a section located between 10 m and 20 m below the crest. In 1981, after the analysis of the structural behaviour, and of complementary observation of the foundation, as well as after tests on materials and simulation by physical and mathematical models to determine the reasons for cracking, a decision was made to carry out repair works. These rehabilitation works consisted of treatment of the foundation, grouting of retraction joints and treatment of crack with resin grouting, after characterisation of the corresponding openings and depths. With the refilling of reservoir, it was observed that the dam cracked again in the same zone [1].

The continuous monitoring of dam´s displacements is fundamental for the safety control of these structures, because it allows the characterisation in real-time or in useful time of static and dynamic response of these structures along its life to the static and dynamic loads (reservoir level variations, annual thermal variations, seismic events). The safety control is based on the comparison between monitoring data (e. g. observed displacements by plumb lines, geodetic methods or, more recently, with GNSS, Global Navigation Satellite Systems) and results obtained by numerical models, usually 3D finite element models. In the case of Cabril dam due to the sharp vertical curvature in the central cantilever no plumb lines were installed in this section. Consequently, until 2016, the displacement monitoring in this section was performed exclusively by classic geodetic methods that not allowed a continuous monitoring (only two observation campaigns per year).Therefore, the use of GNSS is particularly useful since it allows a continuous monitoring of the top of the central section's displacements.

In this conference it will be presented a paper on the validation of the displacements obtained by GNSS, at Cabril dam, using a 3D finite element (3DFE) model, developed in MATLAB, in which the cracking is simulated through joint elements. The 3DFE model was calibrated based on displacements observed by plumb lines (in two non-central sections) and by classical geodetic methods, considering variations in hydrostatic pressure and annual temperature variations [2].

2. GNSS DAM MONITORING SYSTEM

The Concrete Dams Department and Instrument Scientific Centre of LNEC, with the financial support of the Portuguese Foundation for Science and Technology (FCT, PTDC/ECM-EST/2131-2012) and the EDP Group (Grupo Electricidade de Portugal), conclude the installation of the GNSS monitoring system for Cabril dam in July of 2016.

For the GNSS dam monitoring system two permanent GNSS stations were installed: one located on the crest of the dam, in K-L block, and the second located on the left bank, to work as a reference station (Figure 2).

The reference GNSS station was installed on the left bank, on the top of a medium voltage pole of a line deactivated and cut to be about 6 m high. The GNSS receiver of this station is located in a technical cabinet inside of geodetic pillar shelter, close to the former medium voltage pole.

The application of GNSS in the monitoring of deformation of concrete dams involves continuous observation and consequent automatic processing. Since the displacements of concrete dams are, in general, in the order of several millimetres with rates of several millimetres per year, it is required high precision relative positioning to measure such displacements. Since the GNSS antennas must be installed in open sky locations, the antennas of the object points must be installed in the crest of the dam. And the antennas of the reference points must be installed near the dam, in stable zones of the rock mass and outside of the dam influence.

The minimum observation session duration should be one hour, and low pass filters, for noise reduction as moving averages, should be used [3].

Fig. 2 – Location of GNSS stations in the Cabril dam: Reference Station, left bank, and Object Point, crest of the dam

Unfortunately, the GNSS reference station monument is exposed to solar radiation and wind effects. Consequently, it is expected that these environmental factors could cause sub-daily noise in the estimation of the dam displacements due to the thermal tilts of the monument (Figure 3).

Fig. 3 – The GNSS reference station monument (on left, a general view, on top right, the top of the pillar with antenna GNSS, on bottom right, the pillar base)

On the other hand, the GNSS monument built for the crest of the dam is coaxial dual tubes that are not susceptible to thermal expansion by sunlight. In addition, it is also protected from the wind effects (Figure 4).

This paper is concerned with the assessment of the impact of this GNSS monument on the noise in the continuous GNSS time series.

The GNSS receivers of the Cabril dam GNSS System are two Leica GMX902 GNSS, multi-frequency GNSS permanent station (120 channels, GPS L1/L2/L5, GLONASS L1/L2, Galileo L1/E5a/E5b/E5a+b (AltBOC)). Designed for continuous operation with a focus on the essential – the reception and transmission of high precision raw data – the Leica GNSS GMX902 GNSS has very low power consumption enabling it to operate for a long time on backup power. The GNSS antennae are two Leica AS10 GNSS Compact with geodetic precision.

The GNSS data is continuously and automatically processing through the Leica GNSS Spider software.

Fig. 4 – The GNSS monument built for the crest of the dam is coaxial dual tubes (on left, a general view, on right, a detail of the monument top with antenna GNSS)

3. ANALYSIS OF HORIZONTAL DISPLACEMENTS OBSERVED WITH GNSS

The estimated uncertainty for hourly solutions of the horizontal components is about 5 times greater than the estimated uncertainty for the daily solutions of the horizontal components. However, hourly solutions have higher temporal resolution than daily solutions. The application of symmetric moving averages on hourly solutions allows a significant reduction of uncertainty without prejudice to time resolution. Moving averages smooth as a low pass filter and are very easy to implement in time series [3].

The Figure 5 shows the results of the application of 25th order symmetric moving average to the time series of observed displacements, horizontal components, in the centre of the crest of Cabril dam. The green line represents radial displacements observed by GNSS (hourly solution). The light blue represents tangential displacements observed by GNSS (hourly solution). The red line represents tangential displacements of 25th order moving average of hourly GNSS solution. The dark blue line represents the radial displacements of 25th order moving average of hourly GNSS solution. As can be seen in Figure 5, the smoothing of the hourly solutions obtained with the application of moving averages allows reducing the uncertainty without the temporal resolution lost.

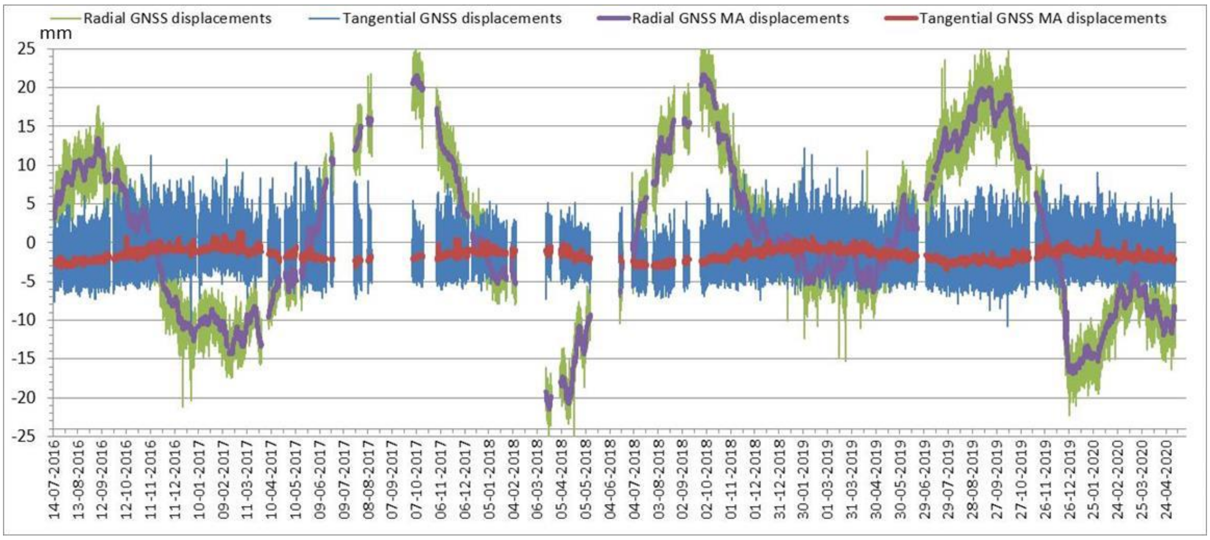

Fig. 5 – Application of 25th order moving average to time series of GNSS observed displacements, horizontal components

The major portion of the observed displacements (Figure 6) is due to the annual thermal variation (up to 45 mm) in the radial direction. The Figure 6 shows the correlation between the observed radial displacements and the average weekly air temperature. The scale of the ordinates shows a correspondence of 2 mm for each 1° C. The temporal lag between the observed downstream-upstream displacements and the average weekly air temperature, of the order of 15 – 30 days, can be explained by the thermal inertia of the dam.

The variation of reservoir level has also an important contribution for the observed displacements (Figure 7), in particular in radial direction. The Figure 7 shows the symmetric correlation between the observed radial displacements and the variation of reservoir level, in particular, during the first four months of 2020.

In Cabril dam no plumb lines were installed on the centre console, but only installed on blocks closer to the dam abutments. The validation of GNSS displacements observed on the centre console was carried out with a numerical model with of 3D finite elements previously calibrated with the displacements measured in two plumb lines installed closer to the dam abutments [2].

The antenna of the GNSS reference station in Cabril dam, installed on the top of a medium voltage pole, should be affected by sub-daily thermal tilts of the pole induced by the thermal expansion of the sunshine facing faces of the pole, since in the hourly GNSS solution time series the displacements repeat themselves every sunny day. The Figure 5 shows that the tangential component is more affected than the radial component.

From the hourly GNSS solutions observed at each object point, in the radial and tangential directions, the respective moving averages of order 25 were subtracted resulting in the dispersion of the hourly solutions observed at each object point without the respective displacements at those same points. The radius of the circle that inscribes 95% of the points is an estimate of the uncertainty of the hourly displacements observed in each object point, the estimate of the uncertainty of the moving average of order of the respective observed hourly displacements being the value obtained by dividing the square root of the order of the moving average (ie, 5), applying the law of propagation of variances.

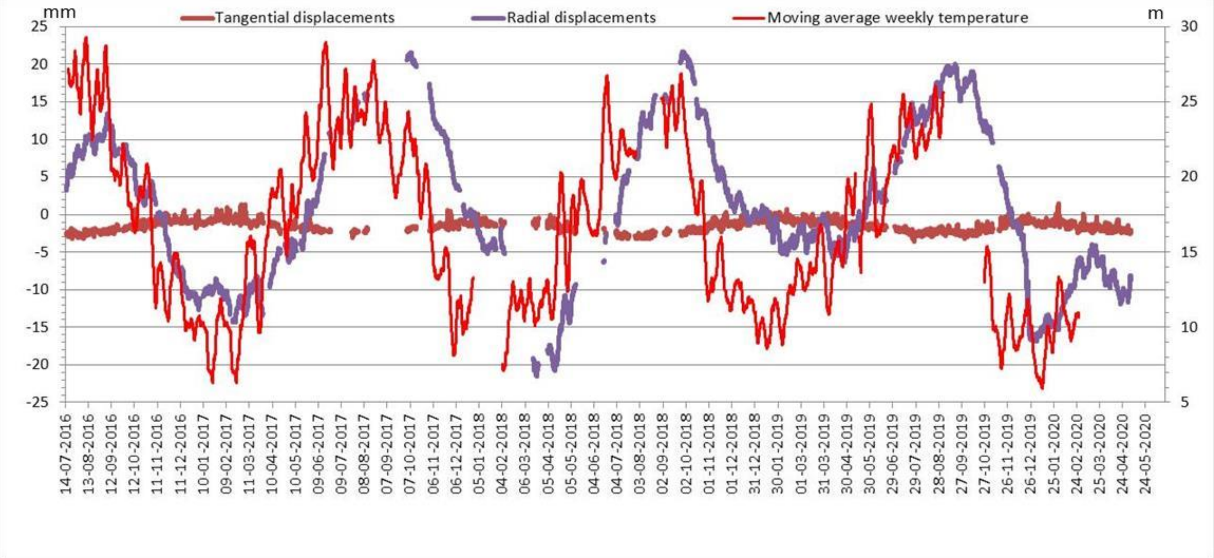

Fig. 6 – The correlation between the temperature and the observed displacements, horizontal components, brown line represents tangential displacements observed by the moving average of GNSS hourly solution, blue line represents radial displacements observed by the moving average of GNSS hourly solution and red line represents the moving average weekly temperature

The Table 1 resumes the GNSS displacement uncertainty estimates in the object point of the Cabril dam, related with hourly and daily solution (similar to the 25th order moving average). The distance to the reference station is the baseline length defined by the reference station and the object point on the centre of dam crest.

The Figure 8 shows two scatter plots: on the left side, the scatter plot of GNSS displacements hourly solution (green balls) and GNSS hourly solutions without the trend (blue balls); on the right side, the scatter plot of 25th order moving average of GNSS displacements hourly solution (green balls) and GNSS hourly solutions without the trend (blue balls). It is possible to see clearly the influence of the sub-daily thermal tilts on tangential component.

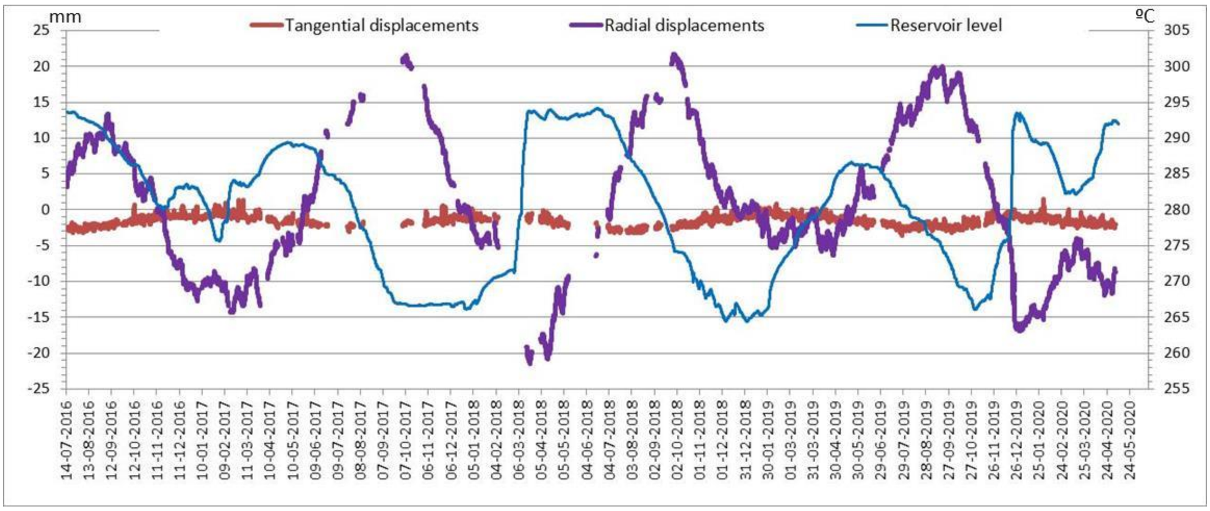

Fig. 7 – The symmetric correlation between the variations of the reservoir level and the observed displacements, horizontal components, brown line represents tangential displacements observed by the moving average of GNSS hourly solution, blue line represents radial displacements observed by the moving average of GNSS hourly solution and light blue line represents the variation of the reservoir level

Table 1 – GNSS displacements uncertainty estimation

Dam	Distance to reference station	1 hour session uncertainty	24 hour session uncertainty
Cabril	240 m	6 mm	0.6mm

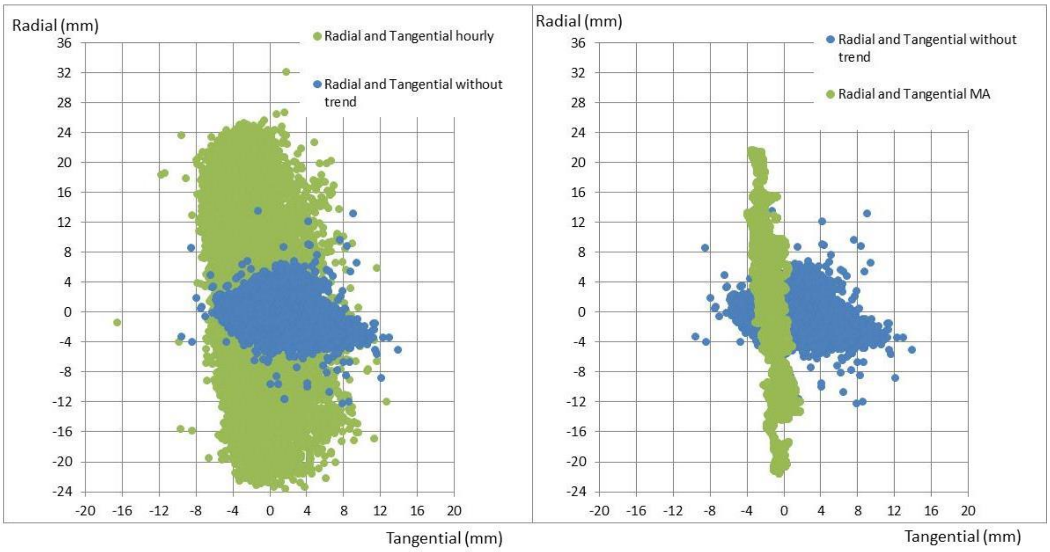

Fig. 8 – Scatter plots of GNSS displacements hourly solution (green balls) and GNSS hourly solution without trend (blue balls), on the left; scatter plots of 25th order moving average of GNSS displacements hourly solution (green balls) and GNSS hourly solution without trend (blue balls), on the right

4. SPECTRAL ANALYSIS OF GNSS DISPLACEMENTS

The spectra analysis of GNSS displacements were computed by the TSOFT software [4]. TSOFT is a graphical interactive analysis software package originally dedicated to the analysis and processing of gravity time series. TSOFT can also be used to process and analyse all sorts of time series like seismic or other environmental signals.

TSOFT calculates spectra and presents the amplitudes in a linear or logarithmic plot, with frequency in hertz or cycles per day. The software uses FFT to calculate the spectrum, it is also possible to calculate phase and power spectra.

The Figure 9 shows the spectrum analysis to the radial component of GNSS displacements (hourly solution), it can be seen that annual thermal signature can be easily identified (left side of the plots), the highest energy, around the frequency 0.0029 cycles per day (1.07 cycles per year). Other peaks it can be seen for the frequencies 1 (period of 24 hour), 4 (period of 6 hour), 8 (period of 3 hour) and 12 (period of 2 hour) cycles per day.

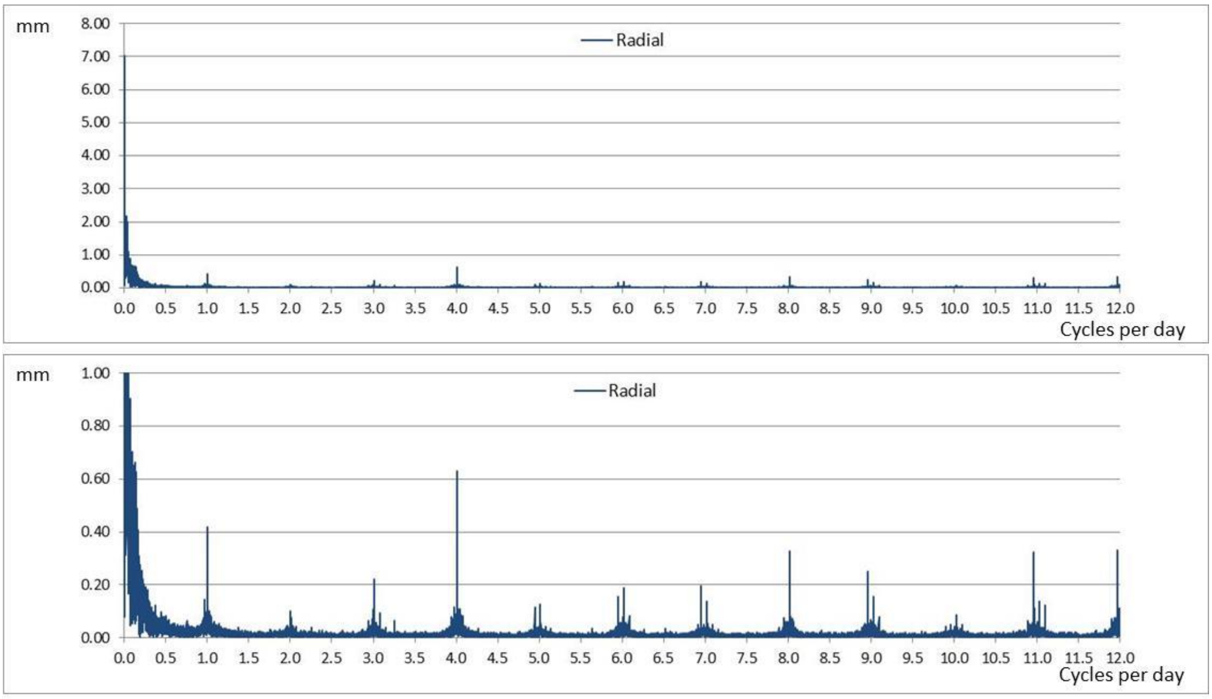

Fig. 9 – Spectrum analysis of the radial component of GNSS displacements (hourly solution): top plot is the full spectrum, bottom plot is a zoom of the top plot

The Figure 10 shows the spectrum analysis to the tangential and vertical component of GNSS displacements (hourly solution), it can be seen that sub-daily thermal tilts signature can be easily identified for the frequencies 2 (period of 12 hour), 3 (period of 8 hour) and 6 (period of 4 hour) cycles per day, for tangential component, and for the frequencies 2 (period of 12 hour), 3 (period of 8 hour) and 8 (period of 3 hour) cycles per day, for vertical component. Other peaks it can be seen for the frequencies 0.0029 (1.07 cycles per year), 1 (period of 24 hour) and 12 (period of 2 hour) cycles per day.

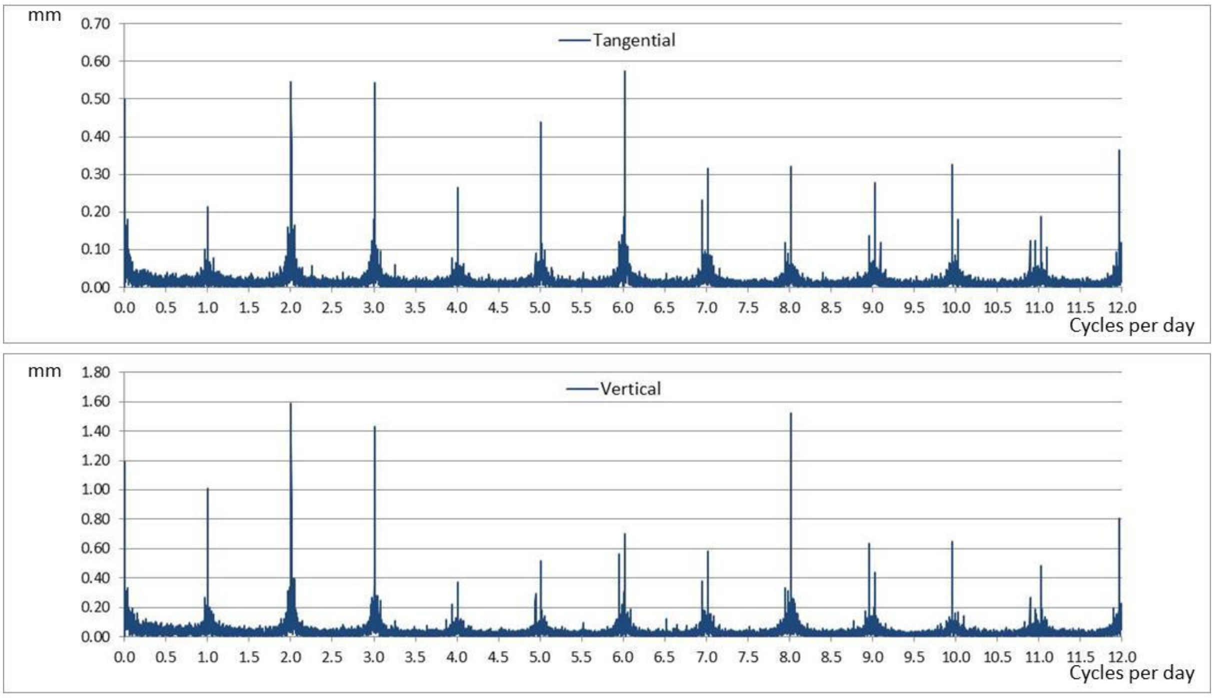

Fig. 10 – Spectrum analysis of the tangential and vertical component of GNSS displacements (hourly solution)

5. CONCLUSIONS

The results of the monitoring of dam displacements with GNSS in Cabril dam show that it is possible to achieve a high level of precision (submillimetre) and a high level of correlation with average weekly air temperature. The sub-daily thermal temperature has a significant influence on tangential and vertical component of GNSS displacements hourly solution and can be easily detected through the spectrum analysis. However this influence is no observable in three components of GNSS displacements daily solution (or 25th order moving average of hourly solution). The GNSS with specialized software for processing continuous position data offers a powerful alternative to conventional monitoring systems. The GNSS equipment is solid state and requires little maintenance and no calibration. Beside, GNSS systems are well suited to being automated. Automation is becoming increasingly important as dam operators strive to control labour costs. Many conventional monitoring systems require frequent recalibration to provide accurate data, and some require manual downloading and time-consuming post-processing of data.

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