Fourier Correlations of Dam Horizontal Movements Time Series

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Abstract ***– Time deformations monitoring of Drăgan dam is done by physically methods (i.e. inverse pendulum) and topographically methods (i.e. optoelectronic). The two deformations measuring systems, built up by these two methods, are different. The existence of different conclusions drawn from these deformations reveals the correlation importance of the two deformation systems. If there is a correlation then the deformations values differences will be provided by measuring errors; if the correlation is not present then the deformations values differences will be provided by coarse errors.***

This paper is intended to identify the problems from the presented systems, that provides wrong deformations and to exclude them.

Fourier analysis [1-3] is used to generate the correlations of deformations measured by these two different methods. There are presented both time correlations for 1D deformations of single measuring point, named (1D along H) correlation, and time correlations for vertical blocs of measuring points (i.e. plots) of the dam, named (2D+t) correlation.

Keywords: ***time series, Fourier correlation.***

I. INTRODUCTION

Drăgan dam presents a double arch concrete structure featuring 120m height and 450m length at the crest. It has 33 vertical plots and generates a basin of about 120 million m^3 of water. Monitoring the deformations of large concrete dam is important to prevent fatal accidents of dam cracking. Dam crust deformations are measured physically with an inverse pendulum with a very good precision (10^{-2} mm) given by an optical coordioscope. The surveying method readings of dam crust deformations are done with an optoelectronic device called total surveying station. This method involves building a surveying network of reference points, from witch are measured sets of readings for the same deformations [4,5].

For plots 7, 12, 19, 24 and 29 the time series provided from inverse pendulums consists in 2010 readings, from May 2000 until November 2005. This is the reason why the time series provided from the surveying targets (i.e. the control points) consists only of the deformations readings of control points placed nearest the measuring points of inverse pendulum.

This paper presents the time series correlations [1-3] for five measuring points and their nearest control points, done only for plot 19, which is the middle vertical axis of the dam.

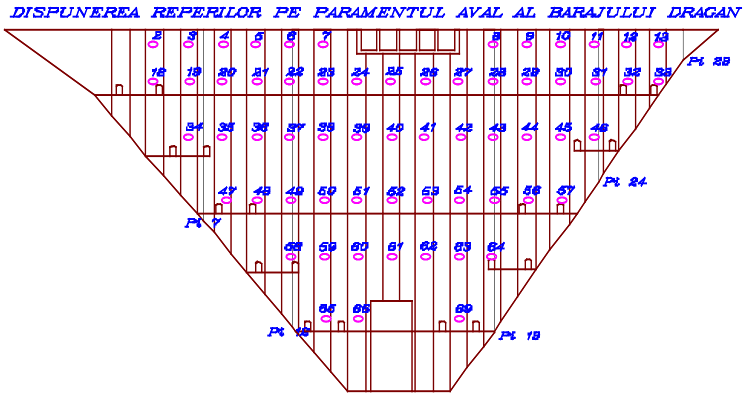
II. METHOD AND SAMPLES

There are two ways to get the correlation information between two time series that have different numbers of readings, i.e. 2010 readings for the inverse pendulum (figure 2) and just 12 readings for the surveying method (figure 3). The first way is to select only the corresponding 12 dates, from the 2010 dates, that matches the dates for the surveying method. The second way is to interpolate the 12 dates from the surveying method and obtain 2010 readings dates, that matches the inverse pendulum time series dates.

In this paper we choose the first way which is to correlate these two different time series. As was mentioned before the correlation process involves two time series over 12 dates. The inverse pendulum time series (1D+t) are denoted by X (figure 4 – the red doted line) and the surveying time series are denoted by XT (figure 4 – the blue doted line).

Furthermore, we consider horizontal deformations (X and Y) of plot 19 vertical axis. The vertical axis of plot 19 consist of five measuring/control points spatially distributed along the plot height (2D information) – i.e. one vertical coloured line from figure 5 a/b. Time series of the vertical axis horizontal deformations gives the (2D+t) surfaces: first upstream-downstream deformations, denoted by HX, for the inverse pendulum readings and second upstream-downstream deformations, denoted by HXT, for the surveying readings.

a



b

Figure 1 a – Downstream face of the Drăgan dam (foto); b – Drăgan dam plots and surveying targets (control points).

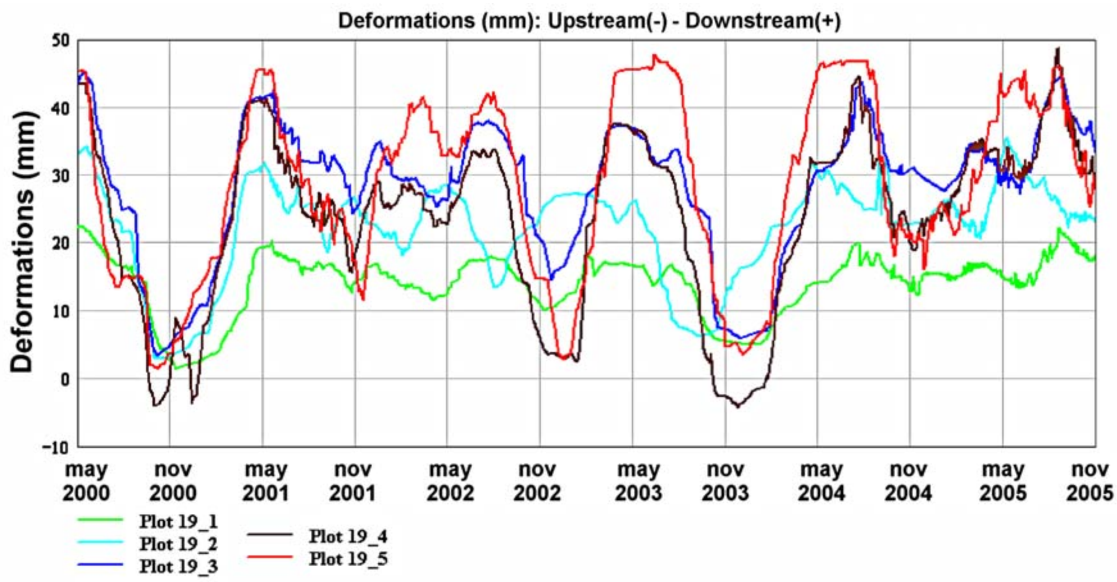


Figure 2 Inverse pendulum deformations readings in five measuring points of plot 19 for 2010 days.

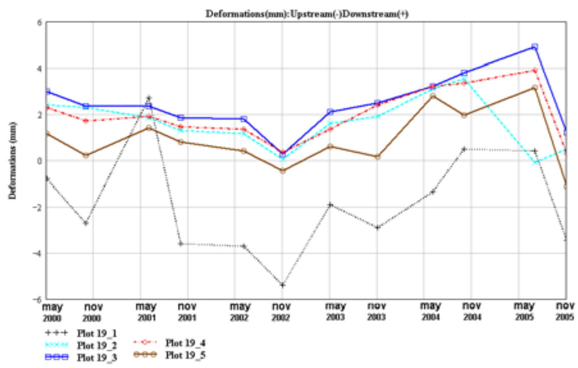


Figure 3 Surveying deformations readings in five control points of plot 19 for 12 dates.

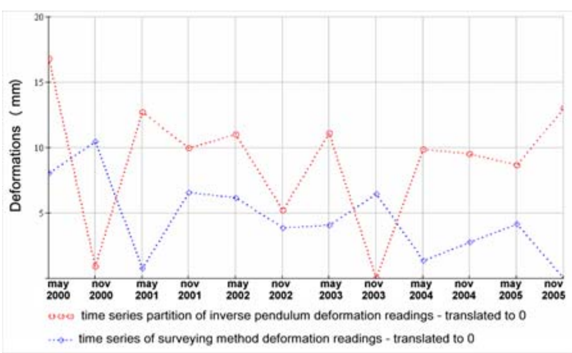


Figure 4 Inverse pendulum (X) and surveying deformations (XT) readings for one measuring / one control point of plot 19 for 12 dates.

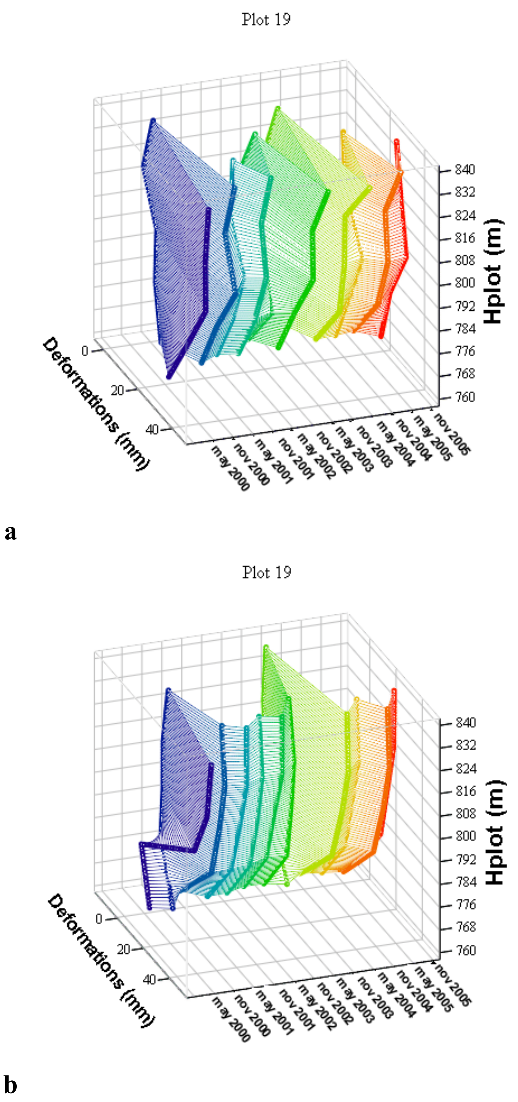


Figure 5 (2D+t) surfaces, defined by twelve 2D interpolated (79 (of 2D) × 12 (of t) points) vectors, which are the horizontal deformations of plot 19 vertical axis: a - for upstream-downstream deformations HX, b - for upstream-downstream deformations HXT.

Correlation process may be a statistical one or a Fourier analysis one. The normalized Fourier correlation coefficient, $NFCC$, can be built from the Fourier analysis, described [1-3] by

$$CnF(f(x),g(x)) = \max_x \left[\frac{\left[|f(x) \otimes g(x)|^2 \right]}{\max_x [|f(x) \otimes f(x)|]^{0.5} \cdot \max_x [|g(x) \otimes g(x)|]^{0.5}} \right] = \max_x \left[\frac{\mathcal{F}^{-1}\left[\overline{F(-k)} \cdot G(k)\right](x)}{\max_x \left[\mathcal{F}^{-1}\left[\overline{F(-k)} \cdot F(k)\right](x)\right]^{0.5} \cdot \max_x \left[\mathcal{F}^{-1}\left[\overline{G(-k)} \cdot G(k)\right](x)\right]^{0.5}} \right] = \max_x \left[\frac{\mathcal{F}^{-1}\left[\overline{F(-k)} \cdot G(k)\right](x)}{\max_x \left[\mathcal{F}^{-1}\left[|F(k)|^2\right](x)\right]^{0.5} \cdot \max_x \left[\mathcal{F}^{-1}\left[|G(k)|^2\right](x)\right]^{0.5}} \right] \quad (1)$$

where $f(x), g(x)$ are two functions, x and k are two Fourier-conjugate variables (i.e. t as time and ν as frequency). From the authors experience the best way to correlate pure time series is the Fourier analysis method. When the information is time-spatially distributed the only way the correlation process can achieve consequent results is by Fourier correlation and not by statistical correlation – as the Pearson coefficient, R in equation (2) [2] – despite the symmetry of the two correlation coefficients.

$$R_{fg} = \frac{\sum_{i=1}^{n} (f_i - \bar{f}) \cdot (g_i - \bar{g})}{\left[\sum_{i=1}^{n} (f_i - \bar{f})^2 \right]^{0.5} \cdot \left[\sum_{i=1}^{n} (g_i - \bar{g})^2 \right]^{0.5}} \quad (2)$$

Table 1 Meaning of Fourier correlation normalized coefficient, $NFCC$, and Pearson statistical correlation normalized coefficient, *R*.

Correlation type	$NFCC$ and R
weak	*0,10 – 0,29*
average	*0,30 – 0,49*
strong	*0,50 – 1,00*

Statistical significance of the correlation coefficient values are mentioned in table 1.

III. RESULTS AND DISCUSSIONS

Fourier correlation of (1D along H) time series has $NFCC$ greater values than 0.601 for the HX and HXT pair (upstream – downstream deformations) and than 0.414, for HY and HYT pair (left side – right side deformations). This means that the horizontal deformations measured by inverse pendulum (HX, HY time series) are strong correlated and measured by surveying method (HXT, HYT time series) and average correlated.

The (2D+t) correlation was done in two ways. In the first way the Lp norm of (1D along H) correlations results is calculated providing the Lp score. In the second way the pure (2D+t) Fourier correlations of surfaces from figure 5a, b are done. The Lp score denotes strong correlations between all horizontal deformations measured by inverse

Table 2 Fourier correlation results (2D+t) time series of plot 19.

1	**Date**	**HX vs HXT**	**HY vs HYT**
2	01.05.2000	*0,928**	*0,895 **
3	01.10.2000	*0,601**	*0,950 **
4	01.07.2001	*0,976**	*0,857 **
5	01.10.2001	*0,909 **	*0,892 **
6	01.06.2002	*0,988 **	*0,891 **
7	02.11.2002	*0,777 **	*0,414 **
8	01.05.2003	*0,944 **	*0,812 **
9	01.11.2003	*0,642 **	*0,753 **
10	01.06.2004	*0,964 **	*0,939 **
11	01.10.2004	*0,841 **	*0,504 **
12	01.07.2005	*0,988 **	*0,865 **
13	01.11.2005	*0,955 **	*0,607**
14	***Lp* score of NFCC's for (2D+t)** ($p = 2{,}5$)	***0,886***	***0,800***
15	**Normalized Fourier correlation coefficient NFCC for (2D+t)**	***0,841***	***0,535***

*has the significance of (1D along H) Fourier correlation, where H is the plot height.

pendulum (HX, HY time series) and by surveying method (HXT, HYT time series). Instead Fourier correlation results of (2D+t) time series denotes that the horizontal deformations measured by inverse pendulum and by surveying method are strong correlated for (HX vs HXT) and average correlated for (HY vs HYT).

IV. CONCLUSIONS

Fourier correlation method is more reliable and accurate for correlation of time-spatially distributed data, like the time series considered in this paper. The surveying method is reliable for periodical monitoring of dams deformations and can be used to make accurate diagnosis of the dam status.

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