Analysis of the Geodetic Monitoring Record of the Ladhon Dam, Greece

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Key words: dam monitoring, autocorrelation, periodogram, hydraulic load

SUMMARY

A 30-year long geodetic record describing the deformation of the 101.5m long, 56m high concrete, gravity dam of Ladhon River in SW Greece was analyzed in order to approach the action of reservoir water level on the dam. This record consists of measurements of horizontal deflections from the dam axis and spirit leveling data of six control stations established on the crest of the dam. Observed displacements were statistically significant against random errors, up to 7 mm and were maximum at the middle of the crown of the dam. The first-order equation analysis proved to be unsuitable to determine any type of relationship between horizontal or vertical displacements and the reservoir level. For this reason signal processing methods, namely the autocorrelation and the Lomb normalized periodogram, were alternately applied.

The autocorrelation function was used to determine whether or not there existed a periodic signal of the displacements of the crest of the dam and in the changes of the reservoir level. Because of the unevenly spaced data, predicted values through a polynomial interpolation were used in our calculations. Quasi-sinusoidal fluctuation in the autocorrelation coefficient was obvious in the displacements of all control stations and the reservoir level, indicating of a periodicity in our time-series.

In order to determine the fundamental frequency of both the displacements and the change of the reservoir level we used the Lomb normalized periodogram, using raw data. The spectral analysis of the data indicated that the displacements of each control station, examined separately, and the reservoir level had a 12-month fundamental period.

This indicates that the Ladhon Dam deforms in response to changes of its reservoir level (up to 20m).

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1. INTRODUCTION

The vast majority of dams till approximately 1960 were of thin-cell or gravity (triangular vertical cross-section) type. Such structures proved very vulnerable to foundation instability (Malpasset dam, Marinos 1994) and to seismic loading (Pacoima, Behr et al. 1998), and occasionally a threat for thousands of people (Malpasset, Marinos 1994; Vaiont, Marinos 1994; China, Yi Si 1998). For this reason the systematic monitoring of their deformation represents a major contribution towards their structural health and reduction or even avoidance of disasters. Yet, for various reasons (confidentiality etc.) detailed reports for long-term monitoring of such dams are very rare in the literature, and the effects of the fluctuations of ambient temperature or of reservoir level on the dam geometry are problems poorly understood. In this article we present the results of a 40-year long geodetic monitoring system of the Ladhon Dam in SW Greece and try to contribute to answering the relationship between hydraulic loading and dam deformation using signal analysis techniques.

2. THE LADHON DAM

The Ladhon dam, on Ladhon River, is a medium size (101.5m and 56m crest length and height respectively) dam. It was constructed between 1950 and 1955. It is a concrete hollow gravity dam with a slant upstream face and a vertical top, in SW Peloponnese.

The reservoir of the Ladhon River dam was formed in a meander-type valley, the geological background of which consists mainly of limestone and shale. During the function period, no serious leakage or stability problems have been reported for this dam. In particular, it suffered no damage from earthquakes which affected the wider area, mainly from the 1966, Ms = 6.0 Megalopolis earthquake (Papazachos and Papazachou , 1989) (max intensity VIII-MMKS)

The dam is used by the Public Power Co for generation of electricity and irrigation of the downstream area.

3. THE GEODETIC MONITORING SYSTEM

The aim of the geodetic monitoring system of the Ladhon dam is to control possible horizontal deflection from the dam axis and vertical displacements of the crest of the dam. All measurements refer to 6 control stations on the crest of the dam, and to reference stations close to its abutments.

3.1 Horizontal Deflections

Two control stations at the abutments of the dam (R1 and R2 in Fig. 1) define an axis, along which 6 monitoring stations (C1 to C6 in Fig. 1) were established on the crest of the dam. During each period of measurements, a high precision theodolite (Wild T2) was placed at the control point, R1, aiming at control station R2, and hence defining a fixed reference axis.

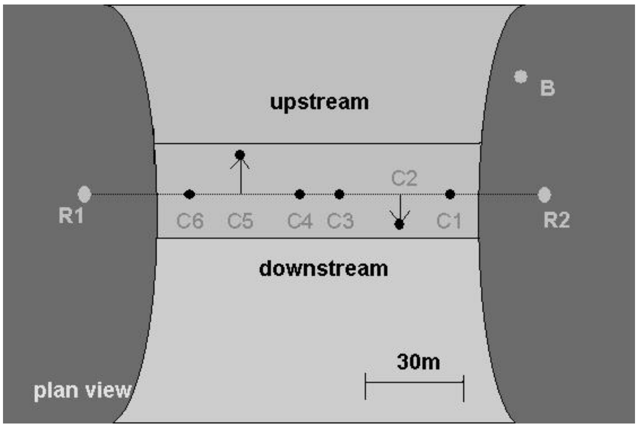


Fig. 1 Principle of measurements of deflections of the dam crest from a straight line. Deviation of each one of the control stations is measured along a rule using a high accuracy theodolite in reference station R1 and pointing to the reference station R2. Deflection is defined as the difference of the corresponding ruler readings between a specific survey and the initial survey for a certain control point.

At each monitoring station a millimetre ruler was placed vertical to the dam axis and the reading of the theodolite axis on the ruler was recorded. Deflection of each epoch and station were computed as the difference of the corresponding ruler readings between a specific survey and the initial survey,

$$d_{ik} = R_{ik} - R_{0k}$$

where
d_{ik} = deflection of epoch i and station k
R_{ik} = reading of epoch i and station k
R_{0k} = initial reading of station k
Readings at the side of the lake were taken to be negative.

3.2 Vertical Displacements

The relative vertical displacement of the control stations on the crest of the dam was measured using high accuracy spirit levelling (Wild N3) relative to a fixed benchmark, on the left abutment of the dam (for location see shown in Fig. 2). Relative elevation changes for each benchmark and each survey period was measured. Vertical displacements (negative for uplifts) were then computed as the difference between values of a specific survey and the initial survey,

$$dH_{ik} = H_{ik} - H_{0k}$$

where

dH_{ik}	vertical displacement of epoch i and station k
H_{ik}	reading of epoch i and station k
H_{0k}	initial reading of station k

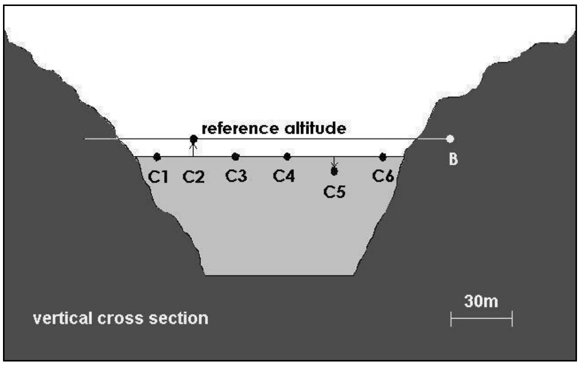


Fig. 2 Relative elevations of each control station are measured relative to reference station B using high accuracy spirit leveling. Vertical displacement in epoch i is defined on the difference between the elevation of a certain point in period j and an initial value at epoch 0.

4. ACCURACY OF MEASUREMENTS

The accuracy of the measurements of the horizontal deformations and the vertical displacements depends on the accuracy of the instruments used. The accuracy of the horizontal deflections was found equal to ±0.68 mm (Pitharouli et al.,2003). This means that computed horizontal displacements above this threshold are significant against random errors (Fig. 3). The accuracy of the vertical displacements is the accuracy of the spirit leveling, about 0.5mm/km (Bonford, 1971). For the short lines discussed here, observed elevation changes are accurate to with 0.07mm (Fig. 4).

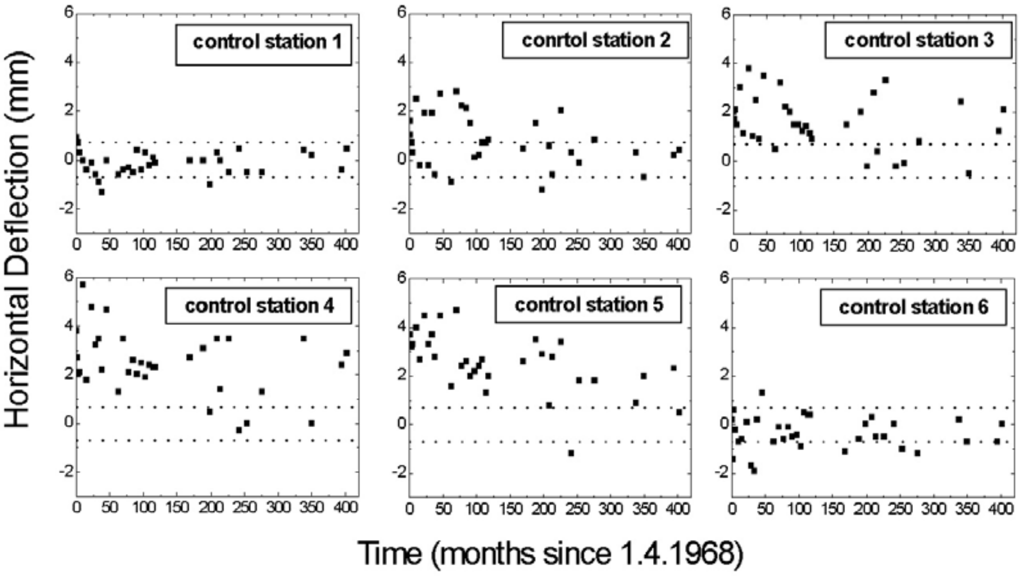


Fig. 3 Horizontal Deflections of the 6 control stations on the crest of the dam vs. time. The area between the dotted lines represents the standard error of the computed horizontal displacements (±0.68mm). The displacements of control stations 1 and 6 (near the abutments) are in this area. The horizontal displacements of the rest control stations are significant against random errors.

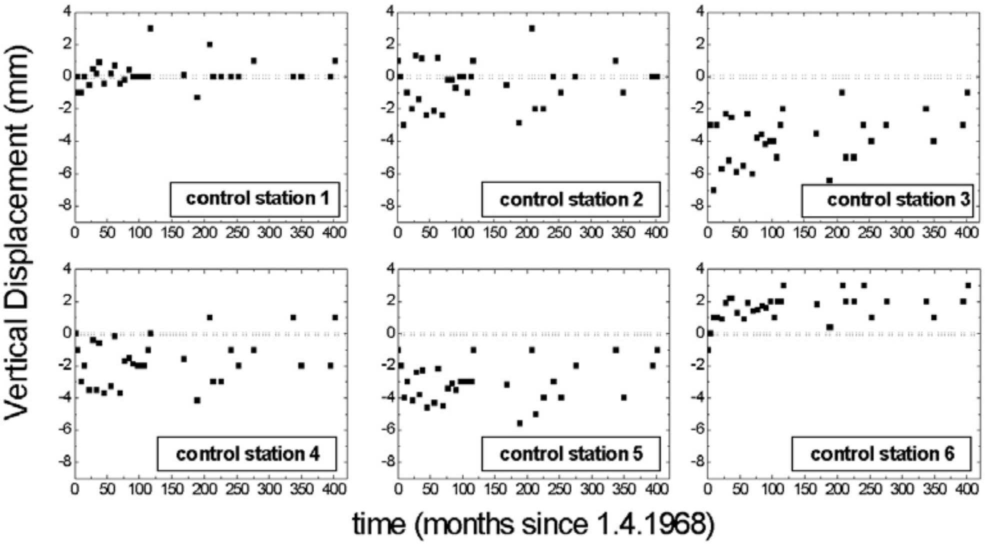


Fig. 4 Vertical Displacements of the 6 control stations on the crest of the dam vs. time. The area between the dotted lines represents the standard error of the computed vertical displacements (±0.07mm). The majority of the vertical displacements are significant against random errors.

5. AVAILABLE DATA

The available original deformation control data include information for the date, the ambient temperature and the reservoir level during the measurement, as well as the horizontal deflection and the vertical displacement of each one of the six control stations. The measurements cover the time interval 1960 and 2001, start several years after the completion of the dam, but they are systematic after 1968, especially at the time interval 1968 - 1978. For this reason, there is no control of deformation of the dam during the reservoir filling period.

Because measurements showed little, if any deformation, spacing between surveys was irregular and sparse. The measuring process however, was totally uniform as far as the method, instrumentation and survey parties are concerned.

6. DATA ANALYSIS

The maximum horizontal deflection and vertical displacement have been found at the control stations C3 and C4 (Fig. 3 & 4). This indicates that the central part of the dam is more sensitive than the rest of it. That was the reason why we decided to analyze the horizontal and vertical displacements of control stations C3 and C4 only. Because the data was more systematic at the time interval 1968 – 1978 we decided to examine separately 2 time periods

- Time period “April 1968 – February 1978”
- Time period “April 1968 – October 2001”, (whole observation time period)

6.1 Signal Processing Methods

Dams are usually affected by the changes of the reservoir level. Since the relationship between the horizontal and vertical displacements of Ladhon Dam was found to be non-linear (Pytharouli et al., 2003) we used signal processing methods namely autocorrelation and

Lomb normalized periodogram to determine whether or not there is any periodicity in the values of the displacements and the reservoir level and in case that there is, what is it's value.

6.1.1 Autocorrelation

The autocorrelation function (Box & Jenkins, 1976) was used to check the presence of periodicity in the values of the horizontal and vertical displacements and the reservoir level. The autocorrelation function of a timeseries F(x_i) is the function that determines the change of the linear correlation coefficient r ($-1 \le r \le 1$) of the timeseries F(x_i), F(x_i+k) which are separated by a constant interval (lag) k (k = 0,1,2…). In the case that there is a periodic signal hidden (because of noise) in F(x), the autocorrelation function has a sinusoidal shape and this testify the presence of periodicity in F(x). In any other case there is no periodicity in the examined timeseries.

The autocorrelation function requires evenly spaced data. The available data was unevenly spaced. The solution to the problem was the predicted values, which were calculated using cubic interpolation at the time interval of 3 months. This type of interpolation was the simplest type that could approach possible spikes in the observations.

Figures 5 and 6 show the autocorrelation plots for horizontal and vertical displacements of control stations C3 and C4 and the reservoir level vs. time lag. The autocorrelation coefficient R_H is plotted in the vertical axis, the time lag *k* in the horizontal axis.

$$R_h = \frac{C_h}{C_0}$$

where

$$C_h = \frac{1}{N}\sum_{i=1}^{N-k}(Y_i - \overline{Y})(Y_{i+k} - \overline{Y})$$

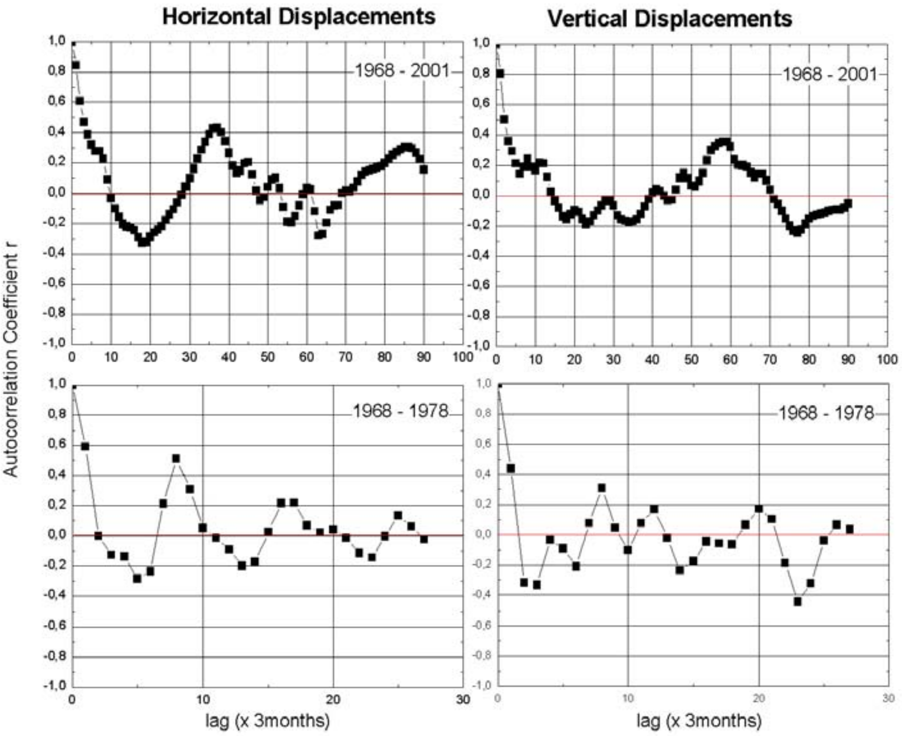
$$C_0 = \frac{\sum_{t=1}^{N}(Y_i - \overline{Y})^2}{N}$$

N	the number of values of the timeseries
Y_i	the value of the timeseries at time t_i
$\overline{Y}$	the mean value of the timeseries
k	time lag

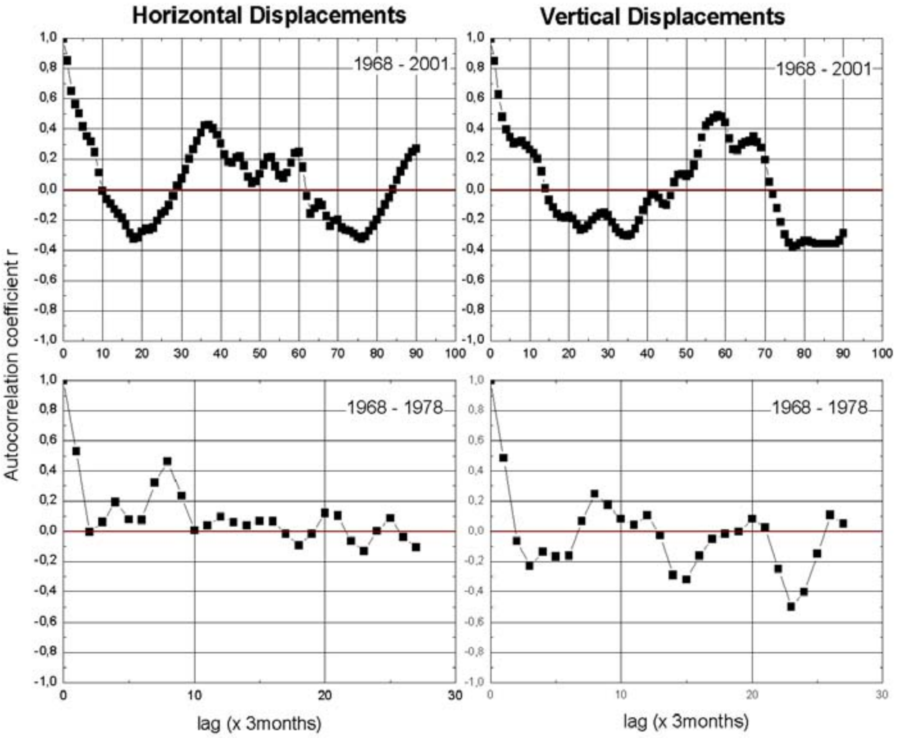
horizontal axis: time lag, k (k=0, 1, 2, …)
(Proakis & Manolakis, 1996)

The change of the autocorrelation coefficient vs. time lag k shown in fig. 5 and 6 has a sinusoidal shape. This is obvious in *all* plots for both time intervals that were examined and particularly in the years 1968 – 1978, where the available data were better. The sinusoidal shape shows a clear periodicity in the values of horizontal and vertical displacements of control stations C3 and C4 and the reservoir level.

The autocorrelation plots in fig. 5 and 6 were the result of a process based on predicted values and not observations. Despite that, the autocorrelation coefficients were calculated *independently* for control stations C3 and C4 and the reservoir level. This means that the possibility the results of the autocorrelation being accidental is very small.



(a) Control station C3



(b) Control station C4

Fig. 5 Autocorrelation plots for horizontal and vertical displacements of control station C3 & C4. All the above plots for both time intervals and control stations that were examined show that the dislocation data of control stations C3 & C4 are likely to be characterized by a periodic signal.

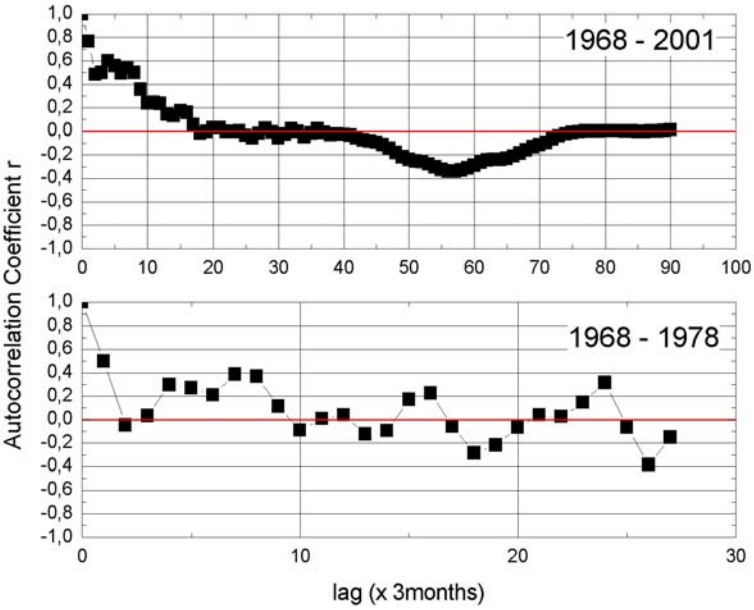


Fig. 6 Autocorrelation plots for the values of the reservoir level. The above plots for both time intervals that were examined show that the fluctuations of the reservoir level are periodic.

6.1.2 Lomb Normalized Periodogram

The Lomb normalized periodogram is a completely different method of spectral analysis for unevenly spaced data. It was developed by Lomb (1976), based in part of earlier work by Vanicek (1969). This method evaluates data, sines and cosines, only at times t_i, that are actually measured (Press et al., 1988). It is equivalent to the reduction of the sum of squares in least-squares fitting of sine waves to the data (Scargle, 1982).

For N data points $h_i = h(t_i)$, i=1, ..., N, with mean and variance given by the formulas

$$\bar{h} = \frac{1}{N}\sum_{1}^{N} h_i \qquad \text{and} \qquad \sigma^2 = \frac{1}{N-1}\sum_{1}^{N}(h_i - \bar{h})^2 \text{ respectively,}$$

the Lomb normalized periodogram (spectral power as a function of angular frequency $\omega = 2\pi f > 0$) is defined by

$$P_N(\omega) = \frac{1}{2\sigma^2}\left\{ \frac{\left[\sum_{i=1}^{N}(h_i - \bar{h})\cos\omega(t_i - \tau)\right]^2}{\sum_{i=1}^{N}\cos^2\omega(t_i - \tau)} + \frac{\left[\sum_{i=1}^{N}(h_i - \bar{h})\sin\omega(t_i - \tau)\right]^2}{\sum_{i=1}^{N}\sin^2\omega(t_i - \tau)} \right\}$$

where τ is given by the relation

$$\tan(2\omega\tau) = \frac{\sum_{i=1}^{N}\sin 2\omega t_i}{\sum_{i=1}^{N}\cos 2\omega t_i}$$

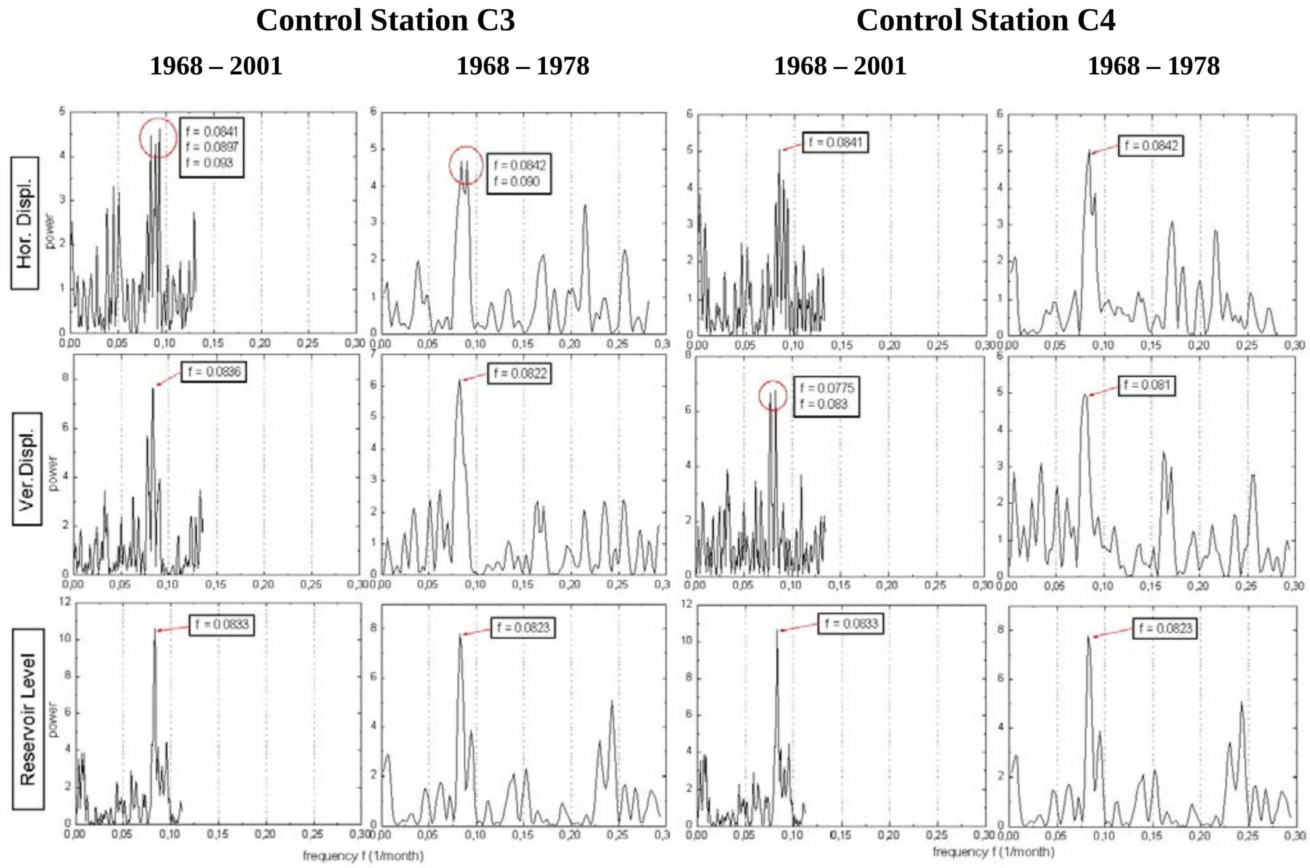
(Press et al., 1988)

Figure 7 shows the computed spectrums for horizontal and vertical displacements of control stations C3 and C4 and the reservoir level. The horizontal axis is the frequency f and the vertical axis is the power given by the equation of the Lomb normalized periodogram.

It was shown that both the displacements (horizontal and vertical) of the control stations examined, C3 and C4 and the reservoir level had fundamental frequency f very close to the same value f = 0.0833. This value corresponds to a 12-month period.

In some cases (horizontal displacements of control station C3 at the time intervals 1968 – 2001 and 1968 – 1978, vertical displacements of control station C4 at the time interval 1968-2001) there were more than one fundamental frequencies with adjacent values. This indicates that such multiple adjacent peaks are obviously the result of errors (during the measurements or the calculating process) and in fact they correspond to one single fundamental frequency equal to f = 0.0833. This means that the fundamental frequency is equal to T = 12 months.

Because the value for the fundamental period, T = 12 months, is based on *independent measurements* and is the same for both control stations C3 and C4 and the time intervals 1968 – 2001 and 1968 – 1978, it is not possible to be an accidental result.


Control Station C3

Control Station C4

1968 – 2001 **1968 – 1978** **1968 – 2001** **1968 – 1978**

Fig. 7 Power Spectrums of horizontal and vertical displacements and reservoir level based on the Lomb algorithm and raw data. In all plots it is shown that the displacements (horizontal and vertical) and the reservoir level are characterized by the same fundamental frequency (f = 0.00833) that corresponds to a 12-month period.

7. CONCLUSION

Linear analysis of the available geodetic data of Ladhon Dam showed no obvious relationship between the deformations of the crest of the dam and the reservoir level. Signal processing methods were used in order to determine a possible more complicated relationship. Autocorrelation method revealed that the displacements of the crest of the dam which are significant against random errors and small (less than 8mm) and the reservoir level were periodic. The Lomb normalized periodogram showed that the fundamental period is the same for all parameters examined and is equal to 12 months. These results indicate that the water pressure is the main cause of the displacements of Ladhon Dam.

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BIOGRAPHICAL NOTES

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