Long-term Geodetic Monitoring of Two Dams in Western Greece

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SUMMARY

The long-term behavior of two dams in Western Greece is analyzed on the basis of geodetic monitoring data. For the Kremasta Dam, the largest earth fill dam in Europe, geodetic observations covering a period of >35 years reveal that the max subsidence and horizontal displacement, about 0.75m and 0.30m, respectively, are observed at the middle of its crown. These values are smaller than the corresponding design values, and can be described as an accumulation of displacements, though with a tendency for stabilization 10 years after the construction of the dam.

For the Ladon Dam, a medium size concrete gravity dam, digital signal processing methods were used to analyse a 30-year long geodetic record testifying to small amplitude (up to a few mm only) vertical and horizontal fluctuations of the of the dam crown. Autocorrelation analysis indicated a periodicity in the horizontal and the vertical displacements and the reservoir level fluctuations, all with a fundamental period of 12 months, as a Lomb normalized periodogram analysis revealed. A causative relationship between reservoir level and dam deformation was therefore inferred.

Evidence presented above indicates that for periods >30-35 years long, during which floods and earthquakes occurred, the Kremasta and the Ladon Dam have retained their structural integrity and their deformation was kept at low levels.

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1. INTRODUCTION

As a consequence of major dam failures, occasionally associated with a great death toll, for instance the Malpasset Dam, France, 1959 (Londe, 1976) and the Vaiont Dam, Italy, 1963 (Kiersch, 1964) authorities in various countries require that dams and reservoirs larger than a certain magnitude are systematically monitored by geodetic and geophysical techniques to ensure their structural integrity and the safety of the public. Yet, reports for long-term monitoring of dams are rare and their deformation pattern remains rather obscure.

In this paper we summarize geodetic data describing the long-term (> 30-35 years) deformation of two different types of dams in Western Greece used for electricity production. The Kremasta Dam, the largest earthfill dam in Europe, and the Ladon Dam, a medium-size concrete dam. Monitoring data analyzed and reported in this article were collected by the surveying teams of the Public Power Corporation (Greece), owner of these dams.

The results of our study highlight the differences in the structural behavior of these two types of dams, and confirms that both structures, which have been tested by earthquakes and high flood events, fully retain their structural integrity.

2. THE KREMASTA DAM

The Kremasta Dam (Fig. 1) is the greatest earthfill dam in Europe (160m high, with a 456m crest length). It was constructed between 1961 and 1966 at a gorge close to the intersection of three rivers, Tavropos, Agrafiotis and Acheloos in Western Greece mainland in order (1) to store water to be used for generation of electricity (storage capacity approximately 4.75 billions m^3) and (2) to control river floodings. The dam is constructed by earthen material taken by the riverbed of the Acheloos riverbed. The impermeable clay core of the dam is protected by semi-permeable material. Due to its construction, consolidation of the dam and subsidence of its crown, with a maximum amplitude of 1.5m at its middle, were predicted.

The Kremasta dam became famous as a suggested cause of induced seismicity during the period filling of its reservoir (a seismic sequence microearthquakes culminating with a M=6.5 earthquake in 1966; Papazachos and Papazachou, 1997).

This Dam has two major problems
(1) Leakage which was controlled by grouting and drainage tunnels in the left abutment.
(2) Local, small-scale deformation and slope stability of the dam outer shell.
While these problems did not represent a major threat, they called for systematic monitoring.

2.1 Monitoring System

The Kremasta Dam is monitored by various instruments (piezometers, accelerometers, etc.), the cost of which was about 1% of the total cost of the dam (82,000,000 U.S $) and geodetic techniques.

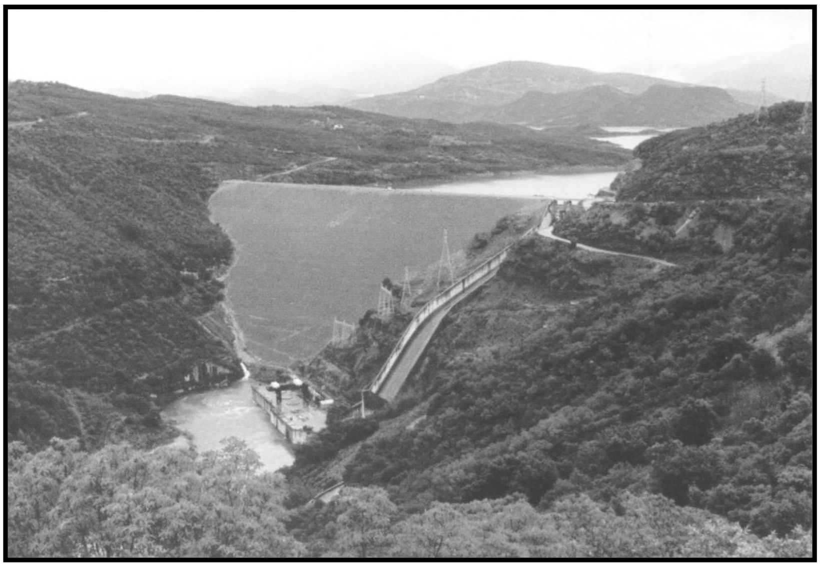


Figure 1: View of the Kremasta Dam from downstream. The spillway and the hydroplant can be seen on the right.

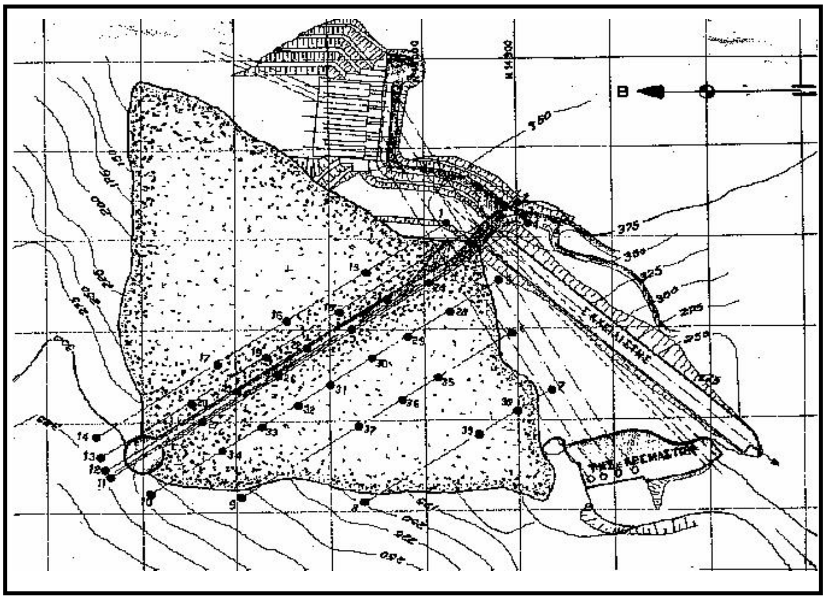


Figure 2: Location of reference stations (points 1 to 14) and control stations (points 15 to 39) of the geodetic monitoring system of the Kremasta Dam. The reference stations are established close to the abutments, while most of the control stations are on the crest and the downstream face of the dam.

The geodetic monitoring system consists of 14 reference stations (points 1 to 14, see Fig. 2) established close to the abutments of the dam and of 25 control stations (points 15 to 39 in Fig. 2) located at the crest and the two faces of the dam. All 14 reference stations are taken a priori stable in this study. Measurements of (1) horizontal deflections and (2) vertical displacements of the 25 control stations are made in reference to the stations R1 to R14, approximately twice per year since 1966.

2.1.1 Horizontal Deflections

The horizontal deflections are measured using a high accuracy theodolite (Wild T2) at reference stations 8 to 14, pointing at reference stations R1 to R7 and thus defining a straight line. The deflection of each one of the control stations (points 15 to 39) is defined as the difference between the deflection of the control station at a specific survey and the initial survey in 1966. The accuracy of the method is a few millimeters.

2.1.2 Vertical Displacements

The vertical displacements are measured using a high accuracy spirit leveling (Wild N2) in reference to a benchmark established at approximately 100m away from the dam. The accuracy of the vertical displacements is ±2mm.

2.2 Available Data

The available data consist of the horizontal and vertical displacements of the 25 control stations and cover a period of 36 years, from June 1966 to May 2002.

Maximum horizontal and vertical displacements, up to 0.3m and 0.75m respectively, were observed at control stations 19 and 22 located at the middle of the crest of the dam (fig.2).

2.3 Data Analysis

A preliminary analysis of the available data revealed that the maximum displacements were observed at the middle of the dam, in agreement with theoretical considerations. Figures 3 and 4 show the horizontal and vertical displacements of points 19 and 22, repectively, in which the displacements were maximum (for location see Fig. 2).

2.3.1 Crown subsidence

Polynomial fitting was used for the analysis of the monitoring data of control point 22. Using the least-squares method a 3rd degree polynomial trendline was fitted to the data. The fit was very satisfactory since the value of the correlation coefficient was high (R = 0.99).

The graph of Fig. 3 indicates that the vertical displacements of control point 22 at the middle of the crest of the dam cumulate over time but they have a tendency of stabilization. The total subsidence, about 75cm, is half of that predicted by the designers.

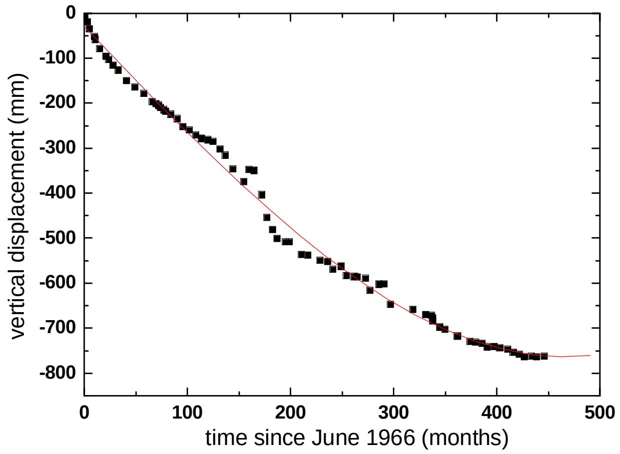


Figure 3: Vertical displacements of control point 22 vs. time (solid squares). A thin line indicates the best fitting 3rd degree polynomial.

2.3.2 <u>Horizontal Deflections</u>

The horizontal deflections of control station 19, the point where the maximum horizontal deflection was observed at the middle of the dam, were modeled using a 4th degree polynomial. Cumulative displacement downstream is of the order of 30cm, and has a tendency of stabilization (Fig. 4).

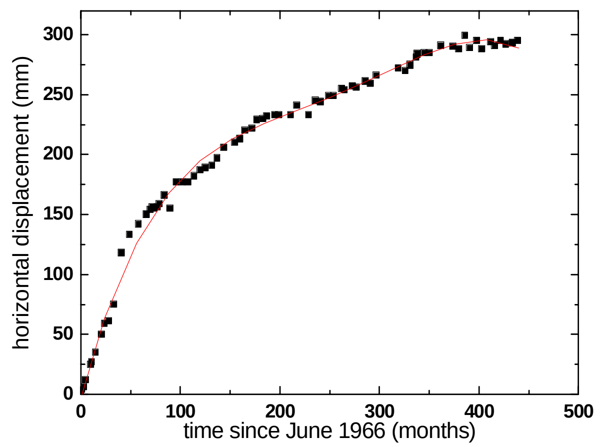


Figure 4: Horizontal deflection of control point 19 vs. time (solid squares). Continuous line indicates a best fitting 4th degree polynomial.

3. THE LADON DAM

The Ladon dam, on Ladon River in SW Greece mainland, is a medium size (101.5m and 56m crest length and height respectively) dam for generation of electricity and irrigation. It is a concrete hollow gravity dam with a slant upstream face and a vertical top (Fig. 5). It was constructed between 1950 and 1955 by an Italian company as a part of the compensation of Greece for the 2nd World War damage.

The reservoir of the Ladon River Dam was formed in a meander-type valley, the geological background of which consists mainly of limestone and shale. During its 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 (max intensity VIII-MMKS; Papazachos and Papazachou, 1989).

Figure 5: View of Ladhon Dam from downstream, showing both spillways in use for the first time since the beginning of the operation of the hydroelectric station in 1955. Photo taken just after the flood period of February 2003.

3.1 The Geodetic Monitoring System of the Ladon Dam

The aim of the geodetic monitoring system of the Ladon 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 (Pytharouli and Stiros, 2004).

The principle of measurement of horizontal and vertical displacements is similar to that used for the maesurement of the displacements of the Kremasta dam. 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. 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 (Pytharouli et al., 2004).

3.2 Monitoring Record

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 limited 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.

3.3 Data Analysis

Dams are usually affected by the changes of the reservoir level. Since the amount of displacement was small (a few mm) and there was evidence of oscillations (Pytharouli et al., 2003) we used signal processing methods, autocorrelation and Lomb normalized periodogram, in order to determine whether there was a periodicity in the observed displacements and whether these displacements were related to fluctuations of the reservoir level.

3.3.1 Autocorrelation analysis

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 describes the correlation between any two values of the time series as their separation changes. In the case that there is a periodic signal in the data, the autocorrelation function is a sinusoidal-type curve.

The autocorrelation function requires evenly spaced data. The available data were unevenly spaced. The solution to this problem was to predict values using cubic interpolation at the time interval of 3 months. This type of interpolation was the simplest one that could preserve spikes in our observations.

Figure 6 shows the autocorrelation plot for horizontal and vertical displacements of control station C3, nearly at the middle of the dam, and for the reservoir level vs. time lag. The autocorrelation coefficient R_H is computed by the following formulas of Proakis & Manolakis (1996)

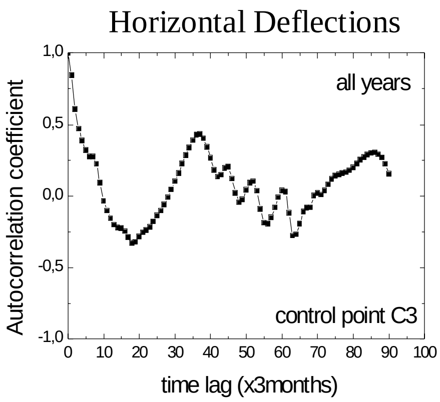
$$R_h = \frac{C_h}{C_0}$$

where $$C_h = \frac{1}{N}\sum_{i=1}^{N-k}(Y_i - \overline{Y})(Y_{i+k} - \overline{Y}), \qquad C_0 = \frac{\sum_{t=1}^{N}(Y_i - \overline{Y})^2}{N}$$

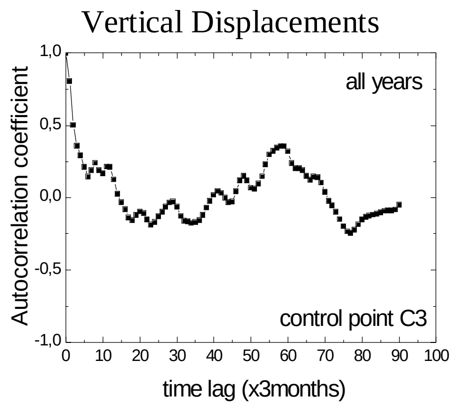
N the number of values of the timeseries
Y_i the value of the timeseries at time t_i
$\overline{Y}$ the mean value of the timeseries
k time lag

Based on our assumptions, time lag values 0, 1, 2, 3 etc. correspond to 0, 3, 6 months.

Both graphs of Fig. 6 have a sinusoidal shape. This was obvious in *all* data examined. The sinusoidal shape shows a clear periodicity in the values of horizontal and vertical displacements and the reservoir level.



(a)



(b)

Figure 6: Autocorrelation plots of (a) Horizontal and (b) Vertical displacements of control stations C3. In both plots the autocorrelation function is of sinusoidal type indicating periodicity in the examined data

3.3.2 Lomb Normalized Periodogram

The Lomb normalized periodogram is a method of spectral analysis for unevenly spaced data. It was developed by Lomb (1976), based on earlier work by Vanicek (1969). 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 spectra for horizontal and vertical displacements of control station C3 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.

From this figure it is clear that both the horizontal and vertical displacements of the control station C3, which correspond to independent variables, and the reservoir level have a common fundamental frequency f = 0.0833.

Certainly, in some cases more than one fundamental frequencies were observed, but with values very similar. This clearly indicates measurement and calculation noise and not multiple fundamental frequencies. Consequently, a single fundamental frequency f = 0.0833 corresponding to a period T=12months (i.e. that of the meteorological cycle) characterizes all data sets and is likely to indicate a causative relationship between dam deformation and fluctuation of the reservoir level.

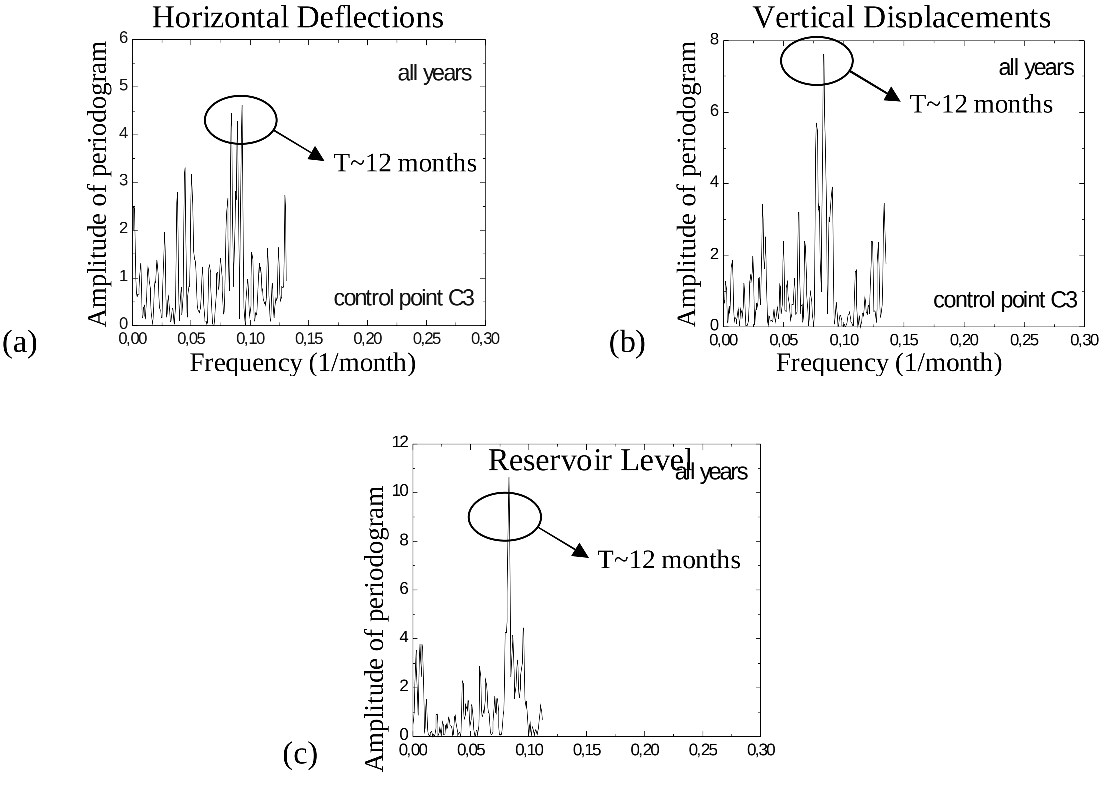


Figure 7: Lomb normalized periodograms of horizontal (a) and vertical (b) displacements of control station C3, as well as of the reservoir level (c). In all plots the same dominant period equal to 12 months is found, revealing a causative relationship between the displacements of the Ladon Dam and the reservoir level fluctuations.

4. DISCUSSION AND CONCLUSIONS

Long-term geodetic monitoring data summarized above are among the very few published for dams. Such data and results contribute to the understanding deformation and kinematics of dams and are very useful in prediction, reduction and prevention of dam failures leading to major destruction.

The analysis of the 36 years long geodetic monitoring of the Kremasta Dam reveals that observed displacements cumulate over time, but with a tendency of stabilization, and that the dam deformations can, at a first approximation, be described using polynomial fitting. Vertical and horizontal displacements of the Ladon Dam over a period of 34 years indicate some oscillation, but their small amplitude (the displacements are in the range of ±6mm, too small for a dam of the Ladon's Dam magnitude) does not permit to identify a possible pattern. Spectral analysis was therefore used to define the response of the dam to its reservoir level fluctuations.

After almost 40 and 50 years after their construction, periods during which strong earthquakes and floods occurred, the Kremasta and the Ladon Dam retain their structural integrity and their deformation is kept at low levels.

The geodetic monitoring of the Kremasta and the Ladon Dam is based on conventional geodetic techniques which are very accurate, but on the other hand time consuming and expensive. A future step is the adoption of new, mostly telemetric GPS-based techniques in order to optimize monitoring.

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REFERENCES

Bonford G. (1971), "Geodesy", Oxford University Press

Box G. E. P and G. Jenkins (1976), "Time Series Analysis: Forecasting and Control", Prentice Hall

Kiersch G., Vaiont reservoir disaster, Civil Engineering, Vol. 34, pp. 32 – 9, 1964

Lomb N. R. (1976), "Least-Squares Frequency Analysis of Unequally Spaced Data", Astrophysics and Space Science, Vol. 39, pp. 447 – 462

Londe P., "The Malpasset Dam failure" Engineering Geology, Vol. 23, pp. 295 – 329, 1976

Papazachos, V. and Papazachou, K. (1989), "Earthquakes of Greece", Ziti Publications

Press W. H., S. A. Teukolsky, W. T. Vellerling, B. P. Flannery (1988), "Numerical Recipies in C. The Art of Scientific Computing", Cambridge University Press

Pitharouli, S., Tsitsos V., Skourtis C., Kontogianni V. and Stiros S. (2003), "Rigidity Control of a Thin Reinforced Concrete Dam", Proc. of 11th FIG Int. Symp. On Deformation Measurements, Santorini, Greece, 2003, pp. 629 - 634

Pytharouli, S. and Stiros S. (2004), "Reservoir level fluctuations and deformation of Ladhon Dam", The International Journal on Hydropower and Dams, Vol. 11 (3), pp.82-84
Proakis J. G. and D. G. Manolakis (1996), "Digital Signal Processing", Prentice Hall
Scargle J. D. (1982), "Studies in Astronomical Time Series Analysis. II. Statistical Aspects of Spectral Analysis of Unevenly Spaced Data", The Astrophysical Journal, Vol. 263, pp. 835 – 853
Vanicek P. (1969), "Approximate Spectral Analysis by Least – Squares Fit", Astrophysics and Space Science, Vol. 4, pp. 387 – 391

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