Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0739

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Statistical analysis of long-term earth dam settlements

Analyse statistique des implantations à long terme de barrages en terre

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ABSTRACT: Earth dams are widely used nowadays for water supply, irrigation and hydroelectric power generation. They are an integral part of modern society's infrastructure and good construction is essential. Given their long lifetime, robust systems for continuous monitoring should be in place for long-term performance evaluation. Earth dams may sustain significant settlements or deformations over time, and these may be due to a number of different factors, such as earthquakes, climate change, unexpected ground conditions etc. Controlling the long-term settlements of earth dams is a critical issue for long-term monitoring and maintenance. This is important for determining the expected freeboard loss, any excessive seepage flow and dam slope deformation patterns. In addition to the magnitude of crest settlements, one needs to understand their spatial and temporal variation patterns which are usually related to different environmental factors. This paper presents long-term (> 25 years) monitoring data from the Kouris earth dam, which is the largest dam in Cyprus. An array of instruments was installed at the crest of the dam and time-domain processing and analysis is performed. A frequency-domain analysis is also performed which reveals a dominant frequency of the monitoring crest settlements which appears to be compatible with the dominant frequency of the reservoir fluctuations. It is therefore shown that the dam crest settlement variations are very strongly related to the reservoir changes. Comments are also made regarding the applicability of different frequency-domain analysis techniques.

RÉSUMÉ: Les données contrôlées du tassement d'un barrage sont analysées. L'analyse du domaine de fréquence est effectuée. Les effets du climat influent sur les installations du barrage.

Keywords: earth dams, embankments, reservoir, seepage, climate effects

1 INTRODUCTION

Many earth dams are built around the world and serve as water supply, irrigation or hydroelectric power infrastructure. Their long-term maintenance is important as this is crucial for their resilience and safety. The International Committee on Large Dams – ICOLD has identified some major threats for dam safety which include seismic activity (Elgamal et al., 1990; Kontoe et al., 2013, 2019; Pelecanos et al., 2013; 2015; 2016; 2018a, 2019a, 2019b; Shire et al., 2013), internal erosion (Bridle & Fell, 2013; Shire & O'Sullivan, 2013, 2016), faulting, climate variation and change (Pytharouli & Stiros, 2005; Gikas & Sakellariou, 2008), hydraulic fracture etc. Climate variations

are an important factor for dam safety as large seasonal changes (e.g. hot summers and cold winters) result in significant reservoir level changes which further affect the water pressures within the dam and the entire stress regime. It is therefore important to understand the impact of climate changes on the behaviour of earth dams and be able to predict and quantify its effects, especially if they become a threat for the dam's safety.

A wealth of studies exist in the literature which cover field monitoring (Kyrou et al., 2005; Dounias et al., 2012; Pelecanos et al., 2017; 2018b), laboratory experiments and computational simulations (Tedd et al., 1997; Alonso, 2005; Charles et al., 2008; Ventrella et al., 2019) for understanding dam performance and safety under various climate conditions. Many of these studies have raised the issue of reservoir-induced dam deformations and attempted to quantify this interaction. However, this is not an easy task and therefore more studies are needed in order to fully understand the effects of reservoir level changes on dam deformations and safety.

This paper presents the results of field monitoring and associated statistical analysis to understand and quantify the effects of climate variation and thus reservoir level changes on the performance of earth dams. Kouris dam, the largest dam in Cyprus was instrumented and the displacement data from over 25 years are analysed and further processed to identify a relationship between reservoir level and dam crest displacements. This work confirms that indeed reservoir level changes affect dam crest deformations and it is therefore suggested that continuous long-term monitoring is needed to keep a consistent observation of the safety of earth dams.

2 KOURIS DAM

Kouris dam is the largest and tallest dam in Cyprus. It is a zoned earth-rockfill operated by the Cyprus Water Development Department (WDD) and serves as the main water storage facility in the country. It was built during 1984-1988 and its embankment consists of a central clay core of low permeability, followed by thin layers of fine and coarse filters. The upstream shell consists of terrace gravels, which are adjacent to the upstream filters and then river gravels covered by rip rap on the upstream dam slope with a small cofferdam at the upstream dam toe. The downstream shell consists in its entirety by terrace gravels with talus deposits, which rest on a thin drainage gallery. Its crest is 570m long and the embankment is 112m high with the highest level of its reservoir at 102m, and its total reservoir capacity is 115 million m^3. Figure 1 shows a cross-sectional view with the various soil layers.

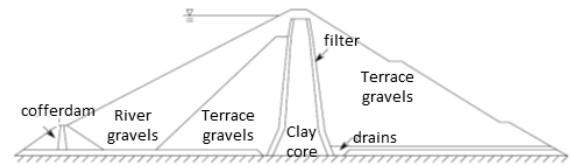


Figure 1. Geometry of the dam

Three independent instrumentation sets are installed on the dam providing monitoring data about the deformations of the dam: (a) Embankment Crest Movement Indicators (ECMI), (b) a vertical geodetic network and (c) a three-dimensional (3D) geodetic network.

The first instrumentation network, installed in 1991, consists of an observation pillar, (fixed point) and six embankment crest movement indicators (ECMI) installed at the time of construction. The measurements of these points are being carried out (irregularly, monthly or bi-monthly) since 1990 by the Cyprus WDD. The horizontal distance and the height difference of each ECMI from the pillar was determined using a Leica TC1101 total station, which provides accuracy of ±2mm ±2ppm for the distance measurements and ±1" for the angle measurements.

Additionally, two modern geodetic networks were installed in 2006. A vertical (1D) and a three-dimensional (3D) control network.

Generally, deformation monitoring is applied by the establishment, the measurement and the adjustment of such network. The vertical control network was established in 2006 (Constantinou, 2013). It consists of 7 control points. Six of them (R1-R6) are bronze benchmarks, located along both sides of the wall on the road at the crest of the dam and in a distance of about 100m between each other. The seventh point is the pillar T2 about 1 km far away, which serves as the fixed reference point of the network.

Three periods of measurements (July and December 2006 (Temenos, 2007) and June 2012 (Pantelidou, 2013)) were carried out for the determination of the height differences between the points by using either (a) the spirit leveling method, or (b) the accurate trigonometric heighting method (Lambrou, 2007; Lambrou & Pantazis, 2007, 2010). The latter two modern systems are extremely robust and much more accurate than the old initial system. Figure 2 shows the position of the instruments on the dam.

Figure 2. Instrumentation on the dam crest

3 MONITORING DATA

Figure 3 shows a comparison of dam deformations (both vertical and horizontal crest displacements) as those were obtained from the three different and independent instrumentation sets over the period 2006-2012. This is the period that was monitored from all three instrumentation sets. It is shown that a very good comparison is obtained between the three monitoring data sets which confirm their accuracy and reliability. Minor observed differences are well within what might be considered "noise" and therefore the monitoring system is proved to be working well.

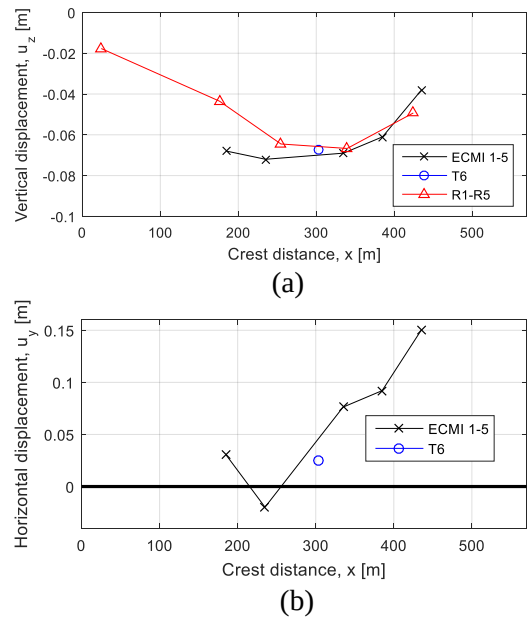


Figure 3. Dam deformations: profiles of (a) vertical and (b) horizontal dam crest displacements.

4 STATISTICAL ANALYSIS

Further processing of the monitoring data was undertaken using statistical analysis. This was used, in particular, to study any relation between the reservoir level changes and the vertical displacement fluctuations and therefore identify any causative relationship between the two. A direct comparison between the absolute values of the reservoir level and vertical displacements is not much helpful because of the large consolidation settlements. Therefore, incremental changes from successive readings

were examined. Figure 4 plots the incremental changes of reservoir level, ΔR, and incremental vertical displacements, Δu_z, from ECMI-3. It is shown that there is a weak periodicity in the peak values (i.e. large values of upward reservoir level change and downward displacements) of both the reservoir level changes and the crest vertical displacements. It is also shown that the peak values seem to occur at similar times, although some minor differences can be observed. It is also noted that reservoir level changes show clearer peaks than vertical displacements as the latter have more sparse (in time) data. This suggests that both quantities exhibit similar periodicity and therefore one could suggest that they have a certain correlation. Moreover, it may be observed that these peak values occur around once a year which may suggest that there are seasonal (climate) variations.

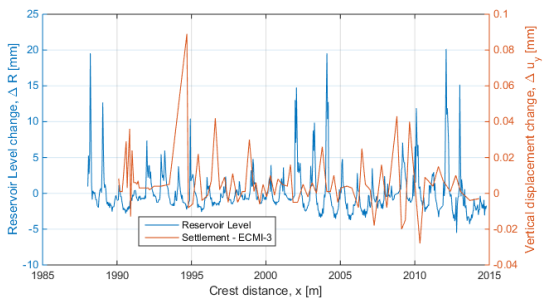
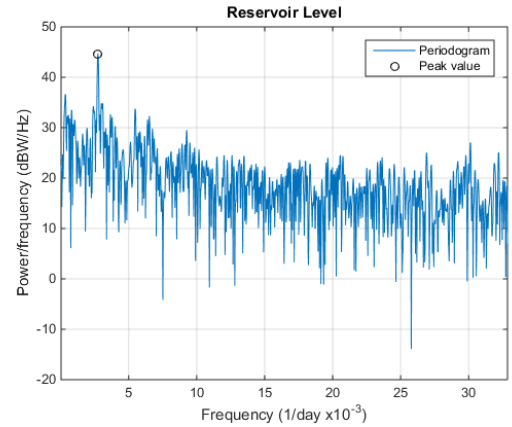
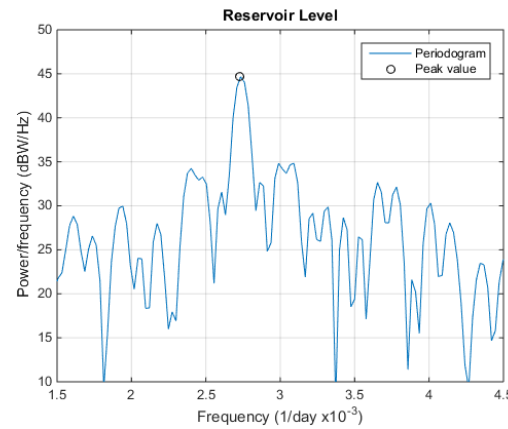


Figure 4. Statistical analysis of monitoring data: differential vertical displacements Vs differential reservoir level.

Since periodicity is observed, a more comprehensive comparison can be made by analysing both time-histories in the frequency domain and identifying their dominant frequencies. Such an exercise is commonly undertaken by Fourier analysis; however, that technique requires equally-spaced sample data, which is not the case here (irregular readings were taken over the study period of 25 years). Interpolation was then performed to generate additional data points to allow a Fourier analysis but this was not successful as it could not identify a single dominant frequency. Another technique was subsequently used instead, which is similar to the popular Fourier analysis, and able to process non-equally-spaced data; that is the Lomb (or Lomb-Scargle) periodogram (Lomb, 1976; Scargle, 1982).



(a)



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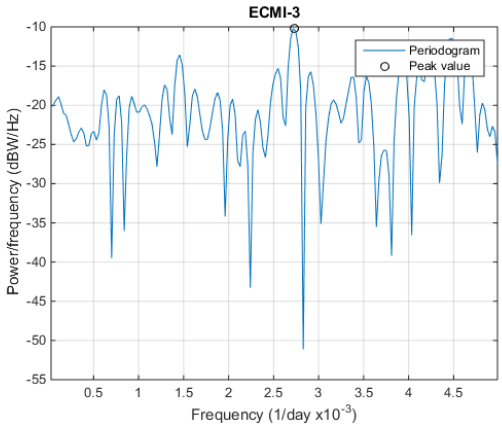
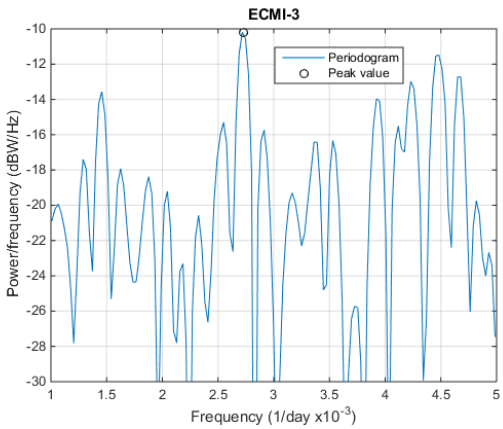


(c)



(d)

Figure 5. Lomb periodogram: (a) reservoir level, (b) reservoir level (detail), (c) vertical displacements and (d) vertical displacements (detail).

Figure 5 (a) and (b) (detail) show the Lomb periodogram for the reservoir level, which shows clearly a single dominant frequency at 2.73 (1/day $\times 10^{-3}$), which means a period of 1000/2.73≈365 days, i.e. a full year. This reinforces the earlier observation that the reservoir level exhibits yearly peaks. Figure 5 (c) and (d) (detail) show the Lomb periodogram for the crest settlements from ECMI-3, which again seems to yield a single dominant frequency at 2.73 (1/day $\times 10^{-3}$), i.e. corresponding to a period of 365 days. This observation is in agreement with earlier suggestions of Pytharouli & Stiros (2005) who performed similar statistical analyses and noted a strong correlation between the frequency of reservoir level changes and dam vertical displacements.

5 CONCLUSIONS

This paper explores the long-term settlement behaviour of earth dams due to climate changes leading to variations of the reservoir level. The study considers the long-term monitoring data from a well-instrumented dam along with relevant statistical data analysis.

The results of this study show that there is an observed correlation between the dam displacements and reservoir level fluctuations which suggests seasonal variations of dam settlements. In particular, it is shown that dam settlements are strongly related to changes in the reservoir level. Further analysis of the monitored response of Kouris dam, including nonlinear coupled hydro-mechanical finite element analyses may be found from Ventrella et al. (2019).

6 ACKNOWLEDGEMENTS

Assistance, data and information were provided by S. Patsali, and E. Kanonistis of the Cyprus Water Development Department. Students C. Temenos, G. Stavrou, C. Constantinou and A. Pantelidou of NTUA and CUT participated in the field measurements and data processing. This contribution is gratefully acknowledged.

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