DAM CREST SETTLEMENT, RESERVOIR LEVEL FLUCTUATIONS AND RAINFALL: EVIDENCE FOR A CAUSATIVE RELATIONSHIP FOR THE KREMASTA DAM GREECE

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Abstract: Crest settlements of the Kremasta Dam (Greece), one of the highest (160.3m high) earthfill dams in Europe, were analysed in combination with the elevation of the reservoir level and the rainfall height for the period 1966 – 2003. Using an analytical approach based on the optimization of the correlation coefficient between some critical parameters (reservoir level, rate of increase of the reservoir level and rainfall) in which a high-pass filter was applied, we determined critical values of these parameters. The significance of these thresholds is that if all of them are at the same time exceeded, the rate of the settlements of the crest is significantly increased. This result is important, especially in view of plans for increase of the reservoir level to the design value, a task never accomplished since the construction of the dam in 1965 because of the threat of increased leakage, already approaching safety limits.

1. Introduction

Excessive crest settlement, if not successfully faced, can be disastrous for the structural integrity for any embankment dam, for it can lead to overtopping; one of the most common causes of failure for such types of dams (Committee on Safety of Existing Dams, 1983). One of the best ways to deal with such a problem is precaution. In particular to understand the mechanisms which affect the crest settlements of such dams and define critical values of the parameters which control settlements, especially slope instability, internal erosion, consolidation of foundation strata, volume change in clay core due to moisture variations, consolidation of fill and reservoir fluctuations (Tedd et al., 1997).

Crest settlement of embankment dams has been studied by many geotechnical engineers who examined the contribution of each one of the above mechanisms separately. One of the most severe cases reported in literature is that of Ataturk Dam (Turkey), the forth biggest rockfill dam in the world (Goltz, 1990). Cetin et al. (2000) reported crest settlements of this dam up to 7m, attributed to improper compaction of the clay core.

On the other hand, the interaction among some of the mechanisms listed above and their effect on crest settlements has not been widely studied. A causative relationship between two of them (reservoir level and rainfall) and dam deformations was proposed by Alonso et al.

(2005) for the Beliche dam in Portugal. Yet, there is still no quantitative approach for this interaction.

In this paper we try to shed some light to the problem of significant increase in the rate of settlements recorded on the crest of the Kremasta Dam (Greece), one of the highest earthfill dams in Europe (Fig.1). This study is a first attempt to quantify the effect of rainfall and reservoir level fluctuations on the settlements of this earthfill dam by identifying upper limits for these two parameters, above which the rate of the crest settlements is significantly increased. The results of this study could be used as a feedback in future efforts to increase the reservoir level to the design value.

This last task has not been achieved till today, > 40 years since the completion of the dam despite its great importance (economical, social etc.). This is due to the fact that for high water levels in the reservoir the amount of leakage observed at the outlet of the drainage channel was significantly increased and sometimes even reached the security limits. Additional rise of the water level would put the dam and consequently the downstream areas at risk.

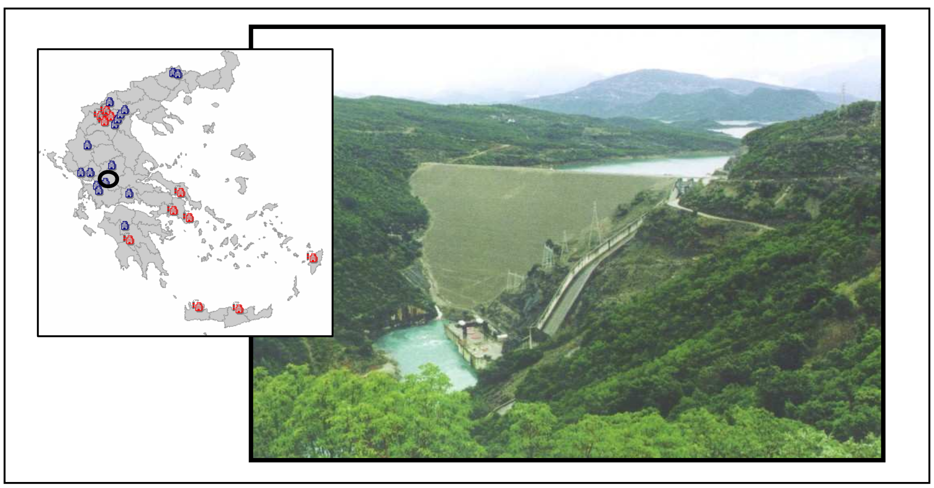

Figure 1- The Kremasta earthfill dam (within circle on the location map) as seen from downstream. The spillway, on the right of the dam, and the power plant (on the toe of the downstream face) are also shown.

2. The Kremasta Dam

The Kremasta dam (Central Greece), owned by the Public Power Corporation of Greece, has a height of 160.3m (crest elevation 287m), a 456m long crest and a central clay core (Fig.2). Its artificial lake covers an area of $81km^2$ and can store up to $4.75*10^9m^3$ of water used for the production of electricity (Public Power Corporation, 2000ca.). The dam is constructed by earthen material taken by the riverbed of the Acheloos river. 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 maximum amplitude of 1.5m at its middle were predicted (ECI, 1974). 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, 1989).

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

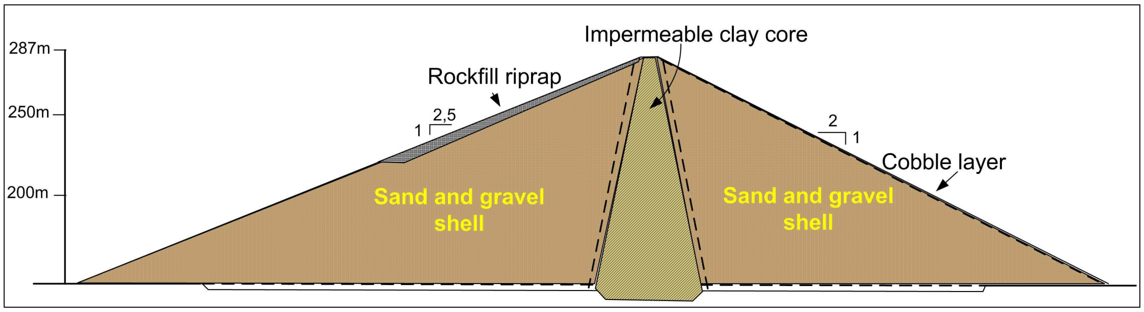

Figure 2- Simplified crosssection of the Kremasta dam

The geodetic monitoring system of the Kremasta dam consists of 14 reference stations established on stable ground and of 25 control stations located at the crest and the outer shell of the dam (both upstream and downstream). Measurements of (1) horizontal deflections and (2) vertical displacements of the 25 control stations are made in reference to the stations on stable ground, approximately twice per year since 1966 (Pytharouli, 2007).

3. Available Data

Available data consist of the vertical displacements of all seven control points located on the crest of the dam as well as the reservoir level fluctuations and the rainfall height at the dam site. Data cover a period of > 35 years from 1966, shortly after the beginning of the impoundment of the reservoir, to 2003.

Lapse time between measurements was not constant, although for some periods there were efforts for measurements twice per year, while reservoir level fluctuations and rainfall height data were almost equally spaced. Measurement procedure was nearly uniform (similar techniques, usually the same instruments, measurements by a surveying party the basic nucleus of which was changing very little over the years, etc), data are completely homogeneous and of the same accuracy. A very limited number of observations were assigned to gross errors and were discarded.

Analysis of observed monitoring data led to displacements which were found statistically significant. In particular it was derived a gradual settlement of the crest with a tendency of stabilization and with a cumulative value of 764mm at the middle of the crest (see Fig.3), and in plan view a bending of the dam with a maximum cumulative displacement of 300mm (Pytharouli et al., 2007).

Vertical displacements examined in this article, were within the security limits defined by the design study (< 1.5m; ECI, 1974) and at a first glance they did not seem to reflect a major problem for the safety of the dam. Still, because of its age (> 40 years old) the dam lies in a period of high risk and thus further analysis of its displacements is required.

4. Methodology

Pytharouli (2007) identified three possible mechanisms affecting crest settlement of the Kremasta dam: (1) creep and/or secondary consolidation of clay, (2) reservoir level fluctuations and (3) rainfall. Among these three mechanisms the principal one is creep while the other two contribute to the increase of settlements in a smaller percentage and under certain conditions. These mechanisms are described by parameters such as rate of crest settlement, rate of increase of reservoir level and amount of precipitation.

The conventional approach is to examine the correlation between the amount of crest settlement and parameters defining the other three effects separately. However, from an empirical examination it was found that crest settlement appeared insensitive to variations of amplitude of the three critical parameters if their overall amplitude was kept under a certain threshold. This led us to examine these correlations only for the values of the three critical parameters exceeding these thresholds.

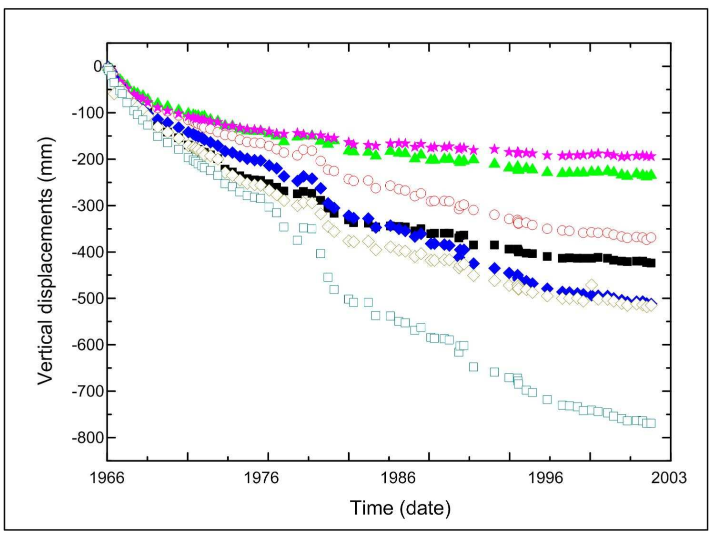

Figure 3- Vertical displacements of all seven control points located at the crest of the Kremasta dam. Maximum displacement (~764mm) was observed at a control point located at the middle of the crest.

These thresholds, however, were unknown. Our idea was to determine them using a technique for optimization of the correlation coefficient between crest subsidence and each one of the other variables in which a high-pass filter of variable amplitude was applied. The amplitude in the filter providing the maximum correlation would therefore indicate the value of the parameter (reservoir level, etc) critical for increased crest settlement.

The following step was to identify the parameters to be correlated. This means that our need was to identify parameters defining each effect (for instance crest subsidence) but also corresponding to time series with common sampling intervals. Since our measurements were not equidistant and various data were collected at intervals very different (see above), it was inappropriate to use raw observations. Interpolations, on the other hand would lead to very noisy results.

For this reason, in the case of crest settlement we used the settlement index.

This is a dimensionless parameter given by the equation

$$S_I = \frac{s}{1000 * H * \log(t_2 / t_1)} \qquad (1)$$

where s is the crest settlement measured in mm between times t_1 and t_2 since the completion of the embankment at a section of the dam H metres high (Charles, 1986). Values of $S_I > 0.02$ indicate that mechanisms other than creep or secondary consolidation contribute to the dam settlements (Tedd et al., 1997).

The settlement index corresponding to each epoch of measurements was then calculated using eq. (1). Seven time-series consisting of the values of settlement index for each of the seven control points of the crest were formed. In order to simplify the procedure, we examined a single time-series consisting of the maximum value of all seven time-series for each sampling interval, i.e. a time series representing the envelope of the time-series describing the settlement index for all seven survey points.

As already mentioned the available time-series of reservoir level and rainfall height consisted of daily values and thus were not directly comparable with the time-series of the settlement index. In order to be comparable (1) they should have the same length *l* with the time-series of the settlement index and (2) their values should correspond to the same sampling intervals as the values of the settlement index.

For this reason instead of the initial time-series of reservoir level and rainfall (1) we used the maximum values of the water elevation in each of the sampling intervals, (2) using the daily rates of the reservoir level fluctuations we calculated an average rate for each the same sampling intervals and (3) using the daily rates of the rainfall we calculated an average rate for the rainfall too.

Hence we had formed time series which were directly comparable. Subsequently, we applied the technique of threshold correlation in these time series, correlating the settlement index and one of the three other parameters each time, after a high-pass filter of variable amplitude was applied. Our aim was to find which threshold (i.e. value above the amplitude of the high-pass filter) led to a maximum correlation coefficient. Obviously, this implies repeated computations with a gradually variable threshold, but shorter time series. The latter is due to the fact that the length of time series correlated depends on the amplitude of the threshold, and data below this threshold were discarded.

The above procedure was automated using Fortran programming. For the needs of this study we developed the PICKUP code which applies the algorithm just described to every two of the time-series under study (Pytharouli, 2007).

5. Data Analysis and Results

The settlement index was calculated for all control points of the dam crest using eq. (1). The time series of the envelope of the settlement index (Fig. 4) was subsequently formed by keeping the maximum value of the settlement index computed for each epoch of measurements.

Fig. 4 shows that despite the fact that the values of the settlements of the crest were within the security limits (see Fig. 3), there were four periods Dec 1980 – May 1981, Sep 1990 – May 1991, May 1994, Oct 1998 – May 1999 during which the rate of displacements was increased significantly (up to four times) above the expected “critical” value of 0.02 reflecting effects other normal creep (see above).

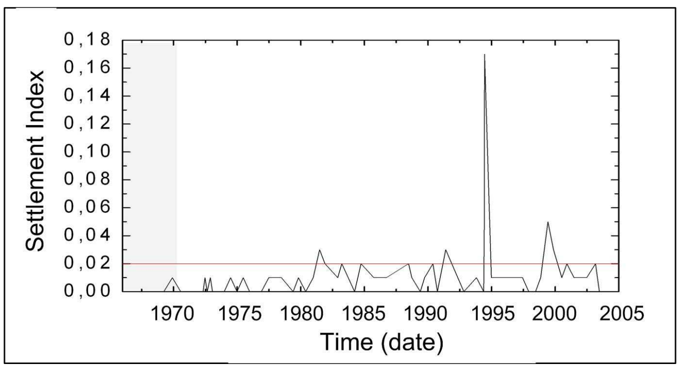

Figure 4- Plot of the settlement index versus time. In the time intervals Dec 1980 – May 1981, Sep 1990 – May 1991, May 1994, Oct 1998 – May 1999 the settlement index is >> 0.02 (horizontal solid line). The highlighted area corresponds to a period of high leakage during a reservoir low-level before extensive works were completed.

Following the steps described in the previous section (Methodology) we determined an upper limit for the height of water in the reservoir above which the settlement index exceeds its critical value (0.02). Fig. 5 shows the change of the correlation coefficient between settlement index and reservoir level for different values of the height of water. It is evident that the maximum correlation occurs when the reservoir level exceeds the height of 270m.

The same process was repeated for the other two parameters, the rate of increase of reservoir level and rainfall. It was found that the corresponding thresholds were 1.00m/month and 130mm/month for the rate of increase of the reservoir level and rainfall, respectively.

As can be derived from Fig. 6, there were several time periods during which the reservoir level, the rate of reservoir level and the rainfall took values above the computed thresholds, but the settlement index did not always exceeded its critical value of 0.02. The question arising is hence under which circumstances did the settlement index exceed its critical value?

As can be deduced from Fig. 6 the four time intervals Dec 1980 – May 1981, Sep 1990 – May 1991, May 1994, Oct 1998 – May 1999 during which the settlement index is > 0.02 correspond to periods during which all three parameters examined exceeded their critical values simultaneously. And these four periods were the only periods during which values above 0.02 of the settlement index were detected. Exception to this was the time period designated by the highlighted areas in Fig.6. This time interval corresponds to a period before extensive works to limit leakage were completed (see above), and hence the overall behaviour of the dam was changed.

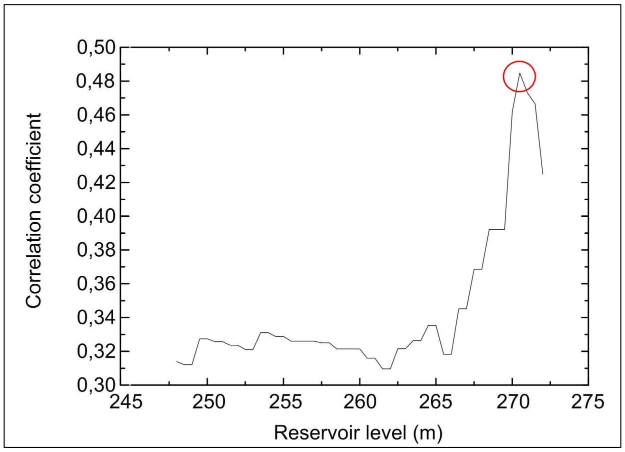

Figure 5- Change of the correlation coefficient between the settlement index and the reservoir level versus reservoir level. Maximum correlation corresponds to 270m of the water level in the reservoir (red circle).

6. Discussion – Conclusions

The data used in this study are a part of the geodetic monitoring record of Kremasta dam covering a period > 35 years long. This is an almost unique dataset that permitted the investigation of the long-term deformations of the crest of an earthfill dam as well as the mechanisms responsible for individual events that took place during the examining period such as the increase in the rate of the crest settlements.

The aim of this study was to quantify the influence of various effects others than creep and the secondary consolidation of the clay core on the crest settlements of Kremasta dam.

Our study was based on the optimization of the correlation coefficient between time-series defining variation of the values of certain parameters of the dam and of environmental processes, after a high-pass filter of variable amplitude was applied to one of these parameters.

The first step in this study was the selection of the appropriate parameters to be correlated, in particular of the settlement rates. The subsequent analysis revealed that an increase of the dam deformation (crest settlement) is related to the combined effect of three parameters when exceeding certain critical values at the same time; the height of the water in the reservoir (270m), the average monthly rate of increase of the reservoir level (1.00m/month) and the average rainfall (130mm/month).

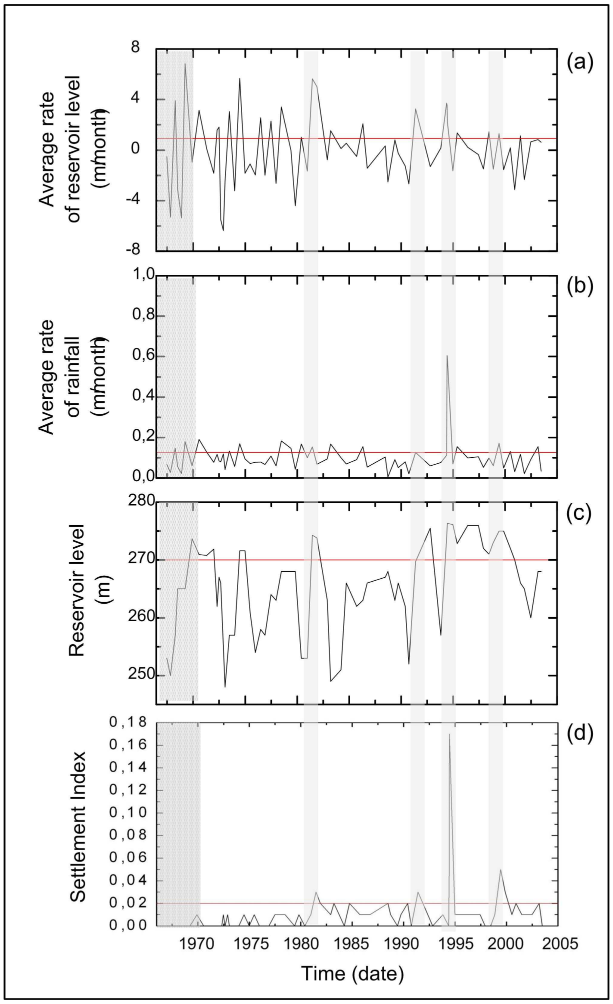

Figure 6 - Plots of (a) rate of reservoir level fluctuations, (b) rate of rainfall, (c) reservoir level fluctuations and (d) settlement index versus time. The horizontal solid lines in (a), (b) and (c) correspond to the critical values (thresholds) determined from the analysis for the three parameters examined while in (d) to the critical value of 0.02 for the settlement index reported in the literature. The four thin highlighted areas on the right side of (a), (b) and (c) indicate periods where the settlement index had values > 0.02. Period before 1970 (dotted areas) correspond to a period during which extensive leakage control works were made substantially modifying the dam behaviour. It should be noted that in time intervals 1971 – 72 and 1997 the reservoir level was > 270m, but since the other two parameters remained below the computed thresholds, the settlement remained <0.02.

The above results are the first results obtained in the framework of an effort to quantify the effect of mechanisms other than creep or secondary consolidation of clay on the crest settlements of the Kremasta dam. Whether our results are valid for other earthfill dams as well, it is not easy to say without the necessary evidence. Still we do not find any reason why the Kremasta dam should be an exceptional effect.

Acknowledgments

The Public Power Co are thanked for providing unpublished data. C. Skourtis, A. Kountouris and S. Stremmenos are thanked for useful discussions.

References

Alonso, E.E, Olivella, S. and Pinyol, N.M. (2005). A review of Beliche Dam. *Geotechnique*, 55(4), p. 267-285.

Cetin, H., Laman, M. and Ertunc, A. (2000). Settlement and slaking problems in the world's fourth largest rock-fill dam, the Ataturk Dam in Turkey. *Engineering Geology*, 56, p. 225-242.

Charles, J.A. (1986). The significance of problems and remedial works at British earth dams. In *Reservoirs: Proceedings of BNCOLD-IWES Conference*, p. 123-141.

Committee on Safety of existing dams. (1983). *Safety of existing dams*. National Academy Press. Washington.

ECI-Engineering Consultants INC. (1974). *Kremasta Project Report, Volume II*. Report prepared for Public Power Corporation.

Goltz, T. (1990). Program with 22 dams suffering. *Engineering News-Record (ENR)*. p. 40-41.

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

Public Power Corporation. (2000). *The Kremasta dam project*. Athens. Unpublished Report.

Pytharouli, S. (2007). *Analysis of the geodetic monitoring record of the Kremasta Dam*. Unpublished PhD Thesis, Dept. of Civil Engineering, University of Patras, 221pp.

Pytharouli, S., Kontogianni, V., Psimoulis, P. and Stiros, S. (2007). Kremasta dam (Greece): Long-term behaviour and performance of the highest earthfill dam in Europe. In *Proc. of 5th International Conference on Dam Engineering*. Lisbon, Portugal. 14 – 16 February. p. 465 – 471.

Tedd, P., Charles, J.A., Holton, I.R. and Robertshaw, A.C. (1997). The effect of reservoir drawdown and long-term consolidation on the deformation of old embankment dams. *Geotechnique*, 47(1). p. 33-48.

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