Investigation of the relationship between rainfall and long-term settlements of an earthfill dam based on geodetic measurements

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ABSTRACT (100-250 words)

Ageing earthfill dams become vulnerable to weather phenomena such as rainfall and flooding, with severe consequences, economic and life threatening, to the communities living downstream. A better understanding of their long-term behaviour and the factors affecting it, is crucial.

A unique data set was used, consisting of the crest settlements of an earthfill, central clay core dam, the Pournari I dam in Greece, the daily reservoir level fluctuations and rainfall height values at the dam site between 1981 and 2015. The dam is 107 m high and its construction was completed in 1981. In previous studies the settlements of this dam, including rates, were found to be within limits and compliant with empirical relationships derived for dams of this type.

In this work we remove the effect of primary consolidation and creep from the settlements and attempt to study the relationship between the residuals and rainfall. We find that consolidation was completed within 4 years since the end of construction (by 1985) and residuals of all points on the crest appear to follow the same evolution pattern. While no direct relationship could be established between the actual settlement observations and the rainfall, residuals seem to have maximum correlation with the cumulative rainfall height over a period of two months before the settlement measurement epoch. Our findings most likely represent a threshold value of rainfall above which the dam seems to be responding rather than a time duration over which rainfall plays an important role to the settlements of the dam.

I. INTRODUCTION

According to the International Commission on Large Dams (ICOLD), there are more than 58,000 registered large (> 15m high) dams worldwide, with smaller dams counting thousands more. Dam safety is crucial, taking into account that hydro-assets are currently facing increased occurrences of extreme weather phenomena, such as flooding, that could compromise their structural integrity. Assessment of the post-construction performance of dam structures is therefore important to ensure that operate within safety limits (Michalis et al., 2016b). Many factors contribute to the growing ageing dam infrastructure crisis, e.g. the increasing population of ageing dams, increasing frequency of extreme weather phenomena and the gap in knowledge about the long-term behaviour of dams. For the latter, relationships and models describing the short and long-term behaviour of dams are still based on empirical equations, e.g. Dascal (1987). Such models are not always representative for all dams, even if they are of similar size and type, due to the large number of factors affecting their behaviour. These empirical models were developed a few decades ago and as a result, they do not account for the increasing rate of changing environmental conditions.

In this paper, we use a more than 30 years long geodetic monitoring record and daily rainfall values covering the same time period to identify the role of an environmental factor, i.e. rainfall, to the mechanical behaviour of a large, central clay core, earthfill dam: the Pournari I dam (NW Greece). To-date, there have been very few studies discussing the role of rainfall on the deformations of earthfill dams based on real data (e.g. Pytharouli and Stiros, 2009). This work aims to contribute towards this direction.

II. THE POURNARI I DAM

The Pournari I dam is located in Western Greece and construction was completed in 1980 while the first impoundment of the reservoir started in 1981. The dam is owned by the Public Power Corporation of Greece (PPC S.A.) and is rated 5th in energy production amongst the hydroelectric power stations in Greece. Pournari I dam, shown in Figure 1(a), is the 5^{th} larger dam in Greece with material volume of 9×10^6 m^3 and one of the largest dams in Europe.

Pournari I is an earth-fill dam composed of sand and gravel material with a central clay core, as shown in

Figure 1(b) while the maximum capacity of its reservoir is 865×10^6 m^3 (PPC S.A., 1981).

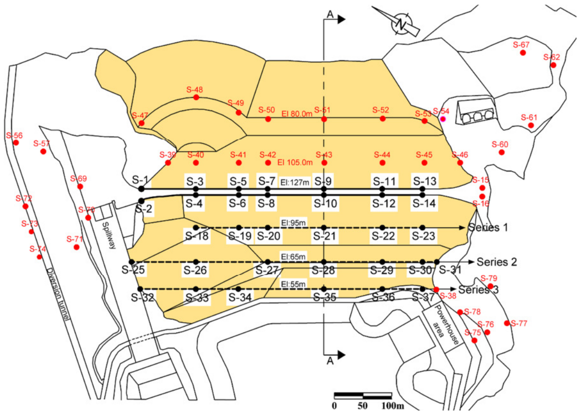

Figure 1(a). Plan view of Pournari I Dam and its geodetic monitoring network. This study only uses observations for points S1-S14, located along the crest (after Michalis et al., 2016).

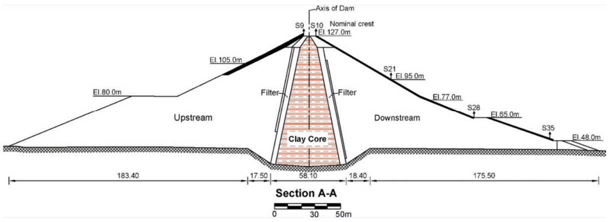

Figure 1(b). Maximum cross-section along A-A (after Michalis et al., 2016)

The central clay core is covered with sandy gravel filters. Rock fill shoulders of varied gradient were constructed at each side of the dam with a step at elevation of 80 m and 65 m at the upstream and the downstream side respectively, as shown in Figure 1(b). The width at the base of the dam is 453 m, its maximum height is 107 m (from the foundation level), while the crest length is 580 m (PPC S.A., 1981).

III. Available Data

A. *Vertical Displacements*

This work focuses on the vertical displacements (at a sampling rate that ranged between monthly and annually) for 13 control stations S1-S14 along the upstream and downstream side of the crest (Figure 1(a)). No data were available for station S4. Data cover a period from 1981 to 2015.

The maximum settlement during the examined time period was recorded at control point S9, which is located at the maximum cross section (Figure 1(b)), with a cumulative value of 623 mm, as shown in Figure 2. This value corresponds to 0.58% of the dam height and falls within expected range Michalis et al. (2016a).

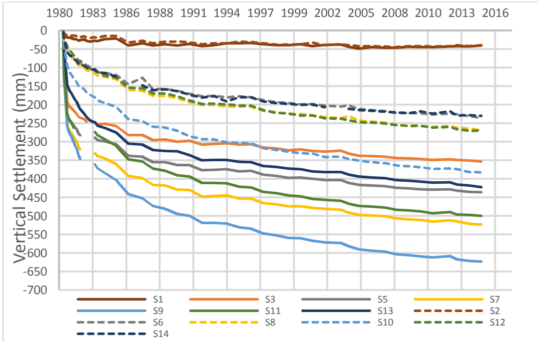

Figure 2. Recorded settlements for the 13 control stations on the crest between 1981 and 2015. For location of these stations, see Figure 1(a).

B. *Daily Rainfall*

Daily rainfall values (mm) were provided from 1/1/1981 to 31/1/2016 (Figure 3).

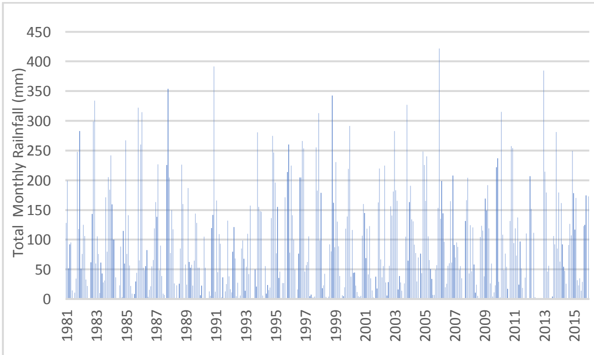

Figure 3. Total monthly rainfall (mm) between 1981 and 2016

The low cumulative value of rainfall shown in Figure 3 during 2012 is not real, but is due to 7 months of missing data.

IV. Methodology

The methodology we followed consists of 3 Steps.

A. *Step 1: Qualitative analysis of the vertical displacements of the control points on the crest*

This Step includes a qualitative analysis of the observed vertical displacements of the crest, in addition to the analysis done by Michalis et al. (2016a). In this study, we compare the magnitude of the recorded vertical displacements between the upstream and downstream side of the Pournari I dam crest and compare findings to studies from the international literature. At the following Steps, we aim to investigate this behaviour into more depth and study the potential influence of rainfall on the mechanical behaviour of the dam. In order to do so, we needed to remove any time-dependent effects, i.e. settlements due to the consolidation of the clay core.

B. *Step 2: Estimation of the duration of the consolidation stages of the clay core*

This step aims to remove the effect of consolidation from the settlement observations. Three stages of consolidation, i.e. initial compression, primary consolidation and secondary consolidation, present in our data, were identified using Casagrande's log time method (Knappett and Craig, 2012), which involves plotting the available values of settlement against the logarithm of the time (Figures 4(a) and 4(b)).

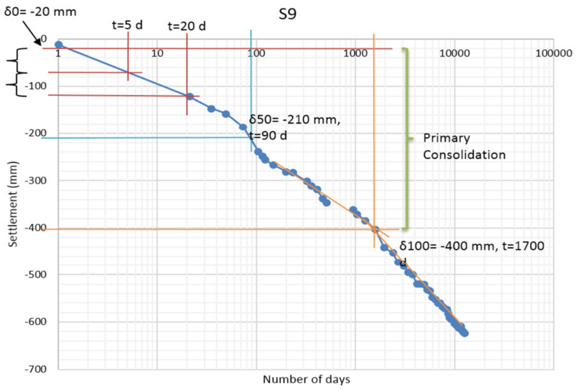

Figure 4(a). Settlement vs Number of Days (log scale for the x-axis) for control station S9

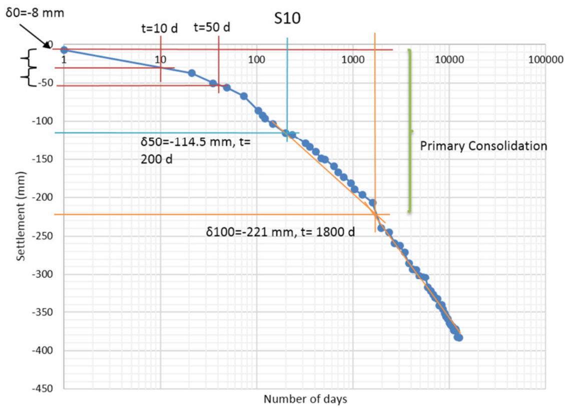

Figure 4(b). Vertical Settlement vs Number of Days (log scale for the x-axis) for control station S10

Initial Compression: The initial compression, δ_0, is measured by selecting two points at the beginning of the graph, for which values of time are in ratio of 1:4 (for example at t=5 days and t=20 days) and measuring the vertical distance between them (difference between corresponding settlement values). The value of settlement corresponding to an equal vertical distance above the first point will give the value of δ_0 (Figure 5)

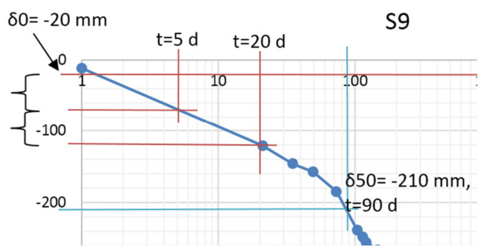

Figure 5. Estimation of δ_0 for point S9

Primary Consolidation: The end of the period of primary consolidation, δ_{100}, is defined as the intersection of two linear parts of the graph (orange lines in Figures 4(a) and 4(b)). The number of days and value of settlement corresponding to the end of primary consolidation were read off the graph. Beyond δ_{100} soil deformation continues at a slow rate for an indefinite period of time. This is known as period of secondary consolidation.

This procedure was carried out using the observations of the settlements for the control stations along the upstream and downstream crest of the dam only (S1 to S14). These observations can be directly related to the consolidation of the clay core. This is not applicable for control stations along Series 1, 2, and 3 at the downstream shoulder of the dam (shown in Figure 1(a) and 1(b)) whose settlements reflect a different mechanism.

Secondary Compression: Regression analysis was carried out for the time period after δ_{100} to determine the effect of secondary consolidation. The best-fit line (because of the semi-log graph) was calculated using Least-squares. The correlation coefficient (r) and the coefficient of determination (R^2) values (Koteggoda and Rosso, 2008) were used as an indication of how good a fit the line is to the data. This best-fit line was used to estimate the theoretical values for settlement corresponding to secondary consolidation. The differences between the observed and corresponding estimated values, i.e. residuals, represent the magnitude of settlements that is not time-dependent. The residual values were then used for further analysis (see Step 3).

C. *Step 3: Investigation of possible causative relationship between settlements and rainfall*

The causative relationship between the reservoir level and the crest settlements of the Pournari I dam has been the subject of previous studies (Michalis and Pytharouli, 2014; Michalis et al., 2016a). In this paper we focus on the potential effect of rainfall on the dam.

In order to establish a possible relationship between the rainfall and change in rate of settlement of the clay core, we calculated the cumulative rainfall values for periods of 30, 60 and 90 days before the dates of settlement recordings after consolidation was deemed to have been completed. We then plotted these values with the settlement values and the residuals calculated at Step 2 to establish the period (i.e. 30, 60 or 90 days) which showed the most correlation with the variation in settlement.

V. Results

A. *Step 1: Qualitative analysis of the vertical displacements of the control points on the crest*

In order to identify the patterns of vertical settlement in the dam, we plotted the data collected for all the control stations along the upstream and downstream crest against time. The period under consideration was between 1981 and 2015, with 53 recordings per station being available for this period.

From these plots we establish that the settlements along the upstream side of the crest are higher than the downstream crest at any time. Also we note that the maximum settlement occurs in the middle of the crest as expected from the international literature. The crest settlement follows a symmetrical pattern with the line of symmetry being the line A-A (maximum cross-section) on the plan view (Figure 1(a)): maximum settlement on A-A (S9-S10), and similar settlement values for S11 and S7 and S13 and S5, respectively. This pattern repeats for the control stations at the downstream side of the crest (Figures 7 and 8).

Differential Settlement: In order to investigate any evidence of differential settlement between the two sides of the dam, we plotted the graphs of settlement vs distance of each control station from the left abutment (points S1 and S2) for the dates 24/02/1981 (Figure 7) and 01/04/2015 (Figure 8).

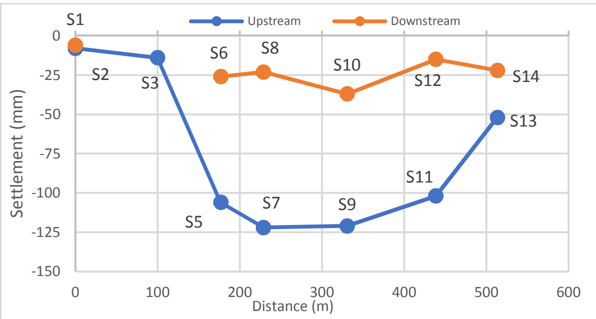

Figure 7. Observed settlement along the dam's upstream (blue) and downstream (orange) side of the crest on 24/02/1981

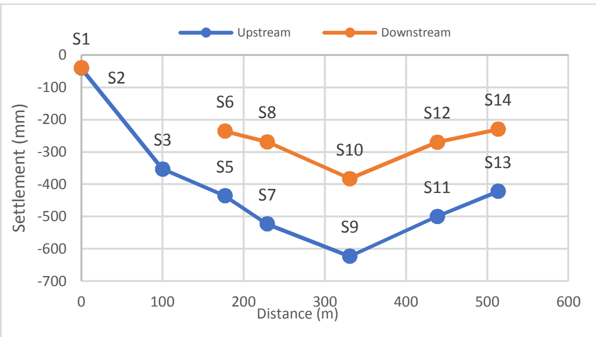

Figure 8. Observed settlement along the dam's upstream (blue) and downstream (orange) side of the crest on 01/04/2015

The results for the readings in 1981 suggest that the initial settlement of the upstream crest was overall higher than that of the downstream. For example for points S9 and S10, which are located along the line A-A on the plan view of the dam, the initial settlement differs by 84 mm. The maximum differential settlement for 24/02/1981 has a value of 99 mm and is between the points S7 and S8.

The differential settlement is larger for the readings on 01/04/2015, with the maximum being 254 mm between points S7 and S8. However, these differences are uniform across the width of the dam, in comparison to 1981.

B. *Step 2: Estimation of the duration of the consolidation stages of the clay core*

Primary Consolidation: Following the methodology described in section IV(B), the period of primary consolidation was estimated for the settlements of the crest. Representative graphs of primary consolidation analysis for the points with maximum observed settlement (points S9 and S10) are shown in Figures 4(a) and 4(b).

Two control stations had to be excluded from analysis as the plots did not follow a consistent pattern of consolidation and there were many irregularities and fluctuations present in the data. These were stations S1 and S3, very close to the left abutment.

Using Casagrande's method described in section IV(B) we establish that primary consolidation was completed for all points on the crest between 1600-1700 days since the first measurement. This value was established graphically, using the plot, and does not necessarily correspond to a time of an observed data point. Therefore, we adjusted this value to the closest time around that time period for which there was a settlement observation. This resulted in a value for δ_{100} equal to 1579 days from the time of the first available observation in 1981, for all points under analysis. This corresponds to approximately 4 years and 4 months since February 1981, i.e. June 1985. From this point onwards, the settlement values increase linearly at a steeper gradient.

Secondary Compression Analysis: Since the settlement values after 1579 days follow a straight line (time axis in log scale), a best-fit line is estimated and its R^2 value for each point under analysis was calculated. The R^2 values for most points are very close to 1, which indicates a good fit (Figures 9(a) and 9(b)).

The theoretical values of secondary consolidation over time were calculated using the best-fit line for each control station. The differences between the theoretical and observed settlement values were calculated and shown in Figures 10(a) and 10(b) for the control points on the upstream and downstream side of the crest, respectively.

From these figures, it appears that apart from small variations, the residual settlements are similar for all control points on the crest and follow a somewhat seasonal pattern (sinusoidal pattern), possibly indicative of environmental factors affecting the settlements. For earthfill dams, such factors are mainly the reservoir level and rainfall (Pytharouli and Stiros, 2009). Since previous studies of the Pournari I crest settlements have resulted in no clear relationship between the settlements and the reservoir level, we further investigate the role of environmental effects focusing on rainfall.

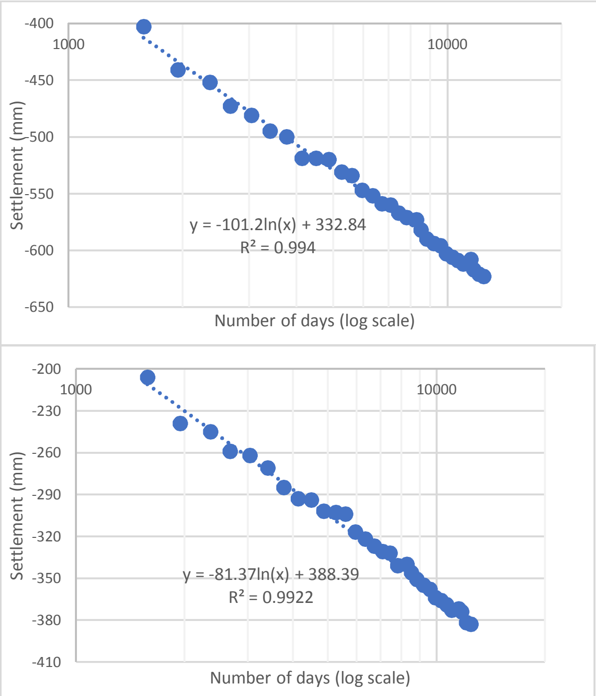

Figure 9 Settlement vs number of days for control station (a) S9, and (b) S10.

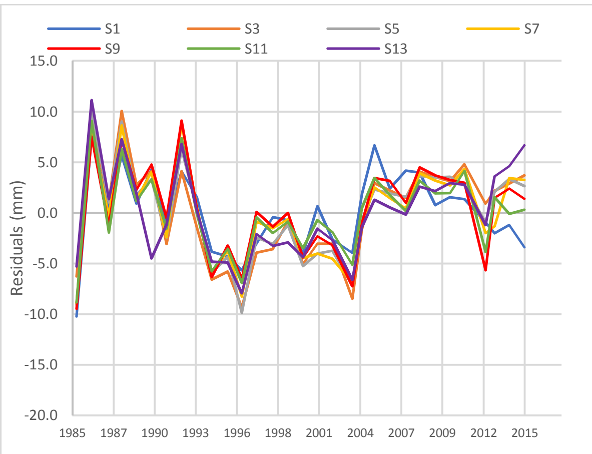

Figure 10(a). Residual settlements for control stations S1 – S13 along the upstream side of the crest

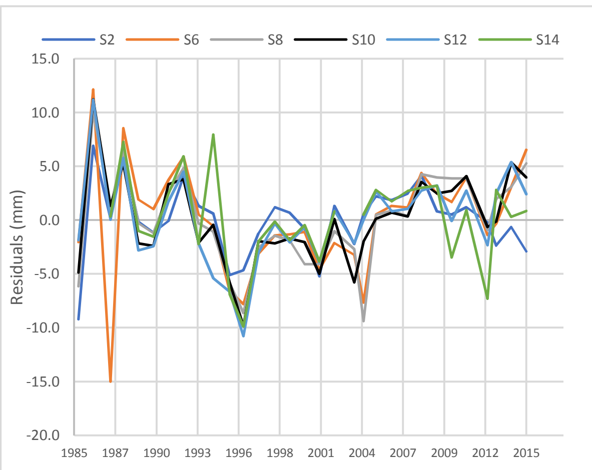

Figure 10(b). Residual settlements for control stations S2 – S14 along the downstream crest

C. *Step 3: Investigation of possible causative relationship between settlement residuals and rainfall*

Figure 11 shows the combined evolution of residuals and recorded rainfall values at the dam site versus time for two representative control points, S9 and S10 (the control stations with the maximum settlements). Comparison of the residuals with the recorded daily rainfall values revealed no obvious direct relationship between the two. Therefore, we examined the effect that cumulative rainfall has on the residual values.

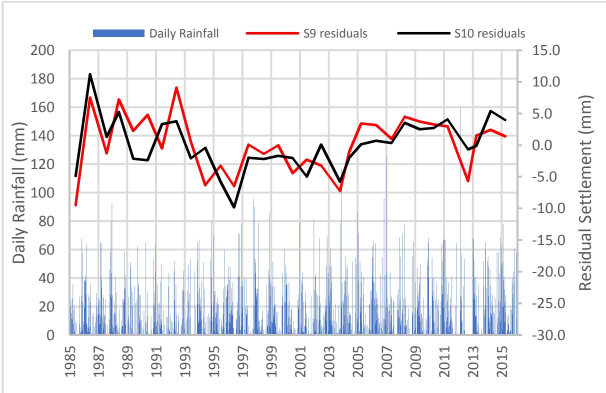

Figure 11. Residual settlements for control stations S9 (yellow - upstream) and S10 (light blue - downstream) and daily rainfall depths (blue bars) over the time period June 1985 – June 2015

Initially the cumulative yearly rainfall values (Figure 12) were calculated and were compared with the settlement residuals for all control points along the upstream and downstream crest.

From the available data the maximum rainfall was found to have occurred in 2003 with a total depth of 1436 mm. From the graph of vertical settlement vs time (Figure 2) it can be seen that between 2003 and 2004 there is a change in gradient of the settlement (steeper).

The same pattern can be seen for 1991-1992 and 2012-2013. However, annual rainfall depth values in 1991 and 1992 are amongst the lower values for the period under analysis; this could mean that the increase in rate of settlement could be due to the simultaneous effect of more than one factors, e.g. rainfall and reservoir level. The effect of such combination has been suggested before to contribute to observed settlements of the crest of earthfill dams (Pytharouli and Stiros, 2009).

After the cumulative yearly rainfall for each year was calculated it was clear that there is a possible correlation between the magnitude of yearly rainfall and the settlements. The sudden increase in the rate of settlement (after the end of consolidation) for various control points over time for the upstream crest and downstream crest could be related to the higher amount of rainfall for the period of a year between the two measurements in question. Hence the cumulative rainfall for 30, 60 and 90 days before each date for settlement reading were calculated and plotted against time. Figure 13 shows the residual settlements over time for control points S9 and S10 along with the cumulative rainfall values for 30, 60 and 90 days before each measurement epoch.

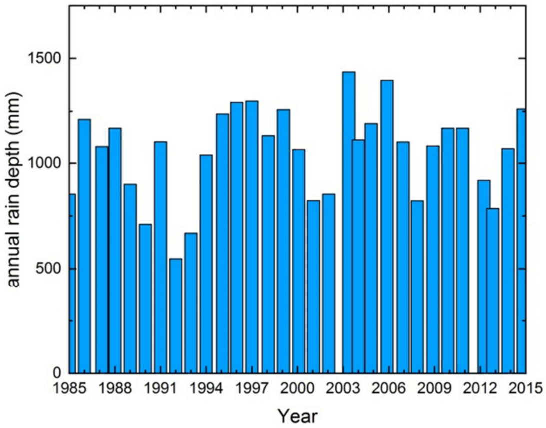

Figure 12. Annual rain depth (mm) at Pournari I dam site.

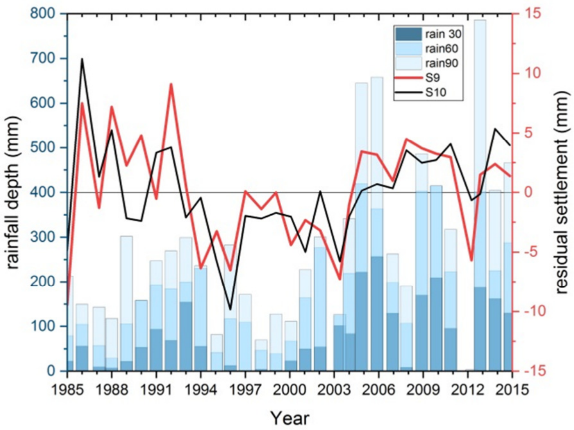

Figure 13. Cumulative rainfall and settlement residuals for control points S9 and S10

Comparing the cumulative rainfall and settlement vs time (Figure 13), a correlation between an increased amount of rainfall and a sudden increase in settlement can be seen. This correlation becomes maximum for the values of cumulative rainfall depth within 60 days prior to a settlement reading.

This comparison was made for all the control stations along the upstream and downstream crest, and results were consistent with these obtained for the residual settlements of control stations S9 and S10.

VI. Conclusions

Without the use of geotechnical data, we follow the methodology suggested by Cassagrande to remove the consolidation effect from the settlements observed on the upstream and downstream side of the crest of the Pournari I dam. We find that consolidation explains most of the observed settlements. Analysis of the residual settlements, after the removal of the consolidation effect shows evidence of the effect cumulative rainfall has on the displacements of the crest. There is strong correlation between residual settlements and the cumulative rainfall depth within 60 days prior to the measurement epoch. It should be noted that this effect is not evident for all measurements epochs, therefore, a more detailed analysis into defining this relationship precisely is ongoing.

VII. Acknowledgements

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