Long-term Deformation Patterns of Earth-fill Dams based on Geodetic Monitoring Data: the Pournari I Dam Case Study

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Abstract. Dam safety is crucial taking into account that the vast majority of these structures are expected to exceed their design lifespan by 2020 alongside with the increasing magnitude of extreme flood incidents. Earth-fill dams deform significantly during the critical phase of the first reservoir filling while the rate of deformations is decreased in the long-term. Systematic monitoring and data analysis enables the evaluation of the on-going performance of a dam, the validation of laboratory models and the assessment of different engineering designs. Relationships describing the long-term evolution of dam deformations are currently not well documented due to lack of available monitoring data.

This study investigates the long-term deformation patterns of earth-fill dams using as a case study the Pournari I dam. A 29-year long dataset was analysed which consisted of geodetic measurements of vertical and horizontal deformations of the dam crest and the reservoir level fluctuations. A comparison was then carried out with the results obtained from other case studies, e.g. the Kremasta dam.

The analysis indicates that the crest settlements of Pournari I dam remained within normal limits for the time period examined. The rate of deformations was also stabilised almost seven years after the completion of the dam, which is longer than the period suggested in the international literature.

Keywords. dam deformations, dam safety, geodetic monitoring, long-term, embankment.

1 Introduction

The last decades, the increasing demand for water, flood control projects and power supply has led to a corresponding increase in the construction of dam structures. However, the vast majority of the existing dam infrastructure is expected to exceed its lifespan by 2020. Heavy rainfall events and more frequent flooding incidents are considered major contributing factors to the failure of earth-fill dams. The rate of failure during the lifespan of a dam is estimated to be 1/10,000 per dam/year. During the first five years of operation this value becomes 1/1,000 per dam/year (Baecher and Christian, 2000) making this period the most critical in the operational life of a dam.

Deformations of earth-fill dams start to take place during the construction phase due to increase of effective stresses among the various zones of the dam and the creep mechanism of the earth material. Dams continue to deform significantly during the first filling of the reservoir, which is considered the most critical phase as seepage resistance, foundation, abutments and reservoir rim are tested for the first time (USSD, 2008). The rate of deformations is decreased in long-term and eventually drops to a small constant rate per year. Factors influencing the deformation rate are: the reservoir level fluctuations, internal erosion, slope instability, creep of the shoulder fill, the effect of secondary consolidation and seismic activity (Tedd et al., 1997).

Systematic monitoring and analysis of dams is a very important tool that provides early warning signs of an impending failure and a better understanding of the on-going performance of the structure. Numerous studies have focused on the analysis of the behaviour and the safety of dams based on monitoring data, e.g. Heck (1984), Dascal (1987), Tedd et al. (1997), Boros-Meinike and Jankowski (2003), Popovici et al. (2004), Alonso et al. (2005), Kyrou et al. (2005), Guler et al. (2006), Szostak-Chrzanowski and Massiera (2006), Pytharouli and Stiros (2009), Kalkan et al. (2010).

This paper presents the post-construction behaviour of one of the largest earth-fill dams in Greece based on geodetic monitoring data. We evaluate the deformations of the control points located on the crest of the dam based on geodetic observations without any geotechnical constraints.

The investigated control points correspond to locations where maximum deformations are anticipated.

2 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 5^{th} 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.

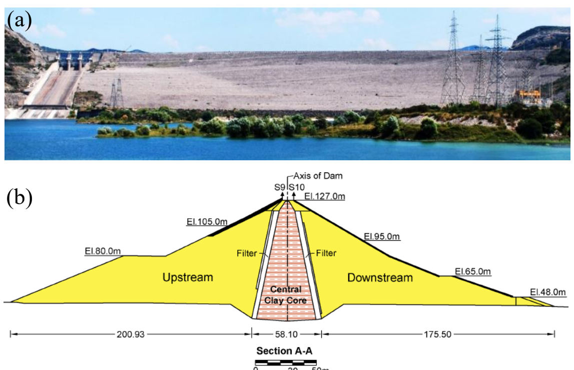

Fig. 1 (a) Downstream shoulder of Pournari I dam with the concrete spillway (left) and part of the hydroelectric station (right). **(b)** Cross section of the Pournari I dam at the location where maximum height is obtained.

Pournari I is an earth-fill dam composed of sand and gravel material with a central clay core, shown in Figure 1(b), while the maximum capacity of its reservoir is 865×10^6 m^3. The maximum and minimum water levels for hydroelectric power production are at an altitude of 120 m and 100 m above mean sea level (AMSL), respectively, with the critical water level for the safety of the dam at 126 m AMSL (PPC S.A., 1981).

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 sides 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).

3 Available Data

The Pournari I dam has been monitored since 1981. The geodetic monitoring system consists of 79 control stations in total located on the crest, the downstream and upstream shoulders, right and left abutments, the spillway right bank and the power station area. The vertical and horizontal deformations are measured using reference stations that are located on stable ground close to the right and left abutments.

The geodetic monitoring record was provided by the PPC S.A. and covers a period of 29 years, from February 1981 to April 2010. The record consists of (1) the horizontal deflections and (2) the vertical deformations of all control points on the dam crest and shoulders and (3) daily values of reservoir level fluctuations. During the period of the first filling of the reservoir (between 1981 and 1984) the sampling rate was every 20 days, while from 1984 onwards this rate was reduced to once per year.

This study is focused on the analysis of the control points S1-S14 located on the crest (see Figure 2) as this part of the dam is the most susceptible to deformations.

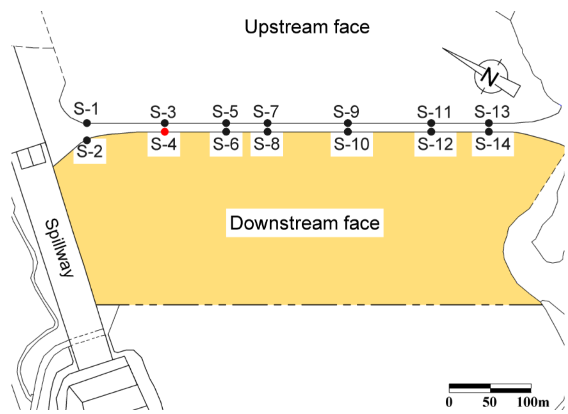

Fig. 2 Location of control points located on the crest of Pournari I dam (the dataset from S4 was not available).

4 Data Analysis and Results

4.1 Crest Settlement

Figure 3 presents the crest settlements of Pournari I dam and the reservoir level fluctuations for the period of 29 years. The reservoir level remained within the operational limits set for hydroelectric power production (i.e. between 100 m and 120 m, PPC S.A., 1981) reaching maximum and minimum values of

119.9 m and 100.6 m on August 2008 and January 1987, respectively.

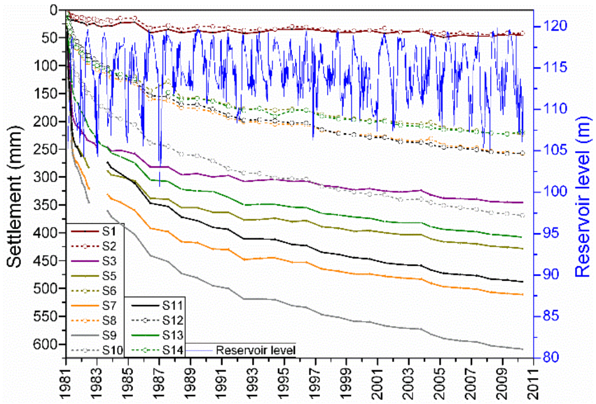

Fig. 3 Evolution of the settlements of all crest control points of Pournari I dam and reservoir level fluctuations. The upstream side of the crest appears to have the maximum observed settlements. The rate of settlements became more gradual after 1988 when the reservoir drawdown level remained relatively higher compared to the period 1981-1987.

The settlements of the crest were developed at a higher rate during the first years of the dam operation which was anticipated. Significant settlements that reached maximum values were also recorded on the upstream side of the crest compared to the downstream crest control points. In particular, the maximum settlement was recorded at the control point S9, which is located at the cross section with the maximum dam height, on April 2010 with a cumulative value of 609 mm (see Figure 3). This value corresponds to 0.57% of the dam height.

The crest settlements were also evaluated using the settlement index (S_I) given by equation 1 (Charles, 1986):

$$S_I = \frac{s}{1000 \times H \times \log\left(\frac{t_2}{t_1}\right)} \tag{1}$$

where s (mm) is the crest settlement between two different measurement periods t_1 and t_2 at each control point located at a height H (m) from the foundation level. Tedd et al. (1997) suggested that if the value of the dimensionless parameter S_I is greater than 0.02, the crest settlement is attributed to mechanisms other than creep requiring further investigation to be conducted. Figure 4 presents the S_I obtained for all the crest control points of Pournari I dam for the period of 29 years. From the construction of the dam (1981) until the last available measurement (2010), the settlement index S_I has never exceeded the critical value of 0.02 which indicates that the deformations at the body of the dam can be attributed to normal anticipated mechanisms (i.e. creep).

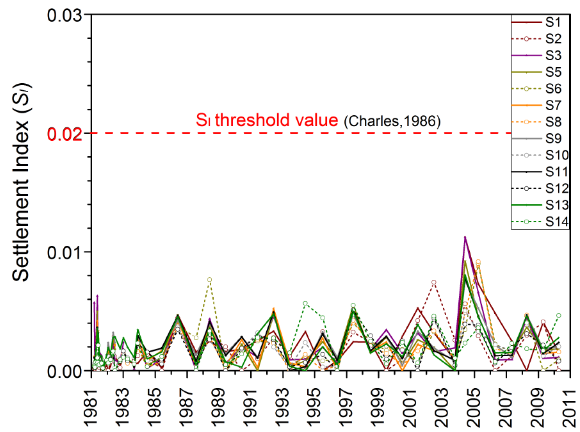

Fig. 4 The settlement index of the crest control points of Pournari I dam has never exceeded the threshold value of 0.02 from 1981 until 2010.

The annual rate of settlement (S_a) was also used to assess the deformations of the crest with equation 2:

$$S_a = \left(\frac{S_{ii} - S_i}{H}\right) \times 100 \tag{2}$$

where S_{ii} and S_i are consecutive yearly settlement measurements and H is the height from the foundation level at each crest control point. Any S_a settlements equal or less than 0.02% of the height of the dam were regarded normal and the dam stabilised (Dascal, 1987). As presented in Figure 5, the annual rate of settlement for all the crest control points of Pournari I dam is stabilised below the value of 0.02% of the dam height almost 8 years after the first impoundment (1981).

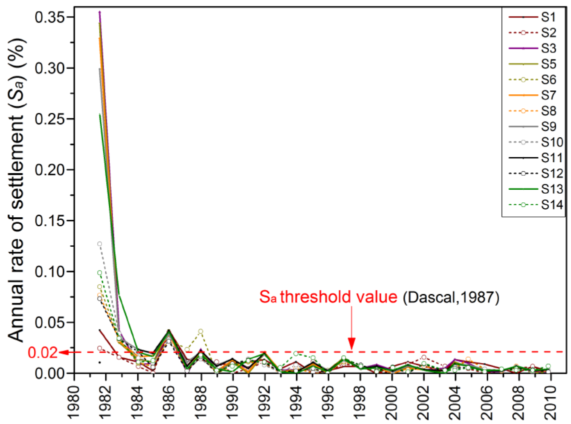

Fig. 5 The annual rate of settlement of the crest control points from 1981 until 2010 was stabilised below the value of 0.02% in 1989, almost 8 years after the first reservoir filling.

4.2 Crest Horizontal Deformations

The horizontal deformations of the crest control points of Pournari I dam is presented in Figure 6.

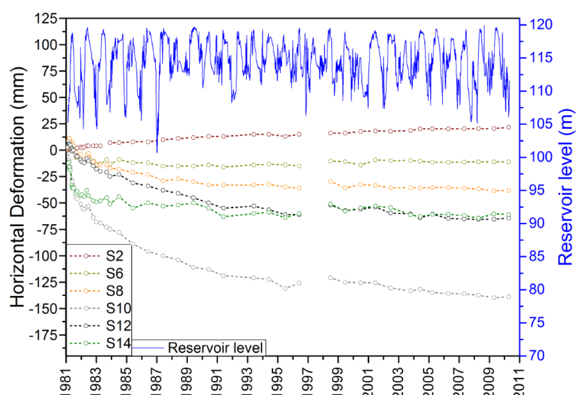

Fig. 6 Horizontal deformations of the crest control points of Pournari I dam from 1981 until 2010. Positive values indicate deformations towards the downstream direction.

Both the upstream and downstream crest control points were displaced in the horizontal direction towards the upstream side of the dam. The rate of deformations reached maximum values during the first years of the dam operation which corresponds to the first reservoir filling and it is gradually decreased after the year 1986. The maximum horizontal deformation was recorded for the control point S10 with a value of 139 mm (see Figure 6). The S10 is located at the cross section where maximum dam height is recorded.

5 Discussion and Conclusions

This study presented the post-construction analysis of the behaviour of one of the largest earth fill dams in Greece based on long-term monitoring data. The 29 year long dataset consisted of geodetic measurements of vertical and horizontal deformations from the crest of Pournari I dam and the reservoir level fluctuations.

The maximum crest settlement (609 mm) was recorded for the control point located at the cross section with the maximum dam height. Similar behaviour was recorded for the Kremasta dam as the maximum vertical deformation (764 mm) was recorded at the maximum height of the dam (Pytharouli and Stiros, 2009).

The settlement index (S_I) was also used to assess the crest deformations of Pournari I dam. The S_I has never exceeded the critical value of 0.02 from the construction of the dam (1981) until the last available measurement (2010), which indicates that the dam deformations can be attributed to normal anticipated mechanisms (i.e. creep, secondary consolidation of the clay core). The same does not apply for the S_I of Kremasta dam which has exceeded the value of 0.02 four periods of time reflecting effects other normal creep (Pytharouli and Stiros, 2009).

The annual rate of settlement of the crest of Pournari I dam was stabilized below the value of 0.02% almost 8 years after the first impoundment of the reservoir. This is not in agreement with the estimation proposed by Dascal (1987) that suggested that the maximum period for the stabilisation of crest settlements varies from 24 to 30 months.

The analysis of the dataset also revealed that the crest deformed towards the upstream direction for the examined period of time which is considered a rather unusual behaviour. Horizontal deformations towards the upstream direction are common for earth-fill dams for the time period after construction and during the first stages of the first impoundment of the reservoir. For the case of Pournari I dam, the direction of the horizontal deformations of the crest for the majority of the control points did not change over time. It should be noted that this is not the case for the horizontal deformations of the control points located on the downstream face of the dam, below the crest level. The upstream movement of the crest is potentially originated by the hydrostatic pressure from the reservoir causing the submerged part of the dam to deform towards the downstream direction but at the same time resulting in an upstream movement of the crest.

The results of this study indicate that the long term behaviour of the crest of Pournari I dam is normal and within anticipated limits. However, it also highlights that the stabilization period of the rate of deformations is slightly different compared to the expected from the published literature. This does not imply that the dam's structural integrity is at risk. It rather highlights the complexity of the deformation mechanisms for earth-fill dams and the fact that dams of similar size and type can behave differently but still operate within safety limits.

Future research entails the investigation of the deformations of the crest and the body of the dam for the period that corresponds to the first reservoir filling. This will enable to quantify the factors affecting the deformations of the dam and will provide an insight of its behaviour.

Acknowledgments: Authors would like to thank the Public Power Corporation (PPC) of Greece S.A., A. Kountouris and T. Sioutis (PPC S.A.) for providing the monitoring record and their assistance. Special thanks to the Management and personnel of the Hydroelectric Station of Pournari I dam.

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