Considerations on the deformation of Ridracoli dam foundation based on the analysis of monitoring data

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Abstract. The behaviour of the Ridracoli arch-gravity dam in the 2002-2020 operation years has been analysed, by applying "statistical" models of increasing complexity to the time series of pendulum and long-base extensometer measurements. The modelling approach has proved robust. A satisfactory estimate of the reservoir load, thermal and irreversible drift components has been obtained for most of the instruments. As expected, the influence of temperature is lower for the instruments deeply embedded in the rock mass. The deformations recorded on the left and right bank of the dam have shown a minor influence of the anisotropic proprieties of the rock mass, well characterized by the mechanical tests performed at the time of dam construction.

1. Introduction

The monitoring of large dams relies on a wide network of instruments, primarily, to permit the continuous control of the structure during operation of the reservoir. The measurement of displacements and pore pressures is also instrumental to back-analyse the deformation properties of the foundation rock mass on a larger scale than that involved in any situ tests performed for the design of the dam. It is therefore possible, based on monitoring data, to verify the design hypotheses concerning the influence of elastic, thermal and irreversible deformations on dam behaviour.

This paper reports some results and considerations concerning the Ridracoli dam response during the last two decades of operation. The analysis focused on the assessment of the overall consistency of the deformation measurements recorded by instruments (pendulums and rock extensometers) at different location and depth, also considering the possible influence of the anisotropic structure of the rock mass (bedding planes). The elastic, thermal and irreversible drift components were recognized by a data regression analysis, based on "statistical" models derived from the experience of previous case histories.

2. Characteristics of the dam

The Ridracoli dam (figure 1) is located in the northern Apennines, at the confluence of two streams near the village of Santa Sofia (FC). Considering the width of the U-shaped valley and the overall geomechanical characteristics of the rock mass at the abutments, a concrete arch-gravity type was chosen. The dam is a double-curvature arch concrete structure 103.5 m high and 432 m long at the crest, subdivided into 27 blocks by vertical joints, resting on a pulvino (36.5 m width) along the total length of the excavation profile.

2.1. Deformability of the rock mass foundation

The entire area of the reservoir and the dam section are located on the outcropping Marly-Arenaceous formation consisting in alternating strata of sandstones, siltstones and marls. Each sequence has a thickness varying from a few centimetres to over 7 m and is uniformly spread over a large area. The local jointing pattern shows three main discontinuity sets (figure 2), namely, the bedding planes (ST, average orientation 218°/27°) and two set of subvertical joints, approximately directed parallel (KKD) and perpendicular (KKI) to the bedding direction. An inactive transform fault was found crossing the left abutment, not far from the bottom of the valley, with an orientation of 140°/80°. It is formed by a shear band, approximately 1.5 m thick, with a core zone of 0.5 m.
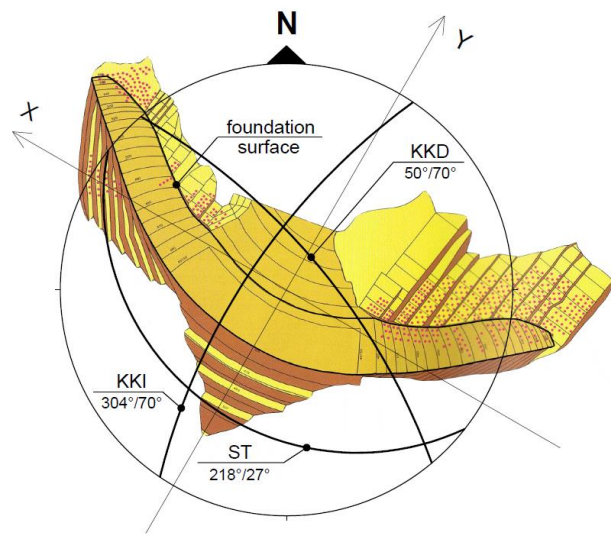

Figure 1. Aerial view in 1981. **Figure 2.** Joint sets at the dam site.

The cross-hole tests performed at the design stage in 15 vertical boreholes, along the curved axis of the dam, gave P-waves velocities generally higher than 4000 m/s. The highest velocities, up to 5000 m/s, were measured in the bottom part of the valley. The right abutment resulted slightly stiffer than the left, possibly for the presence of the fault zone. The effect of the construction of the dam was investigated repeating the measurement in the same boreholes, after the casting of the dam and the grouting of the curtain, within a three-years' time span. An overall increase in stiffness could be detected.

During the construction phase, several in situ tests, including hydraulic chamber tests and plate loading tests, were performed in order to assess the stiffness characteristics of the rock mass under operative conditions, i.e., for the normal stress interval predicted at the rock-concrete interface (2–4 MPa). Special attention was given to the anisotropy of the rock mass owing to its stratified structure. The results of the loading tests performed parallel and perpendicularly to the bedding planes are summarized in table 1. The results, rather dispersed (particularly for the perpendicular loading), suggest a mild anisotropy in elastic modulus, with slightly larger stiffness in the direction parallel to the bedding.

Table 1. Elastic and deformability moduli, E_r and E_t, obtained from in situ tests; data are expressed in the form: *mean value ± st. deviation (lower characteristic value)*.

	E_r // (MPa)	E_t // (MPa)	$E_r \perp$ (MPa)	E_t // (MPa)
Hydraulic chamber tests	19.6 ± 5.5 (16.8)	14.6 ± 5.1 (12.0)	20.3 ± 12.7 (13.9)	14.9 ± 11.9 (8.9)
Plate loading tests	19.4 ± 2.8 (18.0)	17.4 ± 3.0 (15.8)	18.5 ± 10.1 (13.4)	15.5 ± 9.7 (10.6)

Some flat jack tests were performed to determine the rheological properties, particularly of the marly lithotype, by means of long-term loading tests under a sustained pressure of 10 MPa (about 3 times the maximum normal stress induced by the dam). Under these very conservative testing conditions the creep deformation measured after 50 days [1] was about the 60 – 70% of the instantaneous one.

2.2. The monitoring system

Completed in 1982, the Ridracoli dam is provided with a comprehensive monitoring network which controls not only the concrete structure but also the foundation and the reservoir slopes.

The dam foundation is equipped with a great number of instruments, mainly grouped in five vertical cross sections: the main section, two lateral and two intermediate sections. In this study, the analysis is focused on the data measured by inverted pendulums and long-base extensometers (figure 3).

In the main section, the horizontal displacements are controlled with two inverted pendulums fixed at depth of 50 m and 25 m from the foundations level (PR/1-2/1 and PR/1-2/2 respectively). In the same section three multi-point borehole extensometers are also installed, inclined to the vertical of +45°, -5° and -27°, respectively, where a positive angle indicates a borehole axis pointing upstream.

The two lateral sections are equipped with a single inverted pendulum (PR/20-22 and PR/19-21 for the right- and the left-side section, respectively), completely embedded in the rock foundation, and two borehole extensometers. The extensometers are of the same length of those of the main section, but the inclinations are different, +45° and -45°, and are read at the same depth of the inverted pendulum. The intermediate sections have the same disposition of three extensometers as the main section, but without the inverted pendulum.

The measurement data of all the sections proved to be consistent and valuable. Due to space limitation, the following analysis will be focused on the sections with paired pendulums and extensometers. A common feature of these instruments is that both measure the relative displacement between two reference points. The time series of all the measurements cover a period of about twenty years (from 01/01/2002 to 01/09/2020). All the data were acquired with a time frequency of a week, in average, and generally show a trend with a regular cyclic component of annual period.
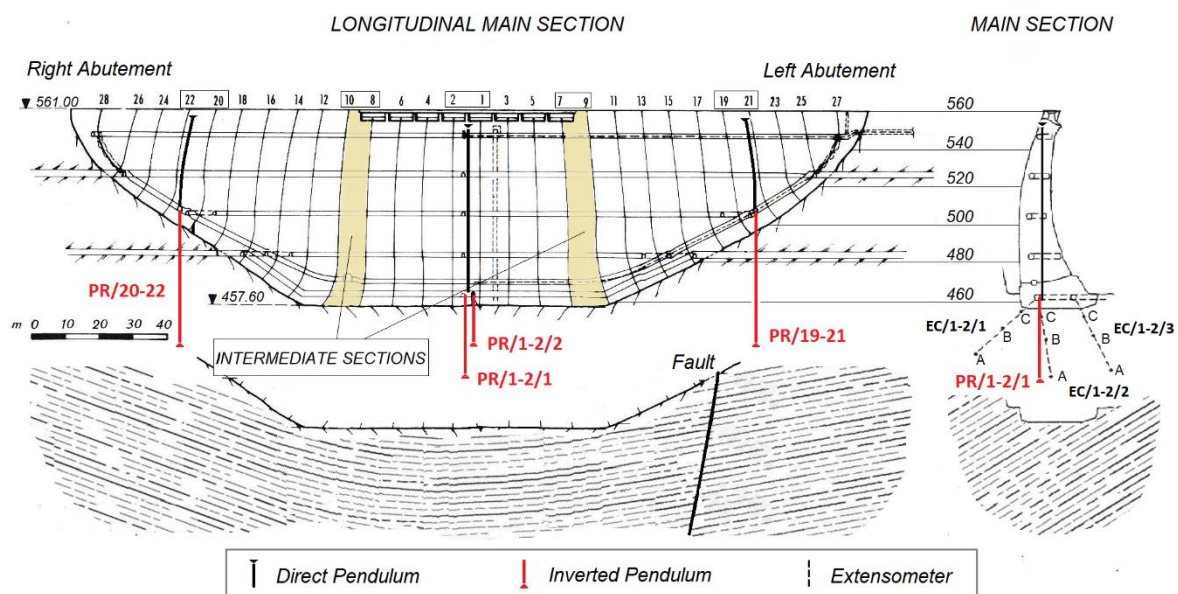

Figure 3. Schematics of the main instruments in the rock foundation (pendulums and extensometers) and relative orientation of the bedding planes along the length of the dam and below the main section.

3. Statistical models for the analysis of monitoring data

In general, the relative or absolute displacement u of a control point of the monitoring system can be considered as a function of the following factors: i) the elastic response (f_H) to water level variation of the reservoir; ii) the thermal deformations inside the structure and the rock foundation (f_T); iii) the unrecoverable strains (drift term) related to anelastic behaviour, mainly creep, of rock and concrete (f_d). Therefore, u can be expressed by the following sum of components, where b_0 is a constant term:

$$u = b_0 + f_H + f_T + f_d \tag{1}$$

The reservoir-level effect (f_H) can be expressed by a polynomial function of the water level H of fourth degree, as effectively observed in many cases, for gravity as well as arch dams [2]:

$$f_H = m_1 H + m_2 H^2 + m_3 H^3 + m_4 H^4 \tag{2}$$

The effect of thermal variations can be modelled by sinusoidal functions of increasing complexity, with yearly (3) [3] or half-yearly period (4) [2]:

$$f_T = a_1 \sin 2\pi t + a_2 \cos 2\pi t \quad \text{with} \quad t = \frac{dd/mm/yy - 01/01/02}{365.25} \tag{3}$$

$$f_T = a_1 \sin 2\pi t + a_2 \cos 2\pi t + a_3 \sin 4\pi t + a_4 \cos 4\pi t \tag{4}$$

For short periods of observation, the drift component can be represented by a simple linear function. But for relatively long time series, it is generally necessary to consider that the drift velocity may change with time. Often the rate of irreversible deformations tends to reduce after some years. This general trend was modelled, in the present analysis, by a piecewise continuous linear function, which requires the total period be divided into a series of time intervals (identified by the progressive times, t_k), each characterized by a different drift velocity d_k:

$$f_d = d_0 t + d_1 t_1 + \cdots + d_n t_n = d_0 t + \sum_{k=1}^{n} d_k t_k \quad \text{with} \quad t_k = \begin{cases} t - \dfrac{\bar{t}_k}{365.25} & \text{for } t < \bar{t}_k \\ 0 & \text{for } t \geq \bar{t}_k \end{cases} \tag{5}$$

A least square multi-linear regression analysis of the measured time series allows to statistically estimate the unknown parameters, i.e., the m_i, a_j, d_k coefficients and the constant term b_0 of the above equations (1-5). This type of regression model has proven satisfactory in many practical cases [2–6], but with some limitations and cautions.

The above equations do not account for possible changes in thermal conditions from year to year. Generally, a good identification of the thermal deformation, by the relations (3) or (4), can be obtained only if the operative conditions of the reservoir do not differ excessively from year to year. In fact, the level of water on the upstream face of the dam influences the temperature distribution throughout the body of the dam [4].

A more serious difficulty is represented by the influence of the hysteretic behaviour of the foundation, quite common for fractured rock masses. It implies that the deformation in the rock mass, for the same reservoir level, is generally different between the filling and emptying phase. Therefore, the assumption of a single polynomial function represents a simplified modelling approach, which sometimes can lead to the fictitious introduction of a "pseudothermal" component in the f_T function. This last drawback may occur especially when the temporal cycles of reservoir level differ little from year to year. It can be eliminated by calculating the thermal component using a deterministic numerical model that explicitly accounts for the effect of thermal variations on the measured displacements.

4. Analysis of the monitoring data of Ridracoli dam

Regression analyses by statistical models of increasing complexity were performed for each instrument (figure 4). While in the simplest analysis (Model **1**) the number of coefficients to be determined was only 8, in the last and more complex analysis (Model **4**) the number increased to 19.
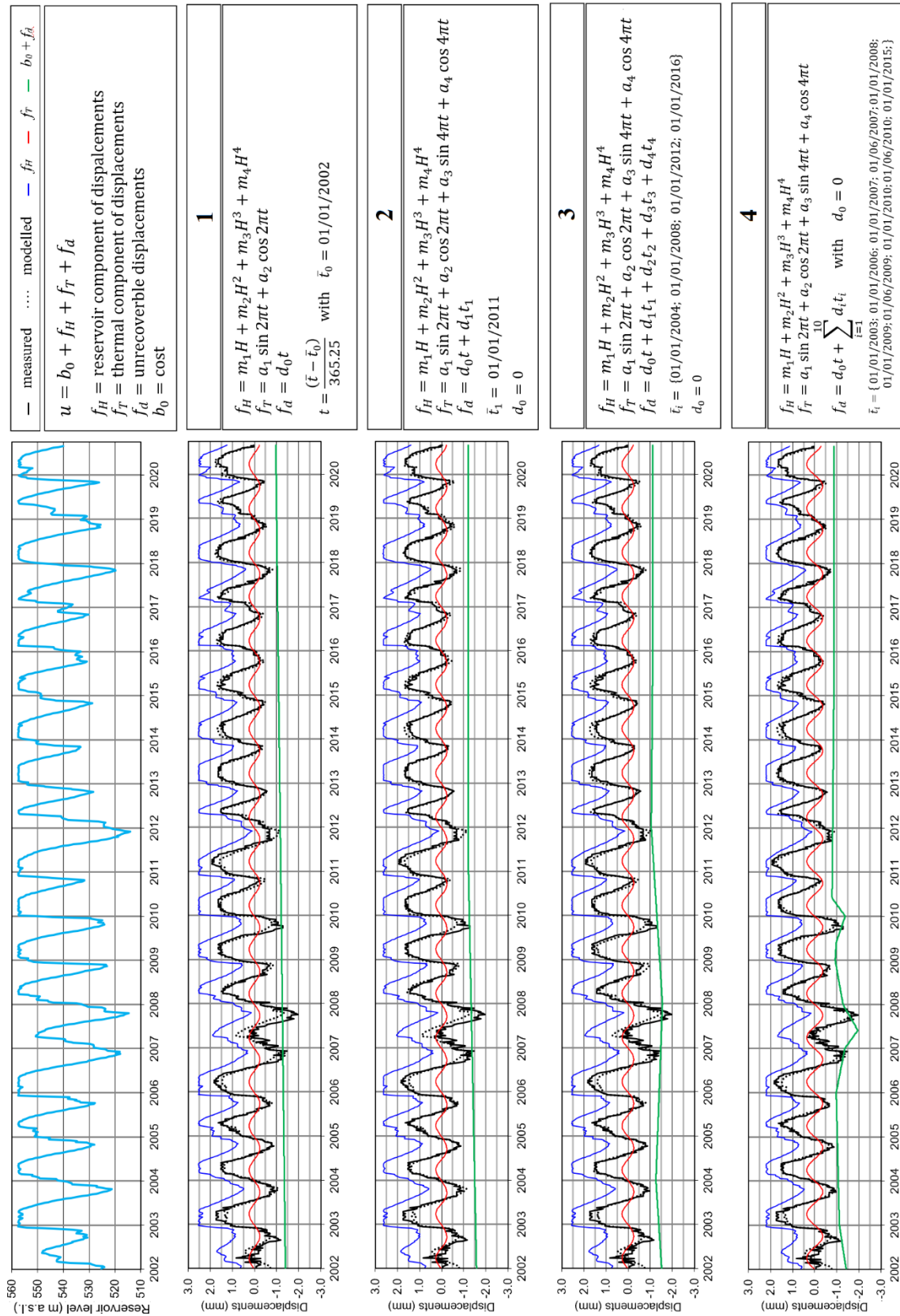
Figure 4. Statistical processing of measures for the pendulum PR/1-2/1

Both the thermal and drift functions were progressively enriched in the different models, while the reservoir function remained always the same. The choice of processing only the data recorded during the last two decades of the dam life (2002-2020) is related to some disturbance noticed in the time series, before this date, and to the particular interest in assessing the present performance of the dam.

Details about the four different statistical estimations are reported only for 50-m long pendulum (PR/1-2/1) located in the main section: see table 2 and the previous figure 4, where the horizontal downstream component of displacement is considered. It can be noted that the correlation coefficient (table 2), relatively high even for the initial analysis (0.928), increases to 0.960 for the last one, with a standard deviation of 0.176 mm.

Table 2. Summary of relevant statistical parameters for the 50-m long inverted pendulum PR/1-2/1 in the main section (analyses with different statistical Models, from **1** to **4**).

	1	**2**	**3**	**4**
R^2	0.928	0.926	0.940	0.960
SD (mm)	0.234	0.239	0.215	0.176
f_H (mm) for H = 560 m a.s.l.	2.856	2.932	2.829	2.446
$\Delta f_d = f_{d,final} - f_{d,initial}$ (mm)	0.43	0.36	0.40	0.55
$\max(f_T)$ (mm)	0.24	0.26	0.28	0.36
day with $\max(f_T)$	24/03	27/03	27/03	31/03

The f_H component of displacement, which depends on the reservoir level, is in the range 2.5-3.0 mm for a water level increment between 515 and 560 m a.s.l. The reservoir component tends to decrease with the increase in complexity of the interpolating function (figure 5). The right graph in the figure shows the fitting between the 'measured' points (obtained solving the (1) for f_H with u equal to its effectively measured value) and the f_H curve of the Model 4.
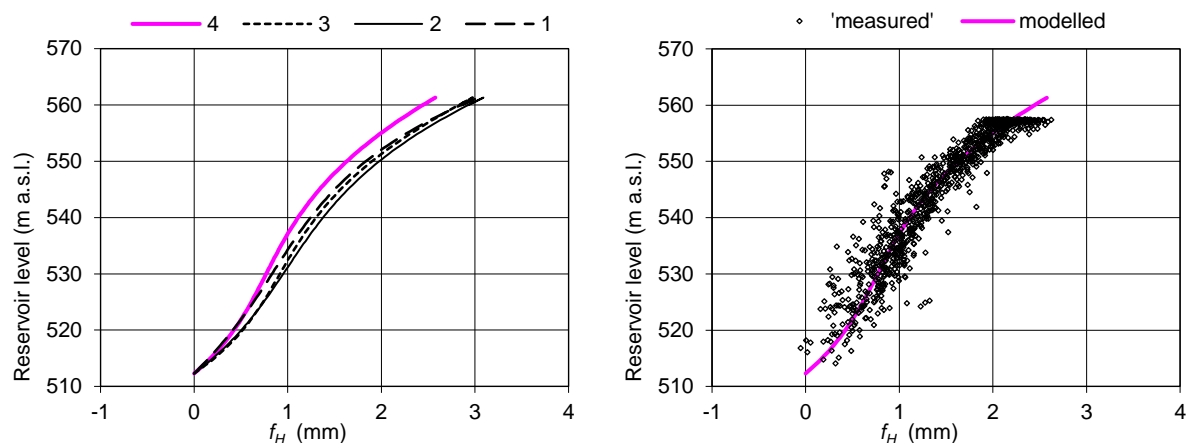

Figure 5. Comparison of the reservoir curves f_H obtained by the 4 different Models (left) and fitting of f_H component for PR/1-2/1 (right).

The reduction in the reservoir component f_H (from Model 1 to 4) is partially compensated by the contemporary increase in the thermal component and, secondarily, by the drift term. Quite surprisingly, the extremal points of the function f_T, for this instrument, do not match the seasonal maximum or minimum of air temperature. The relative shift of about 100 days can be perhaps interpreted as influenced by a "pseudothermal" component due to hysteretic behaviour of the rock mass and the dam.

The drift velocity can be regarded as negligible except for three single short periods in the years 2002, 2007 and 2009-2010, analysed more in detail in Model **4**. In this last model, the aforementioned periods have been discretized by a sequence of short time intervals (half a year), as shown in figure 4.

Two of these periods (years 2002 and 2007) were characterized by unusual reservoir management, due to particularly dry summers that led to incomplete filling phases. Conversely, very low minimum levels of the reservoir (i.e., in 2012) showed no significant effect on the drift term if not associated with incomplete fillings.

An overall similar behaviour in the downstream direction was observed for the other three pendulums herein considered, for which the same discretization into periods with different drift velocities was adopted (once optimised for the PR/1-2/1). The extensometers (EC/1-2/1, 2 and 3) of the main section were processed likewise. The results are summarised in table 3 only for the Model **4**.

Table 3. Summary of statistical parameters determined for pendulums and extensometers.

| | PR | | | EC/1-2/1 | | | EC/1-2/2 | EC/1-2/3 | |
	1-2/2	**20-22**	**19-21**	**A**	**B**	**C**	**B**	**A**	**B**
R^2	0.930	0.953	0.890	0.981	0.938	0.910	0.960	0.942	0.979
SD (mm)	0.282	0.191	0.307	0.110	0.157	0.167	0.040	0.074	0.074
f_H (mm) for $H = 560$ m a.s.l.	2.419	2.029	2.346	2.319	1.689	1.335	0.458	-0.953	-0.997
$\Delta f_d = f_{d,final} - f_{d,initial}$ (mm)	0.31	0.54	-0.05	0.44	0.69	0.55	0.37	-0.37	-0.24
$\max(f_T)$ (mm)	0.57	0.43	0.50	0.28	0.40	0.17	0.09	0.20	0.17
day with $\max(f_T)$	05/03	29/06	15/06	19/06	18/07	28/06	16/07	30/12	13/12

The 25-m long pendulum of the main section (PR/1-2/2) shows almost the same behaviour of the longer one (PR/1-2/1), with similar f_H values at $H = 560$ m a.s.l. and a slightly larger influence of the thermal component. Conversely, all the other instruments, pendulums as well extensometers, display a maximum (or minimum depending on the orientation) in f_T during the hottest summer months. While the extensometers EC/1-2/1 and 2 of the main section exhibit a positive variation in summer (corresponding to a shortening of the base), the extensometer EC/1-2/3, downstream oriented, shows an opposite behaviour. The sinusoidal function (4) tends to give a maximum during summer, from June to August, but not in the case of the pendulum PR/1-2/1 and PR/1-2/2. This behaviour is shown in figure 6 for the pendulums only.
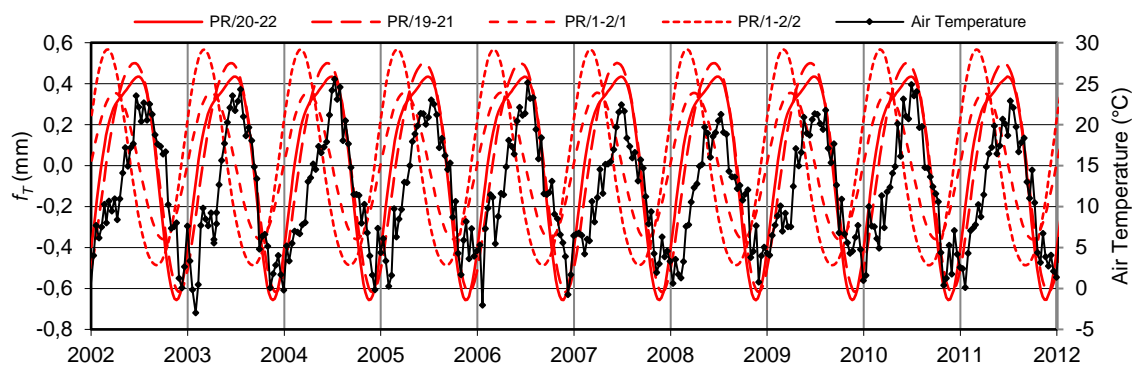

Figure 6. Trend of the f_T function in the period 2002-2012 for the 4 pendulums.

The anisotropy (and spatial non-uniformity) of deformability proprieties along the dam base can manifest as a difference in the amplitude of cyclic displacements of symmetrically located points in the two halves of the dam. The sum of the annual maximum f_T and the f_H estimated value, for a reservoir level of 560 m a.s.l. (see table 3), can be considered as an indicator of this cyclic amplitude. A total value of 2.46 mm and 2.85 mm was found, respectively, for the right and left lateral pendulums (i.e., a 16 % percent difference). Interestingly, the highest displacements occur on the left side, where the bedding planes are less inclined (material anisotropy), the rock mass exhibits a lower small-strain modulus (sonic tests) and, moreover, the foundation is crossed by a fault.

In the right-left direction, perpendicular to the downstream one, the two "central" reverse pendulums show small displacements, in the order of 0.5 mm, not clearly influenced by seasonal alternation (consistently with the overall symmetry of the dam), while the "right-lateral" pendulum exhibits a regular cyclic behaviour of the same amplitude. Finally, for the left-lateral one, a less clear periodicity and a drift velocity of 0.05 mm/y toward the left side of the valley can be detected. This trend however flattens when considering a longer observation time (1984-2002).

The presence of the fault on the left side of the valley seems to also influence the drift term f_d. In fact, as shown in figure 7, in the 2002- 2012 period, the f_d function for all the extensometers and pendulums located on the right side of the fault shows three peaks: in summer 2002 and 2007 and in winter 2009-2010, while the inverted pendulum located on the left side exhibits a different trend, with the lowest R^2 factor, probably because the optimization of the regression function was done for PR/1-2/1. Apart from this local variability, the irreversible deformations, possibly more relevant during the first fillings cycles, were already negligible in the last two decades of dam operation investigated in this paper.
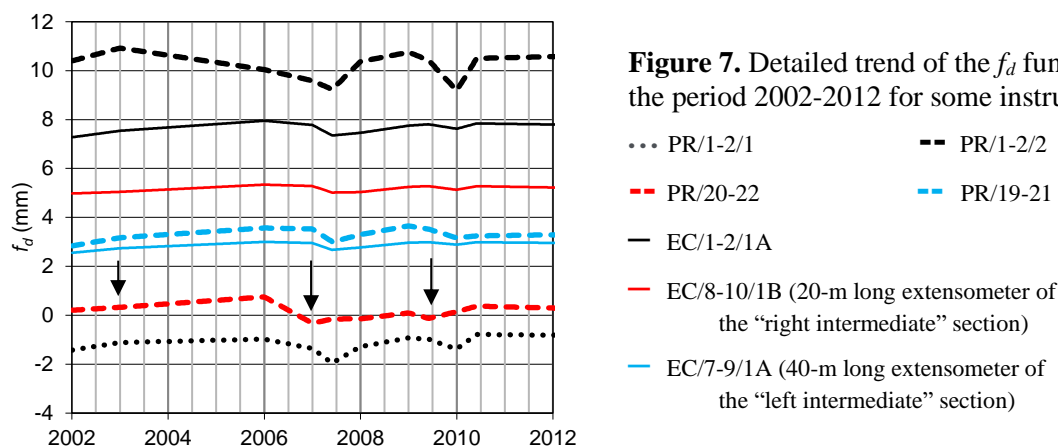

Figure 7. Detailed trend of the f_d function in the period 2002-2012 for some instruments:

··· PR/1-2/1	-- PR/1-2/2
-- PR/20-22	-- PR/19-21
— EC/1-2/1A	

— EC/8-10/1B (20-m long extensometer of the "right intermediate" section)

— EC/7-9/1A (40-m long extensometer of the "left intermediate" section)

5. Conclusions

This paper analyses some of the monitoring data recorded in the rock mass foundation of the Ridracoli dam. Despite some limitations, the "statistical approach" utilized in the analysis of dam displacements in the last 18 years has proven effective. In this period (2002-2020) the irreversible drift velocity seems negligible. The simplified thermal function used for the analysis has given satisfactory results for most of the instruments, with seasonal peaks generally close to the peaks of air temperature. However, the deformation caused by the change in reservoir level represents the dominant influence for all the instruments. The mild elastic anisotropy of the rock mass, highlighted by the in-situ tests, has little effect on the foundation behaviour, also considering the varying orientation of the dam base respect to bedding planes. The presence of a tectonic disturbance (fault) on the left abutment can explain some outcomes of the statistical analysis, particularly, the slightly larger cyclic deformations on the left side of the dam and the time occurrence of the peaks in drift velocity. These peaks seem to occur when the operation of the reservoir is characterized by occasional phases of incomplete filling but, for these periods of less regular operation, also the reliability of the statistical methods tend to reduce.

References

[1]   Oberti G, Bavestrello F, Rossi P P and Flamigni F 1986 Rock mechanics investigations, design and construction of the Ridracoli Dam *Rock Mech. Rock Eng.* **19** 113–42

[2]   Willm G and Beaujoint N 1967 Les méthods de surveillance des barrages au service de la production hydraulique d'Électricité de France. Problèmes anciens et solutions nouvelles *Proc. 9th ICOLD* Congress (Istanbul) pp 529–50

[3]   De Sortis A and Paoliani P 2007 Statistical analysis and structural identification in concrete dam monitoring *Eng. Struct.* **29** (1) 110–20

[4]   Rotonda T and Ribacchi R 1996 Stress- and time-dependent deformations in the foundation rock of a gravity dam *Proc. Int. Symp. Eurock '96 (Turin)* vol 1, ed G Barla (Rotterdam: Balkema) pp 527–34

[5]   Léger P and Leclerc M 2007 Hydrostatic, temperature, time-displacement model for concrete dams *J. Eng. Mech.-ASCE* **133** (3) 267–277

[6]   Tatin M, Briffaut M, Dufour F, Simon A and Fabre J P 2015 Thermal displacements of concrete dams: accounting for water temperature in statistical models *Eng. Struct*. **91** 26-39