Automatic follow-up of the tri-directional displacements of the Sainte-Croix arch dam (Verdon - France) by motorized total station

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ABSTRACT

The dam of Sainte Croix is a 61.5 m high arch dam with double curvature, built in the Verdon Gorges in France from 1973 until 1975. Since its construction, the follow-up of its mechanical behaviour is based on planimetric measurements realized on 32 lava rosettes distributed on its downstream facing. The grid reference consists of 9 survey columns among which 5 are considered and verified fixed. The qualitative assessment of the arch dam mechanical behaviour is very accurate with biannual measurements but the operator wished to improve it in case of particular operating conditions with the possibility of a close follow-up. Among the techniques currently used for dam's surveillance (ICOLD, Bulletin 158, 2018), a solution by motorized total station, completely integrated into the information system, was thus proposed and implemented in July 2016 after numerous tests were realized on all the processing chain. These tests led to an increased reliability of the permanent on-site installation, its connection to the information system called KOALA with features equivalent to those of a classic remote instrumentation (measurements on request or preset, automatic data processing including elaborate topographic calculations, etc.) and the operational maintenance of the system.

The advantages of this measuring system are the continuity of the horizontal displacements time series with the addition of the vertical displacements, a behaviour analysis based on a larger sample of measurements under variable hydrostatic/thermal loads, a lower cost than other alternatives (pendulums and GNSS stations for example) and the possibility offered to add marks for a minor cost.

This paper presents this technological evolution chronologically in a simple and instructional manner for the different parts: material, software, and in particular modelling and validation of the obtained data with historical one.

I. SAINTE CROIX ARCH DAM

The dam of Sainte Croix (cf. Fig. 1.) is a 61.5 m high arch dam (138 m long) with double curvature, built in the Verdon Gorges in south of France on a 33.5 m foundation base from 1973 until 1975. The setting out of the dam in a limestone gorge showing a significant narrowing in the lower part led to a concrete base on which the structure rests. The dam overhangs an underground hydroelectric plant in its right bank, and closes a reservoir of 767 hm^3.

Figure 1. Sainte Croix arch dam

It is the headwaters reservoir of a succession of works on the Verdon river. In addition to its hydroelectric production, the Sainte Croix reservoir is also used as a reservoir for irrigation and tourist facilities in summer.

Under normal operating conditions, the Sainte Croix reservoir usually varies between 469 and 477 m above sea level. The dam is based on limestone foundations with karstic cavities. In the abutments, a grout cut off goes 70 meters deep on the left bank and under the underground plant on the right bank.

At the bottom of the valley, it goes around 40 meters deep under the excavation line. A drainage curtain about 30 meters deep at the bottom of the valley and 60 meters long into the banks completes the grout cut off 10 meters downstream.

The mechanical behaviour of the dam is monitored thanks to:

- planimetric measurements on 32 targets located on its downstream facing,

- a direct pendulum and an inverted one to measure the foundation base displacements with respect to the ground surface,
- and a direct pendulum in the left abutment.

In the first years after the impoundment (which ended in 1975), the structure was moving downstream in relation with the concrete shrinkage/creep and the adaptation of the closest blocks from banks towards the abutments. After this evolution, the almost stabilization of the arch dam, its foundation base and abutments was acquired in the 1980s to make way for a slow upstream displacement, less than 0.1 mm/year at the crest of the crown which commonly occurs on dams of similar geometry.

Concerning reversible effects, given the minor fluctuations of the reservoir, the dam shows no significant displacement related to hydrostatic head variations. However, its shape implies a significant thermal sensitivity in the order of 15 mm annual amplitude between winter and summer at the crest of the crown of the arch dam.

II. HISTORICAL DAMS MONITORING SURVEY AT EDF

Historically, planimetric monitoring survey on EDF dams consists in measuring the horizontal angles on each target point whose coordinates are sought, using a theodolite positioned on survey columns known to be fixed and whose coordinates are known.

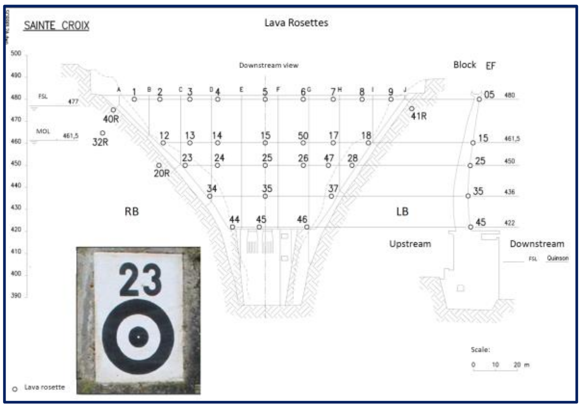

Figure 2. Lava rosettes location on downstream facing of the dam

32 sealed lava rosettes (concentric circle targets printed on enamelled lava plates) constitute these target points on Sainte Croix dam (cf. Fig. 2.). This material has been chosen for its stability over time and for its resistance to thermal and chemical attacks.

Indeed, the use of geodetic survey for dams monitoring requires measurement accuracy in order to measure low displacements as well as a controlled stability over time of the planimetric grid of reference to follow the dam behaviour during its lifetime. At present, the measurement of distances is still little used in the monitoring surveys performed on EDF dams especially because the existing lava rosettes do not allow a suitable precision for this type of measurement. It would require the installation of prism reflectors.

From each survey column, a series of angle measurements is performed using the theodolite positioned within 0.3 mm on a centering plate. It includes the other survey columns and known references as well as the lava rosettes whose coordinates are to be determined.

Two sights from different survey columns (but three or four are preferred) are performed at least on each lava rosette to determine its coordinates. It allows for over determination that is required in the absence of distance measurement.

The accuracy in the determination of each lava rosette's position using these angular measurements depends on the configuration of the planimetric grid of reference: it involves the position, the number and the conditions of fixity of the reference marks as well as the series of angle measurements performed.

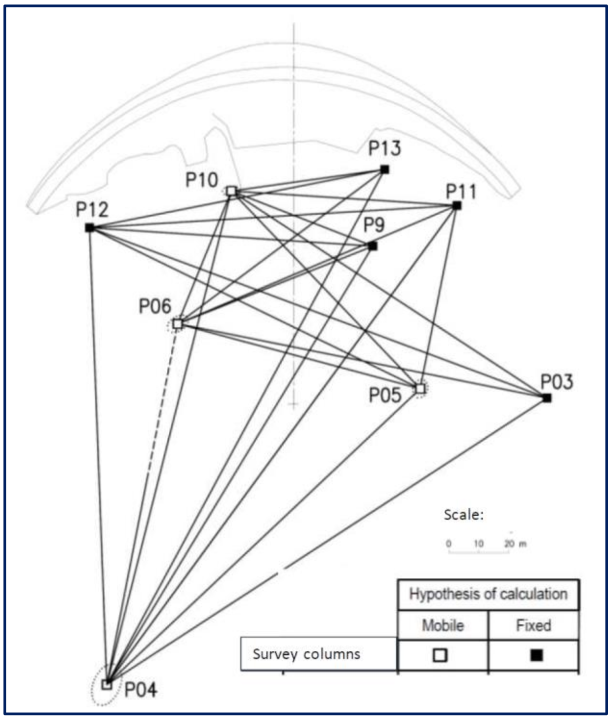

Figure 3. Planimetric grid on Sainte Croix dam

In general, planimetric grids of reference are designed to ensure a measurement uncertainty on horizontal displacements (to 95%) lower or equal to +/- 2 mm for this type of concrete dam.

On Sainte Croix dam, the planimetric grid of reference consists of 9 survey columns among which 5 are considered and verified fixed (constant coordinates over time) and 4 are said mobile (whose coordinates are determined at each monitoring survey based on the fixed references) (cf. Fig. 3.).

On Sainte Croix arch dam, the standard monitoring survey as practiced since the construction of the structure brought full satisfaction in terms of accuracy and stability of the grid of fixed survey columns controlled over time. Nevertheless, the operator wished to have the possibility of a close follow-up of the horizontal displacements in case of particular operating conditions. As monitoring surveys require specific skills, they cannot be realized on site by the local operator, that is to say much more frequent trips of specialized teams would be necessary implying additional costs. The installation of pendulums system on the crown of the arch was considered but because of the geometry of the arch (double curvature) this solution was difficult to implement. Furthermore, this additional pendulums system would have been local because it would have covered only the central part of the arch dam in addition to the left abutment whereas the monitoring survey enables a spatial appreciation of the structure's displacements and of its abutments eventually.

Taking advantage of having a planimetric grid of reference of very good quality, it was therefore decided to study a solution based on automated monitoring surveys satisfying the monitoring constraints on Sainte Croix arch dam in a completely integrated way.

III. Evolution towards an automated monitoring survey completely integrated into EDF information system

For a more frequent follow-up of the arch dam's displacements, a system using total station was thus set up on site in 2008. By increasing the measurements' frequency and having the possibility to trigger remote measurements during particular operating conditions and/or loads (floods, heavy colds, heatwaves, earthquakes, etc), the follow-up of the displacements is therefore refined. In addition, the vertical displacement, not measured so far, is indeed integrated. In general, this integration can be a significant contribution for dams undergoing pathologies such as alkali-aggregate reaction.

This system does not work with measurements on lava rosettes but on prism reflectors using the angular and the distance measurements.

24 prism reflector (LEICA GPM104 type), integrated in robust and durable stainless steel supports, were thus installed on the dam near the existing lava rosettes (Cf. Fig. 4.). These reflectors, targeted from P04 survey column, have thus all been directed to the latter. Only the lava rosettes closest to the right bank, not visible from P04 survey column, were not equipped with prism reflector.

Figure 4. Lava rosette and associated prism reflector

Prism reflector have also been installed near 6 of the reference marks targeted from the P04 survey column, with a geological and geometrical consistency, so as to consider that the movements of the reference mark and the associated reflector are similar. 3 of the survey columns are considered fixed (constant coordinates over time) and 3 other reference marks are said mobile (whose coordinates are determined at each monitoring survey based on the fixed references) (cf. Fig. 6.).

Comparative measurements between the standard configuration and the automated one were initially carried out during standard monitoring surveys without permanent instrumentation. They checked that the automated configuration respected the measurement uncertainty required for this type of dam.

An automated monitoring survey was finally experimentally set up in 2016 with the permanent installation of a LEICA TS30 total station on the P04 survey column (Cf. Fig. 5.), controlled by a Combox equipped with LEICA Geomos acquisition software located in a technical room close to the survey column.


Figure 5. Total station located on survey column P04

Temperature, pressure and humidity sensors located close to the survey column are connected to the

Combox in order to correct distance measurements from atmospheric effects.

Angular and meteorologically corrected distance measurements performed by the Total Station are converted and transferred automatically to the KOALA monitoring application. KOALA retrieves these data, calculates the coordinates and the displacements of each mark automatically. Effective stability of considered fixed survey columns is also controlled.

During this experimental period, manual planimetric monitoring surveys were realized in order to compare results (Cf. Fig. 6.).

For study and methodology qualification purposes, the frequency of measurements was adapted: at the beginning one measurement per hour was performed and then one per day.

Apart from one reflector obscured by vegetation for a long time, most reflector were targeted with a very good success rate.

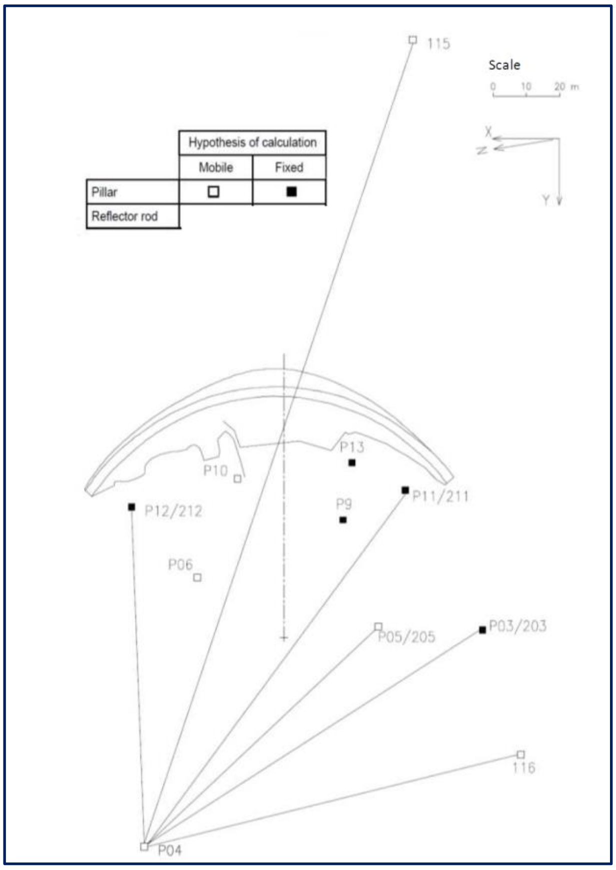

Figure 6. Planimetric grid used during tests on remote measurements

IV. EDF CENTRALIZED DATA BASE AND TOOL BOX: KOALA

A. *Context*

Electricité de France has been the major electric power producer in France since 1946 and it operates many nuclear, hydroelectric and thermal power plants. Since EDF was founded, Engineering Centers have been created to assist the sites of production in all technical fields for the improvement of performance, maintenance and safety.

Within DTG (General Technical Division), the Surveillance Department includes a monitoring sector of the works made of 4 operational centers: three for the hydroelectric plants and one for the nuclear plants.

To be able to improve the surveillance of the civil structures, a single WEB application called KOALA was launched in 2011. It enables real-time behaviour analysis with built-in diagnostic tools and models that transform raw data into corrected data from instantaneous or delayed reversible effects (linked to the hydrostatic and thermal loads, to the rain falls and air temperatures influences). It was a huge evolution to make this web application accessible for all users by Internet (operators, engineering and decision-making centers) with a single database used in 2016 by 1260 users for 330 monitored hydraulic works including more than 15 300 phenomena.

All the data are stored from the raw measurement of a monitoring device to its transformation into physical data (phenomenon) with the retaining of the device parameters (cf. Fig. 7.).

The application shows graphs of raw and corrected data with normality tests. The synoptic view enables the display of several phenomena on an overview sketch.

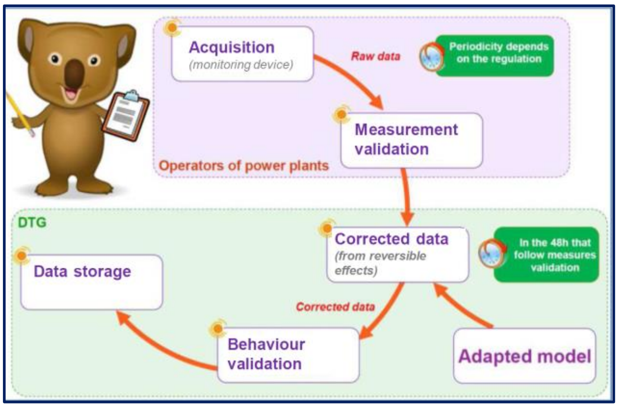

Figure 7. Koala operating principle

This application fully contributes:

- to archiving all the monitoring measurements,
- to a finest analysis of the dam behaviour thanks to integrated data treatment tools: HST (Hydrostatic – Seasonal – Time) and HST-T (Hydrostatic – Seasonal – Time – Thermal) models for example),
- to the safety of civil works: quick detection of any behaviour anomaly of the civil works,
- to comply with the authorized constraints in France within the surveillance of the works.

B. *Topography module of Koala*

The capture and processing of topographic data is done via the KOALA application that includes a module dedicated to topography (cf. Fig. 8.).

This module calculates the position of the points located on the structure, whose position must then be validated by the user. It is also a database that contains all past monitoring survey measurements, but also the grids configuration, the list of used devices, their characteristics as well as the coordinates of all points and their evolution since the beginning of the dam monitoring.

The analysis of the long-term stability of the grid of reference based on the time series is one of the major advantages of this module as it makes it possible to re-play all the data with another configuration in case of drifts detection to be able to correct them.

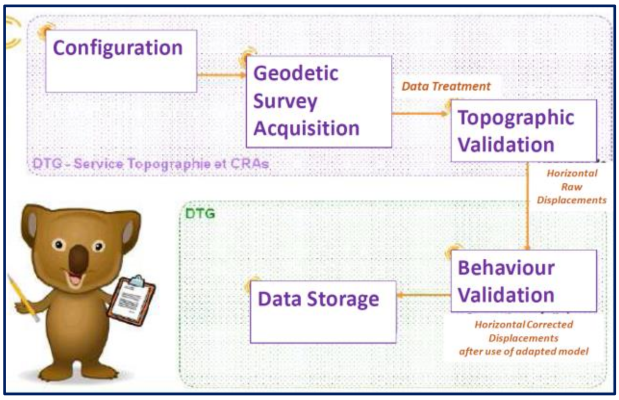

Figure 8. Life cycle stages of topographical measurements

The whole measurement chain – transmission and reception of data from or to the automated theodolite – has been processed to be fully integrated into KOALA's functionalities allowing to use data directly without further manual processing.

V. Models enabling separation of reversible and irreversible effects

The measurements from the various sensors are converted into physical values using formulae in the KOALA data base.

The first method to monitor a phenomenon consists in plotting raw measurements on a graph according to time. In addition, a statistical analysis method will allow identification of influences from various factors in order to “correct” the measurements from these influences. This statistical analysis makes comparisons easier and highlights irreversible changes.

EDF (Wilm & Beaujoint, 1967) has developed and uses the HST (Hydrostatic, Seasonal, Time) method as a powerful tool to interpret the behaviour of dam structures. The application of the method over several decades from hundreds of dams and dykes has confirmed the relevancy of this method.

The HST correction model processes the raw measurements to ensure identical water levels and seasonal conditions. This model is designed for phenomena with immediate or seasonal effects, that generally takes place in concrete dams. Statistical analysis is used to assess the external reversible influences (hydraulic head and thermal load) and to reprocess them to ensure "identical conditions", in order to detect any irreversible effects.

The HST model ignores the potential influence of precipitation on mainly hydraulic phenomena and considers that the raw measurements are the addition of three (3) main factors:

- An irreversible change to the phenomenon over time t and which may tend to be attenuated (adaptation or consolidation) or accelerated (degradation),
- A reversible influence which corresponds to the effects of the hydrostatic pressure,
- A reversible influence due to the thermal state Θ of the structure. In the HST model, it is assumed that each year, on the same date, the deformation due to the thermal state of a structure is the same and depends only on season S in relation to an angle which is 0° on January 1st and 360° on December 31st

It is therefore accepted that the phenomenon Xi is the sum of the 3 functions f1(t), f2(z) and f3(Θ):

$$X_i = f_1(t_i) + f_2(z_i) + f_3(\Theta_i) + \varepsilon_i \qquad (1)$$

t, z and Θ take the instantaneous specific values of the variables for the day of the measurement.

The term ε represents the residue of the model, including measurement errors together with the inaccuracy of the model. The effects of all other causes are considered to be secondary and are ignored for the sake of simplification.

The seasonal effect is the representation of function f3. The hydrostatic effect is the representation of function f2. The corrected measurements are the representation of function f1 + epsilon:

$$Xcor = X_i - f_3(\Theta_i) - f_2(z_i) \qquad (2)$$

A reversible status, also called "T" (Thermal), completes this seasonal function by integrating the delayed effect of the actual daily air temperature. In other words, the model takes into account the difference between the average temperature of a given day and the actual temperature of the day. This corrective function also makes it possible to delay the reaction of the structure to temperature changes.

Consequently, the so-called HST-T "corrected" measurements are no longer influenced by any reversible effect (Hydrostatic pressure, Season, and delayed air temperature).

$\Delta\Theta_R^{[T_0]}$, calculated by recurrence by :

$$\Delta\Theta_R^{[T_0]}(t+dt) = \Delta\Theta(t+dt)(1-e^{-\frac{dt}{T_0}}) + \Delta\Theta_R^{[T_0]}(t)e^{-\frac{dt}{T_0}} \qquad (3)$$

VI. Comparison and Validation of Achieved Results

Planimetric survey are performed on Sainte Croix dam since 1974. A reversible amplitude of about 15 mm is observed on the raw radial displacements measured on crest of the crown of the arch dam (cf. Fig. 9.).

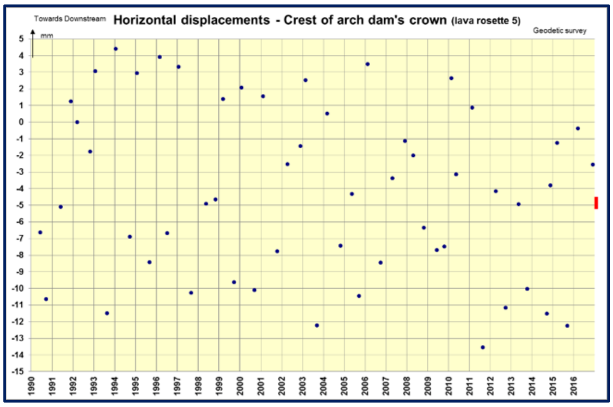

Figure 9. Radial displacements since 1990 – Raw data – Lava rosette 5 located on crest of the crown of the arch dam

A. *Corrected measurements*

These raw data were analyzed with both HST and HST-T models on the period of time 1990 – 01/2017.

Using HST model, the reversible seasonal effect amplitude is around 15 mm between winter and summer, which is about 5 times greater than the amplitude of the reversible hydrostatic effect (cf. Fig. 10.).

Since the dam is fairly sensitive from a thermal perspective, it is possible to reduce the residual dispersion even further by integrating the air temperature deviations with respect to the normal seasonal temperatures. The HST model was then completed with the delayed air temperature measured at Monestier, allowing a better reduction (about 40%) of the residual dispersion by integrating the exceptional thermal episodes. The residual dispersion is then about 2 mm only (cf. Fig. 11.).

Both models are relevant and give the same results: a light irreversible displacement of the arch dam is observed on the crest of crown of arch dam (lava rosette 5) of about 0.1 mm/year towards upstream.

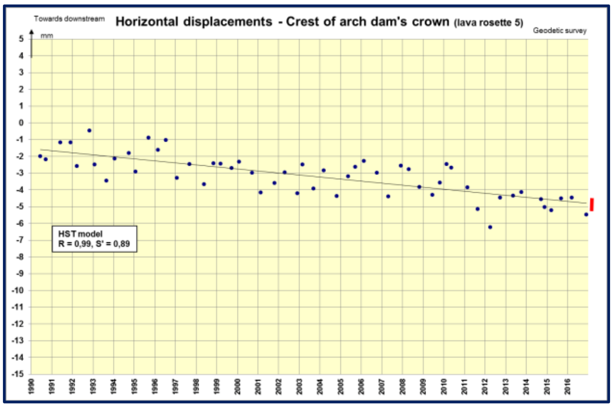

Figure 10. Radial displacements corrected with HST model

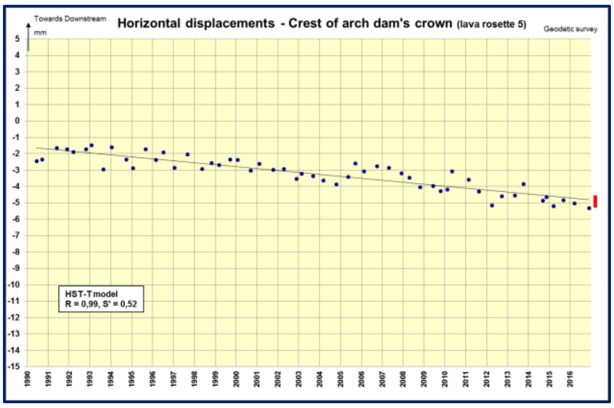

Figure 11. Radial displacements corrected with HST-T model

B. *Raw data reconstitution*

It is possible to reconstitute the daily raw radial displacement of the Sainte Croix arch dam on the crest of its crown (lava rosette 5) based on the algebraic expressions determined by the HST-T model that depends on two variables only for a given date: the reservoir level and the air temperature (cf. Fig. 12.).

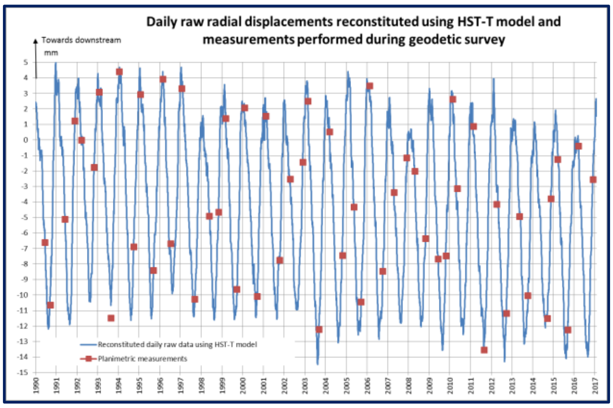

Figure 12. Daily raw data reconstituted using HST-T model compared with measurements performed by topographers during geodetic surveys

The correlation between the measurements performed during geodetic surveys by the topographers and the reconstituted daily raw data based on the reversible effects determined with the HST-T model is excellent.

C. *Comparison between automated raw measurements performed by motorized theodolite and reconstituted raw data using HST-T model*

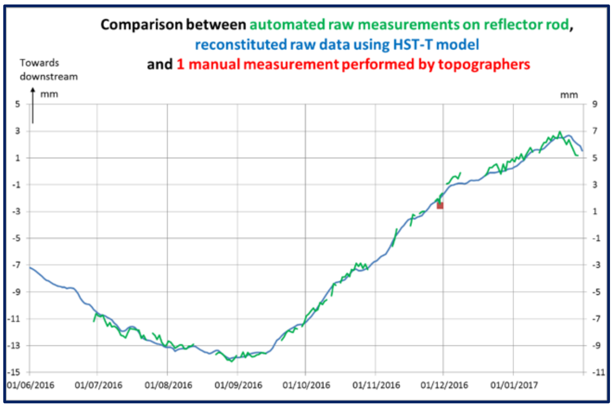

Figure 13. Comparison between raw automated measurements by motorized theodolite on prism reflector, daily raw data reconstituted using HST-T model and one manual measurement performed by surveyors

The high quality planimetric grid and the rigorous methodology applied when performing the monitoring surveys since 1974 with trained and skilled teams of surveyors resulted in excellent planimetric measurements. These measurements allow the setting of good models enabling the separation of reversible effects and the appreciation of the irreversible effect. It is therefore possible to reconstitute the daily raw radial displacements using HST-T model and the available daily air temperature and reservoir level data.

Furthermore, the daily measurements performed with the automated motorized theodolite on crest of the crown of the arch dam give similar displacements to those reconstituted using HST-T model (there is an existing offset corresponding to the configuration and the measurement point modification) (cf. Fig. 13.). The minor residual differences between the two raw data (measurements from total station and reconstituted data using HST-T model) come from measurement uncertainties: topographical on one hand and the possible influence of the external reversible influences during time for carrying out the monitoring survey on the other hand (evolution of air temperature or reservoir water level).

VII. Conclusion

Sainte Croix dam was the pilot site that allowed the testing and implementation of the various elements of all the measurement chain necessary for the use of automated monitoring survey for a closest follow-up of the mechanical behaviour of the dam during particular operating conditions.

The assessment of the relevance of the automated measurements must be based on both the knowledge of a high quality planimetric grid and the rigorous methodology applied over time when performing the monitoring surveys with trained and skilled teams of surveyors. It results in raw measurements of quality that allow the setting of good models enabling the separation of reversible effects.

Several constraints were addressed: increased reliability of the permanent on-site installation, connection to the information system called KOALA with features equivalent to those of a classic remote instrumentation (measurements on request or preset, automatic data processing including elaborate topographic calculations, etc.) and the operational maintenance of the system.

The advantages of this measuring system completely integrated into the KOALA web application are multiple:

- the continuity of the horizontal displacements time series,
- the addition of the vertical displacements for reasonable distances,
- a behaviour analysis based on a larger sample of measurements under variable hydrostatic & thermal loads.

A permanent instrumentation could also be considered for limited periods of time that can be repeated during the dam's lifetime in a "test" mode (emptying of the reservoir for example).

On EDF hydraulic works, some dams that are difficult to access or require close-range measurements are now equipped with automated total station to improve the knowledge of their mechanical behaviour in the context of studies or specific monitoring, especially in particular operating conditions. Moreover, wherever it is possible, links between total station and automated pendulums in foundation are made to benefit the reference grid stability survey.

Finally, it is important to bear in mind that automated instrumentation requires periodic functional and metrological controls. This remote monitoring has a significant cost (routine and scheduled maintenance over time as well as technological obsolescence) which may however be lower than others alternatives (pendulums and GNSS stations for example) with the possibility of adding marks for a minor cost.

VIII. Acknowledgements

We thank our recently retired colleague Gérard Geffraye who has always been very involved to push on innovative solutions for structures monitoring

improvement. Gérard Geffraye is a civil and hydraulic engineer, and a member of the French Dams and Reservoirs Committee (CFBR). He has been working for Electricité de France for 36 years. He began his career in the Hydrological Department, in charge of hydrological studies, weather forecasts and setting-up climatological networks in France and abroad, before joining the Civil Engineering Department, where he has been working since 2000 on dam monitoring and surveillance activities in France and abroad (Africa, Asia and America), as a technical reference person in charge of drafting and verifying the behavioural studies of over 150 structures.

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