Analysis of earthdam monitoring data

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English summary

To understand the long-term behaviour of a dam, it is essential to carefully interpret the measured data, in order to be able to distinguish between the effects of factors such as drift, irreversible events and the ageing of the dam and the effects of other factors not involving ageing processes.

The Hydrostatic-Season-Time (HST) model is presented in this paper. The main components of the basic model are: the effect of the reservoir level; the seasonal effect; and time drift. The rainfall must be taken into account when analysing hydraulic related measurements.

Piezometric levels of a homogeneous embankment dam (15.5 m high) are analysed, as well as variations of the measurements of three 3D crackmeters, installed in a spillway. These case studies are interpreted.

Résumé français : *Analyse de mesures d'auscultation de barrages en terre*

Pour comprendre le comportement à long terme d'un barrage, il est essentiel d'interpréter soigneusement les mesures d'auscultation, afin de pouvoir distinguer les effets des facteurs tels que la dérive, les événements irréversibles et le vieillissement du barrage, des effets d'autres facteurs n'impliquant pas des processus vieillissant.

Le modèle Hydrostatique-Saison-Temps (HST) est présenté dans cet article. Ses composants principaux de base sont: l'effet du niveau de réservoir; l'effet saisonnier; et la dérive dans le temps. Les précipitations doivent être prises en considération pour l'analyse de mesures liées à l'hydraulique.

Les niveaux piézométriques d'un barrage en terre homogène de 15,5 m de hauteur sont analysés, ainsi que les variations des mesures de trois vinchons, installés dans un coursier de déversoir de crues. Le résultat de ces études de cas sont interprétés.

Streszczenie polskie: *Analiza danych pomiarowych dla zapór ziemnych*

Aby zrozumieć zachowanie się zapór w długim okresie czasu niezbędne jest przeprowadzenie dokładnej interpretacji danych pomiarowych w celu stwierdzenia różnic między efektami spowodowanymi takimi czynnikami jak zmiany w czasie, zjawiska nieodwracalne, starzenie się zapór, a wpływem innych czynników nie związanych ze starzeniem się.

W pracy przedstawiony jest model HST (Hydrostatyka-Sezon-Czas) . Głównymi składnikami podstawowego modelu są: wpływ piętrzenia, zjawiska okresowe, zmiany w czasie. Przy analizie danych pomiarów hydraulicznych należy uwzględnić opady.

W pracy przeanalizowane są odczyty piezometrów umieszczonych w zaporze ziemnej wysokości 15,5m, jak też dane pomiarowe z trzech 3D szczelinomierzy umieszczonych w sekcji przelewowej. Wyniki tego przykładu są zinterpretowane.

1. Introduction

Dam monitoring comprises two essential methods:
- visual monitoring; this is a qualitative method which is fundamental because it integrates the complexity of the behaviour of the structure;
- measurements of data; this is a quantitative method which uses instrumentation and analysis of measurements specific to each structure.

Dam monitoring is essential for the follow-up of the dam, from its design to its putting out of service; it is a component of its structural behaviour and of the control of its safety. It is also invaluable to make progresses in the knowledge on the behaviour and the ageing of the dam, and make it possible to improve the studies and expertises in their various technical and economic aspects (Poupart et al., 2000). From this point of view, monitoring is an essential component of progress. It makes possible to tell the owner about, before it is too late, necessary reinforcement and repair works and, in extreme cases, emergency measures ensuring protection of the downstream populations. Statistics show that there is a strong correlation between the most serious accidents of dams and the absence of organized monitoring (Londe, 1990).

The follow-up of ageing is essential. The acceleration - always alarming - of any phenomenon must be detected as soon as possible. A true monitoring of the work supposes that one can follow the evolution of its behaviour in time, substraction of the other variations previously done. This is exactly what stipulates French regulation.

Statistical methods of Hydrostatic-Season-Time (or HST) type were proposed in the years 1960 to analyze measurements of displacements resulting from pendulums in arch dams (Ferry and Willm, 1958; Willm and Beaujoint, 1967; Lugiez and Al, 1970). These methods are currently used in several countries, to analyze other standard measurements (Guedes and Coehlo, 1985; Silva Gomes and Silva Matos, 1985; Seersucker and Lino, 1999; Carrère and Al, 2000). Experience gained for a few decades on several hundreds of dams has confirmed the excellence of this approach as a powerful tool for interpretation of dam monitoring measurements (sea ICOLD reports: Mary, 1948; Yoshida, 1958; Oberti, 1964; Post, 1985; Marazio, 1989; Dibiagio, 2000).

In this document, application of the HST method for analysing hydraulic measurements of earthdam is presented. The essential components of monitoring and analysis of measurements are recalled in section 2 and 3. The HST model is exposed in section 4. This is the traditional model, intended for concrete dams displacements measurements analysis, supplemented by a rain component model. Application to analysis of piezometric measurements is detailed in section 5. An example of the results of its application to analysis of the measurements of cracks in the reinforced concrete walls of a spillway is also presented. Section 6 is devoted to a critical analysis of this method.

2. Monitoring

The types of measurements and the most widespread apparatuses for earthdams monitoring are briefly described below. These measurements relate on the loadings and the response of the work. The two main loadings are:

- water level, measured by visual staff gauge or byv water level recorder (precision: centimeter);
- rainfall, measured by pluviometer installed on the dam site, with daily measurements (precision: millimeter/day).

It can sometimes be necessary to take into account other loadings: the downstream water level, the side ground water, the snow melt. The response of the work is apprehended by measurements of displacements and hydraulic measurements.

Displacement measurements can be of three types:

- surface displacements, measured by topographic measurements -levelling and planimetry- settlements, upstream/downstream and left bank/right bank movements; these measurements need specialized aptitudes, once or twice each year;
- in-depth displacements, measured by instruments which are generally installed during construction (pendulum, inclinometer, extensometer, settlements gages);
- relative displacements, along a joint or of a crack, quantified by instruments generally installed when needed (crack meter, 3D crack meter).

Hydraulic measurements can be:

- drains discharge, measured with a graduated container or by flow gauging weir (weir with liquid level recorder, and use of a weir formula to estimate the flow); they relate to the drains, the relief wells, the zones of resurgence;
- hydraulic loads, measured by piezometers; the open tube piezometer is the simplest system and also the most robust; it can be established at any time in the dam body, but also in foundation, banks, abutments and downstream platform; it is a low diameter drilling, equipped with a casing of few centimeters; measurement is done using a probe giving the difference in dimension between the water level and the head of the stand pipe piezometer; the precision is of the order of the centimeter;
- pore water pressures, measured by pore water pressure cells or vibrating wire piezometers, which are low dimension apparatuses, installed during construction in the dam body or in the foundation; the principle of measurement depends on the type of apparatus (backpressure or vibrating wire); the precision is from 0.1 to 1 kPa (or 1 to 10 cm in water load).

In the dam body, a complete hydraulic monitoring system generally includes several upstream/downstream profiles making it possible to evaluate the saturation of the body of the stopping, and one or more flow measurement points whose role is to detect the appearance and the evolution of leakages zones. The foundation, the abutments, the banks and the downstream platform must also be monitored. Figure 1 is an example of monitoring the dam body upstream from the chimmey drain and base/foundation interface by vibrating wire cells. Figure 2 shows a piezometer system for monitoring the surroundings of this dam.

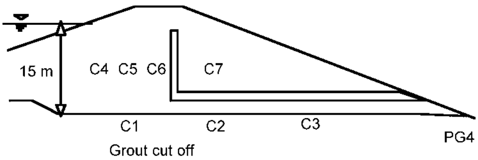


Figure 1. Dam cross section and location of the pressure cells (Chamboux dam).

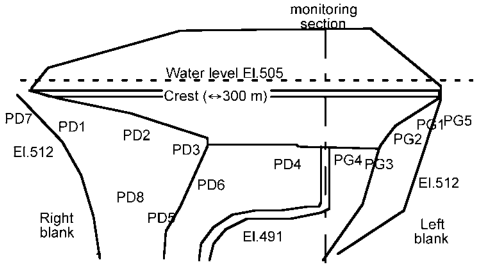


Figure 2. Map sight of the dam and location of the piezometers (Chamboux dam).

For a dam in regular use, periodicity of measurements is known as normal. In particular situations (construction, first filling, full emptying or filling, important repair works), periodicity of measurements is lowered. It is always specific to the structure. It is essential to carry out measurements in a continuous way during time. More than their absolute value, it is indeed the evolution of the phenomena in time which is essential to know. The acceleration of a displacement or the brutal rise of a water pressure are examples of behaviours which are capital to detect in due time. It is also essential to carry out measurements in a homogeneous way during time. The compared analysis of the evolution of several sizes is sometimes essential to conclude. It is in particular the case of the coupling pore pressure/leak flow. The lowering in a leak-flow is an example of behaviour which requires the knowledge of piezometry in the concerned zone: if it decreases, one can show a clogging of materials inside the dam body (which is a normal phenomenon); if it increases, one can suspect a clogging of the drainage device (which is a very worrying phenomenon).

3. Monitoring measurements analysis

The monitoring objective is to sufficiently early detect discontinuities, significant evolutions, irreversibilities, and all show existence of disorders. In the end, these are always great displacements of masses or interfaces, announced by precursory phenomena: rise of pore water pressure, cracks, opening of joints, great elastoplastic deformations. Here are some examples of evolutions which are likely to lead to disorders, even possibly to failures, and whose harbingers are sought by dam monitoring measurements analysis.

Displacements:

- an excessive settlement of the crest, leading to a reduction in freeboard (difference between the altitude of the crest and the one of projected highest

water level), which diminishes the dam safety with respect to the risk of overflow; this settlement can reflect a strong compressibility of the foundation, or a defective compaction of the dam body (insufficient compaction, water content of the soil material too low during compaction);
- sliding starts, in the downstream slope of the dam, banks slopes or water reservoir slopes, calling into question the stability of these slopes; the installation of inclinometers can make it possible to locate the in-depth zone of slipping and to follow the evolution of the slipping.

Piezometry and pore water pressure:
- a high or increasing piezometry in the dam body; such an evolution is always worrying; in this case, the the drain can be circumvented or it can be the sign of slope water input; in all these cases, the dam stability is called in question; if the piezometric line nears the downstream slope, seepages can evolve to a regressive internal erosion (piping);
- a high or increasing piezometry in the foundation or the surroundings, harmful to the structure stability; it can come from a failure in the waterproofing systems of the foundation and abutments;
- a decreasing piezometry; this evolution in general beneficial can come from the dissipation of pore water pressures induced by construction, or a reduction in the permeability of materials by self-clogging.

Leak-flows:
- a decreasing of flows; this decreasing can come from a natural improvement of the dam and foundation water tightness caused by upstream clogging, evolution which is beneficial; this reduction can also reflect a filling of the drains, which are slowly circumvented and so do not control the leak-flows any more; this filling can be the consequence of an internal phenomenon of erosion (suffusion); in this very worrying case, upstream piezometry will increase and the uncontrolled flows can be at the origin of internal erosion (piping) or slips on the downstream slope; only the measurement of the couple piezometry/flow makes it possible to decide;
- an abnormal increase in flows; it can come from a slope ground water , but also from a process of internal erosion (piping); in this last case, collected water can be charged with fine elements coming from the dam body.

A real monitoring of the structure implies to follow the evolution of its behaviour in time, any other cause from variation being suppressed: this is the analysis under "constant conditions". It is precisely what is stipulating by the French regulation relating to the inspection and the monitoring of the dams interesting public safety (i.e. whose possible failure would have serious repercussions on people, whatever their height).

The analysis under constant conditions supposes that one is able to quantify the influence of the two main loadings: water level in the reservoir and precipitations. This is the analysis of dam monitoring measurements. For a dam in use, the loadings cause reversible strain since dimensioning was carried out consequently: the limits of stability or resistance are not reached. The analysis of dam monitoring measurements then makes it possible to change measurements to constant conditions in order to quantify the evolutionary and irreversible phenomena. The speed of evolution can be positive (increase with time), or negative (reduction with time), and can be accelerated or slowed down. This evolution has then to be interpreted in the light of the knowledge of the structure that one has in addition, or which one has a presentiment of: dissipation of the pore water pressures of construction, filling of the drainage curtain, evolution of permeabilities. The periodicity is annual for the synthesis of rough measurements, and biennial for their analysis.

4. The HST model

The HST model is based on three effects. The first one is the hydrostatic effect, which accounts for the variations of measurements in the level of the reservoir. It is represented by a polynomial function - often of the fourth order - of the reservoir level $Z(t)$ at time t:

$$H_n = a_1 z_n + a_2 z_n^2 + a_3 z_n^3 + a_4 z_n^4 ,\; z_n = \frac{Z(t_n)-\bar{Z}}{\sigma} \qquad (1)$$

where $\bar{Z}$ and σ are the mean average and standard deviation over the analyzed period. The second effect is the date in the year, which accounts for the seasonal variations S of measurement, periods twelve months and six months. It is represented by the first two terms of a development in Fourier series:

$$S_n = b_1 \sin(\omega_a t_n) + b_2 \cos(\omega_a t_n) + b_3 \sin^2(\omega_a t_n) + b_4 \sin(\omega_a t_n)\cos(\omega_a t_n) \qquad (2)$$

where $\omega_a = 2\pi / \Delta t_a$ is the annual pulsation ($\Delta t_a = 365,25 \text{ years}$ corresponds to one year). The third effect gives an account of the influence of time, including ageing. Its expression is variable, and depends on the studied phenomenon. This effect is often called "irreversible effect". It can for example be represented by the sum of a linear term, a positive exponential and a negative exponential of reduced time τ_n during the analyzed period $[t_0, t_N]$:

$$T_n = c_1 \tau_n + c_2 e^{\tau_n} + c_3 e^{-\tau_n} ,\; \tau_n = \frac{t_n - t_0}{t_N - t_0} \qquad (3)$$

In order to allow analysis of hydraulic measurements, taking into account the rainfall is necessary. This pluviometric effect P requires to know daily rainfall Q. A simple method is to take the cumulated rain over the last ten days (Crepon and Lino, 1999). The taking into account of cumulated rain over several former periods can lead to good results. One can represent it by a linear combination of the cumulated rain over seven days during the four previous weeks, and cumulated rain over fourteen days from the previous weeks (Plancke, 1986; Bonelli et al., 1998):

$$P_n = \sum_{k=1}^{4} d_k p_k^n + d_5 (p_5^n + p_6^n) + d_6 (p_7^n + p_8^n) ,\; p_k^n = \sum_{j=1}^{7} Q_{n-j-7(k-1)} \qquad (4)$$

The statistical model gives an estimate Y_n of measurement y_n with an error ε_n:

$$Y_n = Y_0 + H_n + S_n + T_n + P_n ,\; y_n = Y_n + \varepsilon_n \qquad (5)$$

The 18 parameters are estimated by multiple linear regression which minimizes the average standard deviation between the centered reduced values, which conducts to maximize the determination coefficient R^2. In order for the analysis to be statistically significant for a risk of 5%, R^2 must be higher than 0.45. To minimize the number of explanatory variables while maximizing R^2, a step by step process of Stepwise type of selection or elimination of the explanatory variables is used. The explanatory variables are introduced gradually according to a criterion based on the test of Fisher-Snedecor (*F*) which measures the increase in R^2, and their selection is called into question after introduction of a new variable. This method is traditional, and it is advisable to refer to the works of statistics and data analysis specialists for more details (cf for example Diday, 1982).

The number of parameters p of the final model is in practice always lower than 18, since variables that are considered not to be very explanatory are not part of it. Values of R^2 and *F*, then the detailed analysis of each effect and the residues make it possible to judge quality of an adjustment. Several calculations are sometimes necessary to lead to an exploitable analysis, by adapting in particular the period of the analysis to the studied phenomenon: it is in particular the case at the time of exceptional circumstances (emptying of the reservoir), or of discontinuities due to interventions on the monitoring device (cleaning of the drains, replacement of a monitoring device). In order to allow a synthesis of the behaviour of the structure, we defined some indicators (table 1).

Effect	Indicator	Meaning
H	$\alpha = \frac{H(Z_{\max})-H(\bar{Z})}{Z_{\max}-\bar{Z}}$	evaluated between the maximum level and the mean level in order not to take into account measurements at low level, too very few (exceptional emptying)
S	$B = \sqrt{b_1^2 + b_2^2} + \frac{1}{2}\sqrt{b_3^2 + b_4^2}$	maximum amplitude which would be reached if the annual and semi-annual effects would be in phase
T	$v = \frac{\Delta t_a (T_N - T_0)}{t_N - t_0}$	speed of annual evolution evaluated from the initial and final values over the analysis period
P	d_1	influence of the cumulated rain from the seven days before measurement

Table 1. Indicators for a HST analysis

5. Application of HST model

5.1 Application to internal hydraulic measurements (Chamboux dam)

Surface displacements (levelling and planimetry) of an earthdam are generally not analyzed by statistical method, because the number of measurements is too low (one to two measurements each year). When settlings are very significant, the method of Asaoka (1978), based on Terzaghi's equation of consolidation, allows to estimate the final compressing from the end of primary consolidation. Deep displacements, as well as the leak-flows can be analyzed by a statistical method of type HST when there are measurements enough. The rest of this part of this document relates to piezometric measurements and pore water pressure measurements.

Piezometric levels of an homogeneous earthdam 15.5 m high are analyzed. The foundation consists of granitic arenas ($k=10^{-5}$ to 10^{-6} m/s). An grout curtain seals it. The embankment comprises arenas of $k=10^{-8}$ to 10^{-9} m/s permeability, upstream from the chimmey drain. The drain is connected to the downstream by drainage cords surrounded by filters. Vertical relief wells emerge in the downstream foot gutter, which recovers drained water. The first filling of the dam was made in 1984.

The system of hydraulic measurements comprises – among others - 13 stand pipe piezometers with direct reading downstream from the dam and 7 pore water pressures cells (vibrating cord) in the body of the dam, in the axis of the spillway (fig. 1 and 2). The statistical analysis of these 20 instruments is carried out over the 1989/98 period, that is to say 9 years and approximately 100 measurements per instrument. The precision is in the order of the centimetre.

On average, on stand pipe piezometers the levels variation is explained to 30% by the variation of the water level in the reservoir, to 19% by rainfall, 15% by seasonal effects and 6% by evolutions in time (fig. 3). For some piezometers, the explanatory share of the rain can reach 38%. Among the six explanatory variables of the rain model, it is primarily d_1 which is explanatory: 12% on average, and up to 30% (fig. 4).

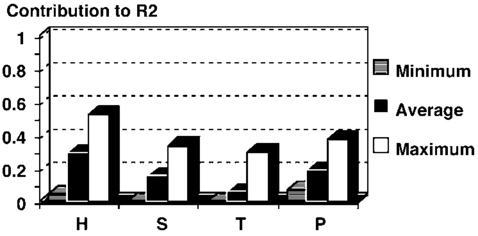


Figure 3. Contributions to R^2 of HST and P effects (average on piezometers)

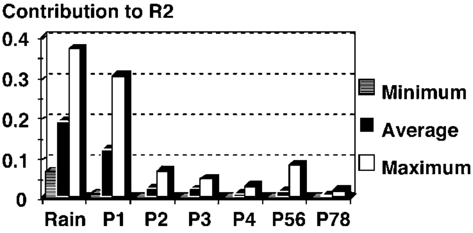


Figure 4. Contribution to R^2 of the parameters of the rain model (average on piezometers)

An example of detailed results is given in figure 5 (curve of rough measurements and variations of level in the reservoir), and figure 6 (results of the analysis). The variation of the levels of the piezometer is primarily ascribable to the variations in the level of the reservoir. The seasonal effect is significant, with a maximum in summer and a minimum right before the winter. It is to be noticed that it is the positive exponential and not the negative exponential which describes the downward trend with time (analyzes under constant conditions), with a minus coefficient.

The values of R^2 and F are written out on cross sections, as well as on a map view (fig. 7-10). The quality of analyses is to be connected to the instruments location. For a number of measurements n>60, the statistical threshold of significance fixed at $F_{1,n}$=4 (resp. 8), which corresponds at 5% risk (resp. 5‰) of wrongly select or reject a variable with each step (fig. 11). The statistical indicators (R^2,F) show analyses of excellent quality, except for the cells close to the drain, and the piezometers located downstream in bottom of valley, behind the grouting curtain, which is completely acceptable because the variations of the levels are weak.

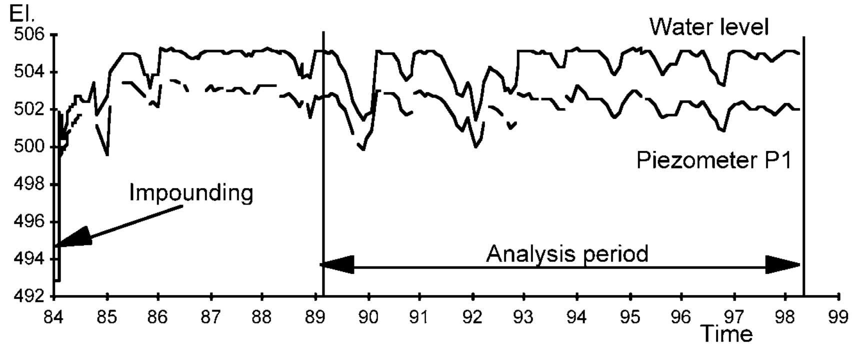


Figure 5. Water level in the reservoir and piezometric level (PD1)

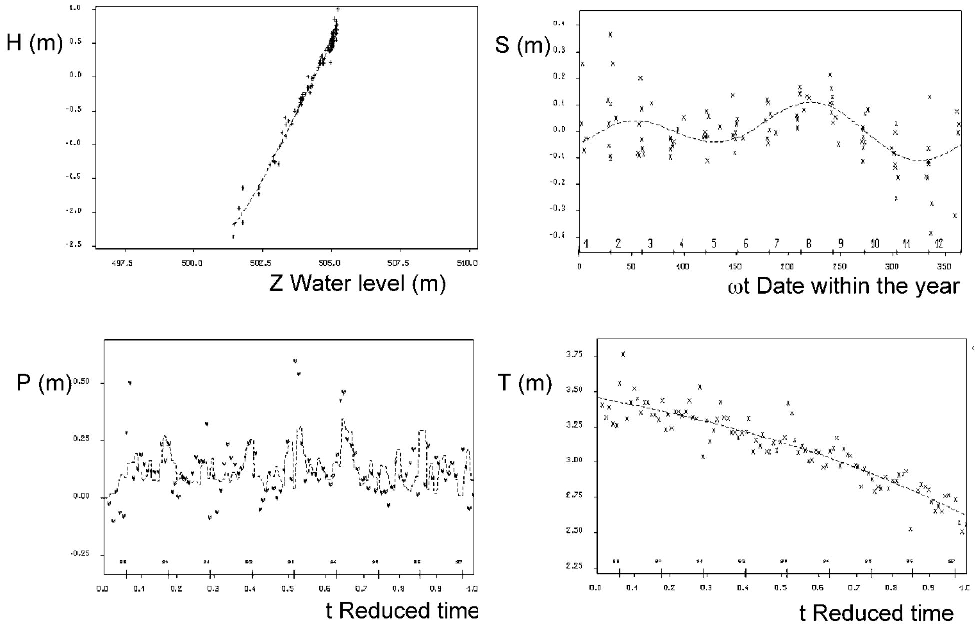


Figure 6. Influence of reservoir water level, season, rain and time (PD1). The curves represent the statistical model H, S, T, P. The symbols represent the effect corresponding to the measurement, that is to say H+ε,S+ε,T+ε,P+ε.

The variations of the reservoir level are also analyzed according to S, T and P: simple regression R^2=0.495 and F(13,100)=7.55 and Stepwise regression R^2=0.410 and F(3,110)=25.55. Analysis of the reservoir level shows a seasonal component (B=±74 cm/an), and a light increase with time of the mean level over the analysis period (v=+16 cm/an), probably caused by two emptyings at the beginning of period.

In the surroundings of the dam, the correct operation of the grouting curtain is illustrated by the decrease, from banks towards the bottom of valley, of the amplitudes of variation of the levels (fig. 12) and of the α coefficient (fig. 13). The grouting curtain is circumvented by banks. It illustrated by values of α near to one on the top of banks. However, it is done far from the dam, since the values of α decrease towards the bottom of valley (fig. 13). The seasonal variations account for 5 to 10% of the total variations and are of delicate interpretation (fig. 14). The evolutions in time of the levels are weak compared to the amplitudes of variation, which is a good indicator for safety (fig. 15). It is the rainfall of the previous week which influences primarily the piezometric levels, in a little more significant way in the bottom of valley than on the banks (fig. 16).

A piezometer located on the left bank, close to the peak, is remarkable: its variations are much more significant than those of the level in the reservoir (549 against 381 cm, fig. 12), partially ascribable to the reservoir level (α=0.48, fig. 13), highest seasonal variations (B=±102 cm/year, fig. 14), highest rainfall effect (fig. 16). This behaviour is due to the presence of ground water from the bank, identified during the project phase. The levels do not present concern. They remain sufficiently lower than the ground level, and do not show any evolution in time.

In the dam body, the lowering of the groundwater, which illustrates the effectiveness of the vertical drain, is highlighted by the decrease, from the upstream towards the downstream, of the amplitudes of variation of the levels (fig. 17) and of the coefficient α (fig. 18). The measured seasonal variations are ascribable to the reservoir level (fig. 19). The evolutions in time of the levels are weak compared to the amplitudes of variation which is a good indicator for safety (fig. 20). Rainfall has a negligible influence on the piezometric cells located in the dam body.

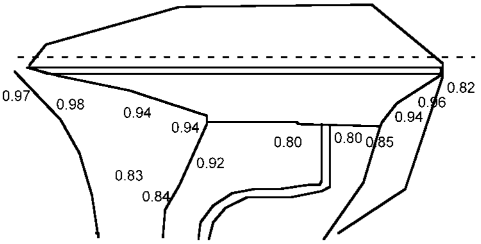


Figure 7. Indication of R^2 on the map view

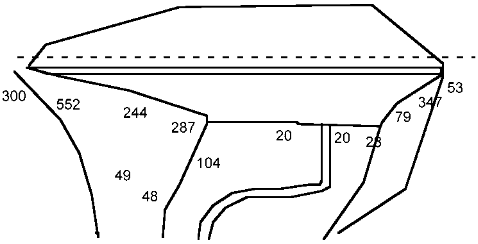


Figure 8. Indication of F on the map view

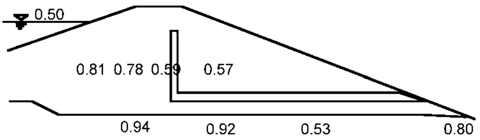


Figure 9. Indication of R^2 on the equipped cross section

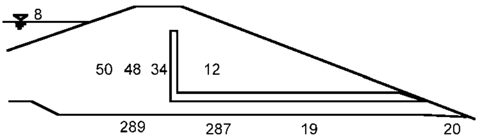


Figure 10. Indication of F on the equipped cross section

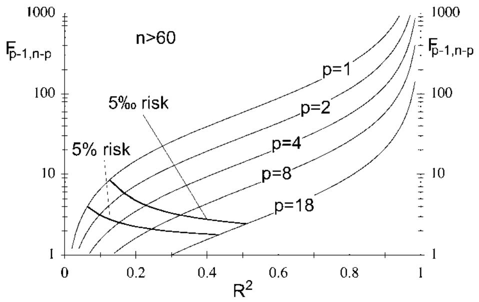


Figure 11. F (Fisher-Snedecor) related to R^2 and the number p of explanative variables for n>60 measurements.

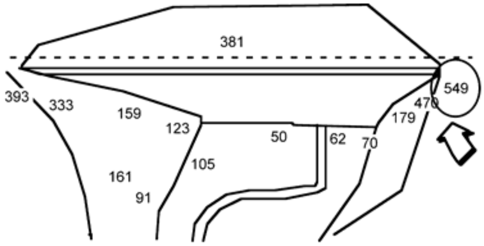


Figure 12. Indication of the total variation amplitude on the map view (cm)

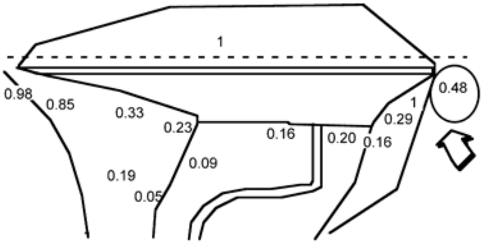


Figure 13. Indication of α on the map view

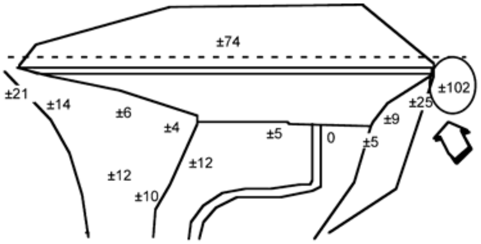


Figure 14. Indication of B on the map view (±cm/year)

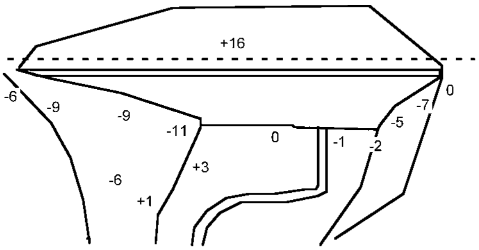


Figure 15. Indication of v on the map view (cm/year)

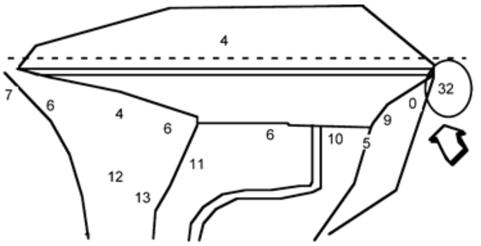


Figure 16. Indication of d_1 on the map view

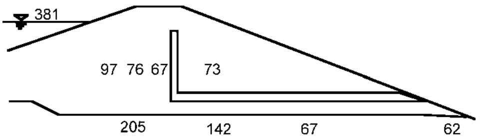


Figure 17. Indication of the total amplitude variation in the equipped cross section (cm)

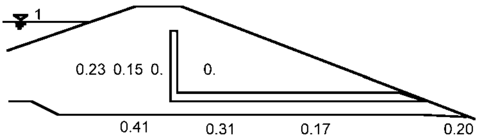


Figure 18. Indication of α in the equipped cross section

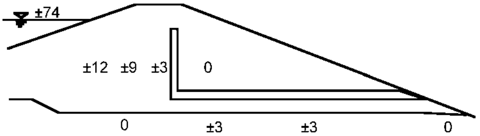


Figure 19. Indication of B in the equipped cross section(±cm/year)

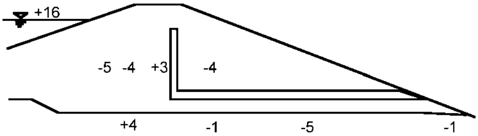


Figure 20. Indication of *v* in the equipped cross section (cm/year)

5.2 Application to displacement measurements on the cracks in side walls of a spillway (Lac des Sapins)

Measurements of three 3D crackmeters located on cracks of the side walls of the spillway of an earthdam are analyzed using the HST model. This 16 meters high dam contains a reservoir of 2 million m^3, and has a monitoring system comprising four cells of pore water pressure, six drains, six stand pipe piezometers, three 3D crackmeters, and a system of topographic bench marks. All measurements are analyzed with HST model, except for topographics for the reasons explained before in this paper. The analysis of measurements of the 3D crackmeters is commented on hereafter; values are usable only since 1996, because the system had before been improved by successive stages, before obtaining regular (problems of access) and reliable (problem of fixings) measurements.

For each 3D crackmeter, X measurement indicates an opening in the horizontal direction, Y measurement (most interesting) indicates a possible movement of the side wall towards the interior of the spillway, Z measurement a shift in the vertical direction. For each of the 3D crackmeters, a drift exists to the Y measurements since 1996.

The result of the analysis of measurements of the 3D crackmeters with HST model appears in Table 2. Detailed results are represented in figures 21 to 23 (curves of rough measurements), and figure 24 (results of the analysis). The variations are primarily due to time, for measurements Y, and to seasonal effects for the other measurements. Pluviometry (influencing the saturation of embankments) is probably an explanatory factor of the variations of the Y measurements of the 3D crackmeters. Unfortunately, measurements of pluviometry are not available.

Y measurement: this is the most interesting measurement for analysis, as it indicates a possible movement of the side walls towards the inside of the spillway. The coefficient of correlation R^2 is good to very good for the three measurements

(0.967, 0.988, 0.800). As previously supposed by visual observation of rough measurements, time effect is in all cases the most explanatory (respectively 90, 98 and 42% of explanation for the total phenomenon). Seasonal effect is significant for V3 (23%). The hydrostatic effect (16%) noted for V3, is to be connected to the measurements remained "high" for this apparatus during the emptying of the reservoir. It is to be noted that, contrary to the other two apparatuses, this 3D crackmeter is located on the reservoir side of the spillway. The noted drifting of measurements show that the chamber walls undergo the pressure from the earth they support and move towards the inside of the channel.

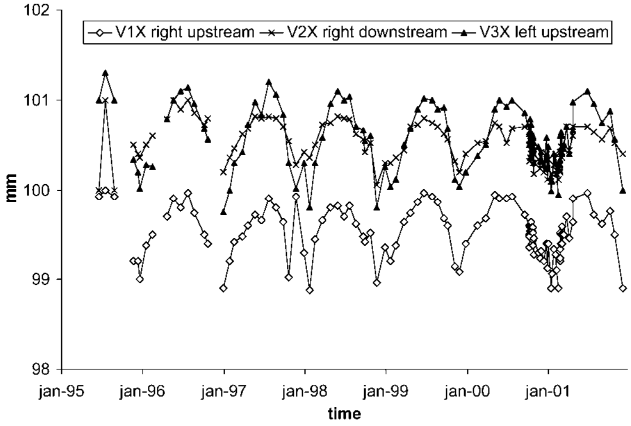


Figure 21. X measurements

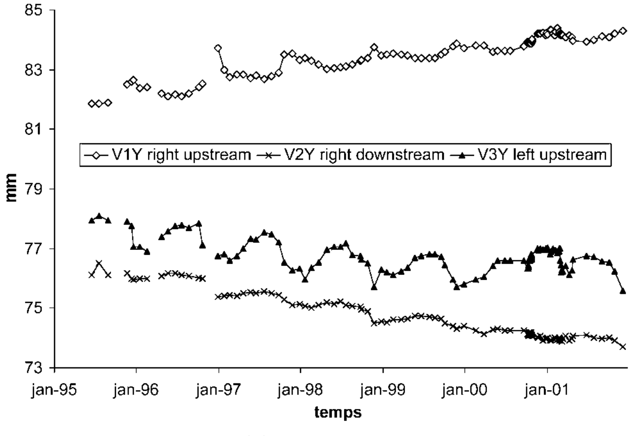


Figure 22. Y measurements

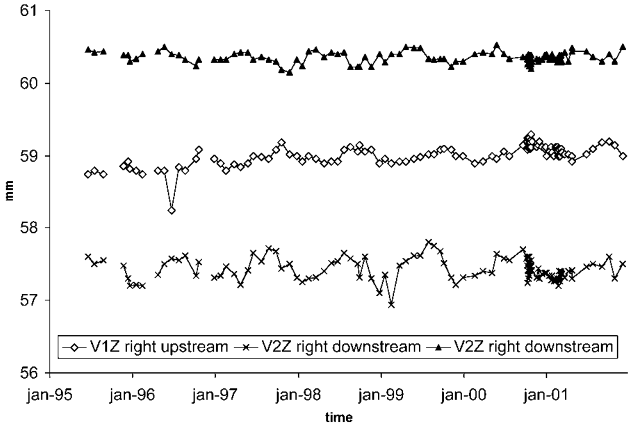
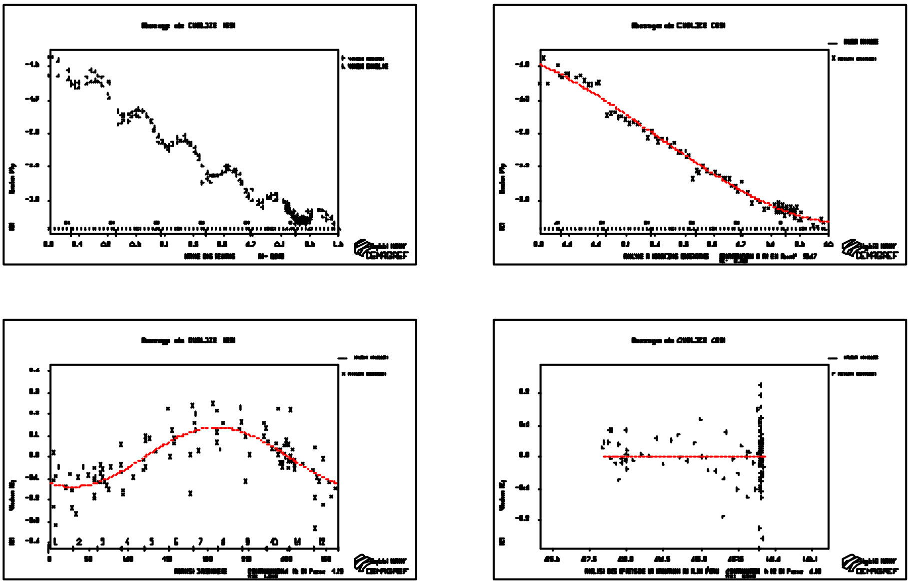


Figure 23. Z measurements



Vinchon V2Y aval droit

Figure 24. Measurements, influence from water level, season, and time (V2Y). The curves represent the statistical model H,S,T.

Instr.	V1Y	V2Y	V3Y	V1X	V2X	V3X	V1Z	V2Z	V3Z
Ampl. (mm)	2.54	2.80	2.50	1.12	1.00	1.55	1.06	0.86	0.37
R^2	0.967	0.988	0.800	0.693	0.510	0.808	0.716	0.565	0.352
α (mm/m)	0.000	0.000	-0.084	0	0.011	-0.013	0	0	0
B (mm)	±0.29	±0.14	±0.59	±0.40	±0.20	±0.54	±0.12	±0.16	±0.08
v (mm/year)	0.341	-0.363	-0.223	0	0	0	0.050	0	0

Table 2. Result of the statistical analysis of the 3D crackmeters over the 1996-2001period

X measurement: analysis quality is poor for V2 (R^2=0.51), it is average for V1 (R^2=0.69), it is good for V3 (R^2=0.81). For the three instruments the seasonal effect is the only one which influences the movements explained by analysis. So, there is no irreversible movement. The hydrostatic effects are negligible.

Z measurement: statistical analysis quality is average for V1 and V2 (R^2=0.72 and 0.57), it is poor for V3 (0.35). Seasonal effect is the only significant one for V2 and V3. V1 very slowly drifts (+0.05mm/year). In the three cases, there is no hydrostatic effect.

Broadly, statistical analysis carried out with HST model (115 measurements) gives satisfactory results on the three 3D crackmeters. It makes it possible to follow the evolution of the irreversible movements of the side walls of the spillway.

6. Discussion

HST analysis is a traditional approach in data analysis. It is used in many other fields (Young, 1998). One of the oldest known examples is Forbes' sinusoidal adjustment (1846) to reproduce the cyclic variations of the temperature of the ground. For dams, this is a robust approach which leads in the majority of the cases to suitable results. It has however two gaps: 1) its parameters have little mechanical signification, 2) it does not take into account the particular structure of the analyzed time series.

The polynomial expression of the influence of the water level in the reservoir is historical. It results from applied material strength to analyze displacements of an arch dam. This explanatory variable is often used by default for the analysis of hydraulic measurements, but a polynomial relation of degree four (or more) between a piezometric level and the level in the reservoir at the same moment is not mechanically justified.

An example of measurement putting at fault HST model is given figures 25 and 26. Figure 25 gives piezometric measurements monitoring the foundation, and located on the downstream platform of a dam. A priori, variations during the first years are proportional to the water level in the reservoir, which should result in a linear relation between piezometric variation and variation of water level in reservoir. But it is definitely not like this (figure 26), and a polynomial law of type (1), even of higher order, would not give an account of it. Moreover, if measurements frequency is not dependent on the water level in the reservoir (which is common in practical cases), these variations can be statistically and accidentally well explained by the polynomial model (1), without any real mechanical explanation. Indeed, when the water level lowerings are slow because of exploitation, measurements are numerous. When the rises are fast because of significant precipitations, measurements are rare. Adjustment will then be carried out to the most common measures, and the result will not be interpretable.

Figure 26 shows that a cycle of raising/lowering of water level in the reservoir is dissipative (hysteresis): the drawn curve is not the same one for a rise (phase 3) and for a lowering (phase 5). Some measurements can indicate an increase in pore water pressure while the level of the reservoir decrease, and conversely. This well-known phenomenon is due to the stocking capacity: variation of porosity or presence of air. It is observed on works (Kjaernsli and Al, 1982; Myrvoll and Al, 1985) and was reproduced in laboratory (Windish and Høeg, 2000). This example illustrates what is the delay effect and the fact that the model (1) cannot give an account of it.

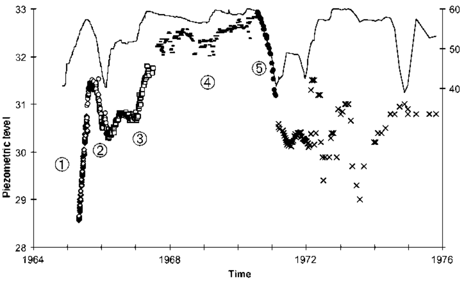


Figure 25. Water level in the reservoir and rough level in a downstreal piezometer, according to time.

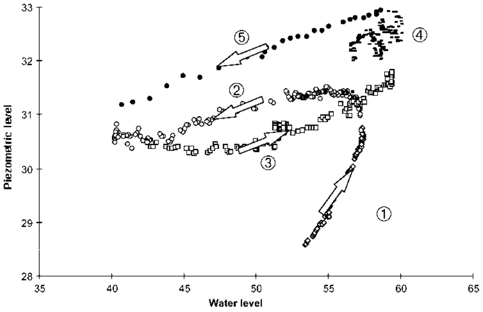


Figure 26. Rough piezometric according to level in the reservoir.

A mechanical approach based on the Impulse-Response-Function of the work was developed to analyze hydraulic measurements (Bonelli and Royet, 2001; Bonelli, 2004). It is based on an integral representation - starting from the Green function - solution of the associated linear parabolic problem. The statistical model which results from it is of type ARMA (Auto Regressive Moving Average), well adapted to time series studies. This type of model is used in many fields (Young, 1998), but still little applied to problems in civil engineering (Owen and Al, 2001). The same approach can moreover be used to analyze the temperature or displacement measurements in an arch dam (Bonelli and Felix, 2001).

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