CISM International Centre
for Mechanical Sciences
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ADVANCED DATA INTERPRETATION FOR DIAGNOSIS OF CONCRETE DAMS

Structural Safety Assessment of Dams

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presented by Dr Eng. Giovanni Lombardi

LOMBARDI
ENGINEERING LIMITED

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1. INTRODUCTION

We all know that monitoring of the dam is one of the fundamental requirements in order to ensure its long-term safety.

However, the best procedure to follow is not always very clear to everybody. Different ways are in fact open and the choice between them is not easy nor simple.

In the following we shall examine a number of aspects both of the problem and of the solutions available today.

Also some warnings will be expressed in matter of instrumentation, reading, data handling, archives, representation and interpretation of records.

Some general or special aspects will also be dealt with.

2. THE PROBLEM

2.1 Theoretical background

First of all let's discuss the general problem of the dam.

Table 1 puts in evidence the most important relationships of epistemic nature we have to face in designing, constructing, operating and monitoring a dam.

The actual dam corresponds only roughly to the designed one, especially because of partially unknown geological features and rock characteristics and also due to a different behaviour of the concrete as expected.

Additionally, while the theoretical design stays unchanged, the actual dam is evolving all along its life.

This implies first of all three activities to be carried out by the engineer in charge:

1. To adapt the design, that means the drawings and the computations during and after construction in order to take into account the deviations from the original idea that have been detected (e.g. depth of the excavations).
2. To compare the dam designed with the actual one in order to try to get a better knowledge of it.
3. To compare the behaviour of the designed with that of the actual dam, in order to better understand this last one.

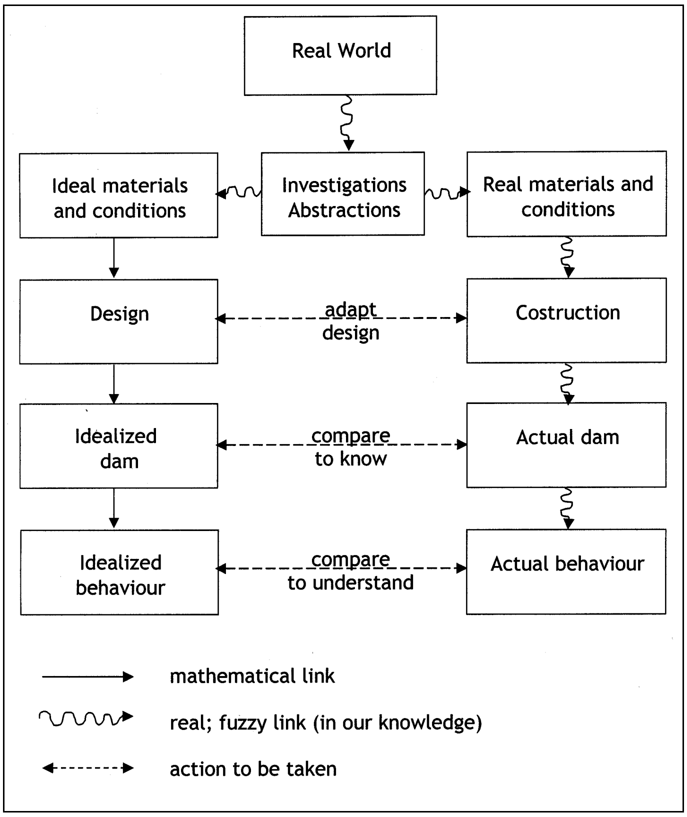


Table 1: The designed and the actual dam.

The last activity includes also the monitoring and the interpretation of the data recorded.

In the table quite a number of fuzzy links are shown. Their characteristic refers obviously to the knowledge we have or can have of them, while of course the phenomena concerned follow strictly the precise natural laws as, for example, the ones of physics and chemistry.

Table 2 refers to the behaviour of the designed, idealized dam and of the actual one.

Again, there are a number of fuzzy links, which must be correctly understood.

So, for example, in computing the behaviour of the dam, the model follows, with a good approximation, a priori defined material laws, while the dam follows in an absolute strict and exact way material laws, which may differ, more or less, from the assumed ones.

There is obviously a main task for the engineering sciences to find out the most exact mathematical representation of the actual physical material laws and to carry out the computations with the greatest possible precision. However, it is not our today's scope to deal with this problem. For the time being, we have thus to accept a number of uncertainties and to find the best way out of them.

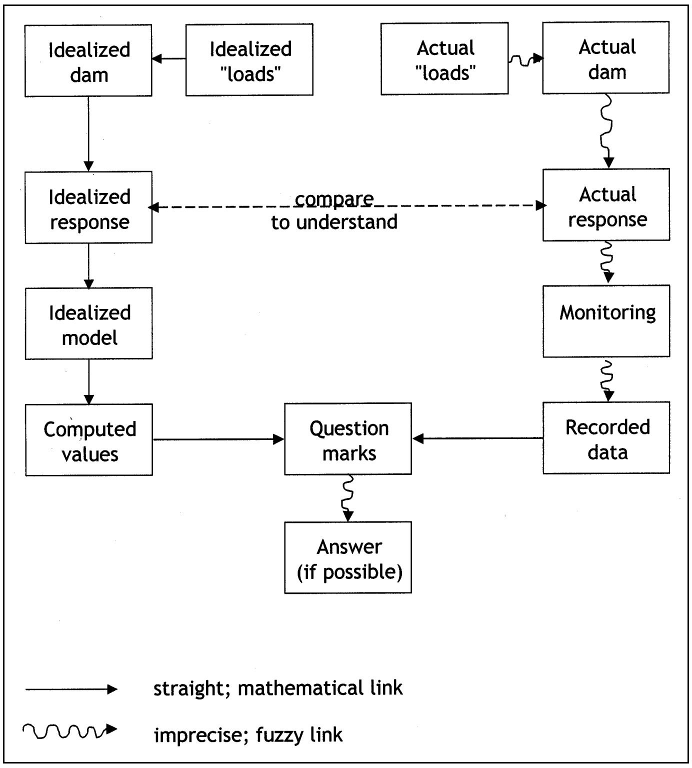


Table 2: Behaviour of the designed and of the actual dam. Compare and interpret the data available.

At the end of the day, we have to deal with values obtained from a so-called deterministic model set up a priori on one side and with data obtained a posteriori from the readings of instruments adequately recorded.
Comparing and interpreting them is in fact our actual task in order to answer a number of questions related to the safety of the dam.

It must however be mentioned that the assumed deterministic model does not always exist, or, in certain cases, is practically impossible to be defined. We will deal with this point later on.
On the other hand, there can be more than one deterministic model for the same variable e.g. for the displacement of a given point of a concrete dam.

Table 3 gives a list of some of them, each one of them may have its validity at a different stage of the project life, depending on the improved knowledge of the dam and its evolution we may have got of during that period of time.

In the following, except where explicitly mentioned, we will consider the deterministic model effectively used at any time as an a priori one in the sense that it exists before the instrument readings are carried out.

DETERMINISTIC MODELS

- based on the structural analysis at design stage
- adapted to the "as built" dam
- refined after a few years of operation (e.g. to adapt the E-modulus to the reality)
- refined after a number of years (e.g. to take care of transient phenomena)
- possibly modified to consider slow, long term evolution
- possibly modified on the base of new scientific knowledges

Table 3: The evolution of a deterministic model.

2.2 The questions to be answered by the interpretation of the readings

It should be clearly understood that the decisions related to the safety of a dam must always be the consequence of an "engineering judgement" and cannot be the result of an automatic, possibly burocratic procedure. Indeed the monitoring of the dam behaviour as well as the refined analyses of the data collected are only a support, but an extremely important and decisive one, to said judgement and thus to the decisions to be taken.

The main questions to be answered by the engineer according **Table 4** are:

- is the dam safe enough at this time?
- will the dam be safe at a given future time?

The questions the monitoring can answer are in fact the following ones:

- does the dam behave as predicted?
- does the dam behave as in the past?
- does any trend exist which could impair its safety in the future?
- and, was any anomaly in the behaviour of the dam detected?

QUESTIONS TO BE ANSWERED

1st group: by the **monitoring system**

- does the dam behave as expected ?
- does the dam behave as in the past ?
- does any trend exist ?
- was any anomaly detected?

2nd group: by the **engineer**

- is the dam safe today ?
- how safe will be the dam in the future ? (short and long term)

The (fuzzy ?) **link** between the two groups is to be set up by the engineer.

Table 4: The safety questions.

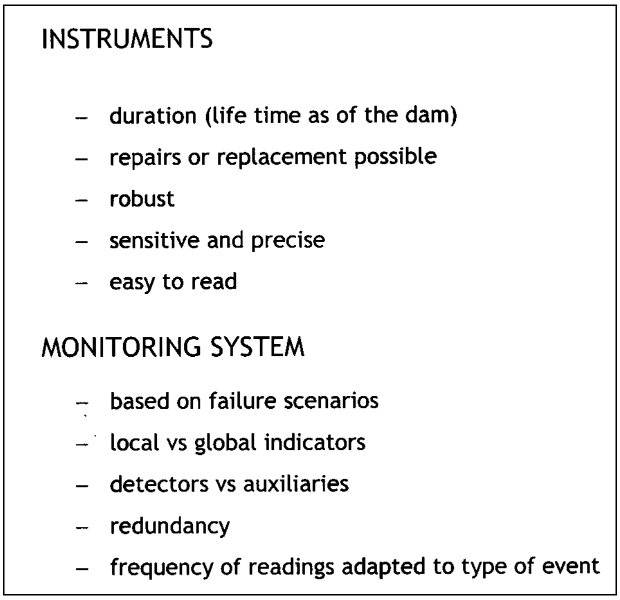
It is then the task of the engineers – or of the experts – to establish the necessary link between the two groups of questions.
It has to be expected, however, that in some cases only a fuzzy link can be defined!

Indeed, on one side the questions to be answered do not refer only to the safety, but also to the operability of the plant and the duration of life of the dam. On the other side, there is additional information beyond monitoring, to be used to support said engineering judgment.

3. THE INSTRUMENTATION

The base for any sound monitoring is an adequately well functioning instrumentation. There is no way to discuss here in detail the types of instruments, but only to mention a few principles, which are unfortunately often disregarded (**Table 5**).

First of all, to ensure the continuity of the monitoring during the whole life cycle of the dam, it is necessary to use only instruments that will last that duration or that can be replaced or repaired without jeopardizing said continuity.



INSTRUMENTS

- duration (life time as of the dam)
- repairs or replacement possible
- robust
- sensitive and precise
- easy to read

MONITORING SYSTEM

- based on failure scenarios
- local vs global indicators
- detectors vs auxiliaries
- redundancy
- frequency of readings adapted to type of event

Table 5: Main requirements for the instruments and the monitoring system.

An exception is nevertheless possible for instruments aimed to follow only a special short-term phenomenon, as could be the initial cooling of the concrete mass; for this scope electrical thermometers embedded in the concrete can be useful and sufficient.

It is also important to make a difference between local and global indicators.
So, the displacement of a point of an arch dam is a global indicator, because it is the result of an integration of the stress field over a great part of the dam body, while the indications of a strain gauge may be influenced by the local properties of the concrete.

Another aspect to be duly considered is the difference between "detectors" and "auxiliaries". In this sense the flow-meter at the end of a drainage gallery may be called a detector as it allows detecting any increase of the total inflow. At the contrary, the measure of the flow of any single drain is auxiliary as it allows finding out which drain caused the increased flow, once it has been detected.

An essential point of view, often disregarded, is that the instrumentation system should be designed in function of possible thinkable failure scenarios and the instruments shall not be just uniformly spread out over the entire dam body, as often observed. In other words, not all the instruments have the same importance in order to detect anomalies, which are significant for the safety of the dam.

In the possible, any value should be read directly and not be the result of a chain of readings, which chain could result to be a device to propagate errors.
Furthermore, the failure of one single instrument would destroy the chain and could jeopardise the reading of a number of the instruments involved.

The well-known aspect of a sufficient redundancy may be recalled. Its scope is to avoid hasty conclusions based on the possible malfunction of a single instrument.

In summary, the instruments should be long-lasting, robust, sensitive, easy to read and precise. It is easily understood that in some cases all these qualities may be difficult to be achieved at same time for all the instruments installed in a dam.

Anyhow, there are practical aspects to be considered and compromises to be accepted.
It is, for example, useless to achieve an extremely high precision if the risk of malfunction is increased. The important is that one can trust the readings.
Also the aspects of economics are to be taken into account.

Additionally, the value of any type of measurement depends widely on the nature of the dam.
So a leak that can be of marginal significance for a concrete dam, may be of eminent importance for a fill dam, if the risk of piping exists.

Likewise, the frequency of the readings should be related to the rapidity with which a harmful event may develop. This aspect of the problem is frequently overlooked in favour of an oversimplified layout of the monitoring system.

Finally the importance of a well-organized archive of the readings may be recalled.
The question of automatic and remote reading will not be discussed here because it represent a quite wide topic.

4. DEGREES IN MONITORING OF DAMS

The practical experience shows that great differences do exist from dam to dam, in matter of the quality of monitoring achieved.

In **Table 6** a trial is done to define categories of dams considering the way the readings are treated.

The last category represents in fact, unfortunately, quite a small minority of the world population of dams.

MONITORING OF DAMS

A. No instruments at all
B. Instruments exist, but do not function properly
C. Existing instruments do function well, but are not read
D. Readings done. Records in archives, but not analysed
E. Readings chronologically plotted, but not analysed
F. Readings plotted and analysed at a glance
G. Data correctly plotted, duly interpreted and safely stored in archives.

Table 6: Observed degrees in dam monitoring quality.

5. ERRORS IN MONITORING

It may be worthwhile to tell a number of case histories of errors which did really occur in relation with instrumentation and interpretation of readings.

Case 1

In a quite particular arch dam, the only instrumentation available, except a geodetic survey, was an extremely great series of electrical strains gauges embedded in the concrete in any position and direction.

The readings of the electrical value were carefully stored on paper during about 30 years, but never analysed.

As some cracks in the arch did appear and had to be repaired, it was discovered that due to an error in the electrical wiring not the wanted strains but the useless temperatures have been read and recorded.

The repairs had thus to be carried out without any support from the instrumentation. The instrumentation itself, the 30-years readings, the archives and the costs involved were all together absolutely wasted.

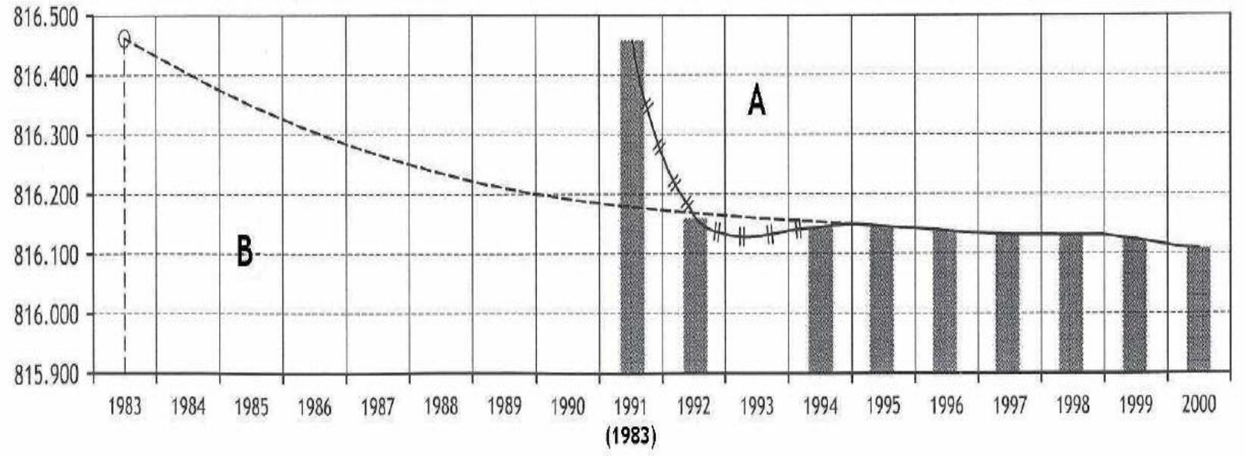
Case 2

The settlements of a fill dam showed a very strange development with a period of upraising (**Figure 1, part A**). The reason of said rare behaviour was in fact that a commercial software had been used to plot the results. Not the actual date of the readings, but their numbering was taken to define the abscissa of the points. The automatic polynomial interpolation did the rest.

Part B of the Figure 1 shows the correct representation.

Quite a lack of critical sense can thus be often noticed among people in charge of dam monitoring and its interpretation.

Settlement of point A-14 of a Rockfill dam



A: original Plot B: correct plot

Figure 1: Use of distorted scales.

Case 3

A multiple arch dam is affected by a light alkali-silicate reaction (**Figure 2**).

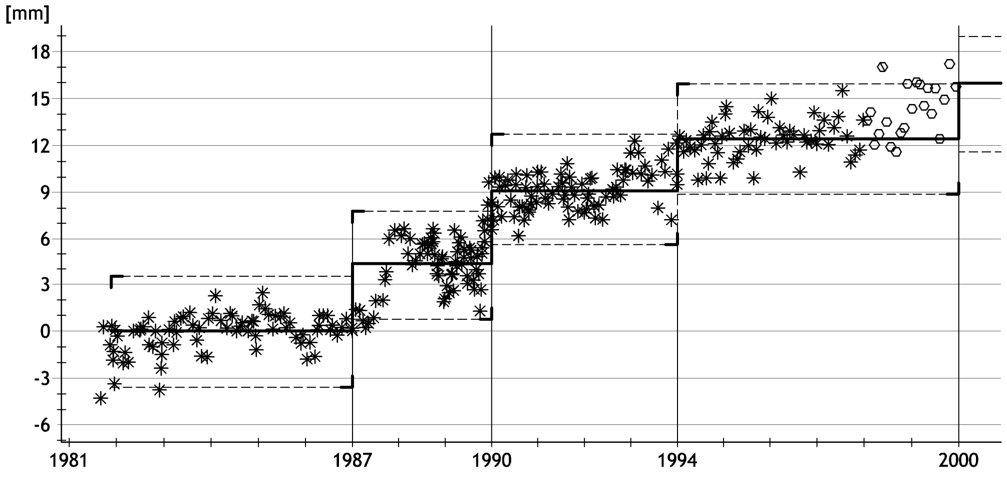


Figure 2: Alcali-silicate reaction subdivided in steps.

The deflections were interpreted by a series of jumps, while in fact a continuous deformation was in act as shown by **Figure 3**.

Again, an incorrect interpretation had happened due to the inadequate model used and to too frequent adjustments of the model.

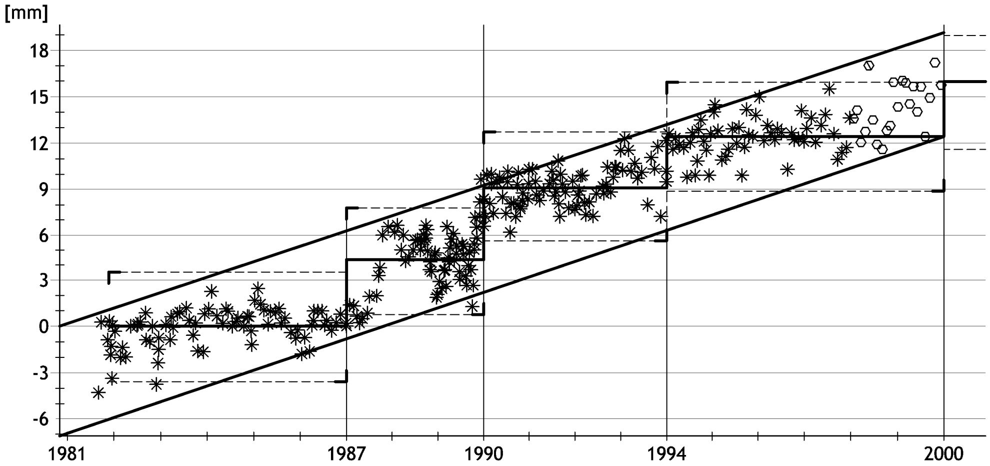


Figure 3: Correct interpretation of the alcali-silicate reaction, as a continuous phenomenon.

Case 4

In the embankment dam of **Figure 4** some vibrating wire pressometers showed a sudden increase of the water pressure in the drawn-stream filter (**Figure 5**).

Due to the fact that the functioning of the gauges could not be directly checked, that a sufficient redundancy was not given and that the possible leakage could not be detected due to the presence of a downstream reservoir, heavy measures needed to be taken, which included the partial draw down of the reservoir.

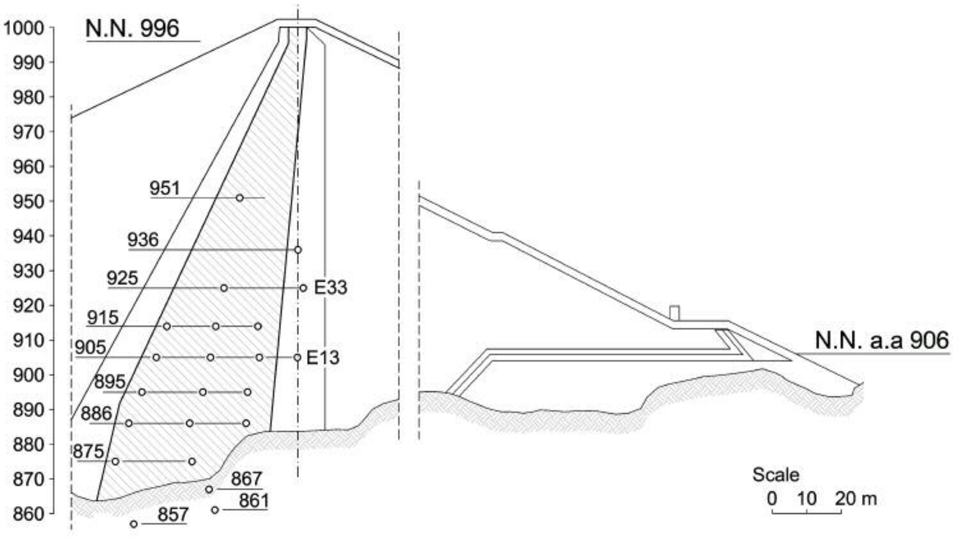


Figure 4: Embankment dam. Two vibrating wire cells (E13 and E33) showed a sudden increase of the water pressure in the D/S filter.

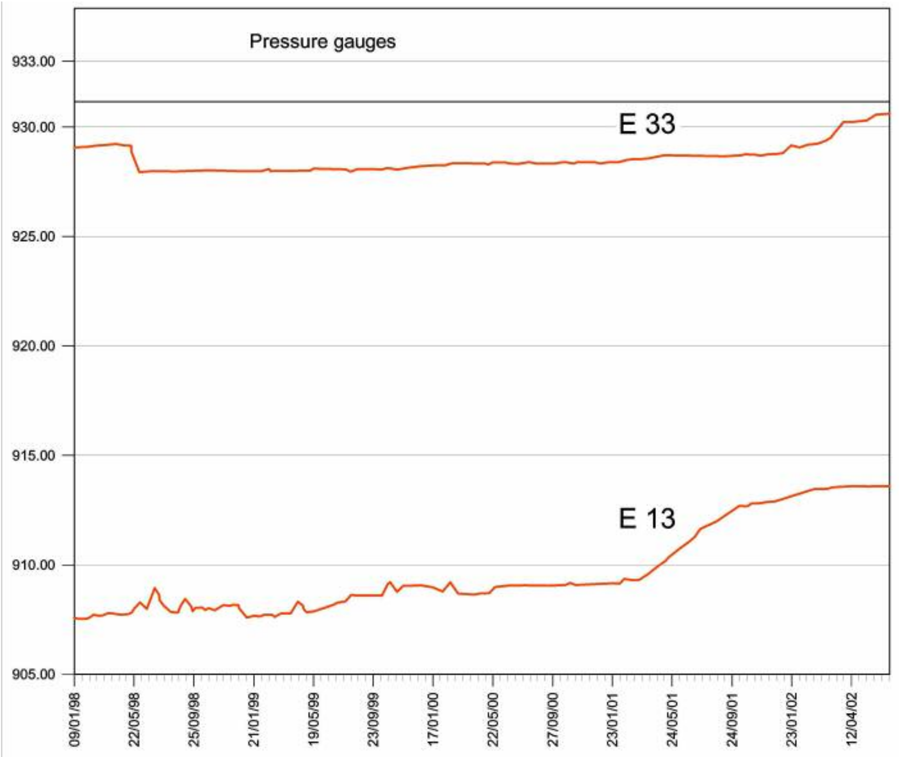


Figure 5: Pressure gauges E13 and E33 of Figure 4.

After extended and costly investigations, it could be clearly shown that the problem was only one of the gauges, not one of the dam. The inconveniencies and the total costs for the owner were nevertheless extremely high.

Case 5

In the next hour we will talk about the case of the Zeuzier dam, where a serious anomaly was detected only months later as it would have been possible to do, due to the insufficiently developed method used for interpreting the readings.

Case 6

At the contrary, a case can be mentioned where complex analyses were carried out to interpret and possibly explain the strange movement noticed at an abutment of an arch dam. As shown in **Figure 6** an extremely precise correlation was set up between the water level and the indications of an inverted pendulum.

After having completed the analysis, it was understood that the movements detected were simply due to organic matter floating on the water surface of the tank of the pendulum. This matter distorted the readings during five years as shown by **Figure 7**.

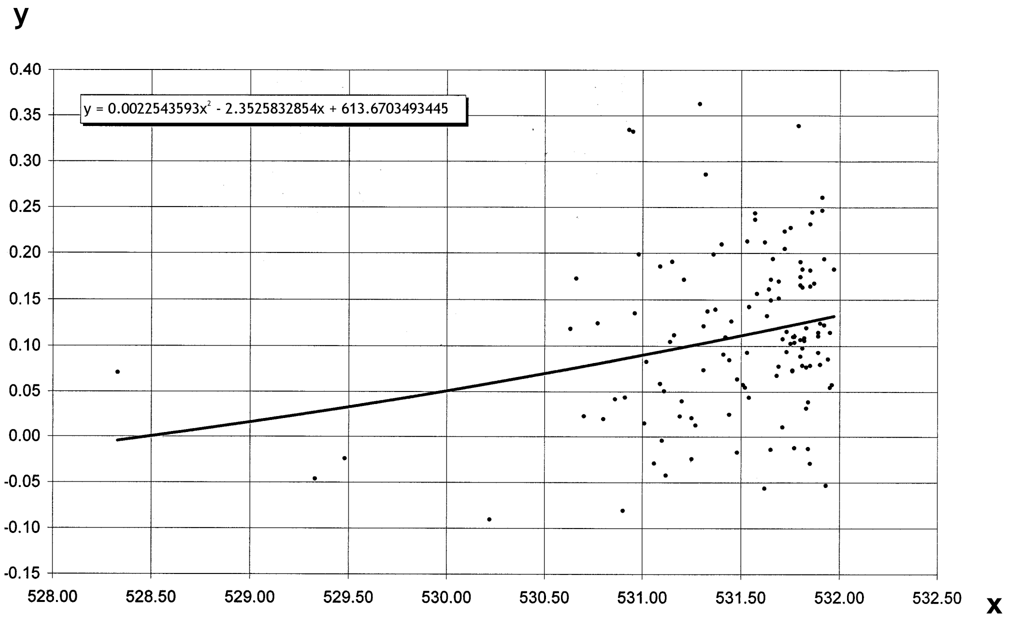


Figure 6: Statistically established correlation between water level **x** and readings **y** of an inverse pendulum.

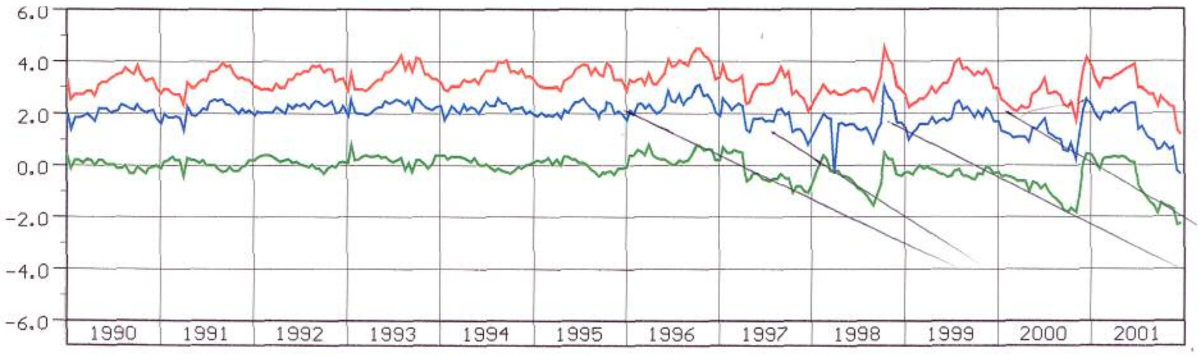


Figure 7: Deviation of the readings of the inverted pendulum due to organic matter in the tank of the pendulum.

Case 7

Any kind of strange interpretations of the readings can be found everywhere. An example can be seen on **Figure 8**. A continuous trend is shown, while only an initial movement took place and a stable situation can be noticed since 1986.

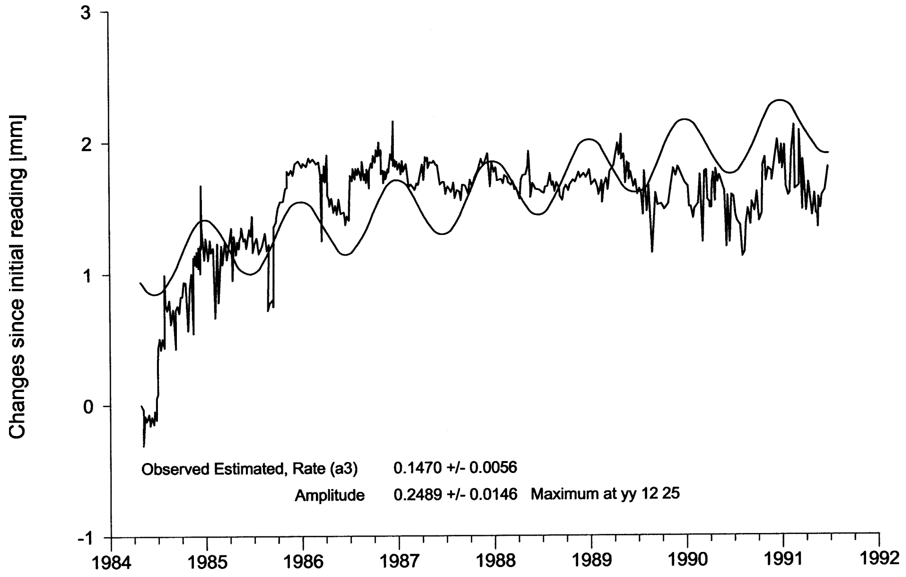


Figure 8: Strange kind of interpretation of readings.

6. INTERPRETATION OF THE READINGS

6.1 In general

The mentioned examples, and many other cases, prove the vital importance of serious and complete analyses of the readings. They show also the need for a sound, critical engineering judgement based on a profound knowledge of the physical laws and sometimes also of the chemical ones.

In the following we will deal only with the aspects involved in the interpretation of the instrumental readings, in the assumption that the various devices are adequate and do function in a correct way.

Should any anomaly be detected, the first duty of the engineer is doubtless to find out whether this anomaly is due to wrongly functioning instruments or whether it is related to the real behaviour of the dam.

In fact, the aim of the interpretation is to place the engineer in the position to be able to predict at any time, with a sufficient precision, the value any instrument should show under given circumstances, in particular under known loading and thermal conditions.

The difference between predicted value and actual reading is, indeed, the true criteria to judge the behaviour of the dam.

This difference, called also residue, includes obviously the effect of the limited precision of the instruments and of the computations carried out, as well as possible errors in reading and transferring the data.
It is assumed that for any seriously monitored dam, precise procedures are actually implemented to eliminate this last kind of errors, for example, in repeating rapidly the doubtful readings of in case of automatic devices, in averaging a number or readings whilst eliminating the extreme ones.

6.2 The usual statistical simulation

A first possible way to interpret the readings in the aforesaid way is to simulate the behaviour of the dam in establishing a pure statistical model.
The essential condition is obviously to have available a sufficient stock of data, that are the readings of a number of past years, which may allow a trustworthy extrapolation into the future.
Considering that during the first years of life some transient phenomena takes place, such a statistic model may be useful only after, let's say, a dozen years since construction, in spite of the fact that the first years of life of the dam are, as a rule, the most risky.

Nevertheless, the usual way consists in selecting a number of functions for a number of arguments and to optimise the corresponding coefficients so to minimize the sum of the squares of the "errors" found on the values.

Table 7 shows a set of typical functions used for the simulation of the displacement of a point of a concrete dam.
The arguments or "loads" in the broad sense are

z = level of impounding
T_i = the measured temperatures at different points of the dam; in fact, a vector of temperature is accounted for
t = the time used to consider the periodic as well as the long-term, "ageing" effects.

1. $\delta = F_1(z) + F_2(T_i) + F_3(t)$: with usually:
   $$\delta = \sum_i c_i \cdot z^n + \sum_j c_j \cdot T_j + c_0 + c_1 \cdot t + \ldots.\ c_n \cdot t^n + c_4 \cdot \log t + \ldots$$
   linear superposition of the various effects.
2. $\delta = F_1(z) + \sum_i c_i \cdot (\sin \omega_i \cdot t - \alpha_i) + F_3(t)$
   assumption of a "seasonal" thermal effect
3. $\delta = F_1(z) + F_2(T_i) + \sum_i c_i \cdot (1 - e^{-k_i \cdot t}) + \sum_j c_j \cdot e^{k_j \cdot t}$
   exponential form for the long term evolution
4. $\delta = F_1(z, t) + F_2(T_i) + F_3(T)$; for example:
   $$F_1(z, t) = \frac{F(z)}{A - Be^{-kt}}$$
   simulation of a concrete hardening

δ = displacement; z = level of impounding; t = time T = temperature
A, B, c_i, c_j, α_i, k_i, k_j = coefficients to be defined

Table 7: Possible mathematical forms for interpreting the displacement of a point of a dam.

The first formula is simply the linear superposition of the effects of the three "loads".

In the second formula, the effect of the vectorial temperature load is replaced by a Fourier analysis on an annual base.

The third case refers to an exponential expression for the long-term deformation.

In the last case two "loads": "impounding level" and "ageing" are mixed together due that a time hardening concrete is taken into account.

Other formulations can also be defined.

Depending on the type of the functions used, linear correlation analysis may be carried out, or precisely not. In this last case other types of analysis must be considered.

It is always very important to pay attention that the single functions used are meaningful from a physical point of view.

The simple statistical correlation as indicated here above present however a number of possible drawbacks.

The most meaningful are mentioned here after.

- The first formulation is simply derived from the principles of linearity and superposition of the theory of elasticity and has thus some limitations.

- The second "seasonal" assumption for the thermal effect disregards the, sometimes important, differences in the temperatures from year to year. It disregards also the influence of the water on the temperature of the concrete mass, which may differ greatly from year to year depending on the water level in the reservoir. For thin dams this is for sure not an adequate approach.
- No one of the four formulations takes into account any kind of viscous, that is of delayed, response to the loadings.

A number of improvements of these formulations are thus possible to better fit the real behaviour of the dam by an optimal model.

6.3 Optimisation of the model

The usual way to optimise the model consists in varying the coefficients of the formulae in order to minimise the sum of the squares of the errors, or mismatches between the model and the readings.

However this can be a quite dangerous undertaking as **Figure 9** do confirm.

An extremely intense and thorough numerical optimisation led to a function for the influence of the water level on the deformation of the dam, which presents a minimum for a certain elevation and increasing values for higher as well as for lower impoundings.

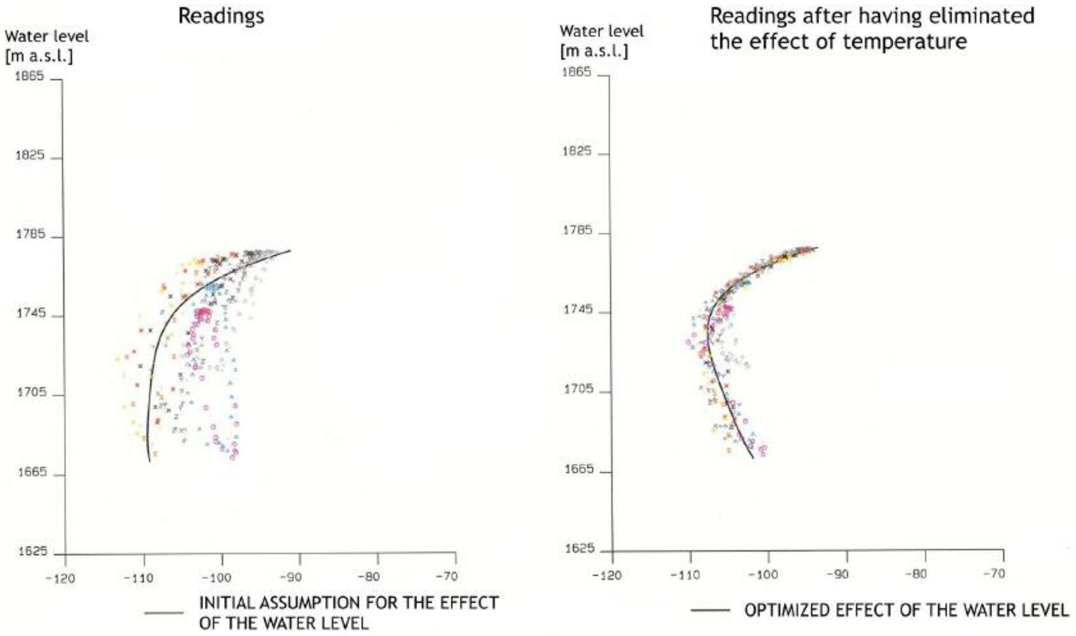


Figure 9: Excessively intense "optimisation" process.

This absurd result is due to the fact that the seasonal operation of the plant makes a certain co-linearity exist between the temperatures and the water level. The two factors are considered to be independent each from another from the statistical point of view, but are in fact physically bounded, at least to some extend. In other words, the fact was disattended that our problem is not a pure mathematical, but an engineering one.

In the reality we have to do with different models depending whether, as already mentioned, a deterministic analysis can be set up or not. Such a model can undoubtfully be defined for values related to the structural analysis like deformations and stresses, but also to some extend for uplift pressures and similar functions.
At the contrary, there is to date no practical way known to establish an exact predictive model for the flow-rate of a drain or the water pressure in a hypothetical fissure in the concrete or in the foundation. Nevertheless, some general rules do exist.

We have thus to do with two different cases shown by **Figure 10**.
If no deterministic a priori model does exist, only a statistical one can be developed on the base of the reading of previous years.

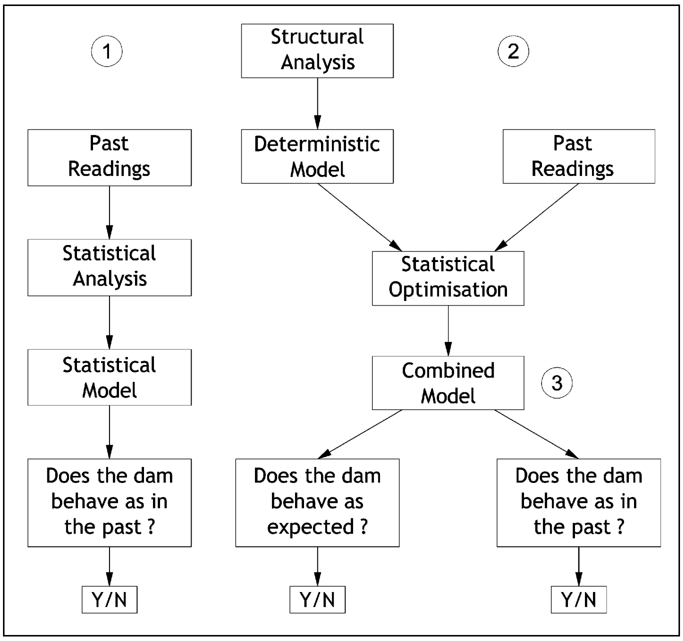


Figure 10: Defining an interpretation model.
Case ①: no deterministic model possible;
Case ②: deterministic model possible;
③ Combined Interpretation Model: MIC

At the contrary, if such a deterministic model exists, it can and must be optimised in applying a number of statistical methods in using again the readings available from former years.

In **Table 8** the types of models available are summarised. Great care should always be taken in updating them. A frequent updating or even an automatic one may hide an existing trend and thus be quite dangerous (see figures 2 and 3).
The model would simply "follow" the dam in its behaviour and becomes rapidly useless as it would not be able to detect any anomaly, but would simply adapt itself to the readings.

For any single function a model needs to be set up.
The usual types are:

Type	Characteristics
Deterministic:	Set up a priori Physical basis No updating
Statistical:	Set up a posteriori Numerical basis Updating Automatic updating
Combined:	Based on a deterministic model Calibrated by statistical analysis of past readings (MIC) Updating at intervals

Table 8: Types of models for simulating the behaviour of dams.

The experience has clearly shown, that often much better results – that means more realistic ones – are obtained in optimising a deterministic model than in trying to develop a purely statistical approach.

In spite of the fact that a certain similitude between the two ways exists, it has to be clearly understood that an optimised deterministic modes is fundamentally a deterministic model, which has been only "slightly modified" to better fit the reality; that is the physical laws. The aim is to correct the unknown parameters, which were assumed for establishing the model.

At the contrary a pure statistical model is a mathematical figure, which doesn't need to know the physical laws governing the behaviour of the dam and that may even contradict them.

However, how much is "slightly modified" would need more investigations in each single case. But in no way a contradiction to the physics should occur nor could be accepted.

Some times the expression "hybrid model" is used, but here also a more precise definition should be looked at.

An example of a successful optimisation can be seen on **Figure 11**.
With the initial deterministic model established about 30 years ago discrepancies to the readings up to 25 mm were recorded, that is about 25% of the amplitude of the readings.
The recently optimised models reduce the discrepancy to about one third that is to 7 mm. This situation corresponds to a errors of maximal ± 3.5% of the overall amplitude.
Additionally a clear long-term trend could be put in evidence.

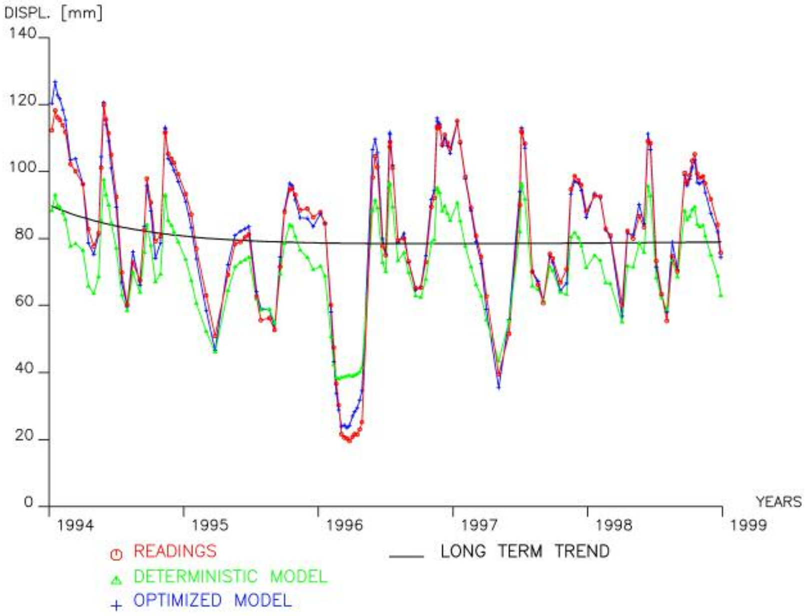


Figure 11: Optimisation of the deterministic model for the radial displacement at the crest of an arch dam.

Indeed, the statistical optimisation must be added to the deterministic model like a transplant. Care should thus be taken to stick as much as possible to the deterministic model. This is particularly important in the case that conditions of operation should occur, which differs significantly from the statistically more frequent ones in the past (e.g. draw-down or impounding in an unusual season).

This last remark calls in the problem of pondering in the same way, or differently, the single past events and records.

In the same context the question must be raised whether the "least squares rule" is the best criterion to be used, because some exceptionally important errors in reading may get much to great a weight.
For example, the rule of the minimum sum of the absolute values of the errors could be more adequate than the "least squares".

Again, these problems cannot be discussed in the frame of this short presentation.

7. POSSIBLE IMPROVEMENTS OF THE USUAL SIMULATION

7.1 The Laplace Transform

Clear improvements of the modelling can be achieved in making use of the Laplace Transform.
The convolution integral, which defines the Laplacian Transform is shown by the well known formula [1] of **Table 9**.

Laplace transform F(t) of φ (t):

$$F(t) = \frac{1}{T_0} \cdot \int_{-\infty}^{t} e^{-\frac{(t-\tau)}{T_0}} \cdot \varphi(\tau) \cdot d\tau \qquad [1]$$

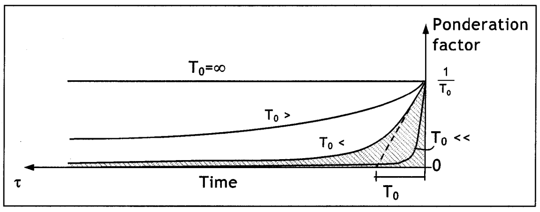


Figure A: Characteristic time T_0 to define the ponderation factor.

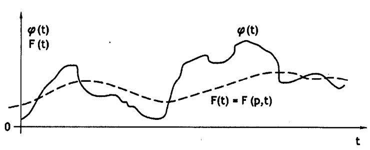


Figure B: Original function φ(t) and weighted average F(t) or transform.

Table 9: Principle of the Laplace Transform.

In fact this Transform can be understood as an averaging of past events in using a variable weighting factor.
The way the factor decreases with the age of the value considered is defined by the Characteristic Time, T_0, as shown by Figure A of said table.

If T_0 is huge all the past values get the same weight. If T_0 is very small only the last value counts.

Figure B of the table gives an example of such a Transform, which corresponds in fact to a kind of smoothening of the original function.

In the case the past values of the function are known for uniform time intervals, the formulae of **Table 10** hold true.

It is indeed quite easy to get finally the very simple expression [6], which allows setting up a straight forward recurrence procedure.

It may be added that obviously similar formulae were developed also for non-uniform time intervals.

Considering a function as known at constant time intervals, Formula [1] turns to:

$$F(t) \cong \frac{1}{T_0} \cdot \sum_{n=-\infty}^{i} e^{-\frac{(i\Delta t - n\Delta t)}{T_0}} \cdot \varphi(n\Delta t) \cdot \Delta t = \frac{1}{T_0} \cdot \sum_{n=-\infty}^{i-1} e^{-\frac{(i\Delta t - n\Delta t)}{T_0}} \varphi(n\Delta t) \cdot \Delta t + \frac{1}{T_0} \cdot \varphi(i\Delta t) \cdot \Delta t \qquad [2]$$

Similarly, for the Function at the same location, but one time step earlier

$$F(t - \Delta t) \cong \frac{1}{T_0} \cdot \sum_{n=-\infty}^{i-1} e^{-\frac{(i\Delta t - n\Delta t - \Delta t)}{T_0}} \cdot \varphi(n\Delta t) \cdot \Delta t = \frac{1}{T_0} \cdot e^{\frac{\Delta t}{T_0}} \cdot \sum_{n=-\infty}^{i-1} e^{-\frac{(i\Delta t - n\Delta t)}{T_0}} \cdot \varphi(n\Delta t) \cdot \Delta t \qquad [3]$$

and thus the following expression holds true:

$$F(t) \cong e^{-\frac{\Delta t}{T_0}} \cdot F(t - \Delta t) + \frac{\Delta t}{T_0} \cdot \varphi(t) \qquad [4]$$

introducing the coefficient:

$$\alpha = e^{-\frac{\Delta t}{T_0}} \cong 1 - \frac{\Delta t}{T_0} \qquad [5]$$

the formula simplifies to a simple recurrence expression:

$$F(t) \cong \alpha \cdot F(t - \Delta t) + (1 - \alpha) \cdot \varphi(t) \qquad [6]$$

Table 10: The linear recurrence formula for uniform time steps.

7.2 Dealing with temperatures

For concrete dams there are various problems connected with temperature.

The first one is the problem of dissipating the initial heat due to the hydration of the cement both during construction and an initial period of the life of the dam.

This problem is especially important for thick dams, but is outside our scope.

The thinner the dam, the more the seasonal temperature plays an important role.

Conversely, the problem of integrating the differential equations simplifies as its tends to become "locally" unidimensional.

There are quite a number of methods to solve the heat equations which are listed in **Table 11** and do not need more explanations, except the newly developed "Laplace Transform Algorithm" which proved to be a quite interesting and powerful tool for tackling many thermal problems in a very easy numerical way.

METHODS FOR THERMAL PROBLEMS

- Analytical solution for simple cases
- Fourier transform for periodic problems
- Numerical integration
- Finite differences
- Finite elements
- Laplace Transform

Table 11: Some methods to solve thermal problems in concrete dams.

In fact, within certain limits, the temperature at a given point can be computed, with an acceptable precision, as a weighted superposition of the value at the previous time interval and the present temperature of a nearby point, for example at the face of the dam.

One may thus say that the temperature in the concrete at a certain depth below the surface corresponds to a smoothed function of the temperature on the dam face.

In proceeding steps by step in the depth, the thermal field of the entire dam body can be defined. Strictly speaking this procedure is correct for the half-space and requires practically a correction for the thermal influence from the other dam face.

Extremely interesting is the fact that due to the linear form of the heat equation any solution can be superposed to any other even if both are derived in using different methods of integration.

Just as an example among many others, one may mention the following:

- use of the analytical solution to define the influence of the average yearly temperature changes (e.g. the "seasonal" temperature based on the Fourier Analysis), and
- use of the numerical method presented here above to take into account the differences between the actual temperature and the "seasonal" one assumed in the first step, in order to correct its results.

Indeed, it has to be reminded that the actual thermal load is by far not exactly a periodic one.

7.3 Delays in the response

The thermal effect mentioned here above is a first typical example of a delayed response of the dam to an external influence. But, it is not the only one, even for concrete dams.
So it has been observed that a certain effect of viscosity (or creep) takes place in the deformation of such dams.
Probably there is the effect of the real viscosity of the concrete, but also a kind of "consolidation", in the sense that water is squeezed out from the pores, joints and cracks in the concrete as well as in the rock mass.
In this case, the real viscosity of the water creates a kind of additional apparent viscosity of the dam body.
This effect is clearly shown by the FES-Model for rock masses, we will talk about in relation with the Zeuzier dam /12/.
A further effect may be a kind of thermal inertia related to the temperature of the water leaking through the masses.

In case of water leaks through the rock or the concrete masses the delay is mainly caused by the porosity of the materials. So, the voids need be filled by water before they can transmit pressure. Therefore pressures and flow rates are subjects to delays in respect to the changes of the impounding level.

The reality of the phenomenon is confirmed by a recent study on a 40 year old arch dam.
As usual, the "apparent" strain in the structure is represented according to **Figure 12** by an elastic and a viscous part. The elastic strain is assumed to react instantaneously to the loads, while the viscous one is represented by an exponentially decreasing velocity with a characteristic time T.

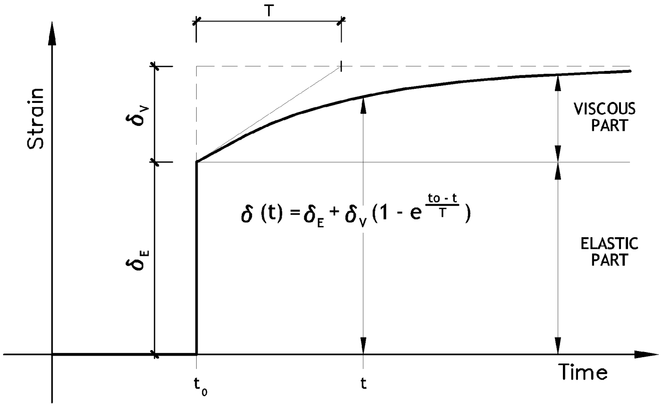


Figure 12: Assumed strain-time function for an instantaneously applied load at time t_0.

The best fit for the displacement of the crest of the dam was found with a proportion of elastic to viscous stain of 4 to 1, and a characteristic time of 60 days.
The result obtained is represented by **Figure 13**.

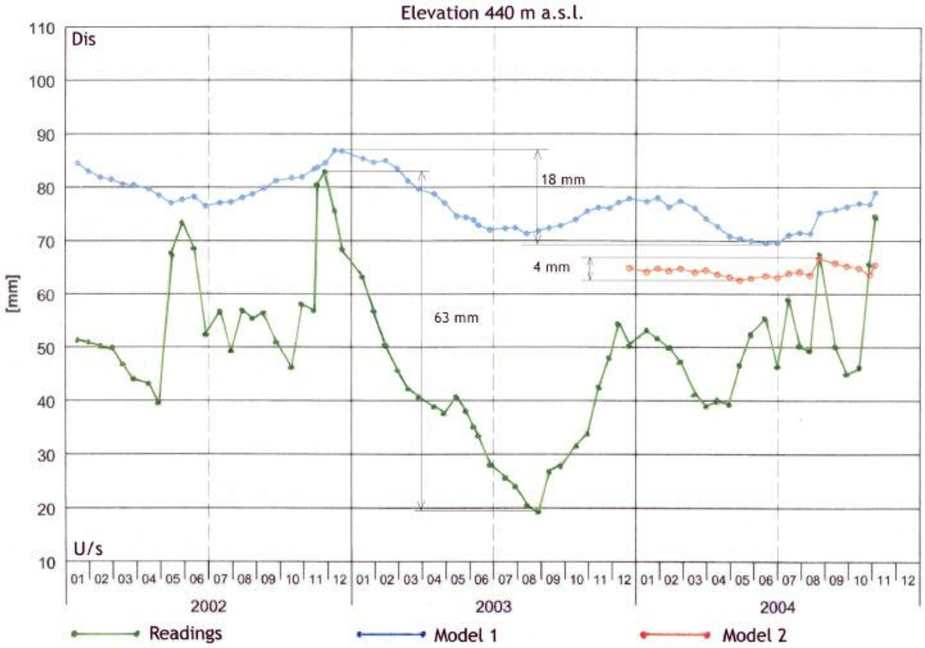


Figure 13: Considering the effect of viscosity on the deflection of an arch dam.

The amplitude of the actual deflection of 63 mm was reduced by the previous model (1) to a residue of 18 mm. It can be noticed that these residues did follow, to some extend, the actual deflections.
The new model (2) which takes into consideration the effect of delay could again reduce said amplitude to 4 mm; this is 16 times less, or just plus-minus 3% of the original readings.
Indeed, the merit of this impressive improvement is due to various effects, we can not develop here.

8. THE THRESHOLDS

The importance of setting thresholds for the interpretation of the readings must be clearly underlined.

They apply to the readings themselves, but much more important to the residues, that is the difference between the single readings and the value indicated by the interpretation model.

These thresholds are indeed warning lines. They put in evidence any change or trend and draw the attention on possible risks for the safety of the dam or other troubles, like malfunction of instruments.

In **Figure 14** the influence of the 1996-total drawdown of the pound had on the leakages entering a valve chamber can clearly be seen. This situation led to adapt the thresholds. In this case there were obviously no risks for the dam safety.

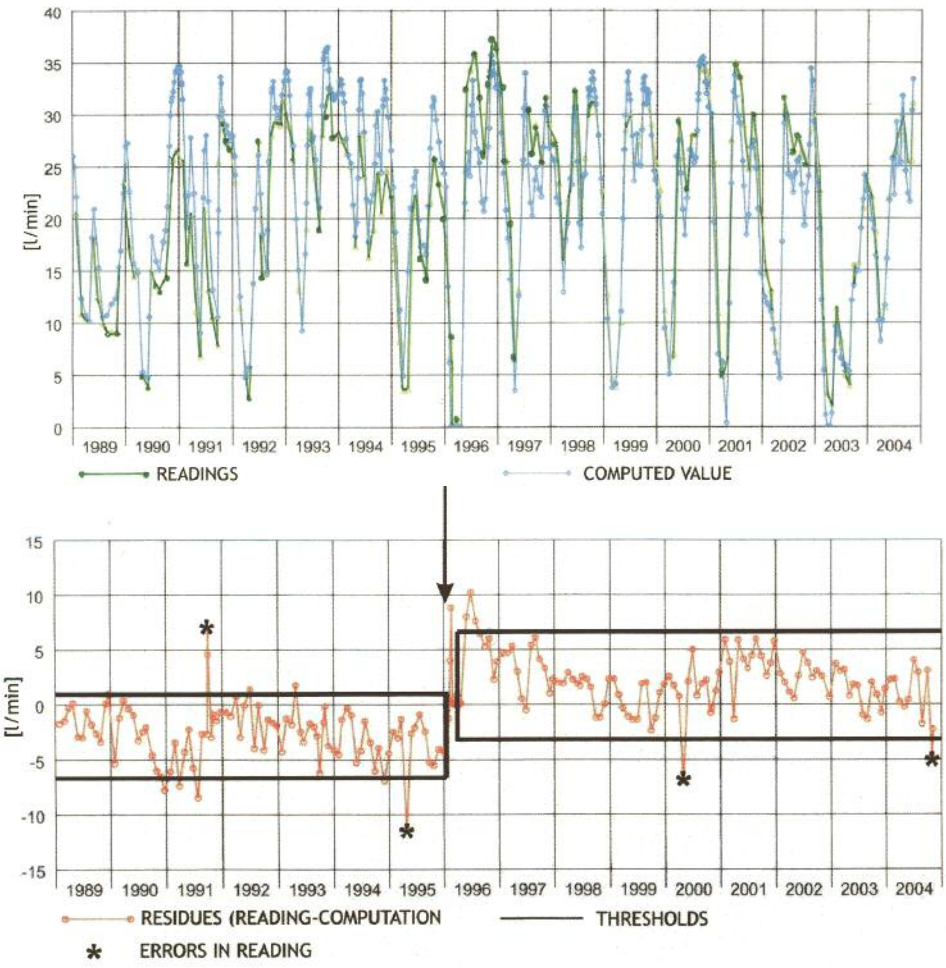


Figure 14: Influence on the leakages due to a total draw down of the reservoir.

In defining the values of the thresholds a number of aspects need be considered like (**Table 12**)

- ignoring obvious reading errors;
- pondering the single readings;
- taking into account a range given by a multiple of the standard deviation, and so on;
- but at first the real importance of a given instrument for the safety of the dam.

The thresholds may also be graduated and subdivided, into various steps like: caution, warning, alert, alarm and so on.

THRESHOLDS

Defining thresholds
- for readings and especially for residues
- ignore obvious errors
- ponder single readings
- consider standard deviation
- graduation: from caution! to alarm!

Extremely important to detect
- malfunction of instruments
- anomalies of any kind
- trends (short and long term)
- dangerous situations

Caution!
- address the right problem

Table 12: Defining thresholds for dam safety.

9. CONCLUDING REMARKS

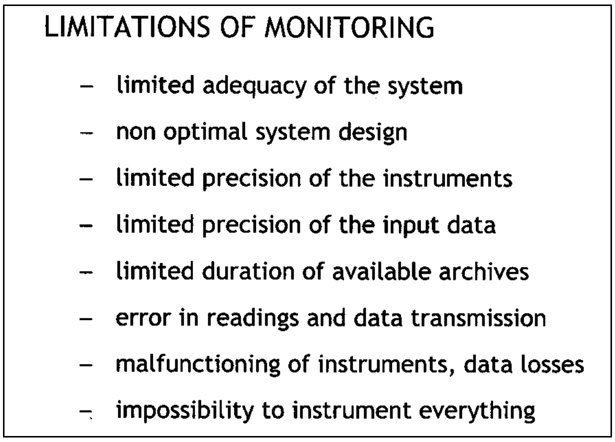
We can now conclude as follows.

A number of remarks were done on the monitoring and its importance for the management of the dam. However, it needs be recalled that it has also its limitations as shown on **Table 13**.

The main point to be recalled in that the monitoring system should be based on "thinkable" failure scenarios.

As it is impossible to instrument everything, additional information is required like visual inspections and periodical safety audits.

Of outmost importance is the interpretation of the readings. Unfortunately, in many cases no sufficient attention is paid to this fundamental aspect of the problem.



LIMITATIONS OF MONITORING

- limited adequacy of the system
- non optimal system design
- limited precision of the instruments
- limited precision of the input data
- limited duration of available archives
- error in readings and data transmission
- malfunctioning of instruments, data losses
- impossibility to instrument everything

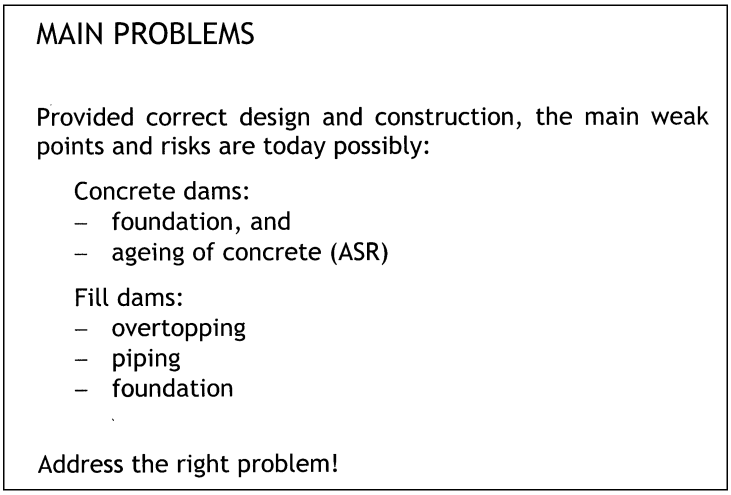
Table 13: Limitation in the precision of monitoring.

Also some times more physics and less mathematics are required.

The main recommendation, at the end, is to address the right problems, that is the weak points of the structure.

In a very rough manner the experience shows (**Table 14**) that the main problems for modern correctly designed and constructed dams are possibly at this time:

- for concrete dams:
  - foundation and
  - ageing of the concrete, especially alkali-silicate reaction
- for fill-dams:
  - overtopping
  - piping, and
  - foundation



MAIN PROBLEMS

Provided correct design and construction, the main weak points and risks are today possibly:

Concrete dams:
- foundation, and
- ageing of concrete (ASR)

Fill dams:
- overtopping
- piping
- foundation

Address the right problem!

Table 14: Main problems.

These problems and risks are mainly due to our ignorance or limited knowledge of the:

- geological and rock mechanical conditions,
- alkali reaction potential,
- extreme floods, and
- precise manner the filters and drains were constructed.

Thank you!

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