LONG TERM BEHAVIOUR OF THREE ARCH DAMS

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ABSTRACT: The analysis of the long term behaviour of arch dams is essential for the evaluation of their structural safety. The present contribution illustrates an approach essentially based on the use of accurate deterministic models, allowing highlighting the non-reversible component of the dam deformations. Three examples are shown for which causes of non-reversible behaviour are discussed.

Key Words: Monitoring, Concrete Arch Dam, Long Term Behaviour, Safety Analysis, Deterministic Model.

1. INTRODUCTION

"Long term stability" is an essential paradigm referred to, explicitly or not, in any safety analysis of dams based on their behaviour.

With different words, one can say that a dam may be considered fundamentally sound, as long it behaves in exactly the same way when subject to the same loads. There are of course a number of restrictions to be taken into account in order to strictly follow this concept.

First of all, the dam will do so only after having reached a certain state of equilibrium a number of years after its construction. This requires, to consider a special period of transition, using adequate tools.

A second pre-requisite is that the significant parameters are adequately monitored and correctly interpreted in short time intervals.

So, a leakage in a fill dam can form and develop, while escaping the Engineer's attention if an adequate monitoring and a timely interpretation are not ensured.

Concrete dams, and especially arch dams, are in this respect easier to monitor because any important event occurring in the dam body or in its foundation will cause a global response of the dam and can thus not escape its detection.

The setting up of a correctly working model representing in a deterministic way the actual behaviour of such a dam is a task requiring as a rule an acceptable amount of efforts. It will provide an excellent reference pattern against which the behaviour of the arch dam can be compared.

Of all the parameters which can be monitored, the movements or displacements of single points are the most significant and the most exactly measured, e.g. in using plumb-lines.

The displacement of a number of points in the dam turns out, at the end, to be the best global indicator of any suspicious behaviour.

The logical scheme is thus:
The loads acting on the arch dam - including the thermal field - define its deformation. Do then the measured deformations correspond to the calculated ones? If not why?
The last question has obviously to be analysed and answered by the engineer in charge of each single case. To do so, additional information is obviously required. This aspect will not be dealt with in the present paper. Its aim is to present three different cases of arch dams, which show, likely for different reasons, an upstream displacement of the structure.

2. DETERMINISTIC MODELS OF ARCH DEFORMATION

The reversible deformations of concrete dams are due to hydrostatic and thermal loads. The aim of a deterministic model is thus to determine the deformation of the dam for any given combination of water level and thermal field. The calculated deformation is then compared to the measured one and the differences between both values have to be analysed by the engineer.
For the preparation of a deterministic model, the influence of the water level on the dam deformation is the result of a structural analysis as schematically shown in **figure 1**.

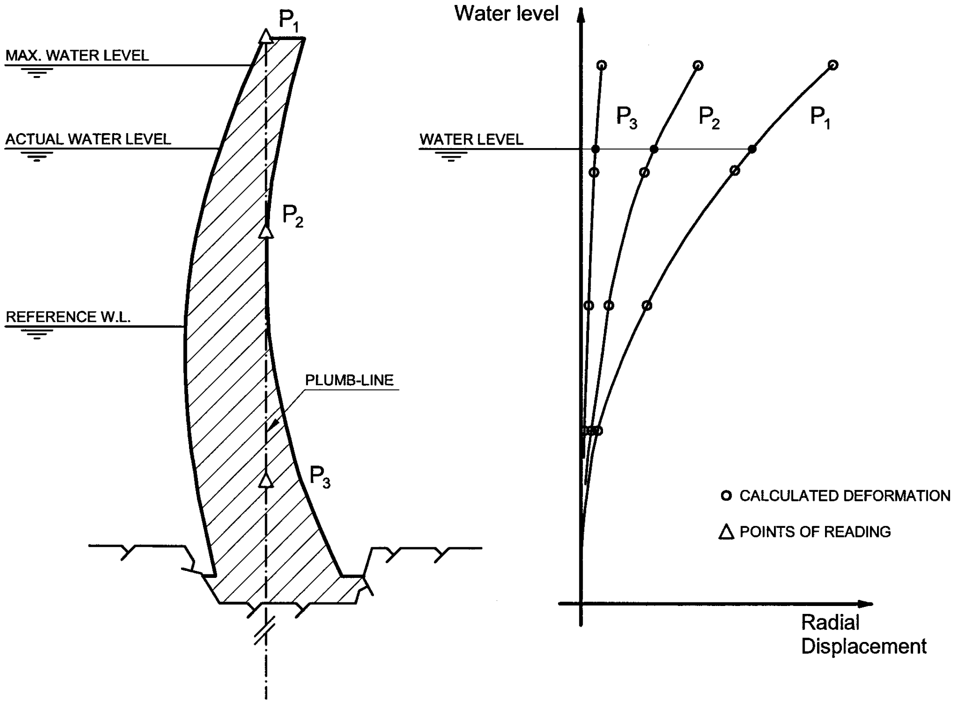

Figure 1: Computed influence of the water level.

The dam behaviour under any thermal field is more complex to be determined due to the quite relevant number of possible combinations to be considered.
For the preparation of the dam model unit temperature fields and unit temperature gradients are considered as shown in **figure 2**.

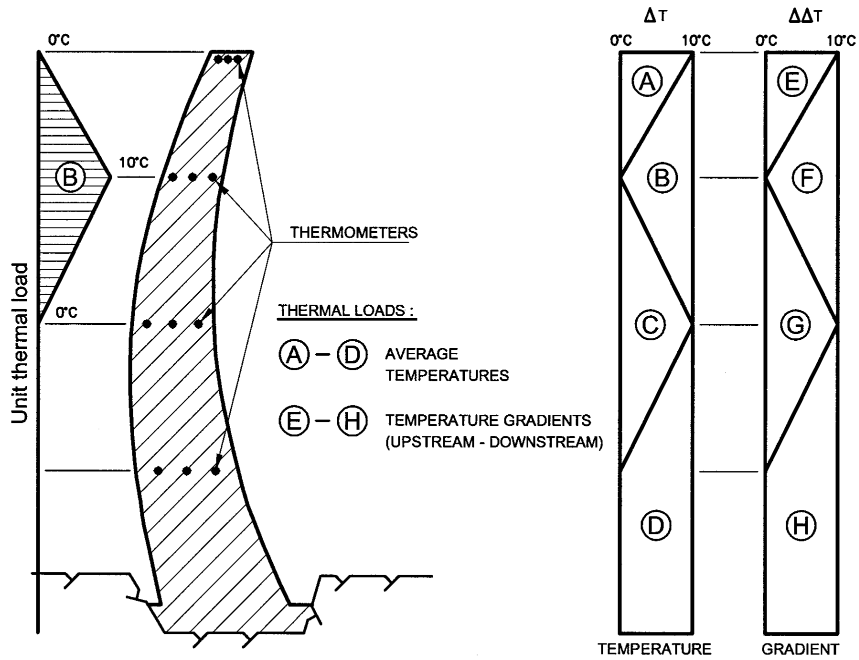

Figure 2: Unit loads for the thermal analysis.

The combination of the unit temperature fields and the gradients allows reproducing quite exactly any measured thermal field in the dam.

For the case histories shown hereafter, complete deterministic models have been established. The analysis of the dam's behaviour is thus essentially based on the difference between the measured and the calculated deformations.

3. THE ZEUZIER ARCH DAM

The Zeuzier arch dam (Wallis, Switzerland) represents an exceptional and quite unique case of damages.

The 156 m high arch dam, built in 1957 was operating since then without any problem. Suddenly, in the fall of 1978, it started to deflect upstream ward. In the first months of 1979 important cracks did appear along the downstream foundation line and the contraction joints on the upstream face started to open (**figure 3**).

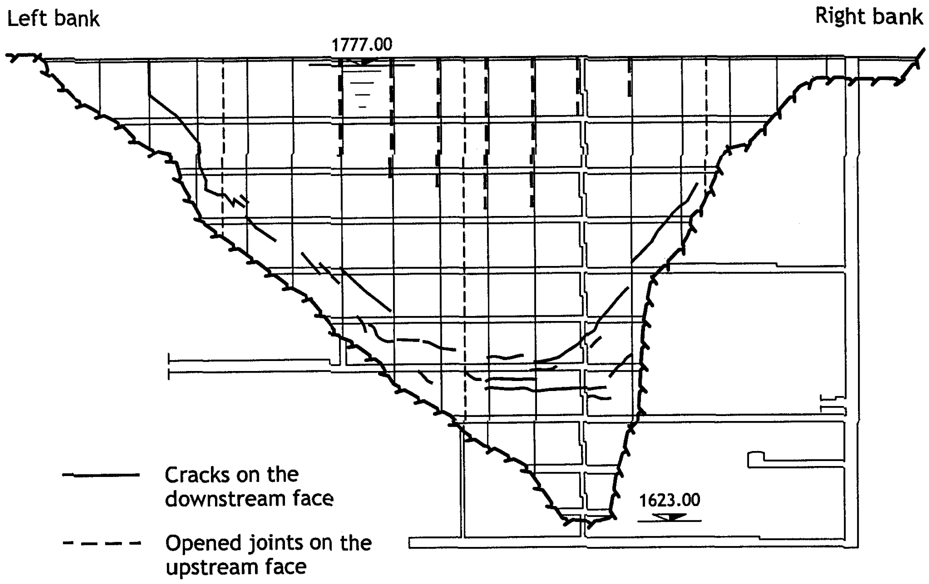

Figure 3: Damages of the Zeuzier arch dam caused by the settlement of the rock foundation.

The reservoir had do be draw down. After lengthy and very careful analysis of this strange behaviour, it could be established without any doubt that the problem had been caused by the construction of an investigation adit in progress nearby (**figure 4**).

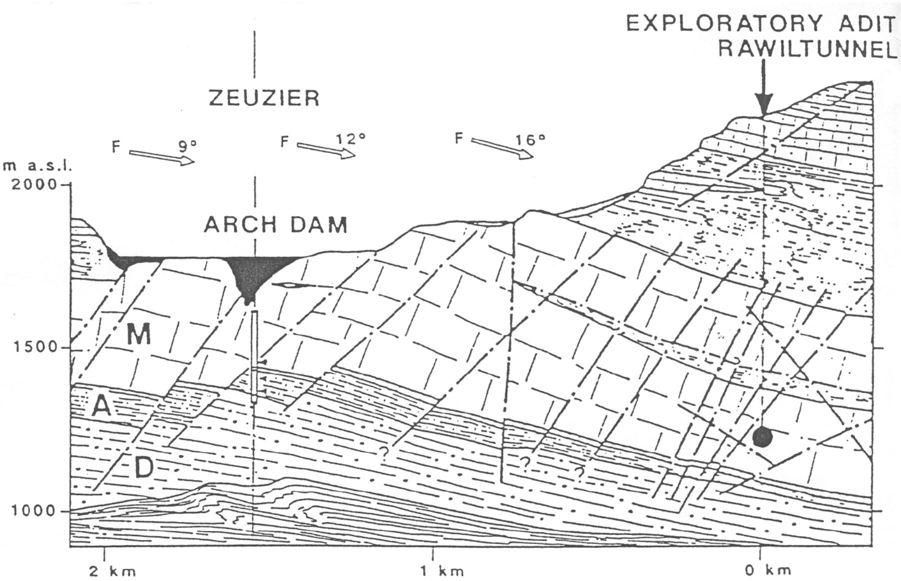

Figure 4: The excavation of the exploratory adit drained the ground water entrapped in layer D, caused the settlement of the region and damaged heavily the Zeuzier arch dam.

Important water inflow into the adit during excavation did lower the pressure of an entrapped ground water volume, causing a settlement of the region the dam is built on, of about 13 cm in the valley axis.

Due to the particular hydro-geological and morphological conditions of the site, the valley started to close. A kind of buckling of the dam took place (**figure 5**), which caused the damages already mentioned.

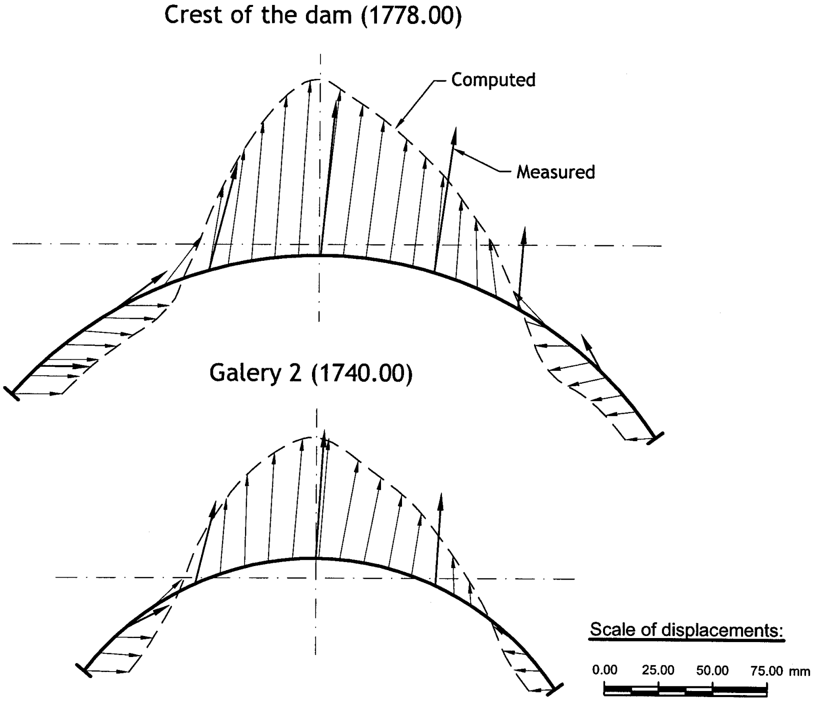

Figure 5: Measured and computed displacements of the Zeuzier dam.

After a certain, not yet final, equilibrium had been reached; the dam was repaired in the years 1982 and 1983 in injecting epoxy resin in the cracks and the contraction joints.

Figure 6 shows the measured upstream displacements of the crest in the axis of the central plumb line, while **figure 7** refers to the reference deformations, or the so called deformations at constant conditions both for the period 1965 to 1989.

This procedure eliminates practically the influence of the water level in the reservoir, as well as the influence of the temperature field in the dam body, obtaining the so-called reference deformation and thus placing emphasis on the actual settlement-induced deformations of the dam.

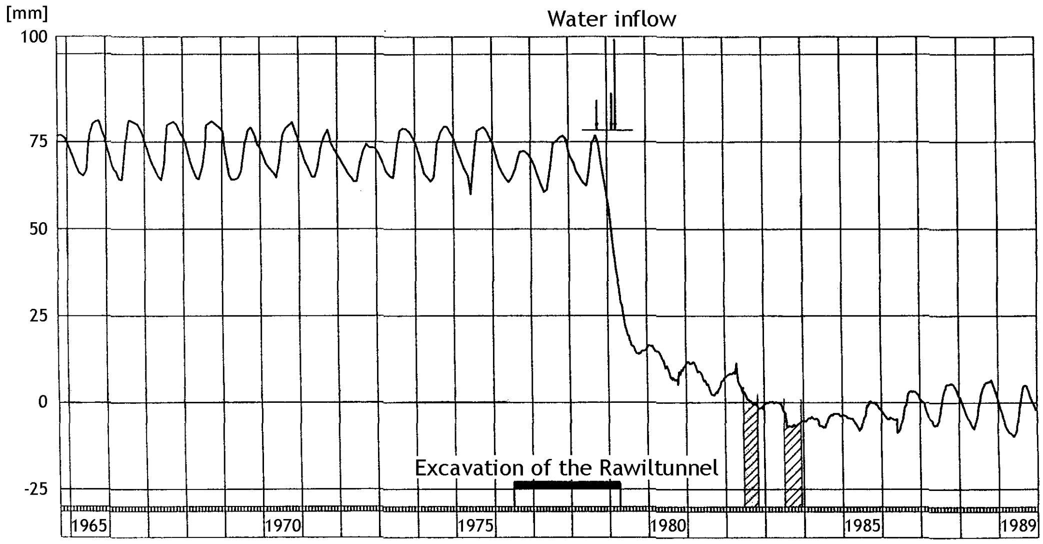

Figure 6: Radial displacements measured at the level of gallery 2.

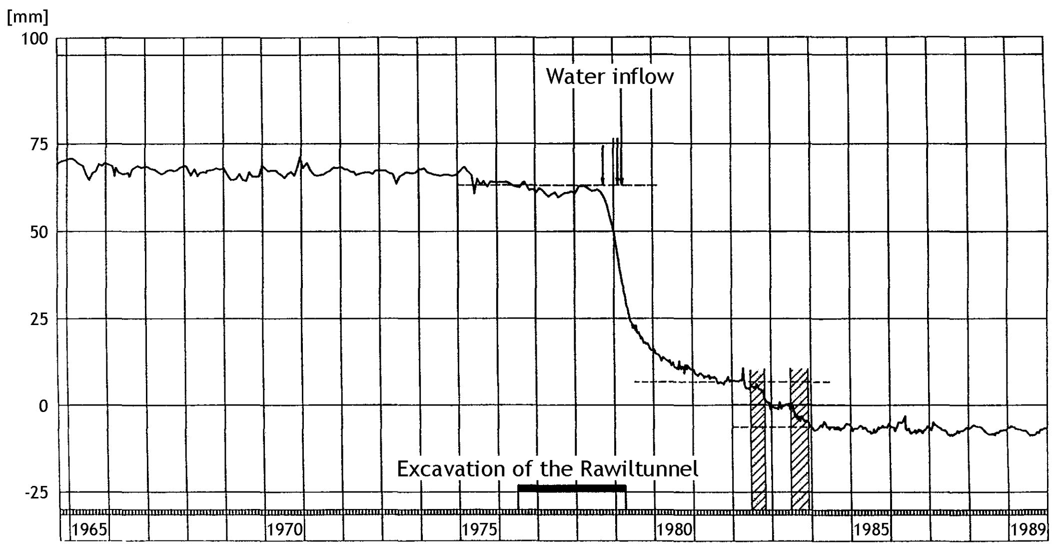

Figure 7: Reference radial displacements at the level of gallery 2.

In designing the procedure for repairing the dam, the assumption was made that the settlements would continue for some more years until a final hydraulic and structural equilibrium would be reached.
As it may be seen in **figure 8**, the continuation of the settlements did actually occur. Surprising is only the fact, that the displacement after 17 years appears to continue along a time-linear function, without, at least up to now, any sign of a stabilisation.

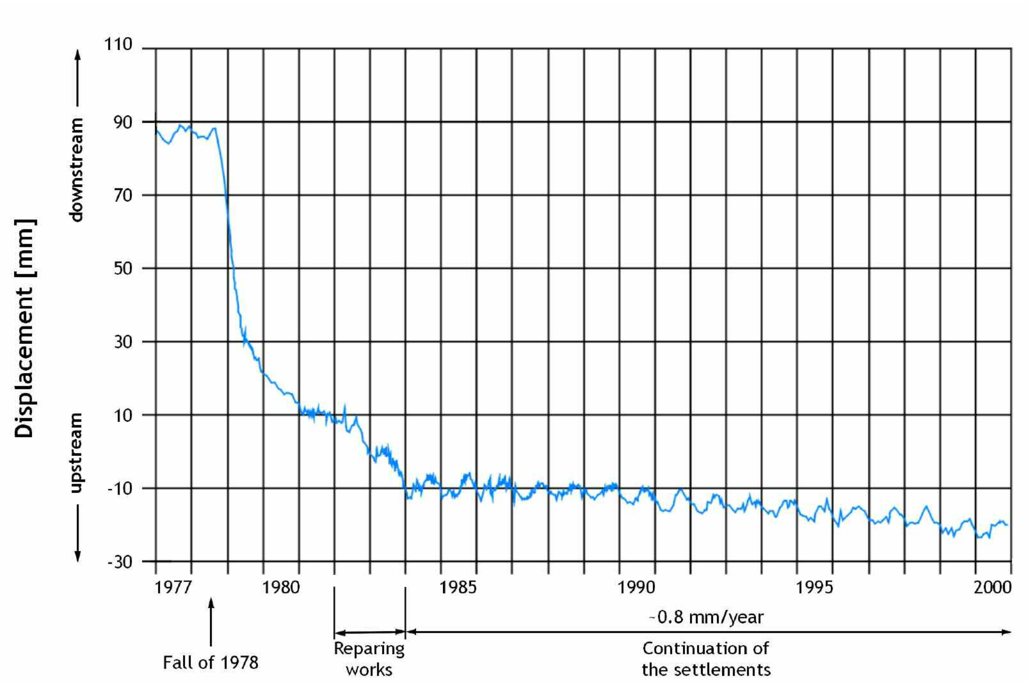

Figure 8: Evolution of the reference radial displacement at the dam crest since 1977.

It may be worthwhile to mention that due to an adequate instrumentation, a carefully monitoring and a correct modelling of the dam's behaviour, displacements as small as 0.8 mm/year in the central part of the crest can be detected and interpreted without any hesitation.
Furthermore, in other spots of the dam, displacements of less than 0.2 mm/year are put in evidence in a very convincing way.

Detailed considerations - not reported here - allow to confirm that in the case of the Zeuzier dam the continuing settlements are to be imputed to the still ongoing drainage of the rock mass. The very weak trend could however be detected only after a few years.

4. ISOLA ARCH-GRAVITY DAM

At present great attention is devoted to understand the anomalous behaviour of the Isola arch-gravity dam (Graubünden, Switzerland).

Figure 9 shows the principal characteristics of the dam: the height above foundation reaches 45 m with a crest length of 290 m.

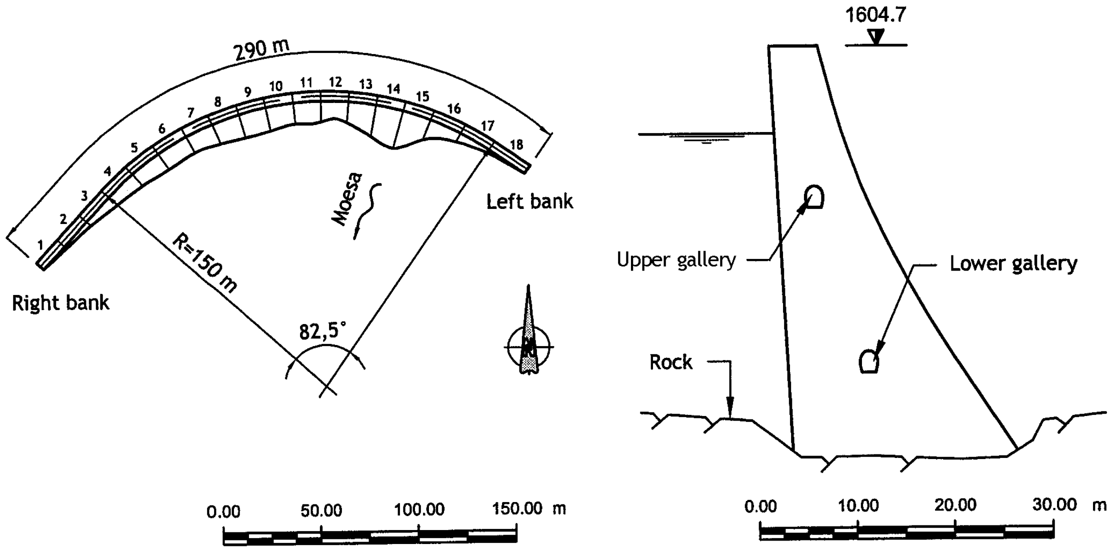

Figure 9: General layout of the Isola arch-gravity dam.

The dam was built in 1959 and after an initial period of about 5 years, started to deflect upstream ward. The central part of the crest moved at first on an average value of 0.3 mm/year, which increased since 1985 to about 1 mm/year (**figure 10**). In 1998 the total upstream displacement at the central part of the crest reached the value of 21 mm without showing, up to now, any sign of stabilisation. A similar behaviour was monitored in the upper gallery, 14 m below the crest, where the total displacement reached about 6 mm.

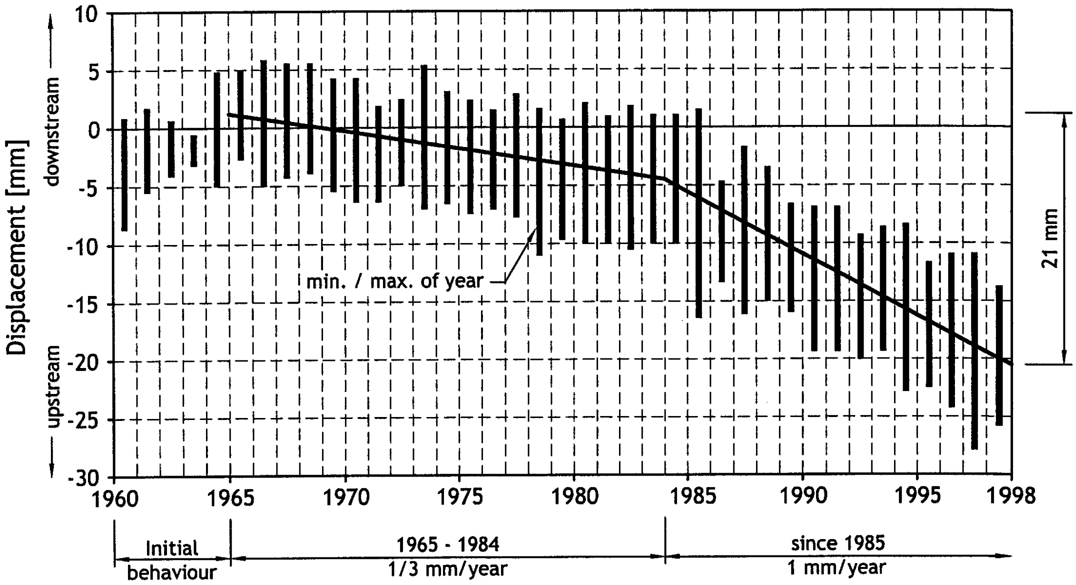

Figure 10: Evolution of the radial displacement of the dam crest since the construction (1960).

During the same time period important cracks appeared in said gallery: the first, more important and visible one, developed on the downstream wall 1.8 m above the invert, while the second one appeared in the upstream corner of the invert itself (**figure 11**). Both cracks opened all along the gallery and, at least for the time being, they haven't reached the dam faces.

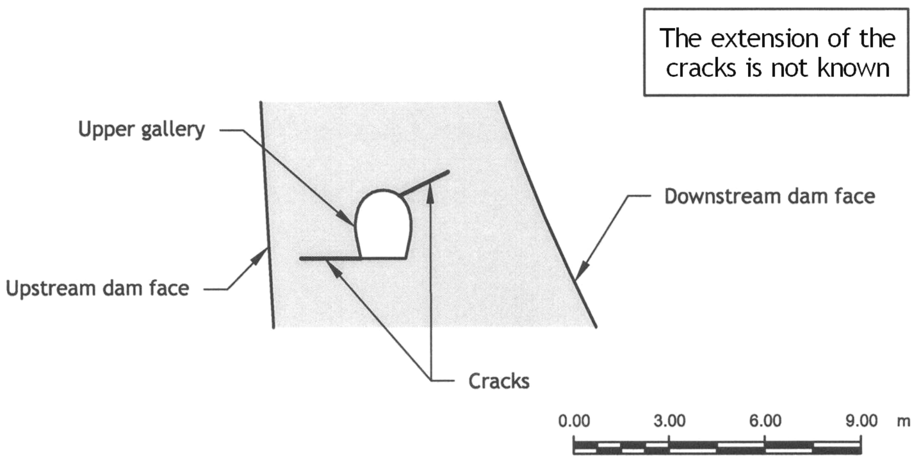

Figure 11: Schematic cross section showing the cracks of the Isola arch-gravity dam.

The downstream crack is monitored and its width is increasing at an average rate of 0.15 mm/year: in 1998 it reached the value of 2.4 mm, as shown on **figure 12**. This crack was clearly recognised at the beginning of the 80s, but was already known at earlier time, at least along certain stretches, and is considered to have formed at construction time. Since 1986 it is known that the crack is continuous along 85% of the dam length.

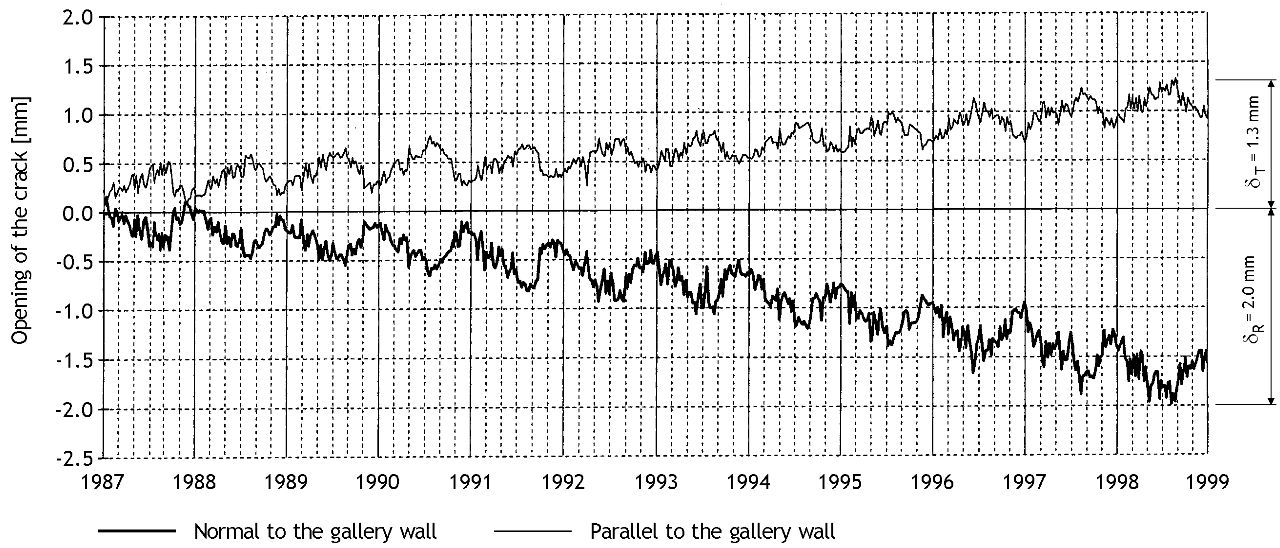

Figure 12: Opening of the downstream cracks measured at block 10.

A parallelism between the displacements of the dam crest and the opening of the cracks can clearly be observed. Different possible causes have been investigated in order to explain this anomalous behaviour. A first hypothesis, the one related to its thermal origin, was intended to investigate whether

- during the construction of the dam a particular thermal situation could have existed, which could explain the cracks, or
- the measured crest displacements could be justified by the release, by the crack propagation, of an hindered state of strain of thermal origin, which could have been entrapped in the structure by the grouting of the contraction joints.

A quite refined analyses was carried out in order to take into account all the influences of facts occurred at construction time and the subsequent operation of the pond such as: the rate of placement the concrete layers, the hydration heat, the artificial cooling, the reservoir operation and the influence of the environment including the air and water temperatures as well as the effect of the solar radiation.

The main conclusions of that analysis can be summarised as follows: the development of the temperature field in the concrete body at early ages wasn't particularly remarkable, but an initial cracking of thermal origin can not be absolutely ruled out. The measured upstream displacements are quite doubtfully originated by the kind of thermal pre-stressing initially considered.

Indeed the investigations carried out in order to clarify the situation are still in progress. The most plausible cause appears, for the time being, to be a kind of an alkali aggregate reaction (AAR). But, further investigations are required to get a final answer to the questions raised.

5. ROGGIASCA ARCH DAM

The 70.5 m high Roggiasca arch dam (Graubünden, Switzerland) was completed in 1965. With a concrete volume of 31'000 m^3 and a crest length of 177 m, it might be considered as an average sized structure. The recorded displacements of the dam crest are shown in **figure 13** for the last 20 years.

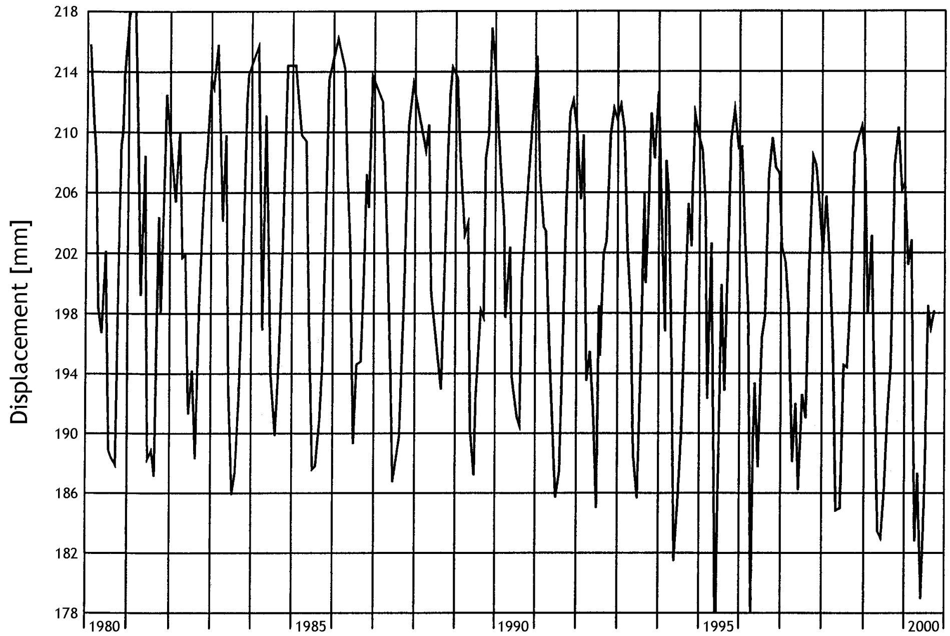

Figure 13: Measured displacements of the crest of the Roggiasca arch dam.

The evolution of the crest displacement during the last 10 years seems to indicate a marginal non-reversible component. In fact the range of the annual displacement seems to move upstream ward. The identification of the observed trend is thus difficult due to the importance of the reversible part compared to the non-reversible one. This trend could be caused by the well-known general climate change or by slightly modified operational conditions.

A better identification of the observed trend as well as a clear answer to the last question is ensured by an accurate deterministic model. **Figure 14** shows the evolution of the reference displacements at the same place, same time period and same scale of the displacement shown on figure 13. By representing the dam position under a reference loading condition a judgement is finally possible:

– the upstream displacements are not caused by the mentioned climate change, since this effect would be corrected by the model,
– after 35 years of normal operation a non-reversible displacement in the direction of the reservoir has started. At present the upstream non-reversible displacement reaches about 6 mm and its value is increasing at an average rate of 0.6 mm/year.

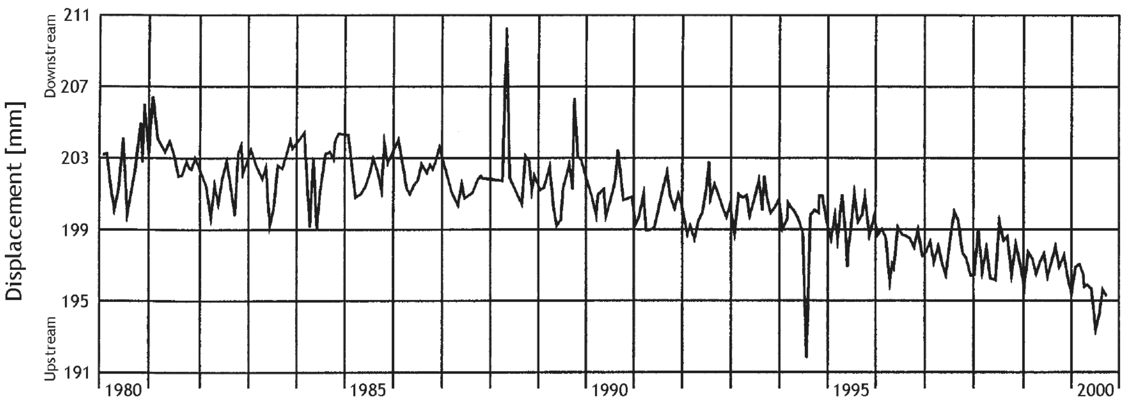

Figure 14: Reference radial displacement at the crest of the Roggiasca arch dam.

To mention that in this case the annual non-reversible part of the deformation is only a small percentage of the reversible one. The identification of the observed trend is thus only possible when using an accurate deterministic model, which takes into account the effective loads and the thermal field acting on the structure.

6. CONCLUSION

The three case histories presented here above allow drawing the following clear conclusions.

1. An accurate monitoring and a precise interpretation of the measurements based on a deterministic dam model and using an adequate procedure can put in evidence even very small deviations and very weak trends.
2. The interpretation of the mechanism beyond the observed long term movements requires, of course, additional information as well as a correct and experienced engineering judgment.