CISM International Centre
for Mechanical Sciences
Udine, Italy

CASE HISTORIES OF CONCRETE DAMS (Structural Cracks)

Structural Safety Assessment of Dams

CISM - Udine 14th December 2004

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1. INTRODUCTION

There are no two identical concrete dams worldwide. Each one has its particular history, but in general their histories do not present exceptional aspects and are relatively peaceful.
Nevertheless, quite a number of interesting and exceptional cases do exist.
I made a choice among them in order to put in evidence a few special aspects – related to concrete cracking for structural reasons – which may be due to the fact that some new problem did appear or that some well known rule was disattended.

2. THE ZEUZIER DAM

2.1 The story

The 156 m high arch dam of Zeuzier (**Figure 1**) was put in operation in 1957 and behaved in an absolutely satisfactory way until fall 1978.

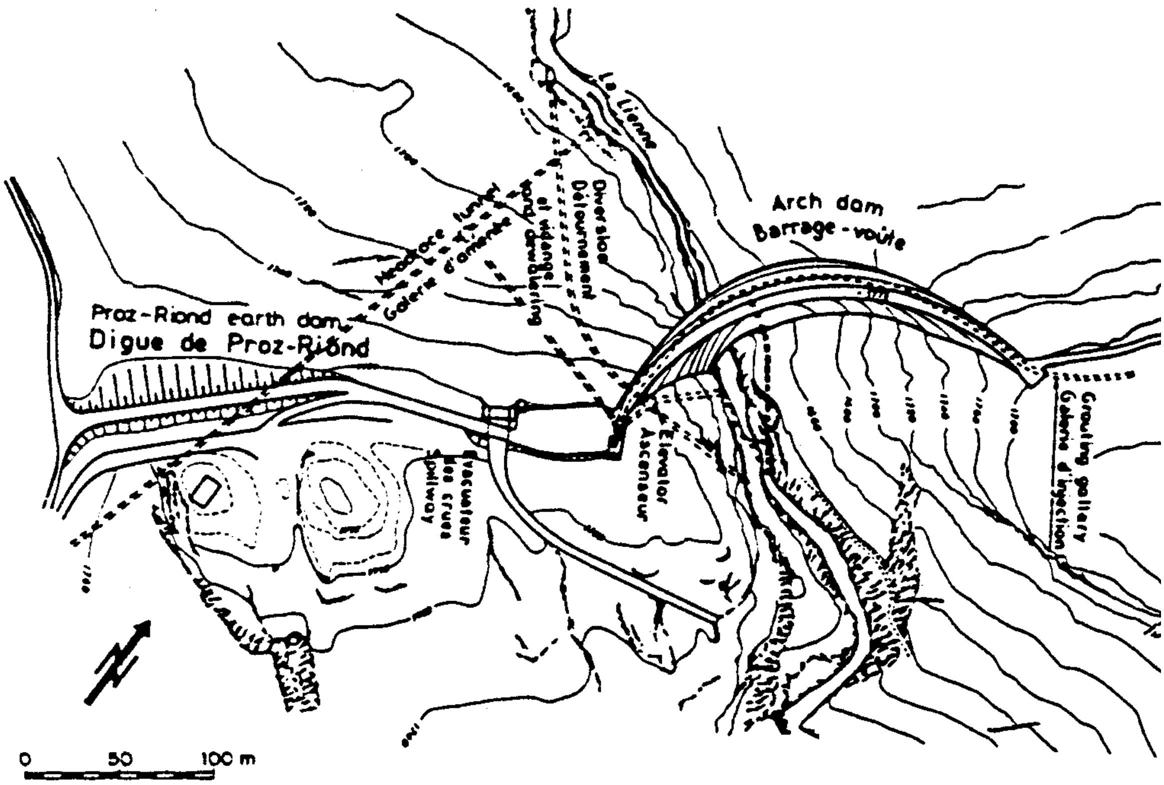


Figure 1: Plan view of the Zeuzier arch dam.

The dam is resting on a sound, thick zone of Malm-limestones as can be seen on **Figure 2**. These stiff limestone layers are subdivided by frequent fissures, so their permeability is high and practically no ground water is present in them. The site, deeply fitted in a strong rock mass, was correctly considered to be well suited for building a high arch dam.

Marly layers, on top of the limestones, in conjunction with the grout curtain ensure the tightness of the reservoir.

However, below the limestones a confined groundwater aquifer did exist in the Dogger-formation protected by an aquiclude formed by a quite marly Collovian-Oxfordian rock layer.

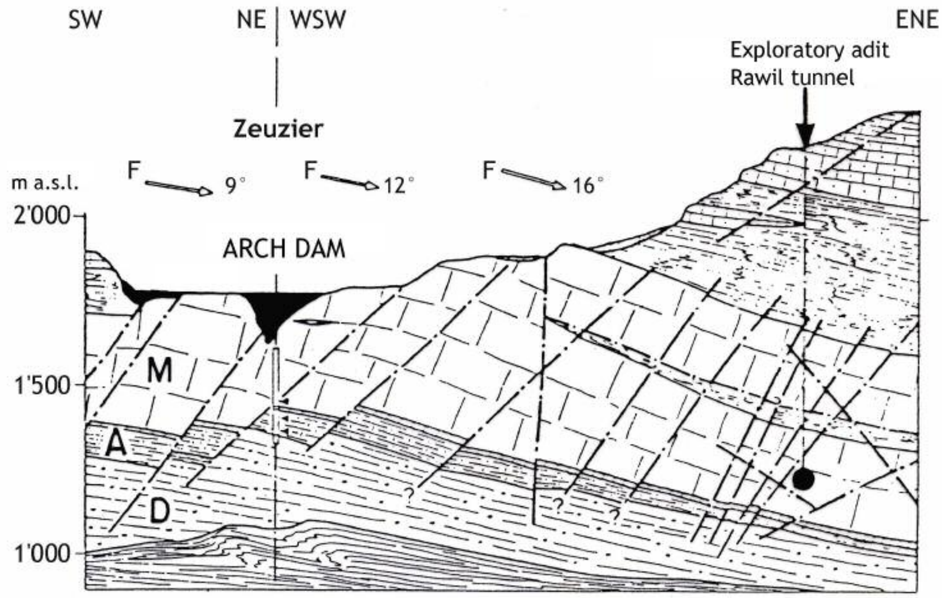


Figure 2: Geological profile through the rock bar of Zeuzier extended to the exploratory adit. The dam is founded on the Malm limestone (M), below which is the Dogger formation (D). The two are separated by the Callovian-Oxford series (A).

Some plastic deformations of the concrete, and possibly also some small ones of the rock foundation, did obviously occur during the first years of operation, but, since then, the dam did behave in a perfect elastic way.

Suddenly, at fall 1978, upstream displacements of the crown of the arches were noticed. They were easily and rapidly detected by the instrumentation, first of all by the pendula.

After some preliminary studies a certain relationship between these movements and the water inflow in an exploratory adit under construction nearby, could be suspected.

At that time the scepticism on such a relationship was wide spread. Many reasons were put forward to deny said assumption; they were:

- the large distance of about 1.5 km between the adit and the dam;
- the fact that the elevation of the adit was some 400 m lower than the valley bottom of the dam site;
- the apparently unbelievable great amount of the settlement in a very firm rock;
- the practically instantaneous effect of the inflow on the deformation of the dam, and
- the fact that the settlements were more important under the dam, than above the adit itself.

With time however, said relationship was clearly confirmed, as can be seen on **Figure 3**, which did convince of the reality of the phenomenon envisaged. Indeed the settlements could be correlated with the inflow rate in the adit.

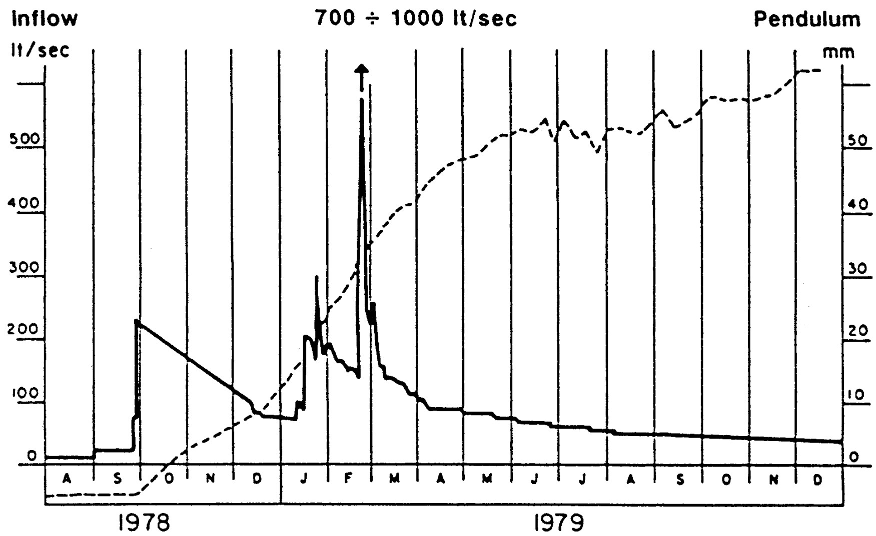


Figure 3: Zeuzier dam. Inflow in the exploratory adit ①, upstream displacement shown by the central pendulum at crest elevation ②, and water volume inflow ③ as integral of ①.

Meanwhile, the movements went on, while the reservoir was kept at low level.
The settlement at the valley bottom reached finally about 13 cm, the valley itself was narrowing by 7 cm and the crest at the dam axis moved 12 cm upstream. Im-

portant cracks, up to 15 mm wide, formed on the downstream face of the dam and contraction joints opened on the upstream one (**Figure 4**).

In the years 1982/1983, as the movements did slow down, the dam could be repaired by grouting the cracks in the dam with epoxy resin and in reinforcing the grout curtain along the foundation line.

1988, that is 10 years after the event, the dam could be re-commissioned for full operation.

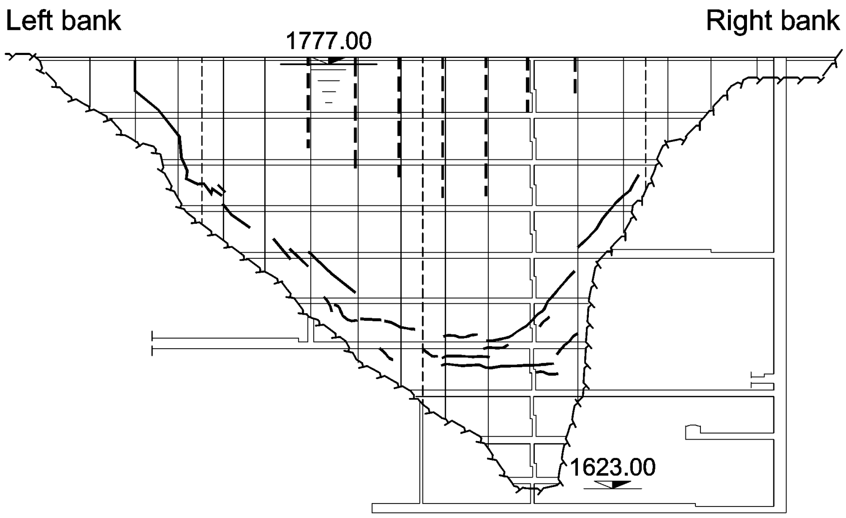


Figure 4: Zeuzier dam. Main cracks on December 1980 (openings above 1 mm; max. 15 mm); upstream joint openings = dashed lines; downstream cracks = solid lines.

The costs of the repairs and the losses of energy production during the period of the imposed draw-down were very substantial.

There is no scepticism nor doubts any longer, on the causes of the settlements, on the damage mechanism, nor on the methods used for repairing the structure.

Since having been repaired, the dam behaves again in a very satisfactory way. Nevertheless, 26 years after the event, some very small movements still go on, while a constant water-flow of about 20 lt/sec from the depth continues to enter the exploratory adit.

2.2 Interpretation of the readings

The dam was well instrumented; in particular with three pendulums, which reacted very precisely and instantly to any movement.

Also the readings were correctly taken and plotted.

Figure 5 shows the displacements of the crest detected by the right-side pendulum in the last months of 1978 and the first ones of 1979 in relation with the envelope reached by the readings in the period 1958-1976.

During September 1978 the line of the displacements changed sharply its direction; crossed about the 10th of November said envelope and went on at a speed of about 5 to 7 mm a month.

At that time no model did exist which would have allowed separating the various effects. Also, no thresholds had been defined.

Consequently there was no mean to trigger an early alarm.

Any kind of explanation of the movements were looked at, as for example the fact that the previous summer was a quite warm one, or that a tectonic activity was going on.

Finally the alarm was emitted in February 1979.

A modern interpretation of the readings would have allowed to be warned already at the end of September 1978 that is 4 to 5 months earlier, as can be understood from figure 5.

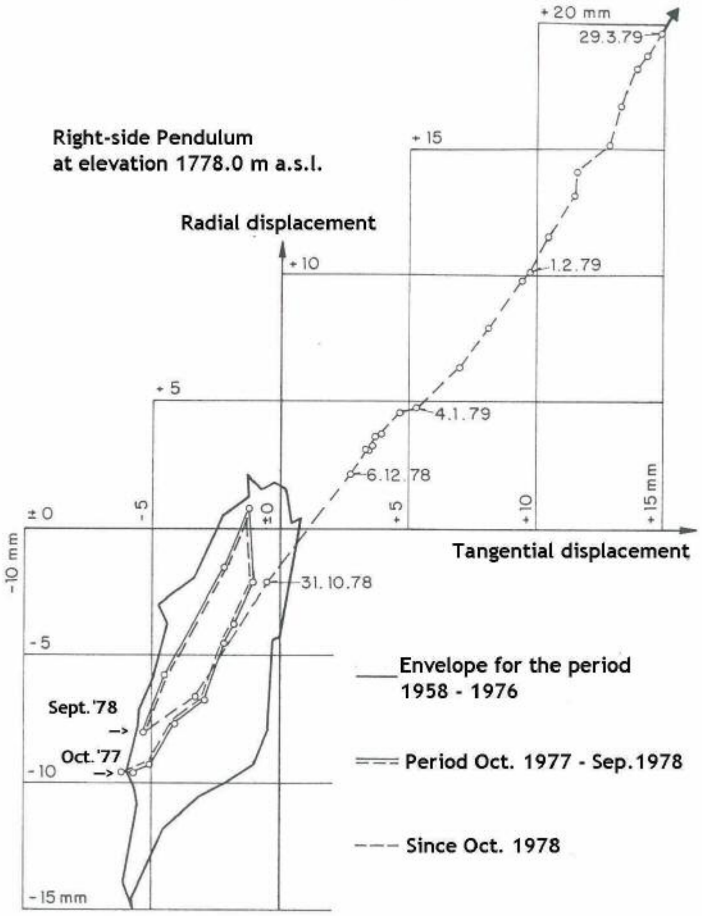


Figure 5: Radial and tangential displacements of the right side pendulum at crest elevation.

2.3 The FES-Model

The event of Zeuzier was a quite special one, as no precedents were known at that time.

In a very schematic way the phenomenon can be qualitatively represented by **Figure 6.**

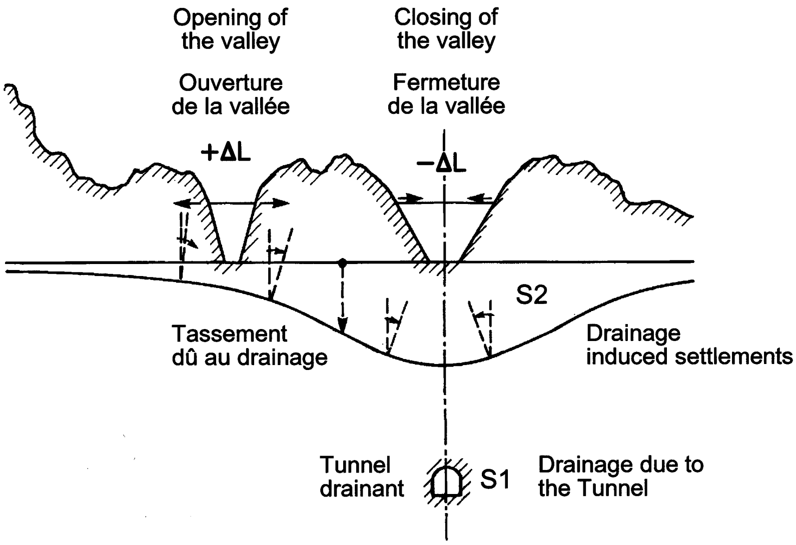


Figure 6: Opening and closure of the valley flanks due to the drainage during the tunnel construction.

While an overall settlement of the site has in itself little or no importance, the change in width of the valley may have heavy structural consequences, particularly in case of arch dams.

Depending on the geological conditions and on the position of the dam site respect to the tunnel, a widening or a narrowing of the valley can occur.

In fact, the settlements are due to the water being squeezed out from the joints and cracks in the rock mass, due to a reduction of the interstitial water pressure caused by the draining of the rock mass.

The phenomenon can be seen as a kind of "consolidation". But, obviously due to the non-homogeneous, non-isotropic and non-linear properties of the rock mass and of its discontinuities, the displacements of the various points at the ground surface will be quite different from case to case and also from the nice smooth curve of the figure.

To quantify the deformation of the rock mass, the so-called FES-Model, for "Fissured, Elastic, Saturated Rock Masses" was established.

Figure 7 shows the model in the case of a single system of joints perpendicular to the compressive stress.
Each point P of the graph corresponds to a total stress σ, an interstitial water pressure p, a strain ε and a ratio α of closure of the joints. The right boundary of the plot, that is the line 0-A-B, represents the dry rock. It is easily understood that a reduction of the water pressure will shift the point P to the right and will thus cause a compressive strain, or a settlement.

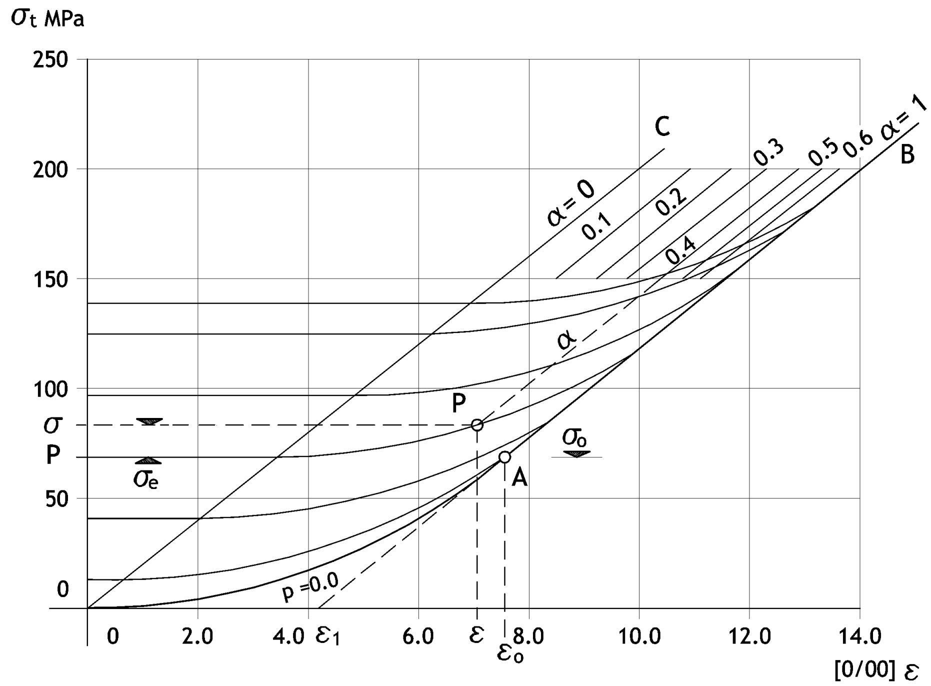


Figure 7 : Example of a FES model of a rock mass:
ε = strain; σ_t = total stress; p = neutral water pressure;
α = degree of closure (α = 1 fissures completely closed, α= 0 fissures completely open); A (ε_0, σ_0) = point of total closure at nil water pressure; σ_e = effective stress;
P (ε, σ_t, p, α) = general strain, total stress, neutral pressure and closing ratio at point P.
== $\Rightarrow$ effect of reducing the water pressure (drainage).

The case of Zeuzier did correspond to a completely unexpected event and represented an unknown phenomenon in the field of dam engineering. It was nevertheless well known in that of Petroleum Engineering.

The Zeuzier dam gave the opportunity to become aware of this type of events and to set up the tools to tackle the problem.

Presently two long high-speed railways tunnels are under construction in Switzerland as may be seen on **Figure 8**.

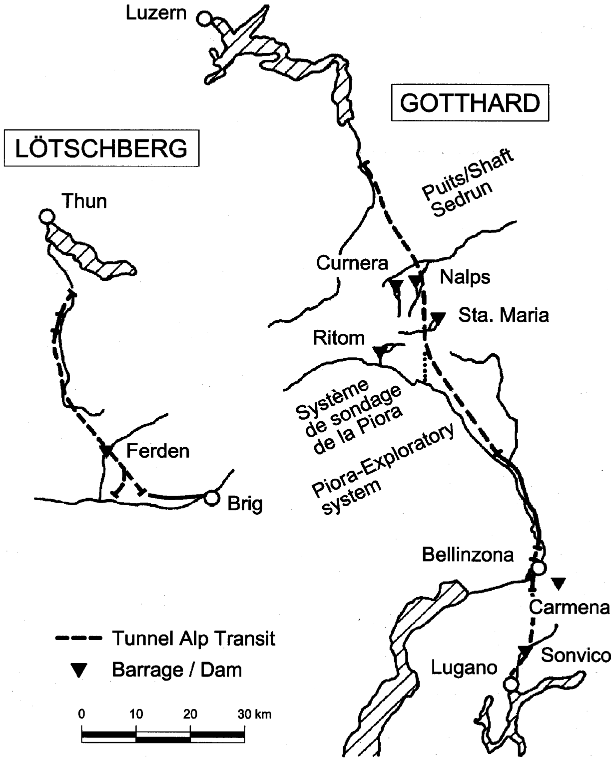


Figure 8: Dams in relation to the two tunnel projects.

Above them a number of dams exist. So the question of possible movements of their foundations cannot be ignored any longer and is presently analysed by 3-D Finite Elements Analysis based on the FES model as shown in **Figure 9**.

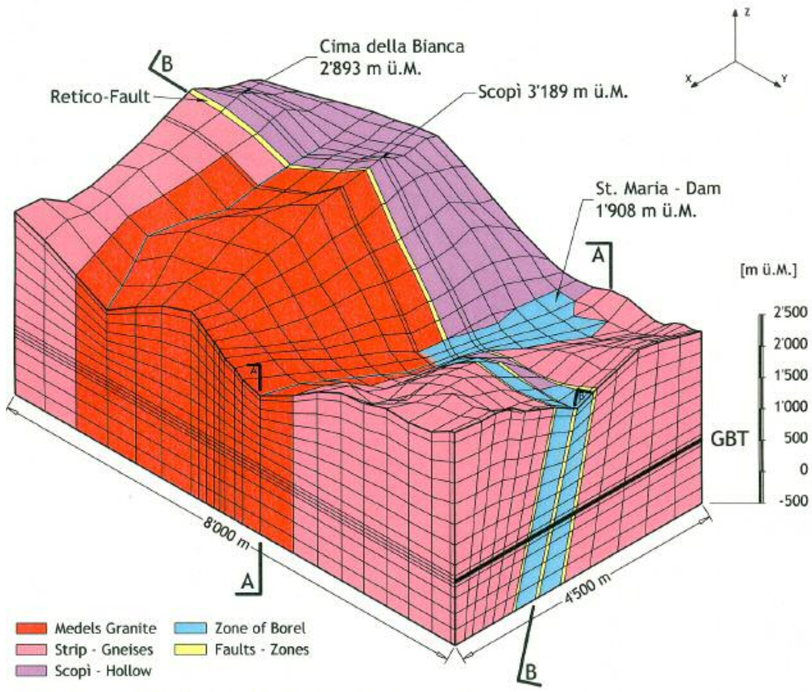
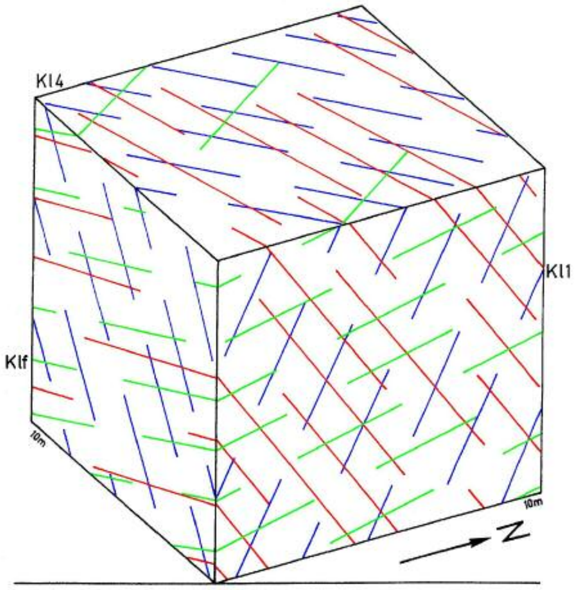


Figure 9: FES - Mesh for a stretch of the Gotthard AlpTransit Tunnel.

For each rock type and zone, a model of the joints configuration was set up **(Figure 10).**



Model for Gamsboden-Gneiss-Granite

Joint systems	Orientation [°]	E [Gpa]	e [mm]	D [mm]	A [mm]	Law Nr.
Kl 1	141 / 66	40	0.6	1'000	75	4
Kl 4	343 / 54	40	0.6	1'000	75	4
Kl f	239 / 21	40	1.3	1'000	150	4

Figure 10: Geologic block with assumed joint families with their orientation and characteristics.

Obviously, according to the afore said, a series of thresholds will be defined both for the deformations of the dams and for the water inflows in the tunnels.
However, it is not our task today to discuss in more details of these questions.

3. THE KÖLNBREIN DAM

3.1 The story

The story of the Kölnbrein dam is a quite different one.
It is even since known that grouting may change the stress field in a certain surrounding zone. It was also known that grouting the contraction joints of an arch dam might induce great stresses in the dam body. Nevertheless, this fact was often disattended, probably because grouting was considered, for a long time, to be

a somewhat strange, mysterious activity situated somewhere between the competences of the engineer, the grouting firm, the geologist and a not exactly specified number of so-called grouting specialists.

This situation had serious consequences for the Kölnbrein dam, a thin arch of 200 m height and 600 m crest length. For grouting the contraction joints, only a final pressure of 15 bar was specified.
Apparently the effects of the grouting were not duly investigated.
No limits for the grout take nor thresholds for the opening of the joints were defined.

Figure 11 shows the opening of the joints produced by the grouting process.

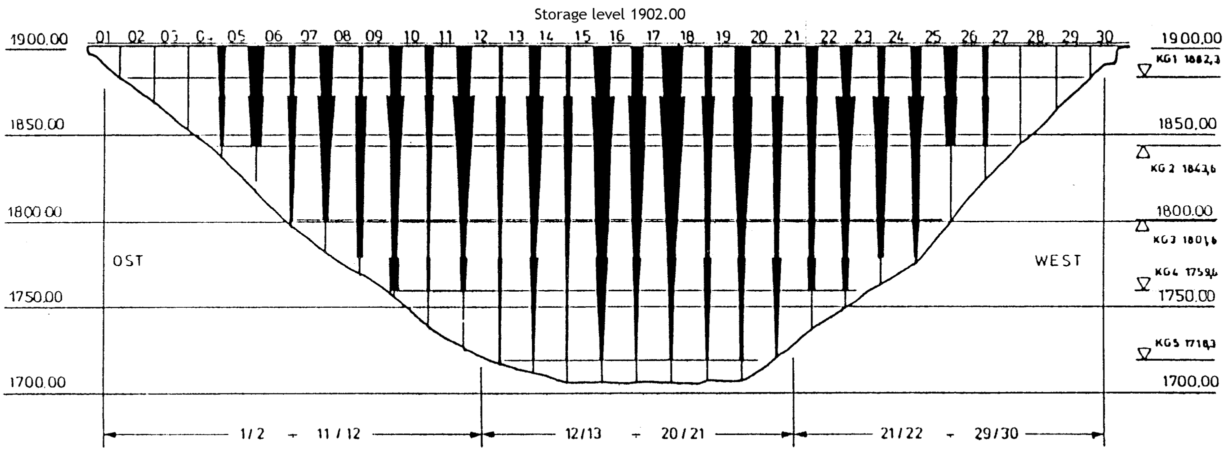


Figure 11: Kölnbrein dam. Opening of the contraction joints due to intense grouting.

The steps in the openings are due to the fact that the grouting was carried out in various stages; that is one stage after each of the three periods of concreting at summer time and an additional campaign at the end.
The alternance of wider and less open joints is due to the sequence of the grouting stages along the arches.
The joint openings at crest elevation did sum up to about 400 mm.
This elongation of the crest produced obviously a deflection to upstream and especially a strong bending near the foundation of the concrete blocks.
The bending produced tensile cracks at the downstream heel, sometimes along the rock-concrete contact, sometimes in the rock itself, sometime finally along the joints of the concrete lifts.

A certain similarity with the case of Zeuzier can be noticed. There was a narrowing of the valley, here an elongation of the dam crest, which caused similar cracks at the downstream heel of the dam.

The first impounding at Kölnbrein induced, as normally, strong transverse forces in the zone of the already fissured blocks. According to **Figure 12** the residual non-fissured upstream part of the cross section could not resist said forces. Tensile inclined cracks did develop and the dam slid on its foundation for a few centimetres.

We may observe the difference of two types of cracks, the upstream and the downstream ones.

These last are due to bending moments and thus started perpendicularly to the dam face and developed towards the inner dam body.

At the contrary, the upstream ones had to start from inside the dam and daylighted on the face forming quite a small angle with it.

This situation was disattended at the beginning and misled, for a certain time, the investigations on the causes of the events.

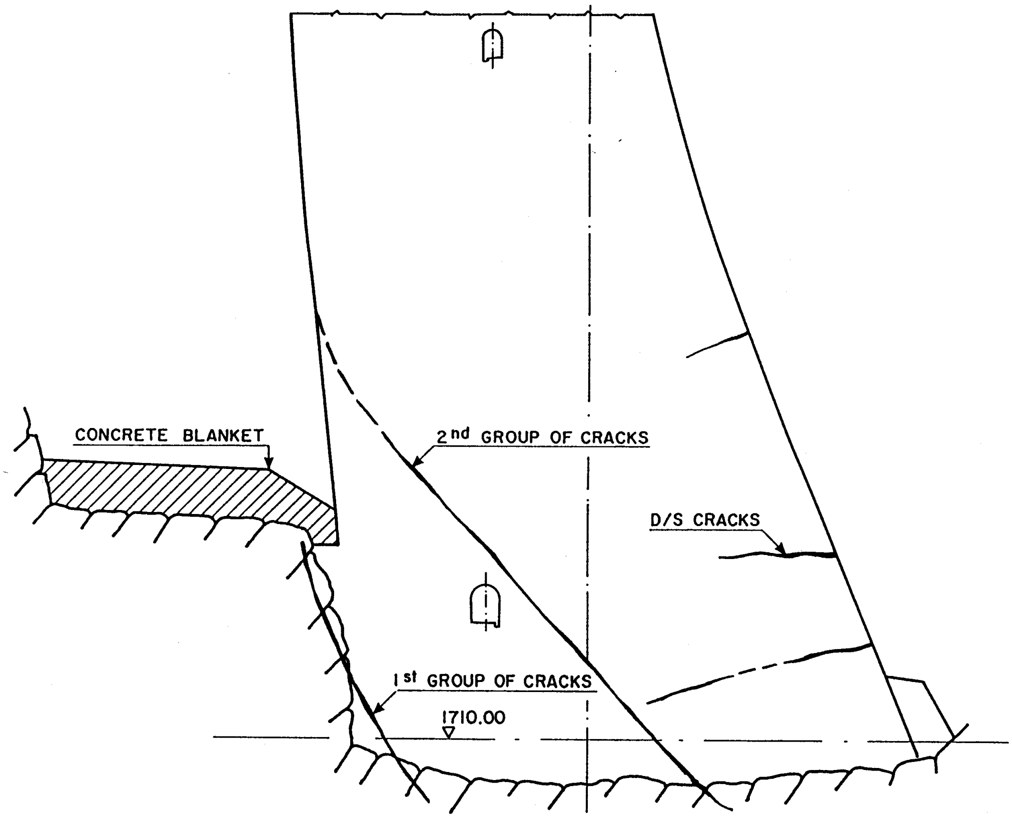


Figure 12: Kölnbrein dam. Typical cracks in the dam blocks.

3.2 The rehabilitations works

Various solutions for repairing the dam were investigated and discarded for different reasons.
Finally, the solution shown in **Figure 13** consisting in a downstream arched buttress was selected.

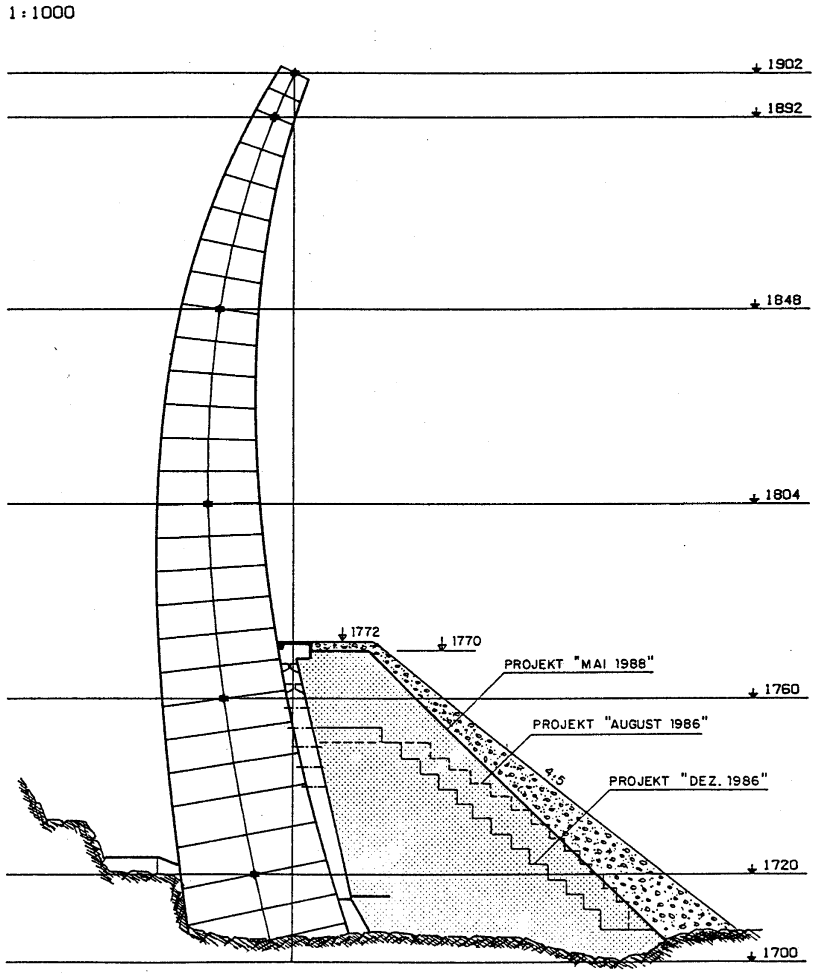


Figure 13: Kölnbrein dam. Stages in the design of the downstream arched buttress.

The transverse forces, up to 1 Mio to (10'000 MN) are transferred from the arch dam to the buttress by 613 neoprene pads of 1 m^2 surface and 10 cm thickness, which are activated on a precise instant during the first impounding, just in creating the contact.
In fact, each one of the nine horizontal rows of pads is put in contact as the impounding level reaches a given elevation.
By the following draw-down a gap of up to 40 mm for the upper row, opens again and the pads are not active any longer.

The system works quite well and the pads need be readjusted only at long time intervals. Obviously, the rock foundation, the upper part of the grout curtain and the lower part of the cracked blocks were grouted with cement but in part also with epoxy resin.

Finally, **Figure 14** shows the development of the total force transferred from the dam to the buttress in function of the water level in the reservoir.
It is impressive to see how exact the actual total force follows the theoretical, deterministic model set up a priori.
The difference or error is only a small percentage of the maximum load.

There is no doubt that a quite unusual solution was found for a quite unusual problem. Like for the Zeuzier dam, it took nevertheless about a decade to develop and implement it.

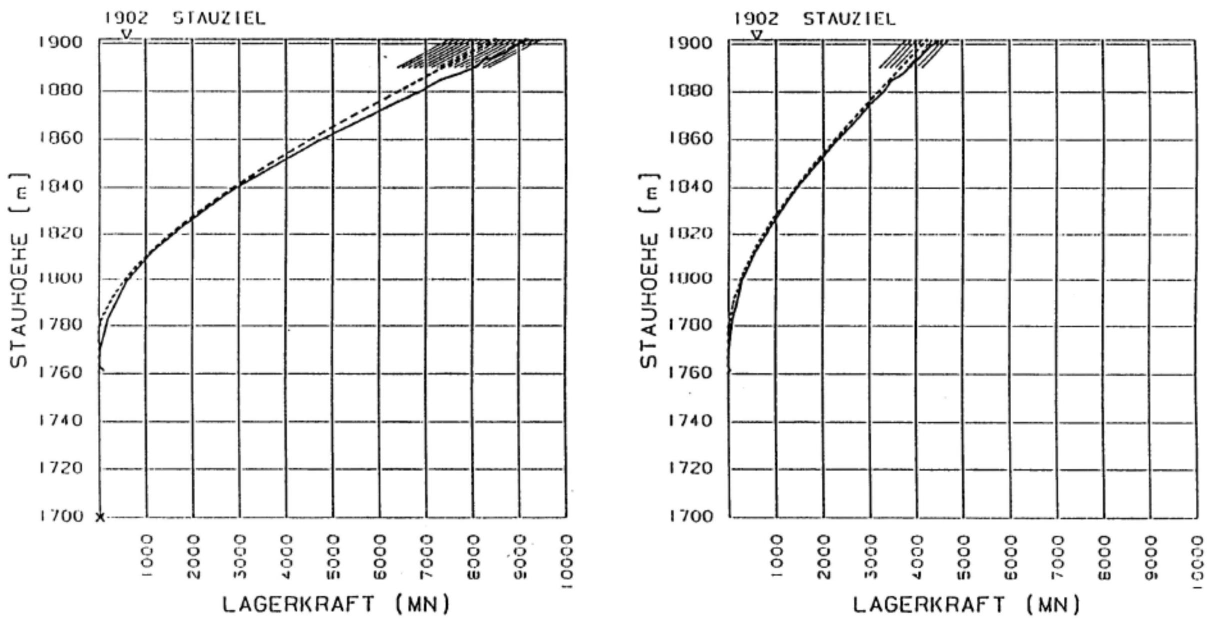


Figure 14: Kölnbrein dam. Forces transferred to the buttress at the first impounding (1993). Total and central part of the dam.

4. THE FLUMENDOSA DAM

4.1 The story

The 115 m high, double curvature arch dam was completed in 1957.

Already at the end of the construction period and immediately after its completion a great number of horizontal cracks did appear on the upper part of the upstream face, as can be seen on **Figure 15**.

New cracks did appear from time to time, but only until 1971 when a kind of equilibrium had apparently been arrived at.

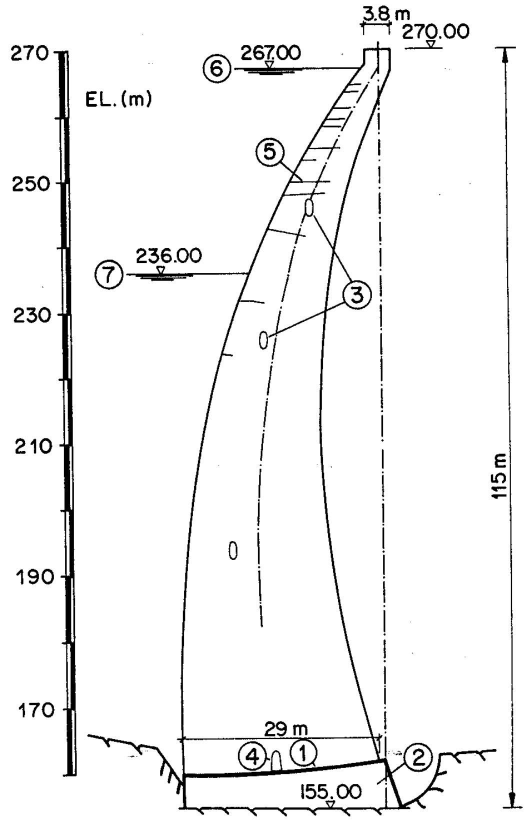


Figure 15: Flumendosa dam. Cross section at the crown.

For about 40 years the reservoir was consequently impounded only to 31 m below the maximum operation level.

As the necessity arose to increment the water storage, various investigations were carried out, which confirmed the crack pattern shown at the same figure. Very often the cracks did follow the lift joints in the concrete, as obviously the same were offering the lowest tensile strength.

The extent of the cracks from the upstream face was increasing from the crest level to a maximum of about 60% of the dam thickness at a point located 15 to 20 m below the crest and decreasing again towards lower elevations.
The origin and the cause of the cracks could be explained in a quite clear and convincing manner.

Due to the strong downstream overhang of the upper part of the dam, the cantilevers are not stable by themselves and need a support from the arches.
To ensure that action the contraction joints had to be grouted stepwise during concreting; that means before the hydration heat could dissipate and the concrete could cool down. The subsequent cooling of the upper arches deprived the cantilever from their support. So, they deflected to downstream and the cracks did form due to the bending moments induced.

The great number of the cracks was due to the poor bound of the concrete lifts already mentioned.

In a certain sense the situation at Flumendosa was about the reverse of the one in Kölnbrein and even in Zeuzier.
In Flumendosa a shortening of the arches in respect to the width of the valley took place. So the cracks appeared this time on the upper part of the upstream face.

4.2 Remedial works

Again, the dam was repaired in grouting the cracks with epoxy resin according to **Figure 16**.
It is obvious that after grouting the stress distribution in the dam body had changed.

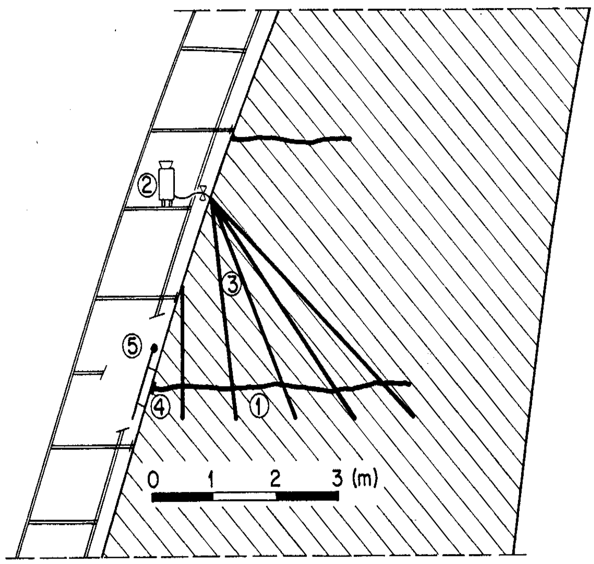


Figure 16: Schematic layout of the boreholes and equipment.

Figure 17 confirms this fact. There is for example a concentration of the vertical stresses near the faces and a reduction in the centre, which fact may be understood as a kind of advantageous pre-stressing in the vertical sense.

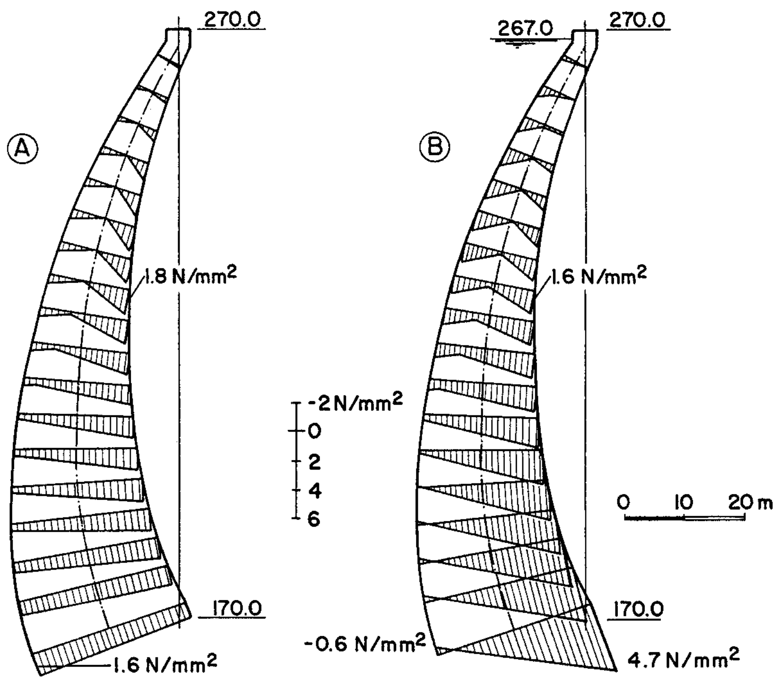


Figure 17: Stress distribution in the crown cantilever after grouting of the cracks. ⒶEmpty reservoir; Ⓑ Reservoir at O.W.L. at summer time.

Obviously, the grouting did not fill only the cracks but also all the voids present in the concrete.

Indeed, 75'000 kg of resin were injected to treat a surface of 13'000 m^2 of cracks. This means an average thickness of 5 mm, which is much higher that the actual opening of the cracks.

The grouting was very successful as the seismic velocity was significantly increased and uniformised as can be seen from **Figure 18.**
Also the seepages through the dam are now totally insignificant.

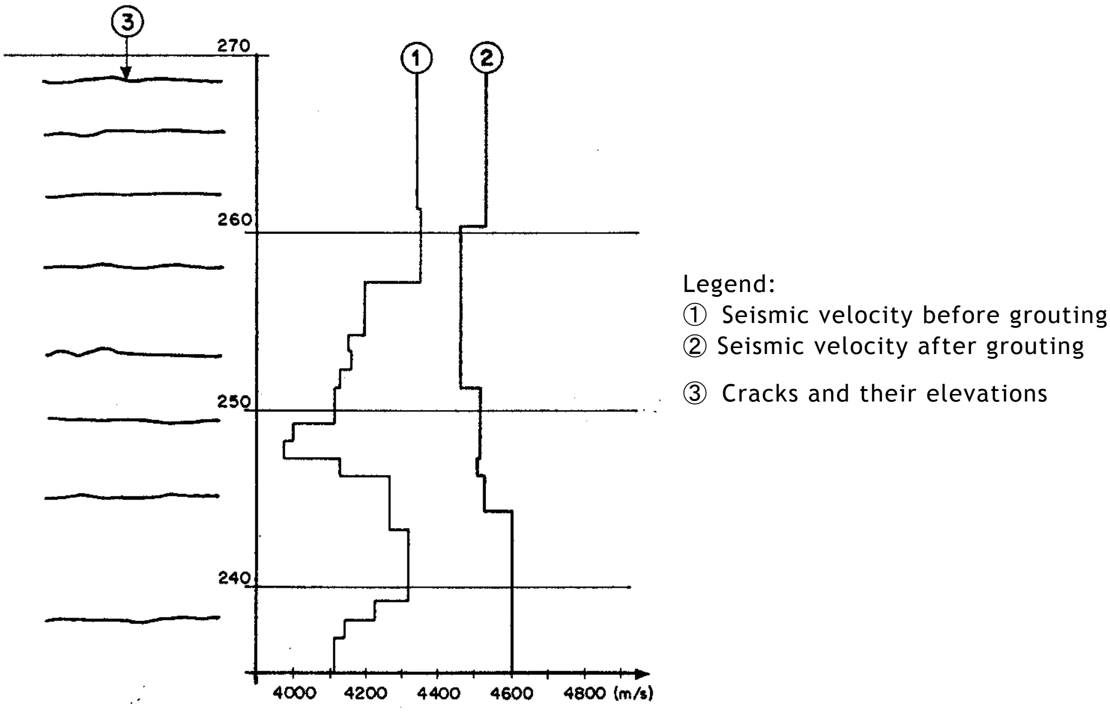


Figure 18: Geophysical investigations in the test block Nr. 17.

5. THE SCIENCE OF CONCRETE CRACKING

The three former examples refer to the cracking of the concrete dams due to structural reasons.
Of course, there are sometimes other troubles with concrete dams. The most "modern" one is undoubtedly the one of the alkali-silicate reaction (ASR).
By the way, only dams younger than 50 years are generally affected by the ASR, older not. This strange remark is due to the fact that the concrete of older dams was not heavily compacted by vibration. Pores and voids exist thus in these dams

which can absorb the products of a possible ASR without creating any significant increase of the volume of the concrete mass, and thus without cracking it.
Additionally, the filling of the voids tightens the concrete and in reducing the seapage, slows down the reaction itself.
Again, this question is outside of the today's scope.

Returning to the structural cracks, it appears, in conclusion, worthwhile to study the actual crack pattern to help identifying the problems that can appear.
Figure 19 is an example of a trial in this direction.

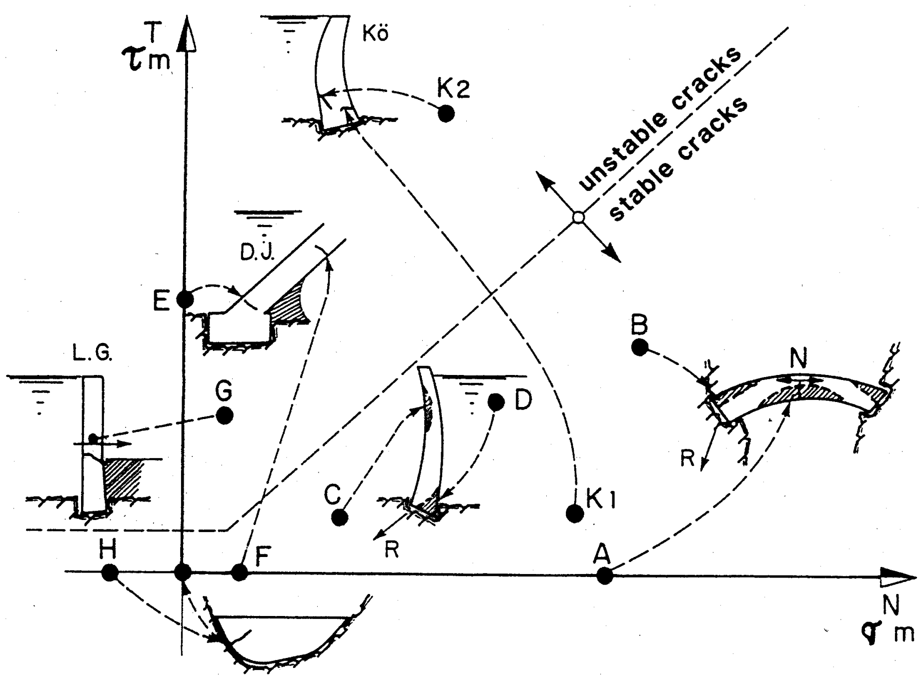


Figure 19: Some typical cracks in arch dams.
N= normal force; T=transverse force; τm=respective stresses

But, in my opinion, the question should be studied in much more depth and engineers should be trained to see and understand the cracks of a concrete structure.

Many thanks for your kind attention.

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