IALAD
Integrity Assessment of
Large Concrete Dams

GROUND-WATER INDUCED SETTLEMENTS IN ROCK MASSES AND CONSEQUENCES FOR DAMS

IALAD - Integrity Assessment of Large Concrete Dams

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by

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1. INTRODUCTION

Since long, if not ever since, it is a well-known fact that a drawdown of the ground water table will induce settlements in soil masses. For example, damages to buildings had occurred very often.

Settlements above oil fields due to extraction activities were also noticed many times and settlements were also observed in rock masses due to pumping for drinking or irrigation water. But this question did apparently not draw the attention of the civil engineers or at least of the dam builders.

The case of the settlements of the rock foundation of the arch dam of Zeuzier, in Switzerland, was thus considered to be a quite exceptional event. It is therefore worthwhile to recall once again these facts, which did show that even strong and stiff rock masses might be subject to movements due to changes in the ground water levels and pressures.

2. THE ZEUZIER 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.

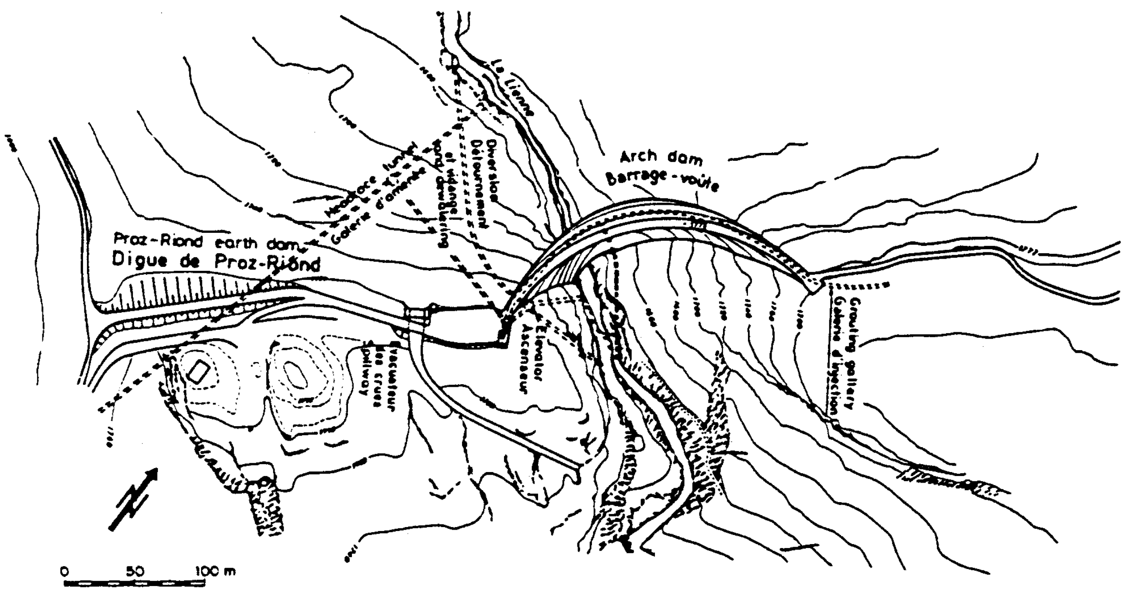


Figure 1: Plan view of the Zeuzier arch dam.

The dam is resting on a sound, thick zone of Malm-linestones 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 the strong limestone, 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.

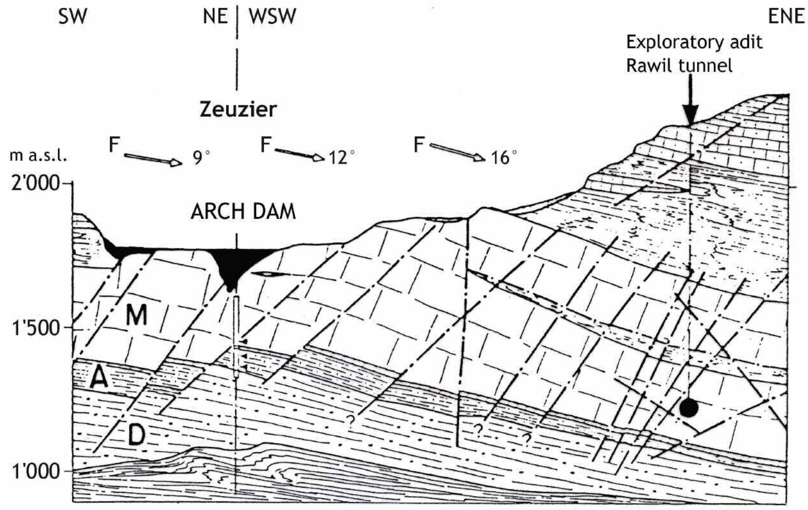


Figure 2: Geological profile through the rock bar of Zeuzier extended to the exploratory adit. The dam is founded on the Malm limestone (M), below which is the Dogger formation (D). The two are separated by the Callovian-Oxford series (A).

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 assumed.

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 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.

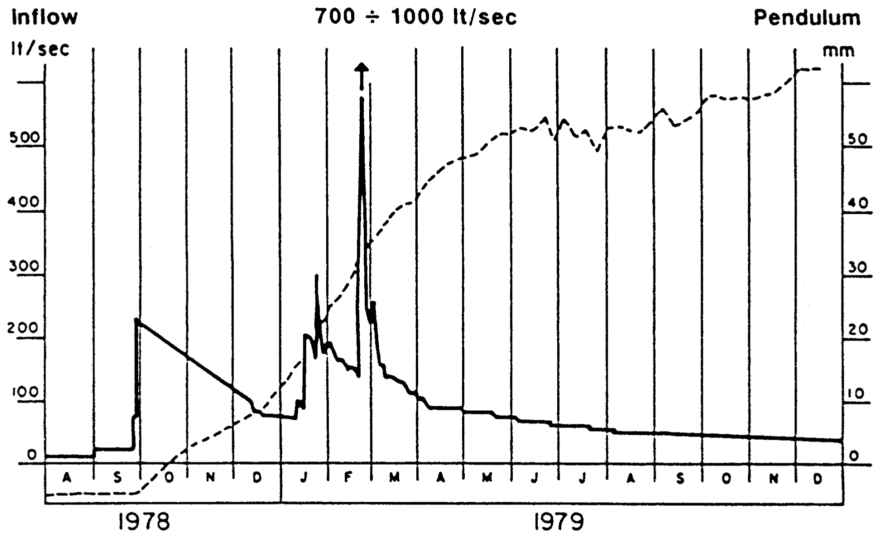


Figure 3: Zeuzier dam. Inflow in the exploratory adit (solid line) and upstream displacement shown by the central pendulum at crest elevation.

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 of the dam axis moved up to 12 cm upstream. Important 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 concrete 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 replaced in full operation.

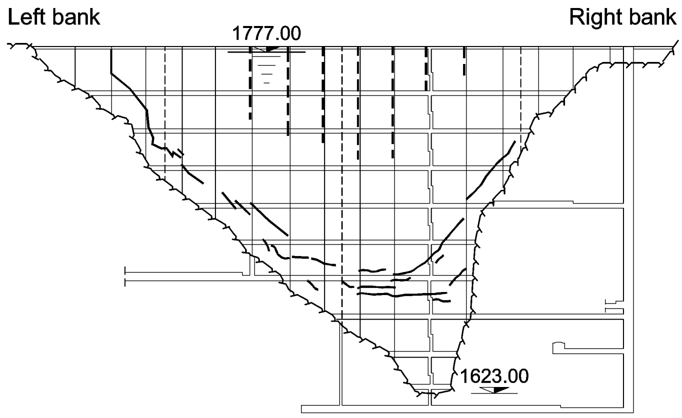


Figure 4: Zeuzier dam. Main cracks on December 1980
(openings above 1 mm; max. 15 mm)
upstream joint openings = dashed lines;
downstream face = solid lines.

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 or doubts any longer, on the causes of the settlements, on the damage mechanisms, 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.

3. THE FES-MODEL

3.1 General

The events of Zeuzier did confirm that the settlements of rock masses due to changes in the ground water conditions may be quite important, may have great financial consequences and can possibly create significant safety problems.
It has however to be recognized that the hydro-geological conditions at Zeuzier were particularly prone to this kind of phenomena.

One of the reasons of the successful salvage of the Zeuzier dam was the setting up and the development of the FES model; where FES stays for Fissured Elastic Saturated rock mass.

With time the model turned out to be a quite powerful tool for simulating the behaviour of such rock masses under situations of said type.

3.2 One-dimensional case

The first step in setting up the model consists in defining the average shape of the various families of joints to be considered.

Their shape will be geometrically approximated as shown in **Figure 5**. A number of fitting functions are available. The pattern of the contact points, that is the "wave length" of the undulations of the joints surfaces as well as their opening at zero compression, with the, non-mandatory, assumption of a linear elastic behaviour of the rock matrix in the stress range to be analysed are very important.

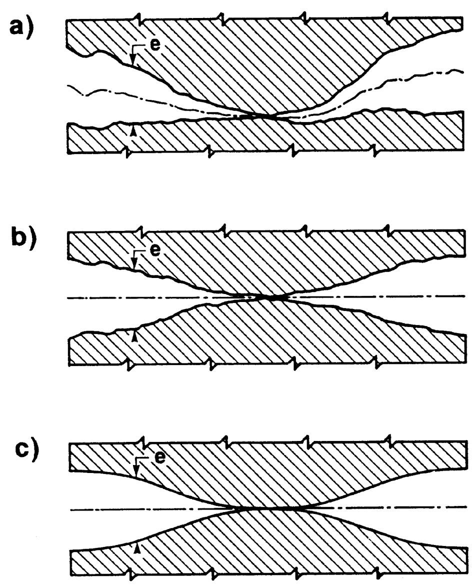


Figure 5: Approximation of the undulations of the joints surfaces:
a) actual surfaces of the joint opening with an irregular mean surface;
b) mean surface transformed to a plane, keeping the opening *e*;
best fit of the block surfaces, using an analytical formula (or a numerical vector). Equivalent smooth opening.

On these basis it was then possible to compute the, obviously non-linear, stress-strain relationship for a dry rock according to **Figure 6**.

A fundamental value is the so-called "closing ratio α" which varies from zero to unity and corresponds for a given stress level to the surface in contact referred to the total surface of the joint.

An important factor is also the spacing of the discontinuities or joints of every family.

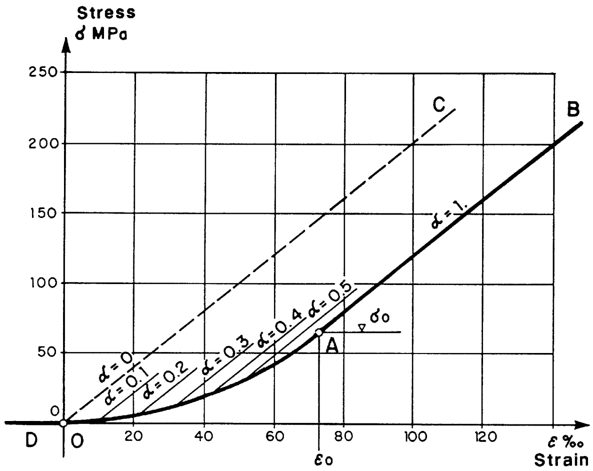


Figure 6: Example of a stress-strain relationship for a dry fissured rock mass (closing curve): α = closing ratio.

Introducing now a water pressure in the actually open part of the joints, the complete one-dimensional FES-Model can be build up as shown by **Figure 7**. Each point P of the plot corresponds to

- a total compressive stress σ;
- a "neutral" water pressure p;
- a strain ε;
- a closing ratio α as defined here above, and
- an effective stress σ_e which equals the difference between the total stress and the water pressure.

Additionally, a "contact stress" on the "closed joint surface" can be defined.

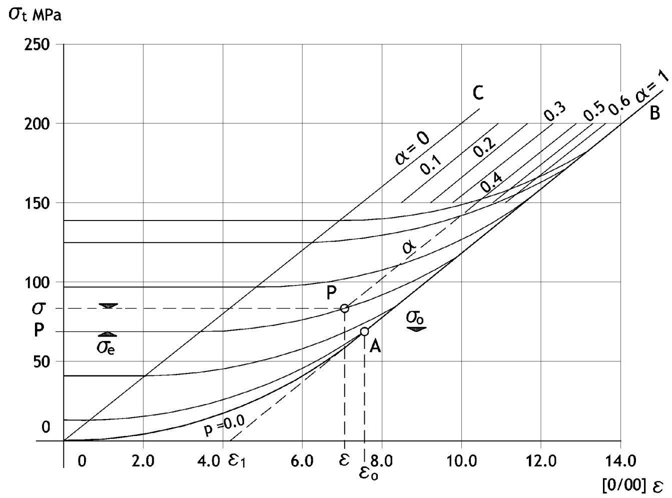


Figure 7: Example of a FES model of a rock mass:
ε = strain; σ_t = total stress; p = neutral water pressure;
α = degree of closure (α = 1 fissures completely closed, α = 0 fissures completely open); A (ε_0, σ_0) = point of total closure at nil water pressure;
σ_e = effective stress; P (ε, σ_t, p, α)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

Very interesting are the four moduli or ratios, which can be defined accordingly to **Figure 8**.

Starting from point H one may define:

- in direction ①, the modulus of elasticity E of the rock matrix;
- in direction ②, the modulus of deformability MD at constant interstitial water pressure (which corresponds to a kind of "consolidation");
- in direction ③, the modulus of settlement MT by reducing the water pressure at constant total stress;
- in direction ④, the ratio of the changes of the total stress to water pressure, which doesn't modify the strain of the rock mass.

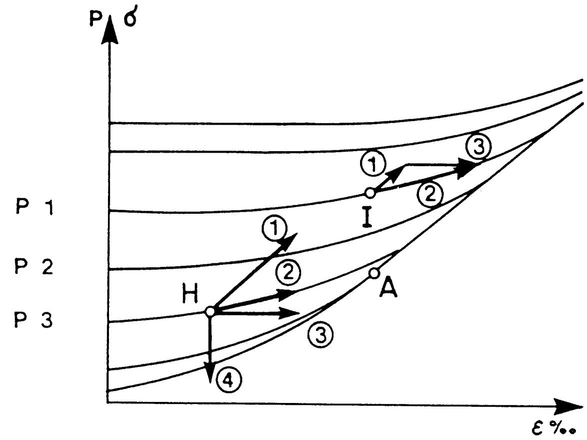


Figure 8: FES model. Significant changes of the stress- stain state:
(1) undrained loading
(2) loading at constant water pressure
(3) drainage at constant load
(4) change of state at no variation of the strain

Obviously the last three values are variable and are function of the state of stress; that means that they depend also on the depth below the ground surface, while E is constant, by definition.

In the problem dealt with hereafter, this modulus of elasticity E is however by far not the most important parameter.

In a similar way, the porosity of the rock mass and its permeability to water or to cement grout may be computed on the base of the sketch shown in **Figure 9.**

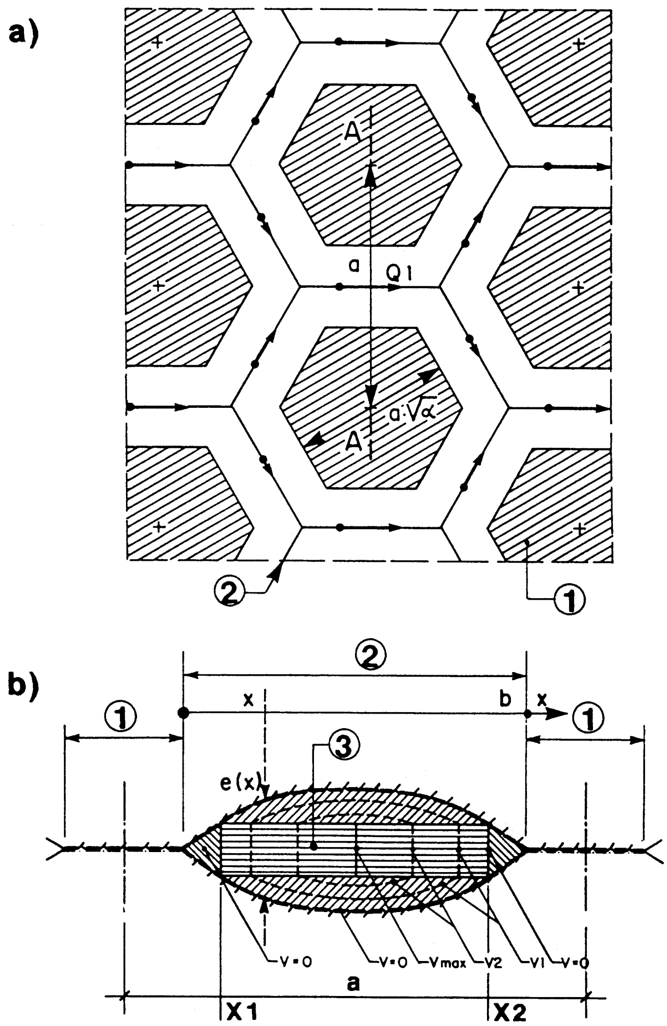


Figure 9: FES model of a fissure along its plane (for hydraulic mathematical analysis): (a) pattern of channels and islands; (b) cross section of a channel; Q1= flow through channel; (1) contact zones: (2) flow paths; (3) semi-rigid core (in the case of a cohesive fluid): v = flow velocity in the case of a Bingham' grout

A factor of the outmost importance for engineering problems is the variation of the permeability as a function of the state of stress of the rock mass. As a result of such calculations **Figure 10** shows the permeability by different initial openings of the joints in function of the depth below ground. The reduction of the permeability with depth is quite impressive and contributes to explain the generally low water inflows in very deep tunnels.

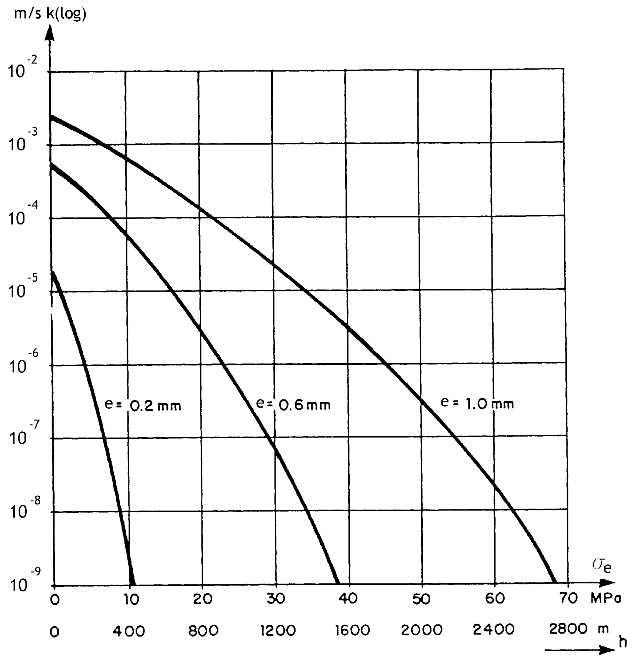


Figure 10: FES model. Permeability of the rock mass as a function of the effective stress: Example shows different joint opening (undulation) values; k = permeability; σ_e = effective stress; h = depth below ground; e = nominal joints opening at no compressive stress

3.3 Three-dimensional case

Up to now the presentation did refer to the uni-axial stress-strain case, as it was first set-up for solving the Zeuzier problem. Since then, the model was developed in order to tackle also three-dimensional problems taking into account different families of joints with different orientations and characteristics, but following always the same principles.

Fundamentally, the FES model takes into account:

- the elastic compressivity of the rock matrix;
- the elastic or elasto-plastic flattening of the asperities of the joint faces under compression;
- if required, the influence of weathered joint walls;
- the effect of the interstitial water pressure, as well as
- the changes of permeability and porosity of the rock mass with the state of stress.

Of course, there would be no problem, for example, to consider temperature induced deformations or other effects, should exceptionally some interest exist in them.

The results of the computations developed for the Zeuzier dam were extremely satisfactory and formed the base for deciding and carrying out the repair works already mentioned.

Figure 11 compares as an example the settlements measured (only at summer time due to accessibility problems) with the computed ones.

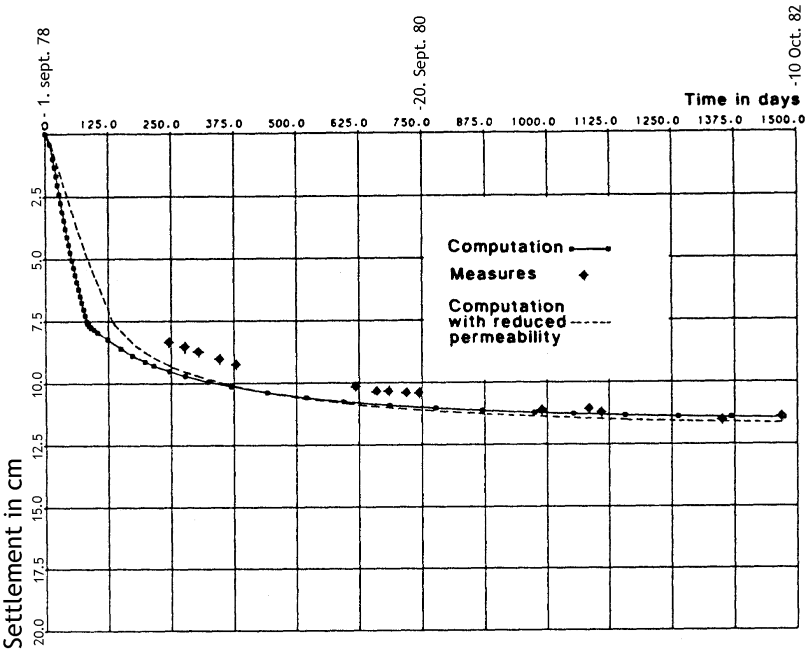


Figure 11: Zeuzier dam. Settlement below the dam versus time.

It might be observed that during about the first 100 days, the settlements did develop quite fast - about one millimetre per day - and that they did slow down sharply to about 1/100 millimetres per day, and later on about to zero. The sharp change of rate is easily explained. In the first period the aquifer was entirely captive and only a reduction of the interstitial pressure took place requiring a limited water outflow just to compensate for the volume reduction due to the closure of the joints.

In the second period the joints had also to be emptied so that the ground water table did lower much slowly; the same happened to the settlements.

In **Figure 12** the total volume of water drained may be seen in function of time.

Considering a steady feeding from the depth, the water volume actually drained from the aquifer by the exploratory adit has reached some 5 mio m^3.

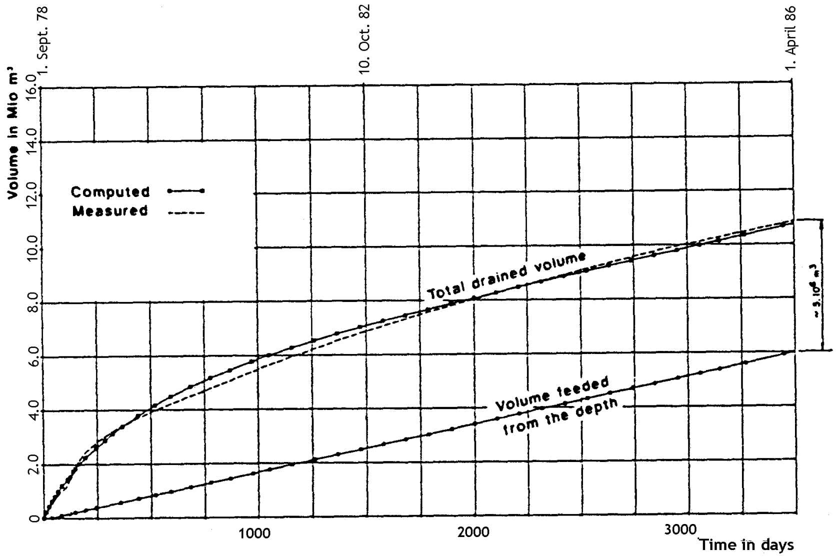


Figure 12: Zeuzier dam. Rate of inflow in the exploratory adit.

3.4 Swiss AlpTransit tunnel

Presently the two main tunnels of the Swiss AlpTransit rapid railway system, the Lötschberg and the Gothard, are under construction. Above and around them a number of dams do exist as shown by **Figure 13**.

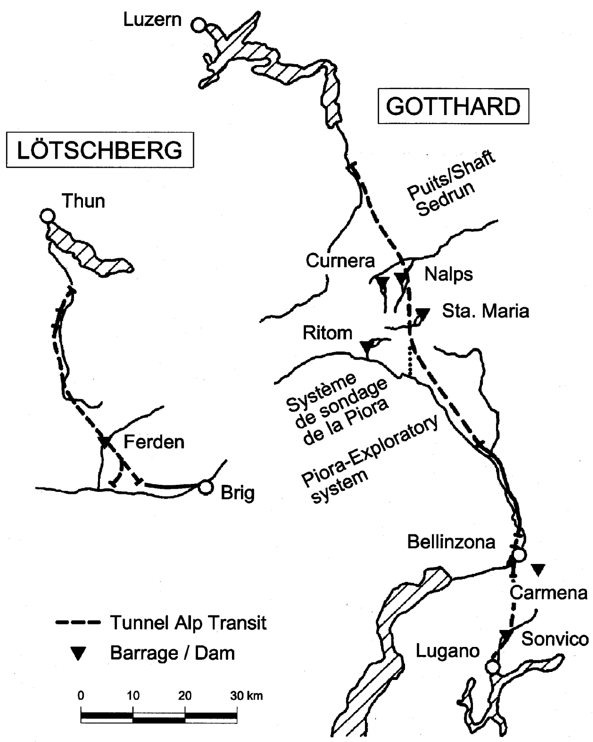


Figure 13: Dams in relation to the two tunnel projects.

The possible influence on the dams of the lowering of the groundwater table due to the drainage caused in excavating the tunnels cannot be ignored any longer.
The Swiss Federal Office for Water and Geology, which is in charge also of the security of the dams, promoted thus a campaign of studies and monitoring in order to create the basis for the decisions to be taken in order to ensure the safety of the populations in any situation.
Particularly sensitive appear to be arch dams, as the Zeuzier case did show.
It can be seen, in a very sketchy way, on **Figure 14**, how the settlements due to the drainage effect can produce a narrowing or, at the reverse, a widening of the valley, depending on the geological and hydro-geological conditions of the rock masses involved, as well as on the position and orientation of the dam site in respect of the tunnel.

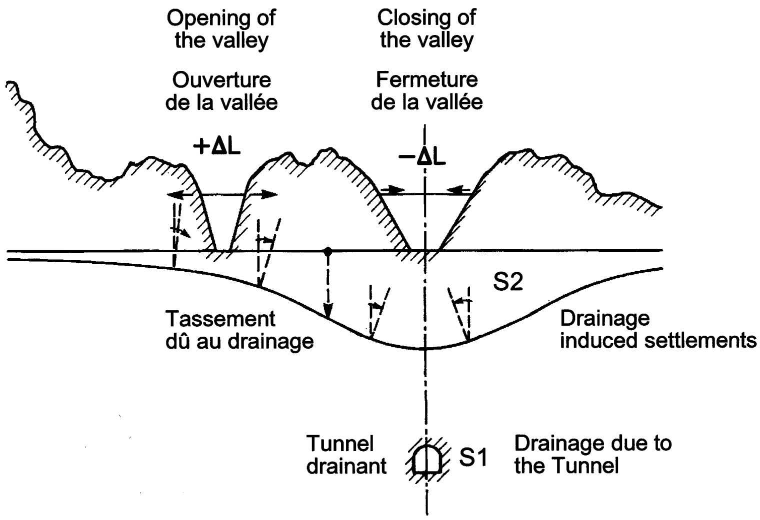


Figure 14: Opening and closure of the valley flanks due to the drainage during the tunnel construction.

Obviously determinant for these settlements is the amount of water inflow into the tunnel, which can of course be influenced to some extent; e.g. in grouting the rock mass around the tunnel.
In order to clarify the question a number of FE computations on the basis of the FES model were carried out.
Figure 15 shows one of them. For each rock type a configuration with specific joint pattern and characteristics was chosen, as shown as an example on **Figure 16**.

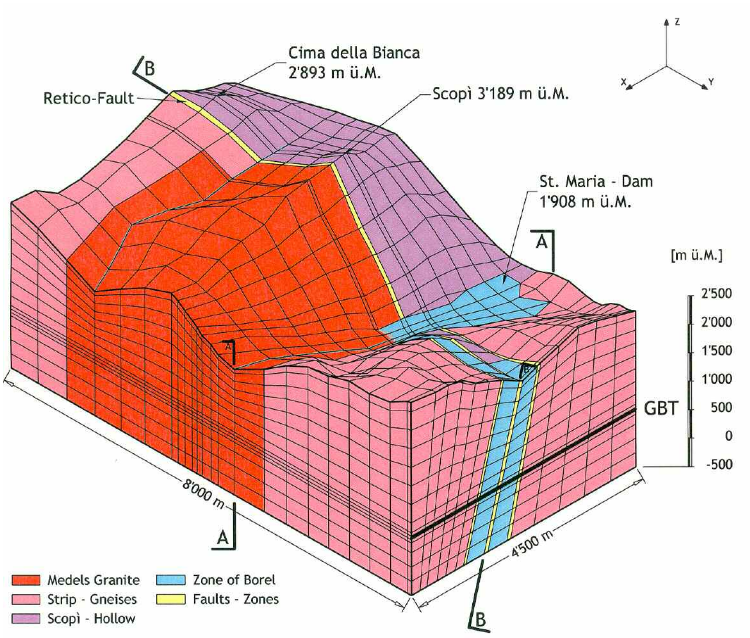
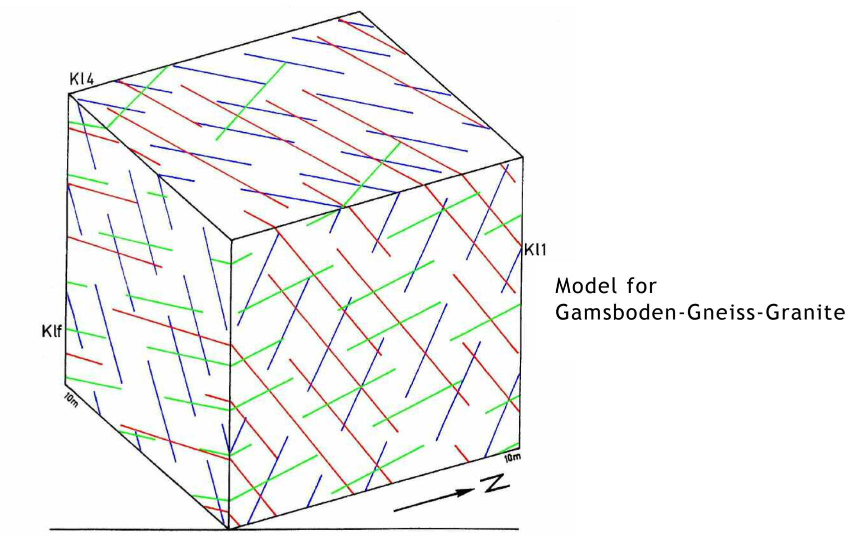


Figure 15: FES - Mesh for a stretch of the Gotthard AlpTransit Tunnel.



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

For each of the three interested arch dams the allowable ground displacement were computed as can be seen on **Figure 17** for elementary "loading cases" to be combined. They include two types of narrowing-widening of the valley, as well as a twisting of the dam site.

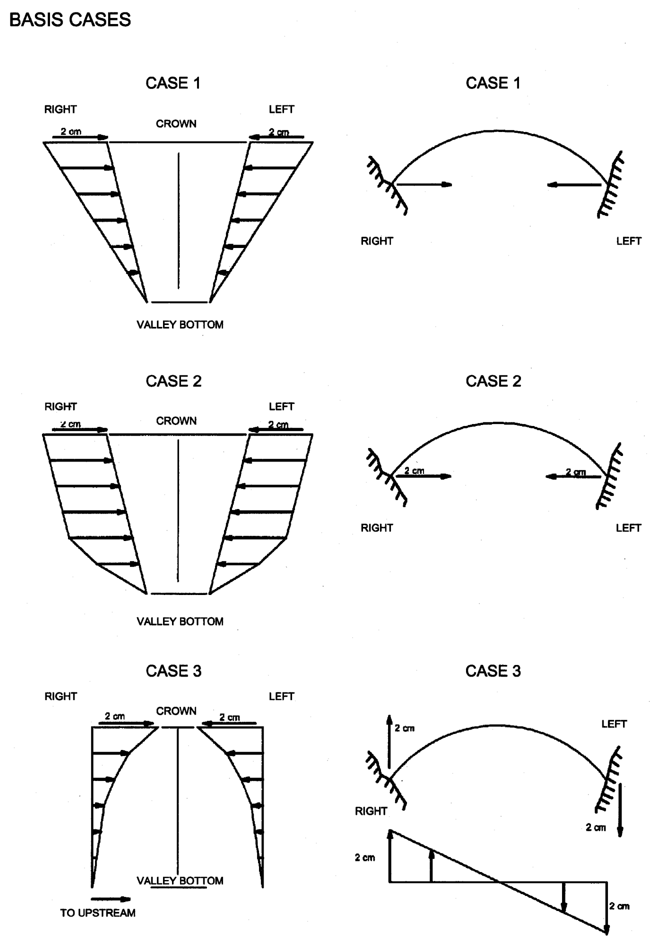


Figure 17: Influence of the displacements of the abutments on the dam. Foundation deformations.

Obviously, the actual behaviour of the dams will be severely and continuously checked before, during and after the crossing of the tunnel excavation below them.

Additionally to the existing usual instrumentation of the dams, two main aspects of the possible movements of the rock surface will be monitored:

- firstly a high precision levelling along the axis of the valleys will put in evidence any settlement related to the advance of the tunnel excavation;
- more important is however the detection of any narrowing or widening of the valley in the region of the dam. Therefore, cross sections of the valley at the dam site itself, but also at some distance upstream as well as downstream of it were instrumented and will be measured frequently.

A first case is already solved: that is the crossing of the Lötschberg tunnel under the arch dam of Ferden, which happened without causing any harm to the dam.

3.5 Local effects due to interstitial water pressure

Up to now, only settlements due to the depressing of the water table were discussed, but obviously the heave due to a raise of the water table may also be of interest. The same occurs when grouting a fissured rock mass.

But, the use of the FES model is not limited to the big scale problems like the ones already dealt with, but may also help to solve local problems, e.g. for foundations of concrete dams.
So, the action of the increased water pressure upstream in conjunction with draining the downstream section may cause a rotation of the dam foundation as a whole. **Figure 18** shows these conditions for a gravity dam.
In case of an arch dam, taking into account this factor may change somewhat the stress conditions of the structure.
Considering these secondary effects, the interpretation of the results of the dam monitoring may possibly be improved.
Additionally, the moduli of deformation of the fissured rock mass do change accordingly with the state of stress. The assumption of an uniform, constant elastic modulus of the rock foundation may thus be misleading.

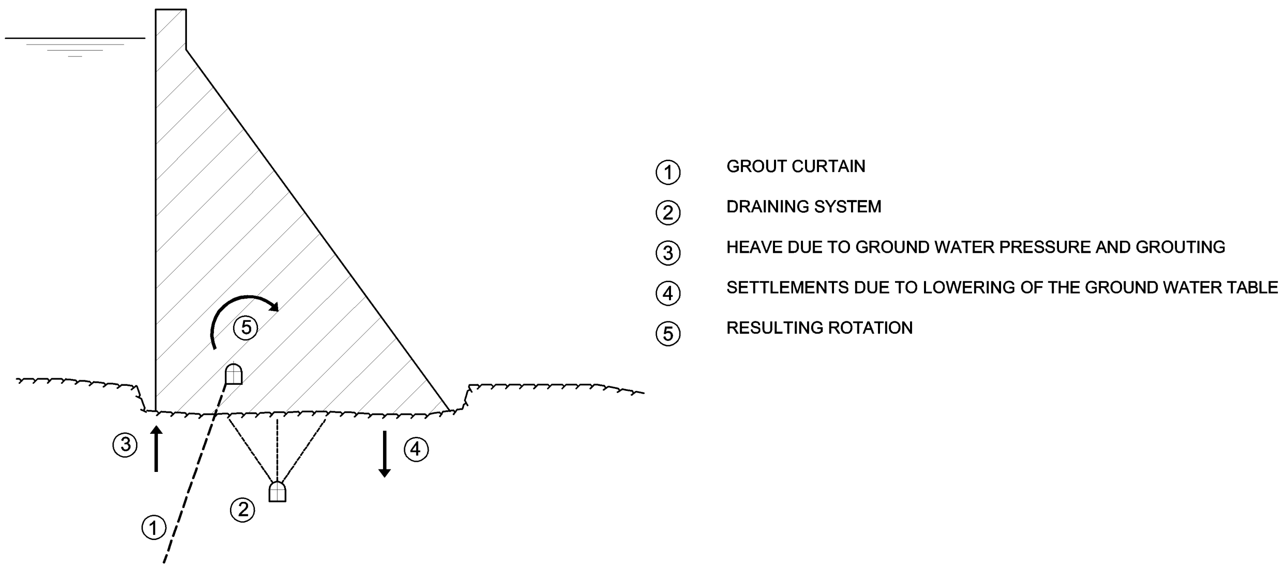


Figure 18: Influence of changes of the interstitial water pressure on the dam foundation.

An interesting case is also the one that did happen to a recently built underground powerhouse according to **Figure 19**.

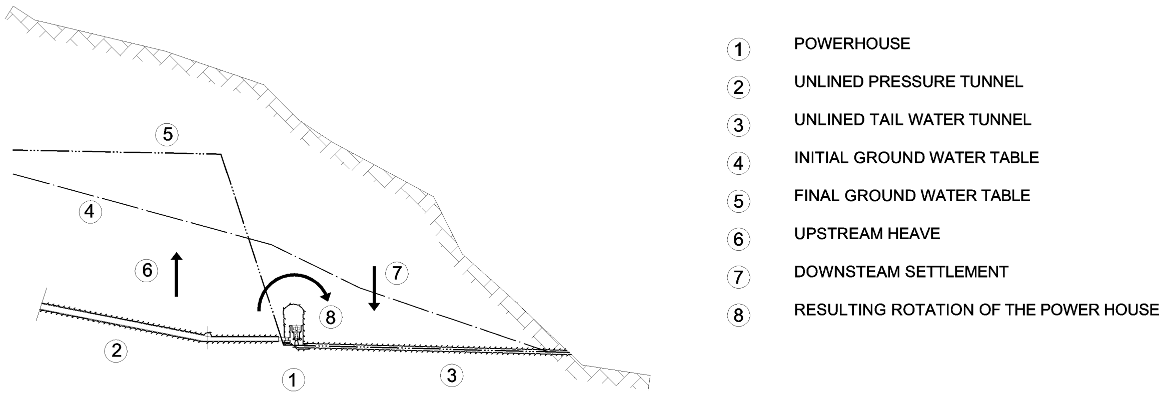


Figure 19: Influence of the changes of the ground water table on the verticality of the power units.

The unlined pressure tunnel did feed the rock mass upstream of the powerhouse, while the tailrace tunnel was draining the same downstream of the cavern.
The combination of the resulting upstream heave with the downstream settlement caused a rocking of the powerhouse and thus some problems with the verticality of the power units.

4. LIMITATIONS TO THE COMPUTATIONS

As in any computation related to big volumes of ground, difficulties may arise from the lack of information on the main parameters, especially if they apply to very deep zones below the ground surface. The experimental determination of the same, is often impossible or at least not affordable.
It is therefore necessary to estimate, as precisely as possible, the parameters that are needed for defining the model. In doing so, an extreme care is required. Indeed, the temptation is very strong to select values, which will allow fine computations, without paying enough attention to a good fit to the physical reality.
It may also be recommended to carry out a complete sensitivity analysis as well as to make a clear distinction between primary and secondary elements of the problem.
The observation of the reality on the field as well as comparisons with known cases are also of the outmost importance.

In this respect, the settlements produced during the construction of deep tunnels should be recorded, even if not of immediate interest, in order to create a database for future scopes. So, for example, the settlements due to the construction of the Gothard highway tunnel (1969-1980) could be used to calibrate some computation carried out, for the deep AlpTransit railway tunnel presently under construction, as mentioned here above. In turn the geodetic path installed at the occasion of the construction of the first rail tunnel (1872-1882), which is periodically levelled since that time, was used for the measurements of settlements due to the highway tunnel.

In spite of the good results obtained to date, some complements of the FES-model are still possible and are presently under consideration. Their aim is to allow some refinements of the computations of settlements as well as to improve the grouting procedure around the tunnels.

5. FINAL COMMENTS

To conclude this brief presentation one can state the following;

- movements of fissured, even very firm, rock masses due to changes of the ground-water table can no longer be ignored;
- of peculiar interest are the settlements induced by the lowering of the ground water table due to the construction of deep tunnels;
- these movements may affect the structural integrity of dams, where arch dams appear to be generally the most sensitive ones;
- but, also more local effects may influence the behaviour of the dam foundation;
- the FES modelling has shown to be a quite use- and powerful tool to solve problems of this kind, even if it can still be complemented in some details.