5 Y

International Workshop on

DAM SAFETY EVALUATION

Grindelwald, Switzerland, 26-28 April 1993

Sponsored by the international journal
Dam Engineering

Co-sponsored by the
International Commission on Large Dams

CIGB
ICOLD

VOLUME 4

KEYNOTE LECTURES

Edited by
H. Kreuzer, R. Dungar
and R. Taylor

Quadrant House, Sutton, Surrey,
SM2 5AS, United Kingdom

Fax: +44 (0)81 770 9982
Tel: +44 (0)81 770 9972

Concrete Dams and their Foundation.
Evaluation for static Loading.

Giovanni Lombardi Dr Eng. Dr h.c.
Consultant civil engineer
Via Simen 19, 6648 Locarno-Minusio
Switzerland

SUMMARY

The scope of the paper is to present a number of remarks and comments related to concrete dams, taking into consideration some recent experiences and developments as well as recalling old, sometimes forgotten, rules for dam design, construction and monitoring. Only static loading will be considered. The relevancy of the following aspects for dam safety will be pointed out:
Concept of safety, dam types, materials, properties of the concrete, concrete technology, aging of the concrete - also Alkali-Aggregate Reaction -, limits for dam dimensions, foundations, instrumentation and monitoring, old versus new dams and finally needs for research.

INTRODUCTION

Every body will agree for sure that it will not be possible, in the time and space allocated, to present here and today a systematic and exhaustive review of all the aspects which may be involved in the safety evaluation of concrete dams under static loadings. I will therefore focus only on a number of topics which deserve, in my opinion, more attention as they were often overlooked. In doing this selection I may have a view somewhat distorted by more or less recent factual experiences!
I also may raise more questions than solving them.

In talking about safety, we should consider not only the case of a total catastrophic rupture of the dam, but also the conditions of future operability of the structure which includes safety against cracking, leakages and, at least to some extend, even against aging.

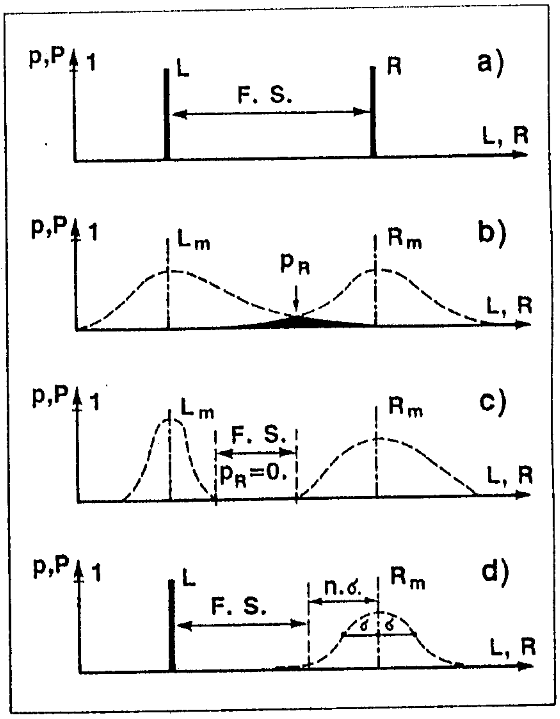
1. SAFETY IN GENERAL

The notion of safety is, in itself, a quite complex question and a number of different interpretations may be proposed.
Anyhow, the principles and aims of any study on safety are obviously very simple; they consist to place the engineer in the position to take the right decisions at the right moment in order to exclude any risk of a given event (like a rupture), or at least to reduce the likelyhood of its occurrence below a certain limit which may be considered to be acceptable by the decision makers, the people concerned, or even the "society"; whatever this may mean!
The difficulties are only two:

- to compute the probability of occurrence of the feared event - which probability has, in our case, to be always extremely small - as well as the connected risk, and
- to define the limits of acceptability for this risk.

To compare the two values will not be a big mathematical problem any longer!

The sad fact is that we generally are able to establish more a less exact mathematical relationships connecting variables together which can unfortunately not be known with the desired precision even in the case their value actually exists. Even more, we may not be able to decide whether our nice mathematical models do or do not fit reality; or better said, whether the reality will obey our models or not!



LEGEND

L = Load
R = Resistance
L_m,R_m = Mean values
σ = Standard deviation
n = arbitrary number
p, P = Probabilities
F.S. = Factor of safety
p_R = Probability of rupture

Figure 1. Concepts for safety

a) Classical definition of the Factor of Safety
b) Probabilistic approach with unbounded distributions leading always to a probability of rupture.
c) Approach with bounded distributions (to cover the expected uncertainities) and reduced factor of safety (to cover the unexpected uncertainities). The probability of rupture may be nil.
d) Concept of significant Resistance (strength)

The first simple and somewhat brutal way followed by the engineers since at least one century is to define a factor of safety with the intention to keep a supposingly well known "Load" far enough away from a supposingly equally well defined "Resistance" or "Strength" of the structure. The magnitude of this factor of safety was intended to cover some not completely unexpected "uncertainties" of both values or some actually unforeseen phenomena. (Figure 1a)

However, since Pascal, Gauss and many others invented the notion of distributions of probability - which laws appear, from the pure mathematical point of view, to be more easily handled when unbounded (that means being at least in one direction infinite), than bounded - a second way was opened and the probabilistic safety theory made a lot of very impressive progresses. (Figure 1b) So that everything - including the failure of any dam - is made possible: it is only a matter of computing the probability of the event and to define the probability of rupture which may be accepted.

That much, that a friend of mine could compute in 10^{-123} the probability for a fly to crush a 1 m^3 high quality concrete block alone by its own weight, just because there seams to be some probability for the concrete block to be as weak as a gravel pile and also some other probability - I don't remember the exact figure of - for the fly to be as heavy as an elephant! (Figure 2)

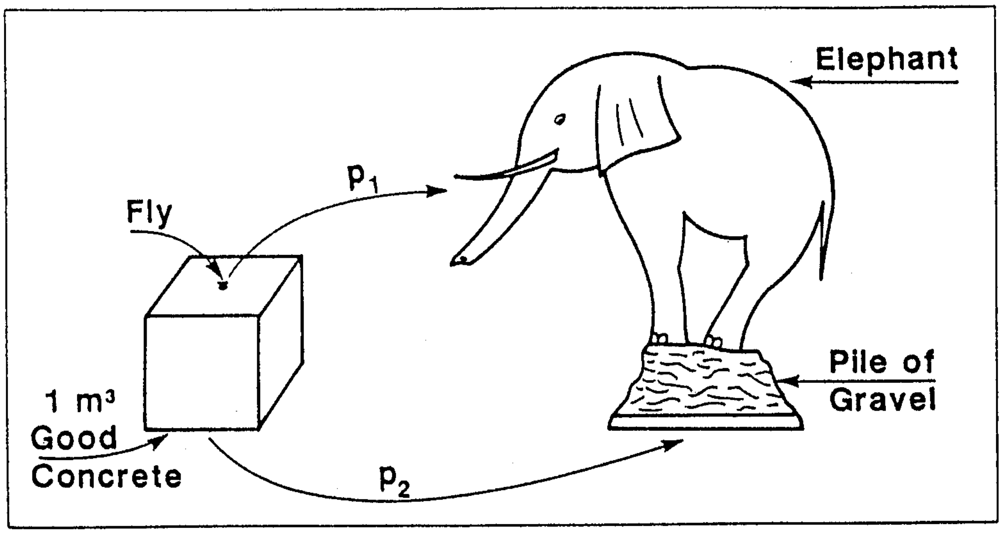


Figure 2. The Probability for a fly to crush a concrete block depends on the probability p_1 for the fly to be as heavy as an elephant and on the probability p_2 for a concrete block to be as weak as a pile of gravel.

I objected that there should be some biological limit for a fly to become as heavy as an elephant, and also that some condition should be found - at least in the specifications for construction - to avoid a concrete mass being as weak as a pile of gravel. But apparently, I was not entitled to make such simplistic objections as I am not a specialist in mathematical probabilistics!

I feel, nevertheless, that above and below a certain number of standard deviations from the mean value of a variable we definitively do not know anything about its probability of occurrence.
Even so far that the philosophical question could be raised whether we are entitled to believe such a distribution really exists and even more that it can eventually be seriously defined and represented by a simple mathematical formula.
I myself also have no difficulty to recognize, for instance, to be unable to work out the difference between a probability of rupture of a dam of one in a million years and that of one in ten millions or even only in 100'000 years. It may also not be that easy to understand why the one should and the other should not be acceptable to the "society".
The only actual explanation, I could work out, for the interest to use unbounded distributions, could be to open a door in order to try to escape from the responsibility in case of a disaster thus being able to invoke some "calculated risk". But, I may be wrong, as I am not well aware of legal questions of this kind!
I therefore definitively prefer to believe that the fly will never crush the concrete block unless the concrete block falls apart by itself with time, for example, due to an alkali-aggregate reaction.

In these conditions, a third way to procede could be envisaged. It would consist in accepting probabilistic distributions but only to the point where an experimentally reliable support for such distributions really exists and remains meaningful. (E.g. down to a probability of 1 in 1'000 for the strength of the concrete). In fact bounded distributions should be used to consider the "expected uncertainities". To cover the still existing, but now significantly reduced, "unexpected uncertainties", a much smaller factor of safety as before should be introduced in the computations. (Figure 1c)
A certain step in this direction was already done, for example, decades ago with the introduction of the so called "significant concrete strength" defined as the average strength minus one or two standard deviations. (Figure 1d).

Another step in this direction is done if one adds some margin to a 100 or 1'000 years flood instead of trying to extrapolate to longer unrealistic periods of return.

At the end, the here-above suggested way of operating consists in using bounded or truncated distributions and in still recognizing, by engineering judgement, some degree of residual ignorance.
Really, in nature everything is limited, except obviously the mathematical expressions for unbounded distributions of probability!

2. TYPES OF CONCRETE DAMS

From the historic point of view, concrete dams can be considered to be the heiresses of the masonry dams of the antiquity, the middle age and the beginning of the new age. Gravity, arch, arch-gravity, buttress and multiple arches were first built many centuries ago.
From the practical point of view I may suggest to distinguish two groups of concrete dams:

- dams with a simple shape, and
- dams with a complex shape.

It is interesting to point out that simply shaped dams as, gravity, arch and arch-gravity dams will present an exposed concrete surface of the order of only 2.3÷2.5 times the cross section of the dammed valley.
Dams with complex shape however, like buttress or multiple arch dams, present a ratio of the exposed surface to the valley cross section much higher, often many times higher, than the above value. (Figure 3)
The people in charge of the maintenance of dams apparently often know better the importance of this ratio than some designer does.

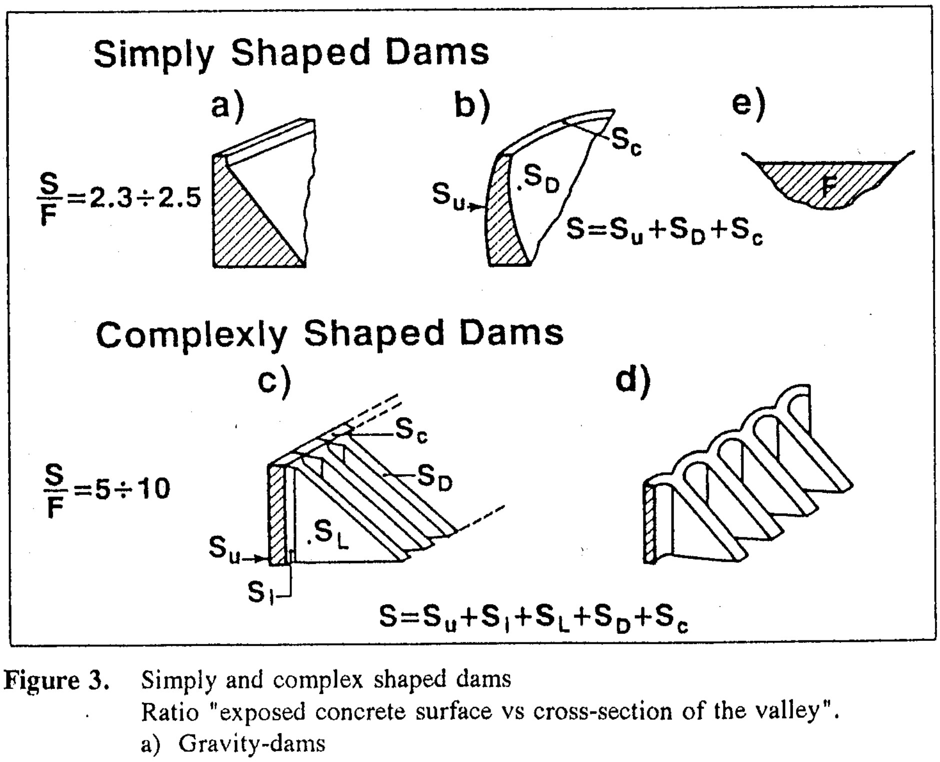


Figure 3. Simply and complex shaped dams
Ratio "exposed concrete surface vs cross-section of the valley".
a) Gravity-dams
b) Arch-dams (also arch-gravity dams)
c) Buttress-dams
d) Multiple arch dams
e) Cross-section of the valley

A complex shape means obviously, as a rule; (i) a thinner structure with more problems related to tightness, and consequently more problems of frost and concrete aging in general, (ii) higher sensitivity to thermal effects and consequently higher thermal stresses with, from time to time, the necessity of a later thermal insulation. (iii) But some time quality problems may also arise due to the more complicated constructional procedure and the higher concrete strength required.

The evolution from masonry dams, to concrete dams with masonry paraments, to pure concrete dams and more recently to Roller Compacted Concrete dams (RCC) is in fact a further expression of the progress of the mechanization and the industrialization expanding progressively also into the field of dam construction.

Even with some delay, the increasing costs of labour versus the costs of materials have reduced or are still progressively reducing the advantages in total costs of complex dams versus simply shaped structures.

However, simpler shape doesn't mean automatically less refined shaping work or less analysis at design stage. Just the contrary may be true.

Finally, in special cases, complex shaped dams may still be justified.

3. MATERIALS

Concrete, as a material for dams, evolved also along this century with highs and downs. For examples the very high water content used in the twenties to ease the placing and to increase the productivity turned out at the end to be a big and very expensive flop, as the concrete did not resist frost attack. A number of dams in rougth climates were rebuild for this reason.

However, for the time being, it appears that the technology of normal, standard concrete has reached a high level of quality and has more or less stabilized since a number of years. But it seems also that in many cases the possibility of a long term alkali-aggregate reaction was disregarded or underestimated at design stage. At present time, at least 100 large concrete dams appear world-wide to have undergone heavy problems of this kind.

In such conditions the safety of the dam is diminishing from year to year and the question arises about the moment when the conditions of safety can no longer be accepted.

An additional point to be considered is the following. As any other property, the strength of the concrete is subject to some variability which defines a certain standard deviation.

As a rule, the tests are carried out on samples sized by, let say, 0.3 m. The computed standard deviation is therefore strictly related to this size of samples, which are, adequate for usual reinforced concrete structures. But, obviously, the safety of a large dam - especially if simply shaped - is for sure not jeopardized by the strength of a 30 cm cube nor of a number of such cubes. The safety of the dam may be affected only by an actual low strength of a larger mass of concrete, for example 100 or even 1'000 m^3. (Figure 4)

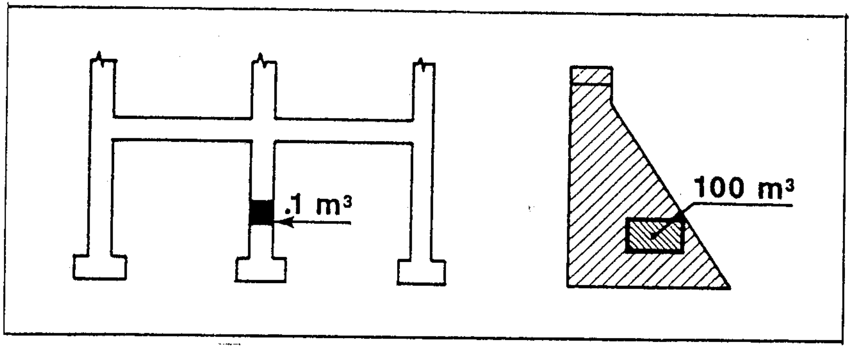


Figure 4. Importance of the standard deviation of the concrete strength
The strength of just 0.1 m^3 concrete may jeopardize the safety of a building. The average strength of as much as 100 m^3 (or 1000 m^3) may just slightly influence the safety of a large dam.

The standard deviation of the strength of such a big volume of concrete is clearly much smaller that the deviation computed on the base of test results on usual cubes or cylinders.
Similar considerations apply obviously to the minimum average strength. It appears therefore that some thinking should and could be devoted to this aspect of the safety of large and more massive dams, and also in defining the allowable stresses. It is felt that, possibly, a different way of computing the standard deviation of the concrete strength should be adopted as the usual one.

While the compressive strength of the concrete is a quite reliable property, this is not the case for the tensile strength. In my opinion, any safety consideration should therefore, be based only on an ultimate stress pattern after having eliminated all the tensile stresses. The so called No-Tension analysis may be used. Concrete in tension is a brittle material, so the moment of a rupture in tension is sudden and unpredictable. Safety against rupture can in fact not rely on the tensile strenght of the concrete! (Figure 5)
No computation based on rupture mechanics or any other method, like the smeared cracks theory, will change this fact, or at least my opinion on this point!

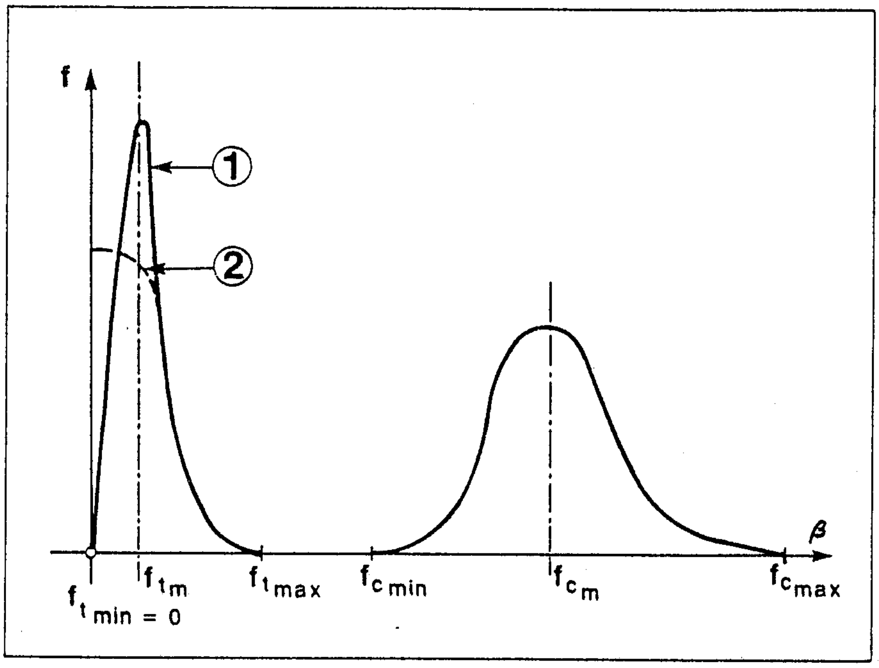


Figure 5. Probability distribution for tensile (f_t) and compressive strength (f_c) of the concrete
① usual distribution for tensile strength
② more realistic distribution.

Evidently, tensile strenght may be taken into consideration for usual operation- based load cases, for instance, to compute the deformations of the dam.
Furthermore, the question has to be raised whether the same tensile stresses should be allowed at any point and at any direction of the concrete structure.
A difference should be made, in my opinion, between upstream and downstream face and also in function of the direction of the principal stresses. More precisely, if a section is affected by tension, one should take into consideration whether this section will have to transmit a transverse shear force or not.

The exact value of the moduli of deformation of the concrete may not be that important as often thought.

Much more decisive, especially for the long term behaviour of the dam is the tightness of the concrete; not only as found on laboratory samples, but obviously the tightness really existing in the dam itself, taking into account lift joints and any kind of defectiveness. Also in this respect the properties of a big concrete mass may not be well represented by laboratory tests or small samples.

RCC (Roller Compacted Concrete) is a new kind of material. As such it will probably lead to new shapes for dams. It does not appear however that definitive conclusions can yet be drawn on this aspect of dam design.

Modern concrete dams do not consist exclusively of concrete. Many other materials as: steel, PVC and other plastics, bituminous materials, grout mixes, resins, silicates, are used in addition to the chemicals required to improve the properties of the concrete mass itself, like workability, water reduction, tightness, setting time, air entrainment, resistance to frost, chemical resistance. It appears to be quite obvious that RCC dams will in any case require the use of some other material - the simplest being normal concrete - to tighten their upstream face in an acceptable manner.

4. CONCRETE COOLING, GROUTING OF JOINTS

The arguments in disfavour of normal concrete as a material for dam construction are well known: they are the shrinkage and the thermal properties of the concrete mass and, especially the hydration heat of the cement, and its consequences. They impose pre or post-cooling, as well as contraction joints and their grouting. All this shall duly be taken into account at design and construction stages. (These disadvantages are reduced and, in some cases, completely eliminated using RCC.)

The influence of the said phenomena on the final safety of the dam is not always well understood nor taken into account in a perfect manner.

The same may also be said, in a more general sense, about the construction procedures, which may in many cases differ from the original thinking of the designer. (E.g. grouting of the construction joints in stages with a different schedule as planned).

Internal stresses and even cracks may be induced at construction stage which may influence the behaviour of the completed dam and therefore possibly also its safety.

Often disregarded are - quite obviously - the consequences of on-the-spot decided "remedial groutings" where, as a rule, any kind of products, mixes and uncontrolled procedures are used.

I would like to say: "Think a lot before and during grouting! You may unwillingly and unknowingly disturb substantially the state of stress of the structure and possibly jeopardize its safety."

5. PERCOLATION AND FLOW INDUCED FORCES

Even the best concrete is never absolutely tight. With time, may be after years, a saturation of the concrete mass - or of part of it - will take place. Consequently a pore pressure will develop in the concrete.

The difference in pressure potential between the upstream water level and the atmospheric pressure - or a reduced water pressure - at the downstream face or at the drainage system must and will create a hydraulic gradient field in the concrete. This field may in fact differ significantly from the theoretical one, but will in any case produce "flow induced" forces which are seldom favourably oriented and may deeply affect the behaviour of the structure favouring the forming of cracks. The reasons for deviations from the theoretical field are due to the non uniform, anisotropic, and irregular permeability conditions of the concrete as well as to eventually existing cracks and micro fissuration.

This kind of phenomena was often ignored, some times with unpleasant consequences.

Two real examples are shown in Figure 6. The first one (Figure 6a) refers to a horizontal section of a gravity dam with drained contraction joints: the second one (Figure 6b) refers to a vertical section of an arch dam with drained bottom joint.

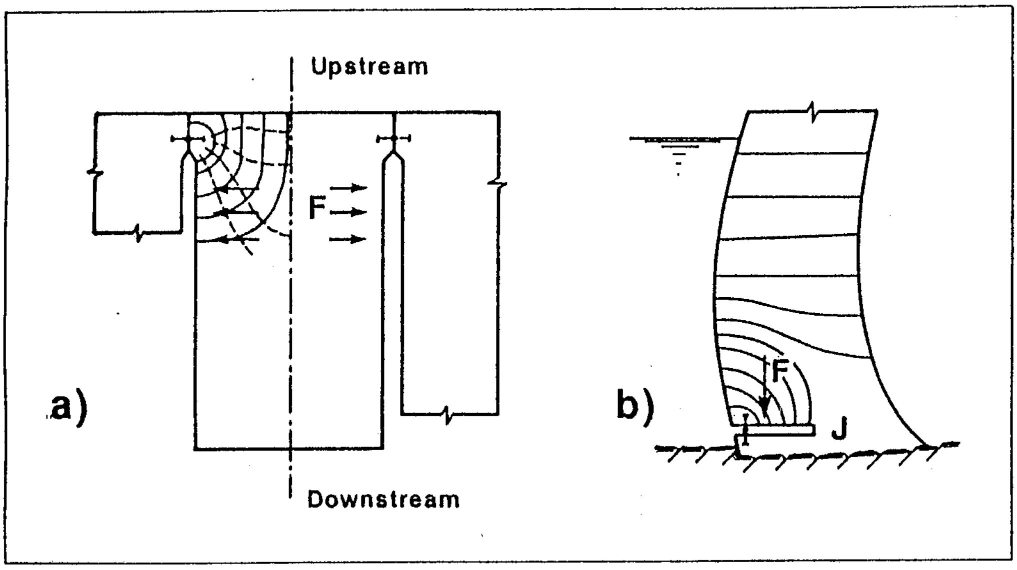


Figure 6. Flow-induced Forces
a) Horizontal section of a gravity dam block with ungrouted drained joints. Flow-net and splitting forces F.
b) Vertical section of an arch with drained bottom joint (J). Flow-net and down pull forces (F).

In the first case, the induced forces in combination with fine cracks of thermal origin have split a number of blocks along their axis of symmetry. The designer had probably his attention focused on the vertical section of the dam and on the reduction of the uplift forces due to drained joints more than on the mentioned flow induced splitting forces in the horizontal direction.
In the second case, the down-pull forces caused by the drained bottom joint were not considered in the computations. In conjunction with the reduced bond strength between the concrete lifts, they were the cause of an important cracking of a dam block.
In fact, it may not be conservative enough to simply consider the water pressure as acting on the upstream contour of the dam cross-section. Sections with different orientations may also need to be introduced in the safety evaluations in addition to the usual vertical and the horizontal cross sections.

6. AGING OF THE CONCRETE

Aging of the concrete assumes various forms; however it may be stated that aging is always related to the presence of waters in the dam body. This refers to leaching out of calcium hydroxide, to frost action but most especially to possible alkali-aggregate reactions (AAR).

To take place, alkali aggregate reactions require, evidently special chemical conditions, regarding cement, aggregates and water, we will not discuss here. But in any case, swelling of concrete, due to physio-chemical phenomena, can take place only in a wet or even better in a saturated environment.
It is thus easily understood how inhomogeneous, irregular, anisotropic, as well as temperature and stress-dependent the swelling process will be, both in its amount and its development with time.
A number of unknown aspects still exist in this field, which must be mentioned and which will require more research in future.

It appears from experience, that a number of interrelated aspects of the swelling process need be duly considered.

- In a not restrained concrete body, the AAR will produce, in presence of water, a volume increase, a possible reduction of the compressive strength with time, but will be accompanied by a fine net of thin fissures and by a very significant loss of tensile strength. Consequently the ratio tensile to compressive strength will diminish along with the years.
- As the concrete body, that is the structure or part of it, can actually not expand completely freely, but is restrained by the rock foundation or by other structural elements, a pattern of restraining forces will appear, which quite easily will overstress the structure causing generally the main cracks one may observe.
- Conversely this stress field will retro-influence the swelling process itself causing even more complicated distortions of the stress and strain fields in the dam.

  The less unfavourable case is obviously the one where the swelling process will induce only compressive stresses in the structure. The worst case is, in general, the one where the tensions will cause big concentrated cracks which may split the structure.
- As the swelling itself depends on the water supply, it is likely to be more intensive at the upstream that at the downstream part of the structure.
- As the swelling is stress dependent, the vertical expansion in a gravity dam will be, for instance, more important in the upper than in the lower part of the section.
- As it depends also on the level of humidity of the air, it will have a different intensity from spot to spot, e.g. be different around the inspection galleries as in the interior of the concrete mass itself.

No doubt, that the overall safety of the dam will diminish with time due to various phenomena of the kind just mentioned.

For that reason, it could be worthwhile, at least in certain cases, to study the opportunity to protect entirely the concrete body from water, by an absolute water tight and safe upstream as, for example, a complete steel lining could provide. Possibly the disappearance of any uplift force, in such a case, could allow a certain saving in the concrete volume, which may eventually pay for the lining. This is more likely to apply for high than for small dams.

7. LIMITS FOR CONCRETE DAMS

It also may be of interest to discuss the practical limits for the design of safe concrete dams.

Due to the concrete strengths achievable today, it is believed that gravity dams up to about 400 m height could be safely built. It may be recalled that the Grande Dixence gravity dam has an height of 285 m and that it behaves in an excellent manner since construction time that is about since 40 years.

For the time being, there seems also not to be a practical limit for gravity dams from this point of view.

For arch dams, a first limit is given by their slenderness number in function of their height. Additionally a limit certainly exists for the value of the ratio crest length (or width of the valley) to the dam height. Above this limit, problems will appear at the upstream heel at the valley bottom. Progressively the arch dams looses also its advantages when compared with a gravity dam (or a fill dam) on the base of cost considerations as well as for structural reasons.

A logical evolution of the shape of the dam in relation to the width of the valley is schematically shown in Figure 7.

Actually, the safety limits for large concrete dams, both gravity and arch, - as well as for complex dams - are to be searched firstly in the conditions of the rock foundation.

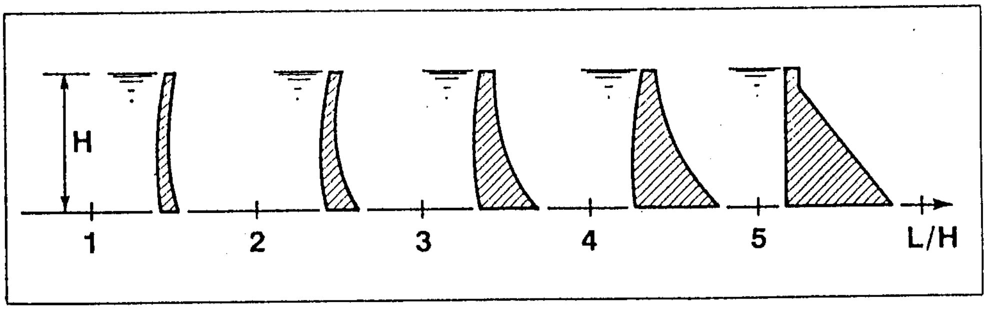


Figure 7. Evolution of the crown section from thin arch to thick arch, to arch-gravity, and to gravity dam in function of the ratio: crest length L to dam height H.

8. ROCK FOUNDATIONS

In fact, the rock foundation of a concrete dam represents often the weak link in the safety and in its evaluation. In addition the knowledge one has of the actual rock conditions and strength is by far not of the same quality nor extend if compared with the information available on the concrete, regardless whether the concrete already exists or will be placed in the future.
At the last, it may be noticed that the analysis done at design stage for the concrete body itself is often more intensive and accurate than for the rock foundation.

For a gravity dam, the blocks founded on the valley slopes present, as a rule, a reduced safety when compared with the blocks on the valley bottom, because the normal force acting on the foundation is reduced while the inclined surface on which the uplift acts is increased. (Figure 8)
The risk is especially high should discontinuities exist in the rock paralleling the slope. The highest blocks of the dam are therefore not automatically the more critical. This was the reason for the rupture of the St Francis dam. (Figure 9)
Steep valley slopes must be analysed very carefully in case of a gravity dam and evidently even more in case of a buttress dam.

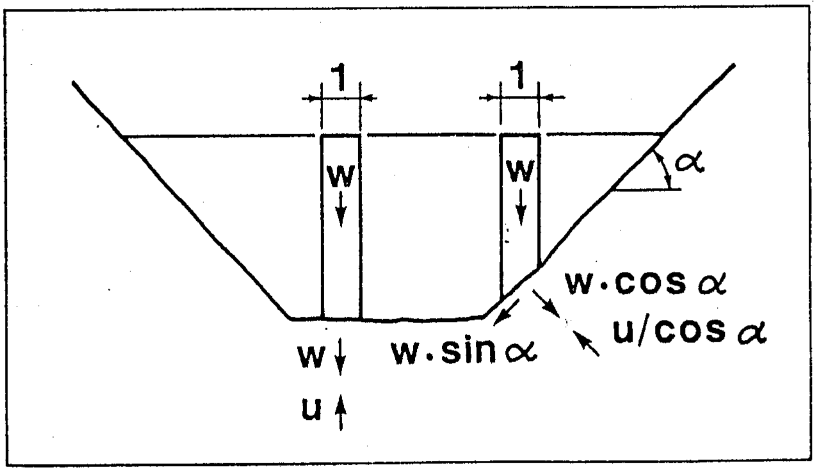


Figure 8. Gravity dam. Reduced safety of lateral blocks.
(W = weight of the concrete block; U = uplift force on a horizontal section)
The normal component is reduced from W to W.cosα.
The uplift force is increased from U to U/cosα.

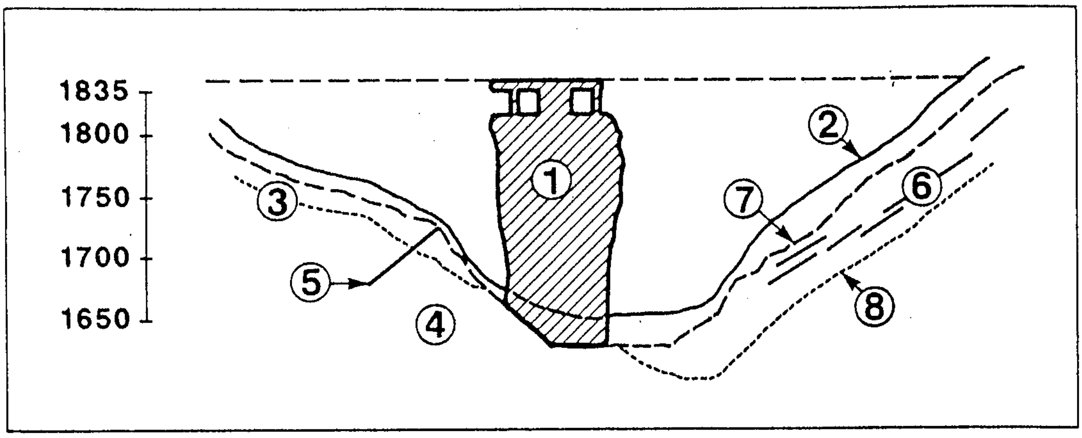


Figure 9. Failure of the S^t Francis dam
① Section of dam that remained standing
② Original ground
③ Conglomerate
④ Schist
⑤ Fault
⑥ Laminated mica schist
⑦ Foundation for dam
⑧ Rock line after failure

Arches were intended originally to dam narrow valleys with steep sides.
Unfortunately very steep valley flanks may be unfavourable as support for arch dams because the rock weigth will provide no, or just a small contribution to the stability of the abutments. The safety of the structure has to rely on other factors like strength or cohesion of the rock mass. The interstitial water pressure in the valley flanks is obviously decisive for the stability of the abutments. This explains the upmost importance of both the grouting and the drainage systems in the valley flanks and the river bed. However for the time being many successes in this field are due more to chance than to a serious scientific approach.

Nowadays a grouting concept based on the grouting intensity (or grouting energy) has shown to have clearly improved the probability of success for consolidation works and grout curtains. Nevertheless more research and new developments are undoubtfully needed in this field.
It is indeed not very satisfactory, from the rational point of view, to use and reuse again old fashioned grouting specifications, which are in any case too simplistic and too rigid to deal with so different rock and dam conditions as encountered in nature. More imaginative thinking is also urgently needed.
I would therefore like to say: "Grout curtains should be designed, non just defined by old fashoned specifications."

Just as a single example, for the need of improvement, I would mention the following. The well known Lugeon test was developed at a time when only 100 m high dams could be considered as a possible future record. Therefore the maximum water pressure for the test was chosen to be 10 bar. But, Lugeon tests up to a maximum pressure of 10 bar are not very appropriate for dams of 250 m high.

The assumption of a linear elastic behaviour of the foundation rock using an estimated, or eventually measured, so called modulus of elasticity (better said, modulus of deformability) disregarding the effect of the intersticial water pressure on stresses and strains, makes obviously the computations a lot easier, but ignores some aspects of the real behaviour of the rock mass.

So the fact, for instance, that both modulus of deformability and permeability are stress dependent and not constant values, is often overlooked.
The problem raised are, clearly, not always very simple, but deserve for sure more studies and investigations.

It may finally be noticed that in case of an earthquake a rapid dilatancy of the rock, that is an opening of the joints, may significantly reduce the acting water pressure, that is the uplift forces, thus increasing correspondingly the effective stresses and the shear resistance of the rock mass. There is some similarity with the dynamic pressure in saturated cracks in the concrete body, which tend to open during an earthquake. (Figure 10) A certain fraction of the apparently higher tensile strength of the concrete and the rock under dynamic loading may be explained in this way.

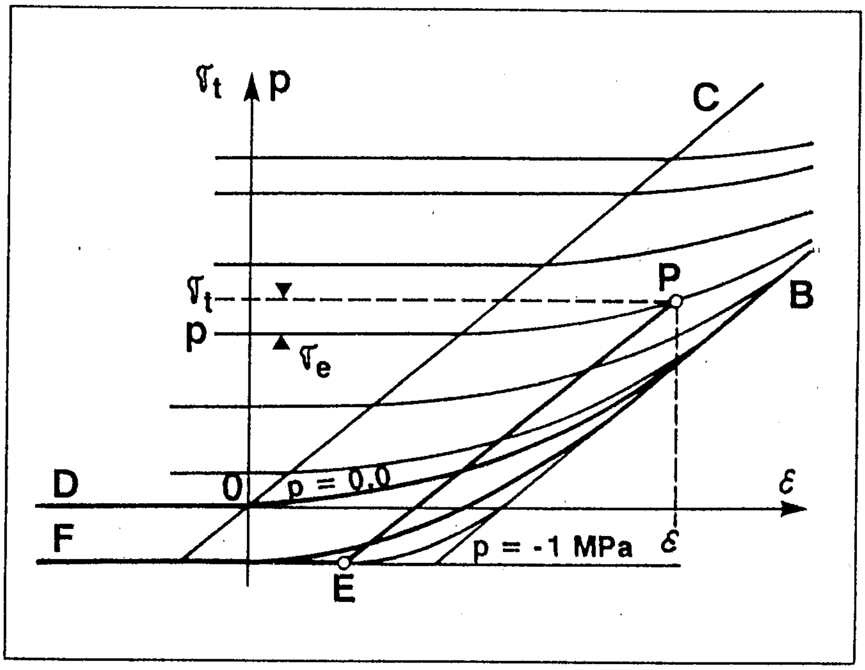


Figure 10. Dynamic behaviour of a fissured rock or concrete mass accordingly the F.E.S.-Model
The line D-O-B for a dry fissured mass represents the characteristic of a fissure in the downstream section of the dam or its foundation.
The line P-E-F is the characteristic for a point in the saturated upstream section of the dam or of the rock.

9. INSTRUMENTATION

No need to underline here the importance of an adequate instrumentation and of a continuous and careful monitoring of the dam behaviour, to ensure its safety all along its life. Or, better said, to detect as soon as possible any abnormality which could be a forerunner of some incoming danger.
The instrumentation shall cover not only the dam body itself but include, obviously, also its rock foundation as well as the surroundings. It should be designed to capture preferably global values, like deformations, than local ones, like strains which may, at the best, be used just to compute local stresses.
Uplift pressures and temperatures can, to some extend, be considered as global values (as they generally detect the existence of a field with some continuity).

Flow rates of collected leakages are, clearly, global or integral values.

It appears to be much more important to install a small number of instruments showing a long term reliability and a good precision, than installing a greater number of fading-away instruments. The possibility of cross-checking (e.g. mechanical vs electrical readings) should be duly considered. "The monitoring must be as simple as possible but not simpler" as Einstein once said, referring to a more general but similar problem.

There are two well-known "schools" in matter of interpretation of the instrument's readings. (i) The pure statistical one establishes relationships between the present and the past behaviour of the dam. (ii) The deterministic method compares the actual behaviour with that of a theoretical model set up beforehand. This model may be adapted later on, should this show to be desirable. I myself clearly prefer the deterministic method as it can be used already for the first filling of the reservoir, which is - as generally recognized - the most delicate period of the dam's life. The statistical model may also drift away along the years without offering a clear explanation of the phenomena involved.

The instrumentation and the monitoring system should be designed at same time as the dam and not added on, at later time, to the already built dam. This excludes obviously not the necessity to modernize, from time to time, the monitoring system.

10. EXISTING DAMS

The evaluation or the reevaluation of the safety of existing dams is sometimes not an easy task. The question, which first arises is whether exactly the same criteria should apply, in a strict way, for the existing dam as for a new dam.

In my opinion, some flexibility in this respect is recommended because:

- there will be more uncertainties e.g. in matter of undocumented constructional procedures (archives are often incomplete o even missing), but
- in some other respect, there will be a lot less uncertainties as a number of material properties and their standard deviations can be intensively tested and will be known with much more precision than the future properties of a new dam at design stage,
- finally, the fact that the old dam after years still exists, is an indication that it had resisted at least loadings of a certain intensity.

11. NEED FOR RESEARCH

In spite of the well developed present state of the art for building concrete dams, a clear need for further research and investigations still exists.

The following fields deserve with priority more intensive and fundamental research and studies:

Concrete mass:

Investigations on Alkali-Aggregate Reactions:

- different types of reaction,
- influence of restraining stresses and anisotropy of growth,
- influence of temperature,
- influence of and on concrete permeability,
- possible means to avoid, restrain or stop concrete expansion.

Cracks in concrete:

Investigations on:

- crack surfaces, and their roughness
- crack characteristics at closure (stress-strain relationship),
- crack permeability and groutability,
- development of uplift pressure both in the static and the dynamic case.

Cooling of the concrete mass:

- better understanding of the induced stress field and cracking potential.

Flow induced forces in the concrete mass:

- better understanding of the actual problem,
- total and effective stresses in concrete.

Rock foundation:

- non linear elastic behaviour,
- non elastic behaviour,
- variability of permeability with stress field,
- better understanding of the effect of drain holes,
- grouting technique to be modernized, and
- its influence on uplift.

12. COMPUTATIONS

In the last decades the computational methods and techniques have tremendously developed . However, difficulties often subsist in trying to explain some peculiar behaviour of certain dams. I may recall that the dam is in fact a problem of physics and not a problem of pure mathematics. A computation can at the best be just a rough simulation of the reality.

Therefore I would recommend to think a lot before starting a computation and even a lot more after having finished it.

CONCLUSION

This last one is, for sure, the most important conclusion I was able to draw from the thinking I did on concrete dams!