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Dam Foundations: Problems and Solutions

GROUTING OF ROCK WITH CEMENT MIXES

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1. INTRODUCTION

In a few years more, two centuries will have passed since Bérigny, in France, injected for the first time a cement slurry into the ground to stabilise a lock that had settled.
Since that time, the grouting techniques developed greatly and were used in numberless structures, especially in hydraulic works and first of all in dams.
Presently, it is a well established tradition to consolidate the foundation and to tighten the surrounding rock mass by grouting them.

During these two centuries a great number of recipe formulae were proposed, an equal number of theories were invented and an even greater number of brilliant ideas were presented, each one being allegedly the definitive answer to all the problems related to the grouting of rock masses.

However, many of these "explanations" lack of any scientific background represent more or less a simple generalisation of a single, or a few, good or bad cases, experienced by its inventor. This all without talking of the many “Specifications” written during this period of time by "Technical Organisations".

A number of said ideas and specifications are still in force, in spite of the fact that one can easily show that they could not pass any serious examination.
Some of them will be discussed later on, but before doing it, the aim of the grouting shall be looked at, while only the grouting of rock masses using cement mixes will be dealt with in the following. [15]

2. THE AIM OF GROUTING

There is a general agreement, that the aims of grouting are

- to increase the strength,
- to reduce the deformability, and
- to decrease the permeability

of rock masses. [1], [8], [9]
It is implicitly hoped that these effects will last for the life time of the dam.

Generally speaking, everyone hopes that some good or excellent results will be achieved in grouting the rock, but the exact targets to be reached are seldomly, if ever, stated. Many specifications will define the grouting works to be carried out. But, which compressive or shear strength, which modulus of deformability of the mass or which tightness of the grouting screen must be obtained is, at the best, only verbally described.

We must recognise that a lot of empiricism still governs this kind of works.
For example, a screen is implemented were an arbitrary Lugeon-value is exceeded in the rock mass. Its depth is limited to half or two thirds of the height of the dam depending on the habits of the designer. Any kind of available specifications are used for the grout mix, the borehole type, their diameter, their distance, the grouting pressures and so on, but only few people is apparently interested in defining and checking the thickness of the screen, that is the thickness of the zone grouted, as well as the coefficient of permeability actually obtained. Additional grouting or drainage works will simply be carried out later on, in case for example an excessive level of the downstream ground water table is detected. Often an excessive amount of money will have been spent uselessly.
Additionally, the lifetime of the screen is expected to be of the order of that of the dam, but not everybody will take care that the grout mix is not leached out by the flowing water during that time.

These few remarks are an invitation to discuss a number of practices, rules and theories that have marked the history and the development of the grouting techniques and are unfortunately still in use, at least at some job sites.

3. SOME OUT-DATED PRACTICES

3.1 Thin grout mixes

A first quite strange practice, still in force, is the use of a series of mixes going from thin to progressively thicker ones. [3], [16]
It is well known that thin mixes produce a very soft grout easily leached out by the water, so the screen will disappear in a small number of years [2]. One of the reasons put forward, is that doing so, the risk of water being sucked from the mix by the dry rock is reduced.

Firstly, this argument is not valid for grouting works carried out below the ground water table. Secondly, it is a lot more preferable to saturate locally the rock in injecting water just before starting the grouting procedure with a stable grout mix of good quality, than using a poor thin mix.
The real reason for said traditional procedure is that too much emphasis is put on the grouting process itself and not enough, if any, on the final quality of the grout set in the cracks of the rock mass; probably because the check is not very easy!

Rock grouting is in fact quite similar to producing a concrete or a masonry: the difference is just that the rock pieces are already in place. To obtain a good result any excess of water must thus be avoided.

Indeed, only thick stable cement mixes can ensure a mechanically strong and a leaching-proof grout. Super fluidificant should be added to the mix in order to increase the penetrability of low water content mixes. [11], [13] Consequently, only the best mix, from the point of view of the final result should be used. As the "best mix" is, per definition, an unique one, only this unique mix must be taken into account for the entire grouting process.

There are still people who judge the success of the grouting only by the volume of grout taken by the rock, while others measure the success by the improvement of the rock properties achieved by the treatment!
Many of the disputes developed on a number of aspects of the grouting process are due to the fact that one party is thinking in terms of thin unstable mixes, while the other does it with stable, thick mixes in the background. These disputes would disappear if only stable mixes were finally to be used.

3.2 Presso-filtration

A theory widely brought forward in former days, but still used from time to time, is that in the case a thin mix is pumped in, the excess water will be pressed out into fine cracks in the rock and the cement grains will finally jam in the fissures thus leading to a thicker, "improved" grout. This argument is, in my opinion, fundamentally wrong, at least for three reasons:

– the water in the mix is understood by the defenders of this thesis, just as a transportation vehicle for the cement grains, disregarding the fact that it is an essential element of the mix, both from the physical and the chemical point of view,
– secondly the presso-filtration will quite rapidly produce plugs in the cracks making impossible the drying out of the grout volume introduced subsequently, and
– finally the suggested phenomena is a quite erratic and unpredictable one.

Presso-filtration is, however, an excellent way to keep alive endless and useless discussions on the grouting process.

3.3 Refusal

Further, strange notions always and everywhere heard are those of "refusal" and "refusal pressure". One should normally understand by such expressions that a natural limit or barrier to the grouting process exists and that the rock masses “refuses” to absorb more grout.
In reality, the experience, as well as theoretical considerations, show that in increasing the pressure the grouting process can be continued beyond any limit, up obviously to the capacity of the pump, which can actually “refuse” to produce higher pressures than a certain value.
Conversely, the grouting process can be stopped any time in reducing or limiting the grouting pressure.

The grout volume taken by the rock mass is, in fact a quite complex function of the grouting process. One shall therefore talk of a "limiting or maximum pressure at zero flow" defined by the operator, not of a "refusal pressure" supposingly dictated by the rock mass (**figure 1**).

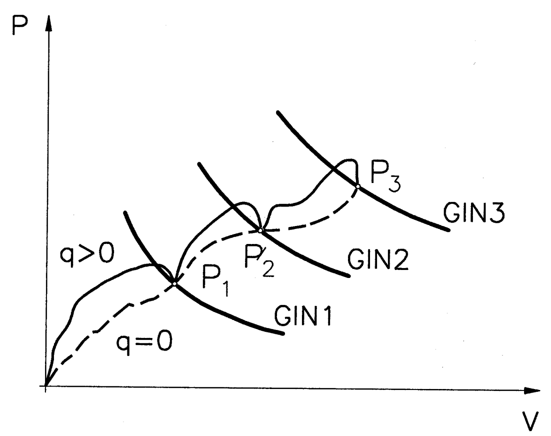

Figure 1:
The grout process can be stopped at any final pressure required or at any volume value by reaching any required GIN value. There is no such situation as "refusal" by the rock.

p = grouting pressure
V = grouting volume taken
GIN = $p \cdot V$
q = flow rate of the grout

3.4 Hydro-fracturing

Hydro-fracturing of the rock mass is also a permanent object of discussions in the frame of any grouting project. In fact, one should make the difference between hydro-jacking, which is the opening of existing joints and cracks, thus the most frequent event, and hydro-fracturing which is the formation of new cracks.
Figure 2 shows an accumulation of grout, that is of energy around the borehole, that suddenly expands opening the crack.

Indeed, the formation of new cracks can generally be expected only in uncracked rocks - at least in a practical sense. If cracks exist in a given direction, they will more easily open than new ones be created; provided of course exceptionally unfavourable stress conditions do not exist in that spot of the rock mass and the orientation of the boreholes is correctly chosen.

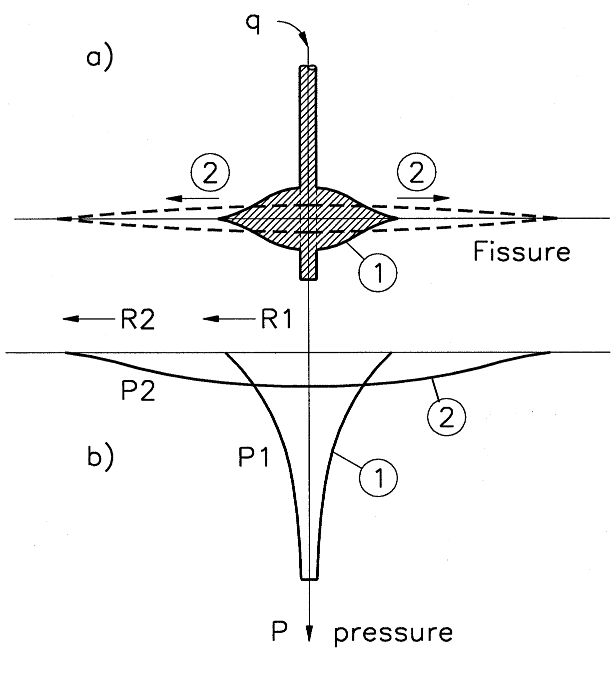

Figure 2:
Hydro-jacking as a kind of "elastic" instability or bifurcation.

a) sudden extension of the open stretch of a fissure at grouting
b) spreading out of the pressure

① before } hydro- jacking
② after
q flow rate of the grout
p pressure
R reach from the borehole

Furthermore, it is hardly understood that there should be any need to grout massive uncracked rock masses and crack them!

Moreover, one should consider that, per definition, grouting is done in introducing into the rock a grout mix by pressure; thus a certain opening of the cracks is unavoidable and even desired. However, an opening of the joints and a filling them by a weak grout will, or may, be harmful for the project. Not so, if a grout of good quality with a high adherence on the rock walls is used. The quality of the complex will improve significantly. By the way, this is the basis of the so called "claquage method". [5]

Finally, uncontrolled opening of joints, thus hydro-jacking, is more likely to occur if water or thin mixes are injected than when stable mixes are used, due to their higher cohesion [4].

In using thick grouts, the reason to avoid or limit hydro-jacking is thus not a fear of damages to the rock but the intention to save an excessive consumption of grout and the related high costs.

3.5 Heave of the ground surface

On many job sites there is also a great fear to be felt of a possible heave of the ground surface due to any grouting. The same considerations are valid as just presented for the case of hydro-jacking. The heave is unavoidable, but care must be taken to limit it, mainly because of the costs of the huge volumes of useless grout possibly wasted (**figure 3**).

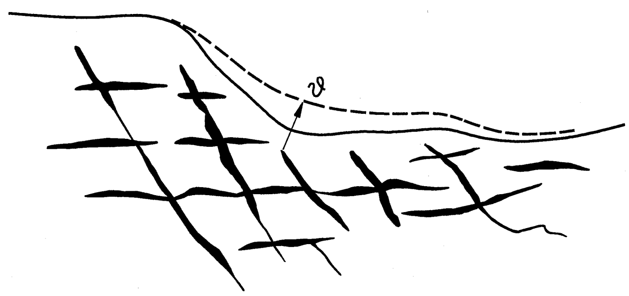

Figure 3:
Unavoidable heave of the surface of a grouted rock mass.

The most amazing work is, for sure, to compare the different rules, in force in different countries, which limit the grouting pressure in function of the depth below the ground surface (or of the distance from any underground opening). Such rules do not make any reference to the rheological properties of the matter pressed-in nor to the geological aspects of the rock mass. So, no difference is made between clear water and the thickest grout mix, while one should easily understand that the penetration, the distribution of pressures and the splitting forces strongly depend of such properties. Also no consideration is given to the type and the interconnection of the joints systems. The risk of excessive heave is thus completely different from case to case. Conversely, the allowable pressures must be related, at least, to said rheological properties as well as to the geological conditions of the site and not only to the depth below the ground surface.

3.6 Use of bentonite

A further confusion is often made in matter of the effect of an addition of bentonite to the cement mix. A decrease of the viscosity and a better penetration are generally claimed, while in fact an increase of viscosity takes place provided the same final strength of the grout is targeted, or even simpler if the same water-cement ratio is maintained.

3.7 Water pressure tests

With the aim of setting up procedures intended to govern the grouting process, there are still many studies going on about alleged relationships between previous water pressure tests and grout takes to be expected.
Such studies are just disregarding the difference in dimension between a cement grain and a water molecule in relation to the joint openings in the rock mass; they also ignore the fact that water is a Newtonian body, while a cement suspension is a Bingham' body. Such researches are thus simply misleading. The grout take to be expected can experimentally be defined only by grouting tests, not by water tests. Obviously, the results of such tests will depend on many, factors starting from the grain size of the cement used. [6], [7]

Consequently, the precise observation and interpretation of the ongoing grouting process itself makes water tests completely useless during the grouting process. Not so, obviously, before and after the grouting works are carried out.

4. SOUND PRINCIPLES FOR GROUTING

4.1 In general

The survival of so many – an even more – illogical ideas and thesis on grouting was a stimulus for a review of the grouting techniques and theories traditionally in use. The result was the definition of a coherent body of principles to be followed for an optimal grouting of rock masses with water-cement mixes.

These principles are in general not new, but were adequately selected from the different and contradictory practices presently in use in different countries. The main aspect is that no contradictions between them nor with the reality any longer exist. This set of rules is often designated as the GIN principles. The GIN concept in a strict sense is, however, only one of these rules, but a new one.

It has to be stressed out again, that the GIN-method is intended for grouting "normally" fissured rock, not cases like karstic, or very soft rock or soils, and obviously not absolutely massive rock masses.

4.2 The GIN-limiting curve

The possible heave of the ground, the risk of hydro-fracturing, the amount of hydro-jacking, the reach of the grout, and in general any damage or good due to, or caused by the grouting, is not only a function of the pressure used. The amount of the grout mix introduced in the ground also plays a dominant role, as the forces produced are not only the result of the pressures but evidently also of the surfaces on which they act. This last one is obviously related to the volume of the grout injected. It is easily understood that to avoid any undesired effect, the combination of high pressures with great volumes of grout taken should be avoided. Indeed, large volumes flowing at low pressure in open void can hardly be of harm, as well as very small grout volumes by high pressure, because the surface on which the pressure acts will be obviously very limited and so the splitting forces (**figure 4**).

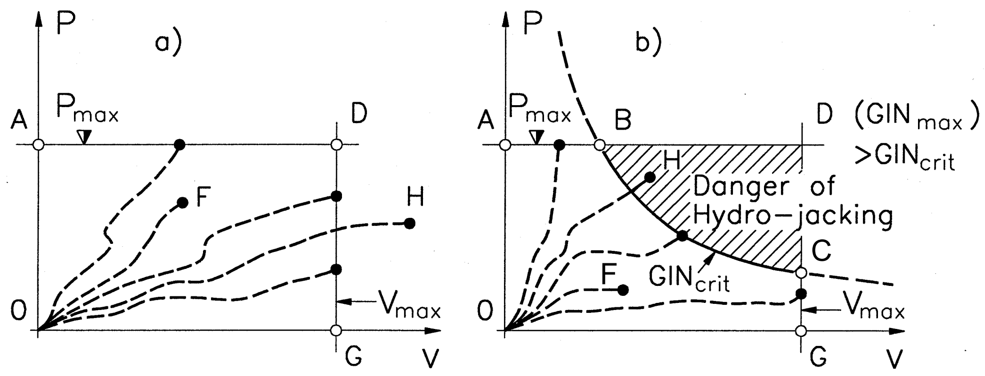

Figure 4: Limits placed on grouting.
a) traditional method limit ADG; b) GIN-method limit ABCG
p_{max} = maximum pressure; V_{max} = maximum take; GIN = limiting curve ($p \cdot V$ = const.)
Grouting paths like F and H are not allowed.
The traditional method is a special case of the GIN method when
$GIN \geq p_{max} \cdot V_{max}$.

In fact, neither the pressure itself nor the volume alone are the determinant factors, but the product of them which corresponds approximately to the energy injected in the ground.
The specific energy "injected" in an one-meter long section of borehole is named the "Grouting Intensity", to which a Grouting Intensity Number or GIN-value does correspond, accordingly to the formula

$$GIN = p \cdot V \quad \text{expressed in} \quad bar \cdot lt/m^1 \quad \text{or in} \quad J/m^1$$

The GIN principle shown in **figure 5** consists in limiting the grouting pressure according to a given GIN value, that is a hyperbola, that excludes automatically said damaging combination of high pressure and large grout volume [10].

The GIN value, in conjunction with a maximum pressure and a maximum volume, must be selected from case to case taking into account

- the geological conditions, as well as
- the scope of the grouting works, and
- the geometrical definition of the problem.

There is no time to enter here more in details on the choice of the GIN value the maximum pressure and the volume limit. The criteria to be followed were published elsewhere. [12], [14]

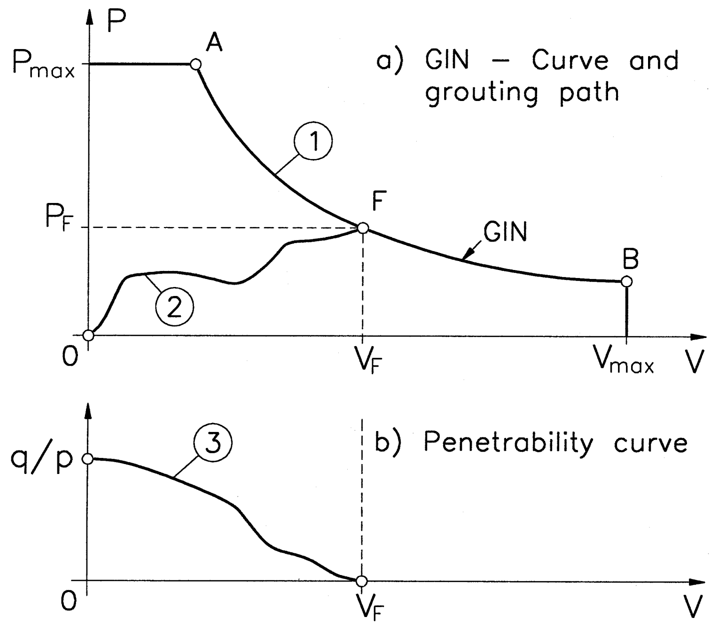

Figure 5:
Grouting process of a single borehole stage (typical)
where:
1 = limiting curve, pressure versus grout take,
2 = actual grouting path, pressure versus grout take, and
3 = penetrability q/p versus grout take
p = pressure
V = grout take (volume)
q = flow rate
F = final point of the grouting
p_F = final grout pressure, and
V_F = actual grout take

Nevertheless, an additional comment is required as often misunderstandings occur. In case the postulated volume limit is reached at a lower then the corresponding GIN-pressure (Point B), then a decision has to be taken whether to stop the grouting, to continue it, to wait for the setting of the grout, to drill a new borehole in the vicinity or possibly to take any other action.

4.3 The proposed rules for grouting rock

The logical conclusions of the previous considerations are summarised by the few rules listed in **Table 1**, that doesn't require any additional comment.

In using these principles the fear for hydro-fracturing and ground heave disappears. There is no need any longer to limit the grouting pressure at shallow depth nor in the vicinity of openings. The limited grouting intensity takes care automatically of these questions.

Table 1: The generally accepted principles of the GIN method

- Define the "best mix" for the project by laboratory tests both from a technical and an economical point of view. Only stable mixes, generally with super-plasticiser, should be used. Thick stable mixes have been favoured by European grouting experts for quite some time.
- Use only a single mix, "the best possible one", for all grouting stages in order to ensure the qualty of the results and to simplify the procedures. This will also avoid wasting grout.
- The split-spacing method for the boreholes is also not a new technique, but it is used in the GIN method as a self-adaptive and self-regulating procedure.
- The use of increasing stage lengths, with depth below ground, is progressively recognised as a way of speeding up grouting and making some, albeit small, savings.
- To inject water in dry water-absorbing rock formations above the ground water table, shortly before grouting, is now accepted as a way of avoiding a sudden blockage in the grouting process due to water losses from the mix.
- Computer controlled procedures are an obvious pre-requisite for optimal grouting works. Many pieces of information can be obtained from these plots. Unfortunately in several projects the graphs were plotted without drawing conclusions.
- No water pressure tests during the grouting works; they are useless and dangerous.
- Definition of the parameters of the GIN limiting curve: p_{max}, v_{max} and GIN-value = $p \cdot V$, (GIN << $p_{max} \cdot V_{max}$), taking into consideration all determinant geological parameters as well as the scope of the works and the related economical aspects.

4.4 Comparison with the classical method

It may be interesting to make a comparison of the GIN method and the classical grouting method (**figure 6**).

The GIN method uses only one stable thick mix of the best possible quality and reduces the limiting grouting pressure as the volume take increases. The traditional method uses a series of different grout mixes keeping a constant limiting (max.) pressure [12].

If one remembers that the normalised pressure is the very parameter of a grouting process – that is the ratio: pressure to the cohesion of the mix – then some common aspects of the two processes appear.

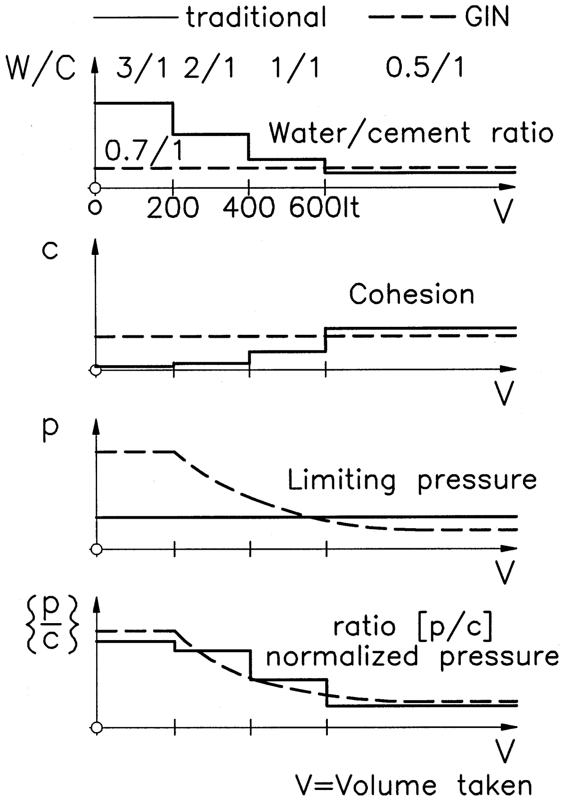

Figure 6:
Comparison, by way of example, of the traditional and the GIN grouting methods. The normalised pressure $p_n = p/c$ is decreasing with increasing volume taken, both for the traditional and the GIN method.

W/C = water-cement ratio
c = cohesion
p = pressure
$\{\frac{p}{c}\}$ = normalised pressure

Really, the only way to stop the grouting process is to reduce the normalised pressure with increasing grout take. This is done in increasing the cohesion by changing the mix, or in a simpler way in decreasing the pressure.

The difference is that the results of the grouting processes are fundamentally different. With the GIN method only the best mix was used, while with the traditional method an unpredictable mixing of a series of unstable grout mixes, many of them of very poor quality, takes place in very different proportions from spot to spot.

5. CONCLUSIONS

After two centuries of empirical trials and subjective theories, the grouting works should finally be designed like any other part of the dam, and not just "specified" in using outdated rules taken from the manuals of any kind of institutional bodies, which did just "freeze in" the practices of former decades.

The GIN method is, I think, a step in the right direction and a help for the Engineer. It is surely not the end of the development of the grouting practice and theory.

First of all however, the scope of the grouting works designed should be clearly defined, better as generally done up to now. The grouting works to be designed shall give more consideration both to the scope of the project and to the geo-mechanical conditions of the rock mass to be treated.

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TABLE 1 – THE GIN PRINCIPLES

- Laboratory testing and site check of the properties of the mix
- Use only stable mixes, possibly with super-fluidificant
- Use only the "best" mix to get the best grout after set
- Use the split-spacing method
- Increase the stage length with depth
- Saturate the rock before grouting
- Real time control by PC
- No water tests during grouting
- "Engineer" the 3 parameters of the GIN limiting curve (p_{max}, V_{max} , GIN = p·V)
- Do design, not just "specify" the grouting work