CONCRETE FACE ROCKFILL DAMS
USE OF GIN CRITERIA FOR CONSOLIDATION AND
IMPERMEABILIZATION OF THE FOUNDATION ROCK

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ABSTRACT

The article discusses the main principles to apply the GIN Method for foundation grouting in Concrete Face Rockfill Dams (CFRD´s). Special mention is devoted to the Pichi Picún Leufú Project in Argentina, where the results of grouting were excellent.

Key words: CFRDs, Grouting, Cement injection.

1. INTRODUCTION

The Concrete Face Rockfill Dam is, among all types of dams, the one which gives rise to the highest hydraulic gradient across the rock foundation.

The treatment of the rock underneath the plinth and the injection of the grouting curtain deserve a careful analysis and specific attention for its realization.

The present note concerns the design and execution of the grouting works based on the criteria of the GIN method. The numerical figures presented should be considered merely as examples for a hypothetical dam with height of the order of 100 to 150 m, and normal foundation conditions. For specific case the numerical values must be adapted to the real conditions of the job site.

In the same way, some obvious aspects of the work, known to experienced people, will not be mentioned.

The excellent results achieved some years ago, for the dams of Aguamilpa, in Mexico, and Pichi-Picún Leufú, in Argentina, represent a clear invitation to profit from the last developments and progress of the method.

Some recent specifications were prepared with the intention of using the GIN method. Unfortunately, quite often they include clauses that refer to old practices, which contradict the requirements of the GIN method.

In what follows, the new and most important criteria of the GIN method are presented as well as the practices for the correct use of the specifications for the design and execution of the works, abandoning criteria that are purely of historical interest and that should not be used any longer.

The present note deals exclusively with cement grouting.

2. GENERAL DESIGN CONDITIONS

The design of the grouting works of a dam of the type hereby dealt with must take into consideration the following aspects:

a) There are no reasons to make an artificial distinction between the so-called "consolidation zone" of the rock underneath the plinth and the "grouting curtain" proper. In fact the point is to treat properly a single zone of rock with grouting to improve at the same time the resistance and the imperviousness of the rock mass. (figure1).

b) The "original" hydraulic gradient in the rock zone to be treated will be very high at a shallow depth – about 15 immediately underneath the plinth – and diminishes quite fast while depth increases, reaching, for instance 1 and even less, in a lower point of the curtain. Therefore, a curtain with a "uniform" intensity is not logical. Besides, in its lower border the real efficiency of the curtain is zero, by definition.

c) It is obvious therefore that the mains efforts in the grouting work should be concentrated in the upper part of the referred zone, where the "intensity" of the grouting must be, evidently, stronger than in any other point at a higher depth.

d) To be efficient, the grouting pressure must be related to the future pressure of the water in the zone considered. The intent is to avoid hydraulic jacking of non-treated fissures.

e) The grouting works must have an effective life similar to the one of the dam proper. This means that the set grout mix must have a mechanical resistance, and specially a resistance against leaching out, sufficiently high; in fact the resistances should be as high as possible

f) The grouting works consist in the introduction, under pressure, of a mixture of water and cement in the discontinuities of the rock. This will necessarily open somewhat the discontinuities. A consequence, the total volume of the rock will increase and the surface of the ground will rise. Therefore the issue is to limit this uprising to acceptable values, since it would be absurd to try to avoid it completely.
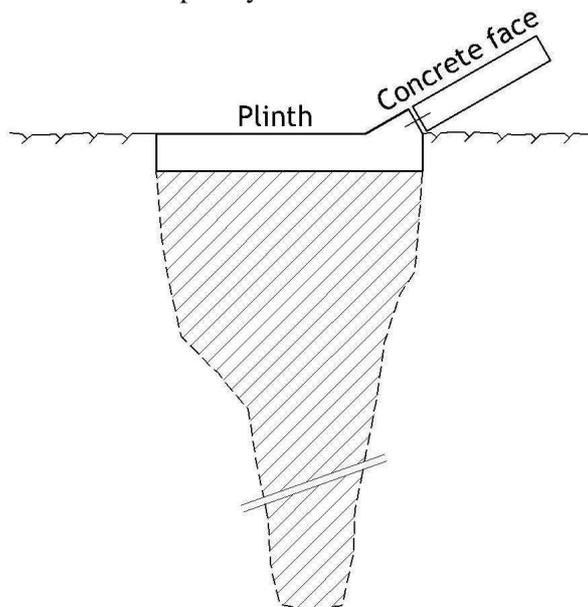

Figure 1 – Rock zone to be treated by grouting (includes "consolidation" and "curtain")

g) The opening of the fissures is unavoidable, but it is also favourable since it eases the grout penetration in the massif that is being sealed.

h) If the grout slurry is of good quality, every fissure (sufficiently open) be it natural or generated by the construction works, will be sealed (provided it is not contaminated with fines such as clay or mylonite) independently of its final opening.

i) Nevertheless, an excessive opening results in a useless waste of grout slurry.

3. PRINCIPLES OF THE GIN METHOD

The essential principles of the GIN Method are the following:

3.1 Grout slurry mix

a) Only one grout slurry mix should be used for the totality of the injection works (consolidation and grout curtain) assuming that the used grout mix is the best one (in the actually real conditions).

b) The slurry must have a minimum possible setting retraction because every retraction generates preferential ways for the circulation of water and a larger possibility of a future dissolution of the mix.

c) The penetration of the slurry in the rock fissures is limited by the diameter of the cement grains in relation to the fissure openings. It is an error to assume that adding water to the mix will improve the penetration of the grout mix (in fact in this case only water will penetrate in the fissures, not the cement).

d) Clearly, fine and super-fine cement are most efficient for sealing the rock fissures, but unfortunately quite often they are either not available or have an excessive cost.

e) The penetration in fissures located at larger distances (obviously in fissures sufficiently open) is achieved for the same grout pressure with the reduction of the cohesion and viscosity of the slurry mix by adding an adequate superplasticiser.

f) The definition of the mix shall be done based on careful laboratory tests to obtain the most favourable water/cement ratio (for instance, 0.7/1.0 for normal Portland cement), selecting the super plasticiser type and the dosing which is the most favourable.

The well known criteria for the cement slurry are:
- Limited decantation (minimum).
- High density.
- Low viscosity.
- Low cohesion.
- Acceptable setting times in relation to the injections to be performed.
- Mechanical resistance, and, specially
- High resistance to leaching (depending on specific cases, the chemical resistance to different agents, should also be taken into account).

The five first criteria refer to the fresh mix; and the two last to set grout mix.

The determining parameters which can be handled to optimise the mix, are:
- Type of cement (considering also the max. grain size)
- Water/cement ratio
- Type of super plasticiser
- Dosing of super plasticiser.

g) The use of bentonite in mixes for rock injection should be avoided because frequently a separation in the grout mix takes place. Bentonite penetrates thus in the rock fissures (and lubricate them) and cement, which has a larger grain size, cannot follow and is left behind.

3.2 GIN limiting curve

The limiting curve for the application of the GIN method is defined by three parameters:

1. The intensity or the GIN number: GIN= p.V [bar.l/m], where

    p = pressure;

    V = grout take in litres per metre of borehole, [l/m] or better, [kg of cement/m]

    (volume to fill the borehole has to be deducted)

    p.V = GIN = constant = "specific energy" [that is grouting energy per m of borehole] = intensity

2. The maximum pressure (at the borehole mouth); p_{max}

3. The maximum take; V_{max}

The limitation by intensity (GIN number) avoids the combination of high pressures with high grout mix volumes: that is high pressures acting over large surfaces. This eliminates, or at least reduces substantially, the risk of hydro-fracturing and hydro-jacking of the rock mass.

The maximum pressure (p_{max}) is primarily a value for the design of injection equipment (pumps, tubes, valves, etc). It has to be sufficiently high (two to three times the value of the future water pressure at that spot – that is at the borehole entrance) so that when the reservoir impoundment occurs, the fissures do not open by hydro-jacking.

The maximum selected volume of the grout take (V) is not an absolute boundary, but an indication of the necessity to take a decision, which could be at any grouting stage:

- to continue the grouting operations;
- to stop the grouting and restart it later on (after setting of the mix)
- to stop the grouting definitively;
- to abandon the borehole and drill another one nearby.

Additionally a critical value is also generally defined as, for example: $V_{cr} = 0,5$ GIN / p_{max} [l/m],
(or else, V_{cr} = something between V_{max} / 20 and V_{max} /10)

When, in a stretch of injection in a borehole, this value is exceeded other borings in the proximity should be done, at least up to the depth of the stretch in question, or better reaching a greater depth (obviously, a minimum distance from a borehole to the next should be kept).

The selection of the GIN number depends on the geological conditions of the site and on the design of the project. It should be chosen at the beginning (for example, 1500 bar.kg/m) and adjusted during the development of the works. Nevertheless abrupt and frequent changes in the parameters chosen should be avoided, so as not to complicate the control and analysis of the injection works carried our.

It is clear that the distance "d" between borings (e.g. in the grout curtain) and the GIN value are interrelated. (the relationship approximately is: d is proportional to $\sqrt{GIN}$. Obviously both values are dependent of the characteristics of the rock and on the requirements of the project.

3.3 Saturation of the rock

In certain cases, dry rock can absorb water from the slurry. This will cause an increased friction between the cement grains and stop the grout penetration into the fissures due to the lack of lubrication by the water.

(The same effect is caused by the loss of water escaping through the fine fissures, leaving the cement behind).

It is therefore important that at the beginning of the grouting works the rock is saturated. For that, before starting the grout injection, it is necessary to inject a certain volume of water in the borehole (obviously only in the stretches above the phreatic table).

3.4 Stopping the grouting

The grouting stops when the grout flow rate attains zero (or a very small figure) while the product p.V reaches the prescribed GIN value.

In practice it is also possible to exceed the established GIN value, for example, in 10%, stop the grouting and wait some minutes to see whether the product p.V sufficiently approaches the GIN value, while the pressure decreases slightly and slowly.

Obviously the injection works should stop when the pressure reaches the maximum pressure value (holding it for some minutes), or when the maximum volume is reached (to make a decision).

4. MAIN ERRORS TO AVOID

4.1 Maximum pressure as a function of the depth

It is not logical to limit the grouting pressure based on the depth of the stage being grouted, irrespective if the depth is counted from the ground surface of from a gallery.

This limitation is useless in itself since the GIN limit, automatically reduces the pressure near the ground surface or near a gallery in function of the value of the grout take, which will be higher near the ground than at depth.

The general limitation with depth mentioned here above can be dangerous since it can lead to stop the grouting prior to the point where a natural equilibrium is reached.
Besides, it creates confusion and useless complications in the job site.

4.2 Water pressure tests

Water pressure tests (for example of the Lugeon type) are useful to evaluate the permeability of the ground prior the execution of the grouting works.

However they should be absolutely avoided in already grouted zones, since the   pressurized   water enters in the fine fissures where the grout slurry was unable to penetrate, and may create additional openings in already grouted zones, damaging the effect of the grouting work already carried out.

The check of the injection work must be done with control borings grouted with the same grout slurry and following the criteria described here above; water pressure tests for the scope of control should therefore never be used.

Additionally, the water pressure tests may only indicate the existence of water losses, what does not allow to infer the groutability of the zone. Indeed, the loss of water depends on the number and the

opening of all fissures while the grout take is dependent only on the wider fissures. Only the test by injection in control borings can clear this question besides indicating the value of the grout take still possible.

4.3 Frequent changes

Quite often, in many projects the bad habit of frequently changing the grouting parameters and the quality of the grout slurry can be observed. Because of this, there are persons that love to have at their disposal a large series of different grout mixes, probably to play a role as "grand chef de cuisine" that manages many recipes.

In fact, it is possible to notice that often these changes are decided by psychological reasons and are generally based on superficial and ephemeral impressions or result from "local events" without incisiveness.

A serious work may, of course, require occasional changes in one or more parameters. However, change decisions should only be taken based on a rational basis resulting from a serious study supported by a sufficient amount of reliable data.

5. OPTIMIZATION OF DESIGN

The optimization of the design of a grouting work for foundation treatment, as mentioned, shall take into consideration the following (numerical values are simple examples):
   a) Make three grouting curtains with different length (for example nominal 6 m upstream, 10 or 12 m downstream and a deeper curtain in between at the centre). In this way one can get a treatment underneath the plinth with: three rows immediately under the plinth; two in the middle part and ending with one in the lower part of the curtain (and a similar disposition in wider plinths where there are more than three rows).

   b) The injection stretches must be staggered, increasing their length with depth, that is, they should not have constant length (for example, do not specify an uniform length of 5 m, as it is usually done). For example, the following can be considered:

   - first curtain, stages with lengths 1, 2 and 3 m;
   - second curtain, stages with lengths 2, 3 and 5 m;
   - third curtain, stages with lengths 3, 5, 8, 12...12 m.

   In this way the stages will be staggered in the three curtains and a more uniform treatment is obtained, with decreasing intensity from the surface to the bottom.

   c) Each row is completed (in a certain stretch) before starting the next one. Each row is done with intercalation of the drilling between the ones of the previous series (space splitting).

   d) The grouting starts obviously with the lateral rows and ends in the central one.

   e) It is advisable to carry out deep preliminary borings, spaced, say, 48 m, with tests with water pressure and grout slurry tests in order to define the depth in the zone that requires to be grouted.

   f) The depth of each curtain borehole is defined in relation to the grout takes that, in nearby borings, exceed the critical value V_{CR}, increasing some metres, (say, 5 m) in the zones where large absorptions were observed. There are no problems, if, for example, in certain stretches of the curtain the tertiary holes are longer than the secondary ones, or if the secondary are deeper than the primary ones. This arrangement allow to limit the length of the primary holes without

assuming too many risks, since there will be a compensation of the eventually insufficient length by the following series.
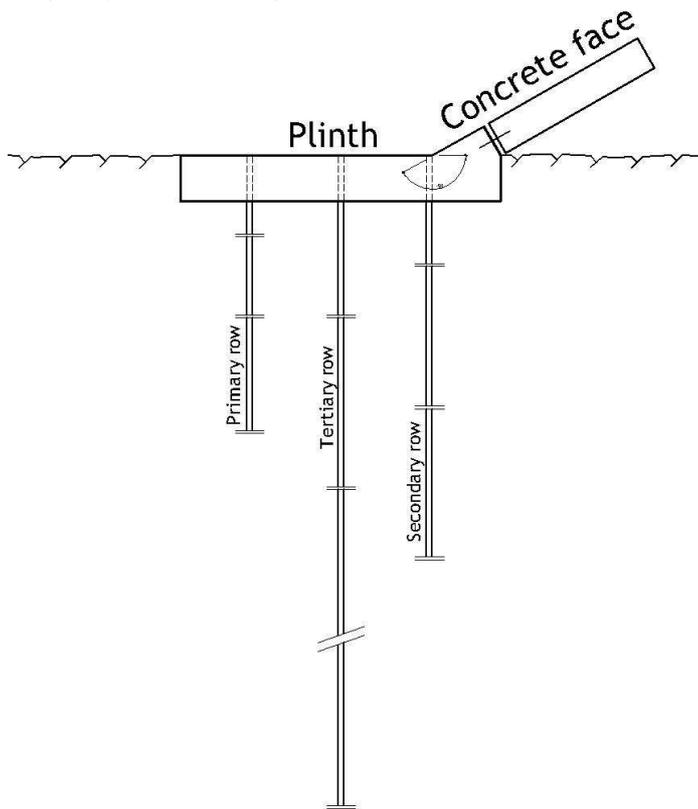

Figure 2 – Possible arrangement of the stages in grouting curtain with three rows.

g) The same rule can be used to reduce the length of the secondary holes and of the tertiary ones, if the take in the primary or secondary holes are small. Nevertheless, as a safety measure, a minimum depth of each series of drillings should be established.

h) The orientation of the drillings should take into account, as far as possible, the orientation of the main local discontinuities, but obviously a certain systematisation is necessary. In the first and second curtain the borings could, for example, be normal to the plinth base and those of the third curtain be vertical. With this scheme the crossing of all discontinuities will be achieved more easily. In certain stretches it could be convenient to incline all the borings of the three curtains upstream, to get away, for example, from the rock surface downstream, or to stay away from any special geologic feature.

6. DRILLINGS

It is noted here that the drilling of the boreholes can be done with any method and equipment (rotary, percussion, roto-percussion, and borehole hammer). The important thing is that after the completion of the drilling the boreholes are carefully cleaned with high pressure water jet, to prevent that the perforation dust makes difficult the penetration of the grout slurry in the rock fissures.

7. ANALYSES OF RESULTS

The optimization of the grouting work requires a very careful record of all the events occurred during the carrying out of the works, as well as a permanent interpretation of the data. The best conditions can

be achieved nowadays with continuous follow up of the grouting process on a computer screen, an adequate programming of the injections and the processing of the data in real time.

The realisation of a grouting curtain (or a row of boreholes) can be considered successful if a clear reduction of the grout take is achieved in a series as compared to the previous ones. A reduction of the take in the order of 25 % to 75 % corresponds to a good average value.

In the analyses of the results of a grout curtain it is highly recommended not to limit the study to values of the take per metre of borehole (l/m), but to analyse as well the total takes of slurry per unit of surface of the curtain.

To achieve this, the surface of the grout curtain is divided in 100 m^2 elements (or up to 200 m^2) and evaluating the take of all boreholes included in each unitary surface selected.

When this value (the average grout take in the surface) exceeds a certain limit (for example, 100 l/m^2 or up to 200 l/m^2), the reason for this situation should be investigated and the corresponding decisions taken. The most common reasons are: escape of the grout slurry (towards downstream or upstream), escape towards galleries or caves, geological features such as faults, karsts, presence of or very fractured rock.

Obviously what is said above refers more to the grout curtain proper and less to the case of consolidation of large volumes of rock.

8. PRELIMINARY TESTS

In spite of the auto-regulatory nature of the GIN method in relation to the quality of the rock, it is appropriate, as a general rule, to develop a programme of preliminary tests to define the essential parameters (value of the GIN number, distance between borings, etc) in each one of the geologically and geo-mechanically different zones, in which the grouting work will have to be carried out.

Whenever possible the tested curtain sections should be incorporated in the definitive work. Should the expected results not be achieved, it would be always possible to complete the treatment of the rock with additional injections.

9. TYPES OF PLINTH

Traditionally, the plinth was placed completely upstream of the concrete face. However it is also possible to locate part of the plinth downstream of the face, as depicted in Figure 3 (this, however may have some interference with the placement of the embankment material).

One advantage of this second design of the plinth is that in the long range it does not need to depend on the anchors for its stability, since the weight of the embankment tends to stabilise it, at least in the downstream part.
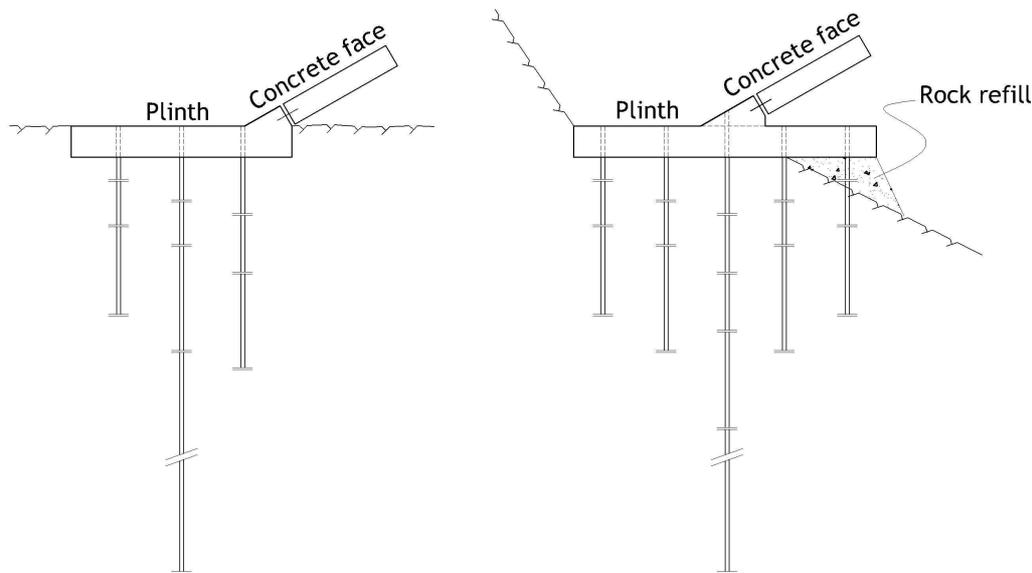
Figure 3 – Possible arrangement of the boreholes for a "traditional" and for a "wide" plinth.

Another advantage of this design is that it can decrease the volume of excavation in rock, in the upstream direction especially in the areas where the surface of the ground is steep or almost vertical. In this way the stability of the slope is improved due to the limitation of the depth of the excavation.

Of course, all there factors depend on the morphology of the site.

For constructive reasons it is advisable to design the plinth without folding it, that is, in keeping the same plane up- and downstream of the concrete face. If the rock surface downstream of the face deeps down, it may be convenient to reshape the plinth base surface by filling the deeper spots with a good quality concrete as a "rock replacement".

It is not necessary to repeat that the foundation of the plinth and of the "rock replacement" concrete, must rest over a firm, non-erodible rock surface which can be grouted in a normal way. If this is not the case, the adjustment of the design will be mandatory.

It is obvious, as mentioned before, that the higher potential hydraulic gradient in the foundation rock, occurs immediately below the plinth, reaching values of 15 or more. The gradient will be reduced in the treated zone, diminishing with depth until it reaches its absolute minimum in the lowest part of the grout curtain.

It is also mandatory that immediately underneath the plinth, the grouted zone of the rock is as wide as possible, while the "thickness" of the curtain will be reduced with the increased depth under the plinth.

For this reason it is necessary to grout the rock underneath the section of the plinth that lies downstream of the face, below the embankment. It is recommended therefore to locate the downstream row of grout holes in the covered part of the plinth, provided this part is sufficiently wide, while the upstream rows as well as the main deep curtain will take place in the uncovered part of the plinth, that is upstream of the concrete face (or, if necessary in the wedge of the plinth which supports the concrete face).

10. ANCHORING OF THE PLINTH

To grout underneath the plinth it is necessary to anchor it in the foundation rock.

Clearly the number of anchors has to be determined by structural analysis. They should not be designed for the maximum pressure of the GIN curve (p_{max}), but rather to the pressure that will be actually reached by the grouting up to the moment when the grout slurry could escapes from the one or the other side of the plinth. The design pressure in the anchors can therefore be evaluated as a function of the width of the plinth and is easily defined.

Once again it is stated that if the contact between the plinth and the foundation rock opens, there will be no problem because it will always be completely sealed. In addition it can be observed that the pressure of the reservoir water will force the plinth against the foundation surface.

It is finally repeated that in all cases the grouting should stop when it reaches the GIN curve. There is no sense (as it was sometimes done by error) to proceed up to the maximum pressure in every borehole. If this is done, the plinth will be uplifted generating unnecessary costs.

11. FINAL COMMENT

The principle mentioned here above were implemented with excellent results at the Pichi Picún Leufú dam in Argentina.

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