The International Journal on
Hydropower & Dams

SELECTING THE GROUTING INTENSITY

Issue four, 1996 (pp. 62-66)

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Our Ref.: 102.1-R-80

Selecting the grouting intensity

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The GIN (Grouting Intensity Number) method, introduced several years ago, has been generally well received and has now been used at a number of projects. However, the question has often been raised as to how to select the optimum value of GIN at a given site to achieve the best result. The answer may be found in three different ways (or by a combination of them): theoretical, experimental and observational methods. The most effective value results from finding a balance between the natural conditions of the rock mass, design requirements and the economic aspects of the grouting process.

The basic concept behind the GIN-Method (Grouting Intensity Number) for rock grouting has been published recently [Lombardi and Deere, 1993[1]].

Generally the method has been well received in the professional world and has already been adopted at a number of job sites, mainly for consolidation and curtain grouting for dam projects.

Like any other practical method, GIN has its limitations. Its use is not intended (at least so far) for the treatment of soils, nor is it appropriate to use it for the simple grouting of karstic formations. (A volume criterion is much more appropriate for filling karstic cavities.) The method is also intended primarily for use with grout mixes which show a certain cohesion or yield point, as for example stable water cement suspensions, that is for Bingham bodies. Some other limitations may also become apparent with time and experience.

These limitations may explain some inappropriate applications of the method which may have led to some unsatisfactory results, possibly as a result of excessive initial enthusiasm. The method itself, however, should not be blamed for some less than perfect results.

The excellent results obtained at many dam sites are encouraging and more numerous than the few failures to date, the reasons for which are not known or adequately reported.

A critical question which confronts both designers and field engineers is how to select the value of the 'Grouting Intensity' actually to be implemented at a given site, to achieve a certain goal in the best possible way.

Some clarification is required on this point. In this paper the criteria for the choice of this value will be discussed. It must be remembered that the GIN is not simply a magic number to be freely selected.

The fundamental design parameters for grouting works have to be defined or computed on the basis of precise theoretical considerations or experiments, in a similar way to the process for determining the required strength of the concrete for any important structure.

1. Review of the GIN method

The so called GIN method is not only a way to define and select the value of the 'grouting intensity', but should be considered as a kind of philosophy or practice referred to in the grouting of fissured rock masses to improve their strength, to reduce their deformability and permeability or to combine these goals.

It is thus worthwhile to recall briefly its main characteristics, which are the result of many years of study and practice in design offices and at job sites.

The aim of the method is to obtain the best possible results not only in the short term after finishing the grouting process, but throughout the whole lifetime of the project, that is, for many decades. Damage to the rock mass (or the structures) should also be avoided, and all this should be achieved at the lowest possible cost and in the simplest possible way.

The main principles of the philosophy are as follows:

- Determine as precisely as possible the properties of the rock masses to be treated, so the grouting process can be rationally designed and not just 'specified' as has often been the case, as former specifications decades old and developed in different circumstances have been used for new projects without having been appropriately adapted [Lombardi, 1987[2] and 1990[3]].
- Define as precisely as possible the objectives of the project to avoid grouting where other methods, such as drainage, could be more appropriate and less expensive, and also to avoid grouting more extensively or intensively than required.
- Use a mix of good quality, that is, a mix which will guarantee the long-term properties such as mechanical strength and resistance against leaching-out by water percolation.
- As cement is the most common and cheapest grouting material, grouting with water-cement mixes (normal or micro-fine cement depending on the joint opening) should be adopted for almost all rock grouting cases.
- Adopting a 'stable' grout mix, that is, a water-cement mix without excess water, is the only way to obtain a high quality grout after setting. Furthermore, only the behaviour of stable mixes is predictable, and the risks of hydrojacking are significally reduced [Deere and Lombardi, 1985[4]].
- Use only a single mix for the entire grouting process, that means, only the best possible one. This further simplifies the grouting process and avoids mistakes at the job site.
- Use a superplastifier to reduce both the viscosity and the yield point of the mix, so the same grouting distance can be reached with lower grout pressures.
- Avoid water pressure tests in the boreholes during the grouting procedure, as they are meaningless with respect to the grouting process itself, costly and time-consuming. (On the other hand, water tests before and after grouting to check the results achieved are worthwhile).
- Saturate the rock mass above the groundwater level just before grouting, to avoid water being sucked out of the mix by the dry rock. Such a water loss can lead to an immediate blocking of the process.
- Adapt the length of the grout stages to the rock conditions, that is, mainly the frequency of the discontinuities or joints. In practice, this means longer stages for greater depths.
- Continuously record the grouting data on a personal computer.
- Finally, select an adequate GIN limiting curve. This point will be discussed later on.

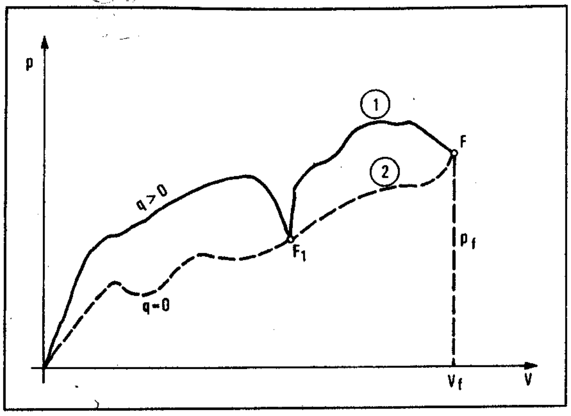

Fig. 1. Schematic sketch of the development of the pressure during a grouting stage versus volume of grout taken (grout path): 1 = actual pressure at the borehole mouth while flow rate $q > 0$; 2 = "pressure at rest", that is by flow rate $q = 0$; F_1 = intermediate stop; F = final stop of the grouting with $V = V_f$ and $p = p_f$, thus $GIN = V_f \cdot p_f$.

2. The GIN concept

The 'grouting intensity' has been defined as the product of the final grouting pressure times the grout take per metre of borehole at the end of the grouting process of a single borehole stage.

$$GIN = p_f \cdot V_f \qquad \ldots (1)$$

where p_f = final pressure
and V_f = final grout take per metre.

Fig. 1 shows the possible development of the grout pressure versus the volume injected. Generally the pressure will increase during the grouting process, but not steadily, while the volume take always increases. Irregularities in the pressure curve can often be explained. For example, a drop in the pressure may be caused by the opening of a new grout path or a hydrojacking effect.

The grout pressure at the borehole mouth is obviously influenced by the hydraulic losses along the borehole and along the grout paths in the rock. These losses are the result of the flow rate q, the viscosity η, and the cohesion c of the mix, which is actually a Bingham body, see Fig. 2.

As soon as the process is stopped, the flow rate being nil, the 'pressure at rest' is only a function of the cohesion of the grout mix and of the rock mass properties. Thus, stopping the process corresponds to a pressure drop. The grouting intensity concept is based on this final pressure (at rest), because the pressure at the grouting time is greatly influenced by the rate of flow which in turn depends on the operator and the way he conducts the process.

As a rule, the grouting process could continue indefinitely with increasing pressure, and obviously with a continuously increasing volume take. Incidentally one sees immediately that the usual notion of 'refusal' does not bare any real physical meaning. In fact this notion only indicates that the grout flow will stop at a given pressure; that is to say the flow will resume as soon the pressure is increased further.

The 'grouting intensity', as the product of the grout take multiplied by the final pressure, is a fairly acceptable approximation of the energy injected into the rock mass, while the energy losses during the grouting process itself can be disregarded.

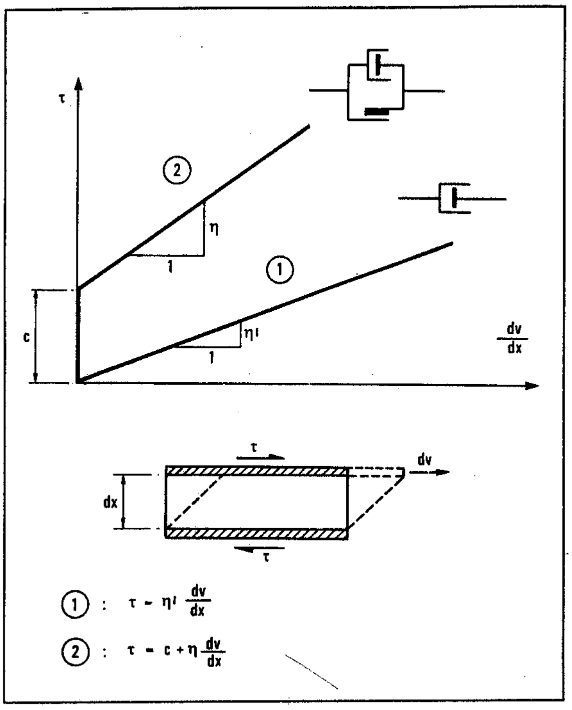

Fig. 2. Rheological properties of grout mixes. 1 = Newton Body; 2 = Bingham Body.

As the process can be stopped at any time, that means at any pressure, it can obviously also be stopped at any grouting intensity value selected, as shown in Fig. 3.

Limiting the grouting intensity means limiting the injected energy, and thus limiting the risk of damaging the rock mass. In fact, the dangerous combination of a high pressure acting on a large volume of mix not yet set is automatically excluded.

However, the concept of grouting intensity also has another meaning.

At rest, the pressure p is a function of the cohesion c of the mix, the distance R reached by the grout, and the equivalent opening e of the joint. Thus

$$p \cong \frac{R.c}{e} \qquad \ldots (2)$$

[Lombardi, 1985[5]].

The volume taken per metre is, by approximation:

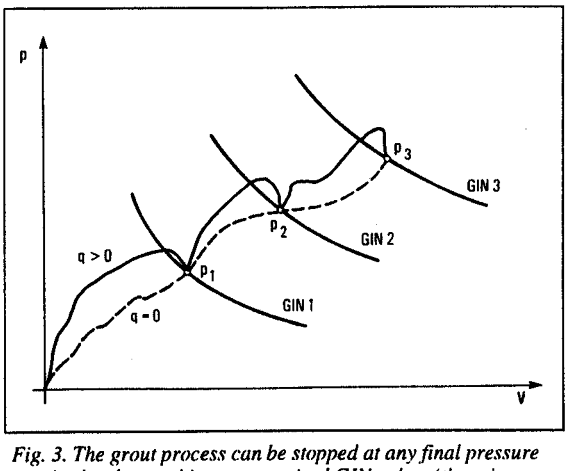

Fig. 3. The grout process can be stopped at any final pressure required or by reaching any required GIN value, (there is no such situation as "refusal" by the rock).

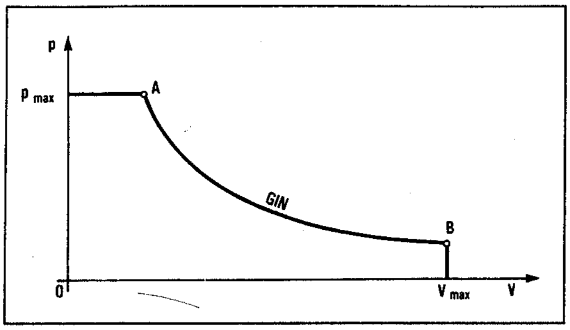

Fig. 4. The limiting GIN curve is defined by a GIN value (grouting intensity), a maximum pressure and a maximum volume take.

$$V \cong R^2.e \qquad \ldots (3)$$

thus the intensity

$$GIN = p.V \cong R^3.c \qquad \ldots (4)$$

no longer depends on the opening e of the joints (which is in fact the most difficult parameter to establish). For a given GIN value, and for a specific mix with cohesion c, the grout will reach approximately the same distance from the borehole regardless of the actual opening of the joints. This statement is extremely important.

Obviously to obtain the actual distance R as a function of the GIN value, a large number of factors needto be considered such as:

- geometry of the various joint systems;
- number of joints per metre (RQD), or their frequency;
- the nature of the joint surface inside and outside its plane;
- irregularities of the joint surface such as roughness, and so on;
- the part of the joint surface actually open; and,
- (obviously) the rheological properties of the grout mix.

For practical purposes these factors can be summed up in an 'overall groutability factor' K, thus having:

$$GIN = p.V = c.R^3/K^3$$

with,

$$K = R.\sqrt[3]{\frac{c}{GIN}} \qquad \ldots (5)$$

or,

$$R = K.\sqrt[3]{\frac{GIN}{c}} \qquad \ldots (6)$$

This last formula shows that for a given rock structure, for which K (or the groutability) may be considered constant:

- the reach R will increase with $\sqrt[3]{GIN}$
- and decrease with $\sqrt[3]{c}$, thus wholly justifying the use of a superplastifier in the mix.

Finally, again with some approximation, the GIN value is also a criterion for the splitting force exercised by the grout. This force is obviously a function of the pressure, but also of the surface on which it acts. This surface may be considered to some extent to be related to the volume of grout not yet set [Lombardi, 1985[5]]. It can thus be easily seen that the splitting forces cannot exceed a given value which is related to that of the GIN.

In this respect, great attention must be paid to the fact that when using a Bingham body, the pressure will decrease very rapidly from the borehole wall away, because of the cohesion of the mix. Thus, the usual reasoning, which assumes a constant grout pressure acting on a joint surface of undefined extension to compute the uplift or the splitting forces produced by the grouting and acting on the rockmass, is completely unrealistic.

As simple and interesting as the above formulae may appear, they obviously hold only to certain limits. In contrast with the traditional way of thinking, any grout process will produce movements in the rock mass as the mix is unavoidably introduced into the joints by pressure. The joint must therefore open, at least to some extent.

If the grout pressure is too high, the joints will open too much, and a significant fraction of the grout volume will be consumed near the borehole, so the distance reached will be smaller and the take will be greater than expected. Possibly, further increased pressure may produce 'hydrojacking' or 'hydrofracturing' of the rock, which is not generally desired.

It may be recalled that the definition of the GIN limiting curve comprises a GIN value, but also a maximum pressure and a maximum take, see Fig. 4.

3. Defining the GIN parameters

It appears to be logical, and even obvious, that selection of the correct GIN value would require the knowledge of the groutability parameter K to be introduced into Eq. (5). It may also be clear that the GIN value will have to be defined for any zone of the project with more or less homogeneous rock conditions, depending on its groutability and the objectives to be achieved by the design in that zone.

Three ways are theoretically available to define this groutability K.

The first could be a mathematical method, starting from the exact or simplified description of the actual joint sets in the rock mass, and trying to simulate the grouting process. It appears that this way is only possible for very simple theoretical joint configurations, so that the results obtained may be used only as a first rough estimate for further investigations. Furthermore the exact pattern of all the actual joints will never be known with sufficient precision at every spot of the rock mass. This method may be used only in simple cases, for example when grouting single cracks in a concrete mass [Turcotte, Savard, Lombardi and Jobin, 1994[6]].

The second method is an experimental one. It consists of carrying out a field test and measuring the distance reached by the grout during the grouting process as a function of the different GIN values. Such tests should be repeated for every single 'homogeneous' region of the rock mass.

Such a field test would in any case be highly recommendable, but cannot always be carried out for various reasons. The number of measurements required would be very high because of the scatter of the reach to be measured at different elevations and in various directions, as well as for different grouting pressures.

The measurements should be carried out in a number of control boreholes drilled at different distances from the field test. Different coloured grout mixes can be used to recognise the origin of the grout from each grouting stage.

Should a measured reach R_i be defined with sufficient precision, then, according to Eq. (5):

$$K = R_t \cdot \sqrt[3]{\frac{c_t}{GIN_t}} \qquad \ldots (7)$$

where suffix t represents test; and,

$$GIN = \frac{c.R^3}{K^3} = \frac{c.R^3}{c_t.R_t^3}.GIN_t \qquad \ldots (8)$$

will be selected if R is the required reach and c the actual cohesion of the grout mix.

The third method is the observational one. The grouting process can be started with a provisional value for GIN based on previous experience or on literature data (see Fig. 5), which can be adjusted during the grouting process according to the results obtained.

An interesting example of such a procedure can be observed in the way a grout curtain for a dam is generally carried out and continuously analysed using the split-spacing method.

Starting with a certain GIN value, primarily holes are drilled at a selected distance, secondary holes are then inserted half way between them, continuing in the same way with tertiary, then quaternary holes, and so on.

From one borehole series to the next, the grout take will diminish, while, as a result of the GIN concept, the final pressure will progressively increase and will finally arrive at the prescribed maximum pressure.

Increasing pressure from one borehole series to the next is an indication that the first series had sealed the wider joints and that the following series is doing so with the remaining less widely open joints.

The rate of reduction of the take from one series to the following one may be used as a reasonable criterion to conduct the grouting operation. Practice shows that an average halving of the take at each step may be considered to be an excellent result. Obviously single rates of 25 per cent or 75 per cent are quite common and must be accepted. (An example of good grouting results is shown in Fig. 6).

If the observed rate of decrease is too low, this means that the GIN value used was also too low for the selected spacing. In this case, the GIN value should be increased or the distance from borehole to borehole should be reduced.

The opposite should be done if this rate of decrease is unnecessarily high.

It should be noted, however, that the procedure is in any case quite self-regulating.

All in all, the problem consists of balancing the cost of the grouting itself with the cost of the boreholes, so as to reach the most economical combination possible.

In doing so, it must be kept in mind that at any grout stage (that means at a given grouting pressure), the wider open joints will be grouted to a greater distance than the thinner ones. Therefore a sufficiently tight grout curtain can be achieved only if a minimal number of borehole series are carried out in a row, at best using the split-spacing method. Consequently the grouting pressure will increase from series to series.

For reasons of economy, the holes of the last series are likely to be bored only at depth where the take of the nearest holes of the previous series have exceeded a certain limit of the take, defined for example as:

$$V_{lim} = 0.5\,\frac{GIN}{p_{max}} \qquad \ldots (9)$$

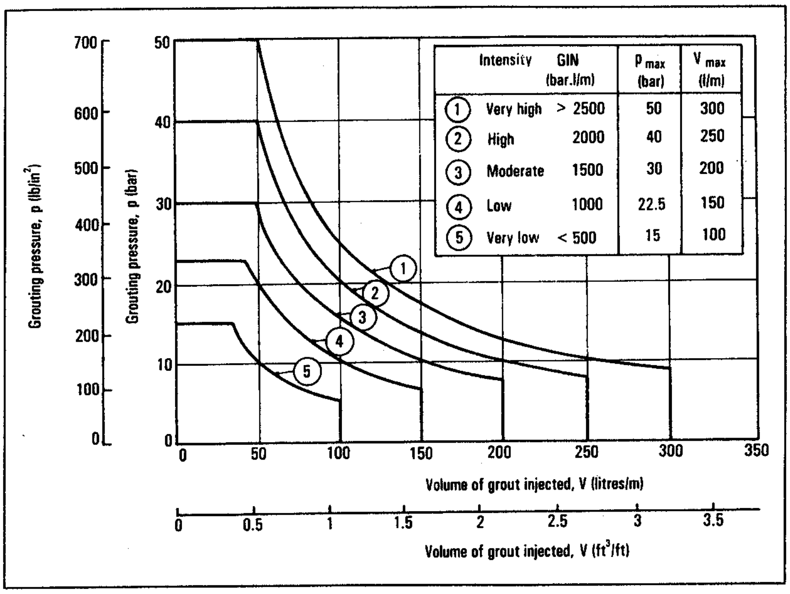

Fig. 5. Set of "standard" GIN limiting curves which may be helpful as starting guidelines.

For practical reasons, the grouting pressure must be limited. The definition of the maximum pressure is in principle independent of the GIN value selected, and must be selected on the basis of the objectives of the project.

In the case of a grout curtain, for example, it is usual to select a pressure that is twice to three times the future water pressure at that spot. By doing this, the opening of the joints by the actual water pressure at a later date can be avoided to a great extent.

The maximum take must also be defined as a function of the local conditions, considering for example, the risk of losses of grout as a result of leaks to the surface or to some cavity.

As a result of these considerations, it is understood that various GIN values can be used at the same time at different spots on a single job site, even if only one mix type is used.

4. Comparison with the traditional grouting method

Traditionally the grouting process has been conducted stepwise from thin to thicker mixes as certain limits of take have been successively reached. A comparison with the GIN method may be interesting.

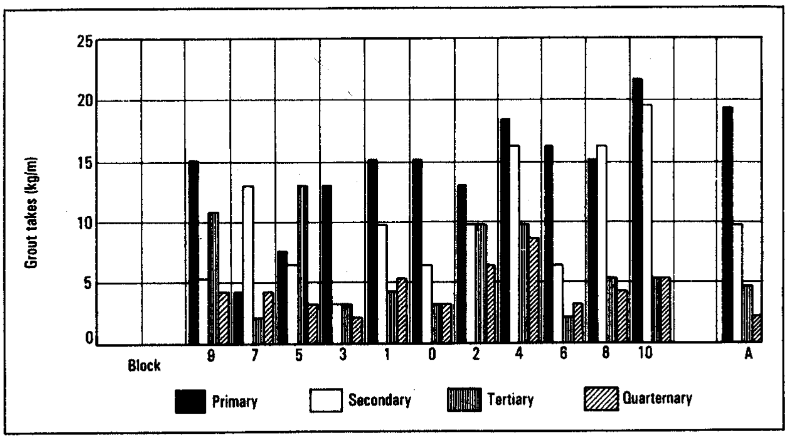

Fig. 6. Example of reduction of the average take from series to series in the case of consolidation grouting of a dam foundation. Design GIN = 1500, p_{max} = 40 bar. Result of 11 dam blocks. In A, a theoretical halving of the take of each series is shown for comparison. In this case the selected GIN value appears to be completely adequate for the designed borehole pattern.

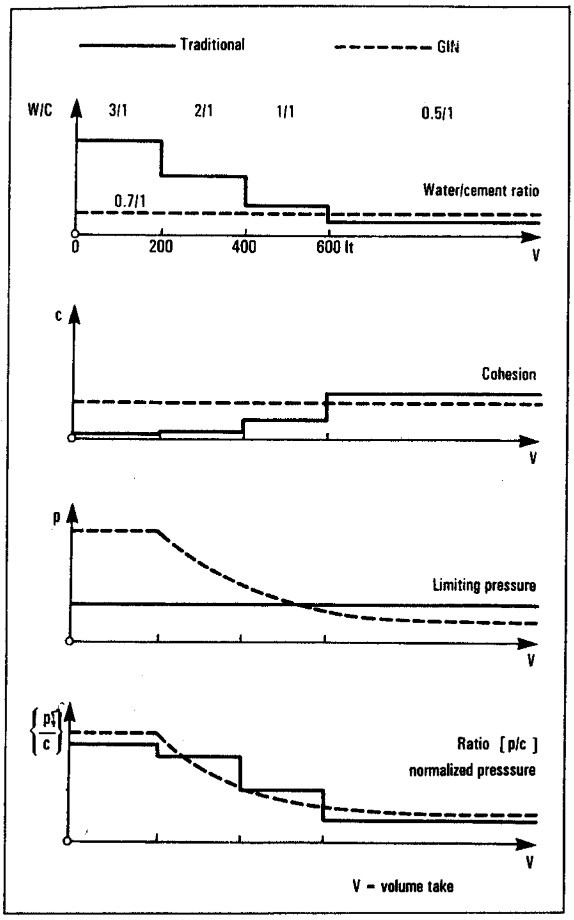

Fig. 7. Comparison, by way of example, of the traditional and the GIN grouting methods. The normalized pressure $p_n = p/c$ is decreasing with increasing volume take both for the traditional and the GIN method.

Eqs. (2) and (4) can also be written as follows:

$$\frac{p}{c} \cong \frac{R}{e}, \quad \text{or} \quad p_n = \frac{p}{c} \cong \frac{R^3}{V} \qquad \ldots(10)$$

which means that the most significant parameter of the grouting process is really not the actual grout pressure *p*, but the 'normalized pressure' of the dimensionless ratio $p_n = p/c$ (which in practice may lie between 10^5 and 10^7, always using stable mixes).

Furthermore the value V/R^3 could be understood as a kind of 'groutable porosity of the rock mass'.

As Fig. 7 shows, both for the traditional and the GIN methods, the normalized pressure p_n tends to decrease with progressive injection. The difference between the two methods is as follows. In the traditional way, this decrease is obtained in changing stepwise to thicker mixes with increasing cohesion. On the other hand, following the GIN rule in using a unique mix, 'the best one', the pressure will be progressively reduced while the cohesion is constant.

Finally, the GIN method can be seen primarily as being a good way to achieve an excellent grouting result, by avoiding low-strength, easy to leach-out, unstable grout mixes caused by an excess of water.

5. Concluding remarks

It is common knowledge that the properties of fissured rock masses are, as a rule, quite heterogeneous and anisotropically distributed in space. Any grouting procedure must take this into account.

Therefore, some scatter must always be expected in the results of any grouting work, and thus accepted. However, it appears that the GIN method automatically compensates at least for a significant amount of the uncertainties to be encountered.

Because of the remaining scatter, even the use of GIN does not preclude any further thinking by the designer and also the operator of the plant.

As a result, it is not possible to prevent inappropriate use of the GIN method, and thus some mishaps cannot be completely avoided.

With practice, the above considerations on the GIN method will appear absolutely evident to the user, provided, however, he has cleared from his head the tales of grouting he has heard about over many years.

Finally, it should be stressed that the correct GIN value to be used is the result of a good balance between the natural rock conditions and the design requirements.

It is also influenced by the relative costs of boring and grouting activities. ◊

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