Practical application of the GIN concept (Part 1)

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Designer’s overview
The GIN concept is a self-regulating approach of controlling simultaneously both the injection pressure and rate of injection, to avoid a combination of high volumes and high-pressure, whilst at the same time setting defined limits on maximum volume and maximum pressure. In general terms the GIN concept aims to optimize the grouting process. In particular, it aims 1) to grout only where absolutely necessary, in this way avoiding any waste of grout and 2) to use highest practicable grouting pressures without causing any damage, in order to enhance the efficiency and success of the grouting operation.

This concept was first introduced more than 30 years ago by Eng. Lombardi and Eng. Don Deere, with the intention of avoiding damage to the fissured rock formation, whilst greatly improving the efficiency and effectiveness of grouting operations. One of the intentions of the process is to equalise the radius of flow in fissures of varying widths.

Remarkably, with all the advancements in grouting over the last decades, the GIN concept has remained largely intact and has proved to be a reliable tool to manage efficiently the grouting process under varied conditions in numerous projects worldwide. With its well-founded physical basis, its generality, and finally its simplicity, the GIN concept clearly and consistently illustrates that grouting does not, and should not, represent an obscure art.

Contractor’s overview
Bachy-Soletanche personnel have been using the GIN concept for rock grouting for more than 30 years in a wide range of rock conditions, from karstic limestone, through finely fissured chalk, to heavily fractured sedimentary and volcanic formations, and have come to value the technique for its simplicity and efficiency, to the extent that it is now a prime consideration when reviewing any rock grouting solution for either block consolidation/impermeabilisation, or as a grouted cut-off.

The GIN technique is considered not so much as a method of grouting, but simply as a tool, one of many essential tools used by the grouting engineer to achieve a successful outcome. As with any tool used in any type of work, it requires understanding, skill, and experience to be able to employ it effectively in the workplace. Furthermore, GIN grouting involves experienced observation and interpretation throughout the grouting programme. Based upon the initial observed results, the GIN value, and the various injection parameters, should be adjusted where necessary during the course of the grouting programme, but thereafter, the objective should be to change as little as possible to maintain a consistent strategy.

The technique has proven itself on worksites where other techniques have failed, and has delivered a high quality of ground treatment in challenging rock conditions, whilst at the same time providing significant economic benefit for both client and contractor alike.

For success and maximum efficiency it is essential that the technique, as with all techniques, is configured to suit the local ground conditions. This may seem obvious, but there have been many cases of specifications and grouting strategies being too rigidly applied, sometimes simply copied from elsewhere, in the expectation that these can be imposed on the ground, and that the ground will comply. Clearly, it will not, and thus this approach is predestined for failure.

Within the Bachy Soletanche group, the GIN concept of fissure grouting in rock is seen as a major advance in the practical application of rock grouting technology. This view is also widely held amongst practising contractors due to the simplification of the core injection process, the self-regulating control of excessive hydro-fracture pressures, and the improved facility for comparison and interpretation of the grout injection data across numerous phases of injection.

On the following pages, some general technical aspects related to GIN grouting will be discussed. In the next Groutline issue (Match 2016), several case histories of projects in which Bachy-Soletanche has been involved are presented.

Technical aspects related to GIN

Basic rules for GIN injection
When it was introduced some 30 years ago, the grouting intensity number was just a numerical value, defined as the product of injected grout volume and applied pressure, GIN = P.V. However, over time, with technological advances and improved field experience of the approach, further aspects related to grouting of fissured rock masses have been developed and incorporated within GIN injection.

Despite various developments, the basic GIN concept itself has remained unchanged across the industry, so that today there is a broad consensus as to what constitutes the essential features of this technique, which can be summarized as follows:
• application of a single GIN value, the product Pressure x Volume, which is constant for all stages and boreholes, or (at least) all stages within a given phase of injection, and preferably for the entire grout programme. The GIN boundary curve defines the limits within which injection should be executed.

• application of a rheologically stable grout mix whose design and constituents is appropriate for the rock conditions and desired residual permeability.

• use of a single, rheologically stable, grout of low water-cement ratio. Without this, it is impossible to compare grout absorptions between different phases and injection on a similar basis.

• establishment of a maximum injection pressure.

• application of a minimum effective flow rate, the equivalent of a refusal criteria, to terminate injections if injection flow rates become too low to be practicable.

• establishment of consistent injection parameters for maximum pressure, maximum volume, and uniform injection rate up to the point at which the GIN curve intersects the GIN envelope boundary curve.

• once the injection has reached the boundary curve, a progressive reduction in the maximum pressure, following the GIN boundary curve as the volume increases, continuing up to the point at which either maximum target volume, or minimum flow rate, are recorded.

• estimation of the target volume, based upon knowledge of the rock formation and the required ground treatment geometry.

• plotting of results in the format of an Equivalent Lugeon, provides an indirect measurement which allows an approximation of the rock mass transmissivity with water. This can provide a very useful means of observing in real time the progressive reduction in permeability achieved by successive phases of grouting, and even during an individual injection.

• execution of test grouting as direct unambiguous way to confirm the appropriateness of the mix design and grouting parameters.

With the appropriate planning, equipment, and control systems, GIN grouting is very simple to apply in practice. The function ‘Equivalent Lugeon’ has been recognised by many practitioners. This function, calculated on the basis of the ratio between the viscosity of the grout and the viscosity of water, is useful for tracking the evolution of the injection, and the progressive reduction in permeability and transmissivity. It is noted that Equivalent Lugeon is actually a rather inappropriate and controversial name for this parameter, and its use gives rise to misunderstanding and resistance amongst the grouting fraternity. However, since this phrase is already widely used, it is difficult to change its name without generating confusion.

Establishing the GIN value
In general terms the GIN concept helps to obtain the best grouting result with minimum effort. The three underlying parameters to achieve this are the grouting intensity number itself, the maximum pressure and the maximum (target) volume. The GIN value is the product of P, the injection pressure, and V the cumulative volume. It is a constant for any given injection, so that the pressure decreases as the injection progresses. The plot of this function forms a limiting boundary curve. (See Figure 11), which helps to avoid a combination of high pressure and high volume, which could have the potential of damaging the rock formation and risking surface heave. The curve, plotted with P on the y axis, and V on the x axis would at infinity by asymptotic. The extent of the curve is therefore limited by a cut-off at P_max (maximum allowable pressure), and a cut-off at V_max (target injection volume for the injection stage).

The definition, purpose, and the selection of appropriate values for the GIN, P_max and V_max are discussed below.

GIN value
The choice of the proper grouting intensity number (GIN) itself is based on both, geological conditions as well as on the project design and requirements.

Before addressing the determinant geological factors, it needs to be noted that the GIN concept has been specifically developed for, and is therefore intended only for, fissure grouting. Like for any other grouting method, special attention must be paid to larger voids, which should be filled with a low mobility grout (LMG) or another appropriate low cost material. This confutes the sometimes still existing misconception that GIN grouting is generally not applicable in limestone. In fact, numerous foundations composed of fissured limestone have been already successfully grouted using the GIN technique. If local conditions, such as the presence of large dissolution features often associated with this type of rock, called for it, a corresponding special treatment to fill these voids was simply adopted.

As with the choice of the proper grouting method, be it fissure grouting or void filling, the selection of the adequate GIN value depends on the local site conditions and the expected final result. Whether the purpose of grouting is to reduce the permeability of the rock mass or to strengthen the foundation, the GIN value on a site can be generally correlated to certain geotechnical zones. Where a site is characterized by highly variable rock mass conditions distinguishing several geotechnical zones, this might indicate a need to apply different GIN values. Generally, for rock masses of good quality, a higher GIN value can be used, whilst in weaker zones of lower strength, grouting should be performed more cautiously, by applying...
a lower grouting intensity. Table 1, as a rough indication, shows the relationship between some common GIN values, the grouting intensity scale, and in accordance with the above, gives a direct correlation with the geological rock mass quality.

Thus, **Grouting intensity number, GIN ~ Rock mass quality**

<table>
<thead>
<tr>
<th>Intensity</th>
<th>GIN [bar.</th>
<th>RMR</th>
<th>RQD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>&gt; 2’500</td>
<td>81-100</td>
<td>very good</td>
</tr>
<tr>
<td>High</td>
<td>1’500 - 2’500</td>
<td>71-80</td>
<td>good</td>
</tr>
<tr>
<td>Moderate</td>
<td>1’000 - 1’500</td>
<td>41-70</td>
<td>fair - good</td>
</tr>
<tr>
<td>Very low - low</td>
<td>&lt; 500 - 1’000</td>
<td>&lt;40</td>
<td>very poor - poor</td>
</tr>
</tbody>
</table>

It is worthwhile noting that, in contrast to many other fields of engineering, the design of a grouting job strongly depends on the rock mass - a natural medium which is not designed by ourselves. As consequence, there is always an unavoidable uncertainty in the definition of the generic mechanical or hydraulic parameters, and the engineer must be aware of this variability when using those parameters as basis for the grouting design.

It frequently occurs that the actual rock mass conditions do not correspond to the ones anticipated and assumed in the initial design phase. If this discrepancy becomes significant, it might indicate the need to change the grouting intensity according to the new findings. Optimally, the GIN value for any given rock formation should be chosen at the beginning of the design procedure, and kept constant for each phase, or for the whole, grouting programme. For some sites the GIN value might require to be adjusted after the initial results are analysed, and possibly even reviewed further as the grouting works progress. However, any abrupt and frequent changes are to be avoided in order to keep the control and analysis of the grouting as simple as possible. Occasional modifications might be necessary, but should be always based on a rational basis to avoid the grouting becoming confusing and obscure. It is noted that test grouting sections on the site into the actual rock mass allow

in this lowest part the real efficiency of the curtain is by definition zero, the requirements for the grouting intensity might actually also be defined less stringent in this lower zone.

In this way unnecessary grouting in zones of minor importance can be avoided, while the main effort can be focused on the most relevant zones. This helps to significantly optimize the whole grouting process.

Accordingly, the GIN number itself incorporates both geological and project design aspects. The intensity is therefore directly related to the rock mass quality as well as the relevance of the grouting result for the project.

Once selected, the GIN value controls the injection parameters within a safe working envelope. However, the GIN value needs to also reflect the constraints of the practicable values for the minimum flow rate and minimum controllable pressure of the grout pump (typically 200-300 l/hr, and approximately 2 bars).

For any given grout type, and injection rate, the evolution of the GIN value over the duration of the injection will depend upon the rock conditions, the grout rheology, and the injection rate. Once the plot of $P \times V$ reaches the boundary curve, the injection flow rate, controlled by computer piloted grout pumps, is progressively reduced or increased automatically to maintain the product $P \times V$ at or just below the GIN curve until either the maximum target volume is injected, or until the flow rate reduces to a minimum practicable level, at which point the injection is complete.

When establishing a GIN value it is therefore also necessary to consider particularly the likely flow rate during the latter stages of the injection, (approaching the target volume) to ensure that this is compatible with the minimum practicable flow rate for the grout pump, and grout gelling properties, to avoid line blockage.

Application of a single GIN value allows direct comparison of the
THE GROUT LINE

Graphical and numeric data for individual borehole stages, and for the various phases of injection. It also allows the grouting engineer to rapidly assess and gain a feel for the progress of a single injection and/or the progress of the grouting programme, either by observation of the real-time plot of the GIN curve and the evolving GIN value during the injection, or by visual inspection of the graphical plots on completion of the daily injection programme. Figure 1 gives typical examples of the evolution of the GIN value, within the GIN boundary curve.

**Maximum injection pressure**

The maximum pressure limit $P_{ \text{max} }$ serves mainly to select the proper grouting equipment, such as pump, tubes and valves. Like the GIN itself, it should be defined so that it complies both with the rock mass properties and project requirements.

If the purpose of grouting is, for example, the impermeabilization of a dam foundation, the maximum pressure should be chosen according to the expected future water losses and uplift pressures after impounding. It has to be sufficiently high in order to avoid a fissure opening when the reservoir is impounded. A common value for the maximum pressure at the borehole mouth is around 2 - 3 times the future water pressure at that location. Another important aspect to be considered when selecting the proper maximum pressure is the allowable hydraulic gradient of the rock mass. In this: the higher is the hydraulic gradient the higher shall be the maximum injection pressure.

In practice, the maximum pressure can be set in a number of ways. The most reliable method remains certainly the execution of grout test sections on site in the same conditions using the proposed mix design. Another indirect method is to conduct hydro-fracturing tests in the pre-injection investigation boreholes, and to apply a factor of safety to the measured hydro-fracture pressure. In contrast to grouting test sections, for hydro-fracturing tests there is no volume constraint for the water, which is first of all risky. Secondly, acknowledging the difference in water and grout mix, a careful evaluation of the test results by an experienced person is required to be able to extract the desired information for the actual admissible grouting pressures. Alternatively, an estimation may be made with the confining overburden and surcharge pressure, or the limit may even be set on an empirical basis based upon previous experience in similar rock conditions and/or depths of injection.

It is important to recall that the GIN technique is actually self-regulating. Any possible adoption of the pressure with depth to avoid grout outflow or damage due to too higher pressures,
as is sometimes erroneously done, becomes therefore superfluous. Following the GIN concept, the grout takes near the surface or gallery, where the fissures generally tend to be rather open, automatically increase, while the pressure remains rather low. At depth, on the other hand, the openings are generally smaller so that less grout is absorbed. As shown in Figure 2, the grout path in this latter cases (grout paths 3 & 4) is steep reaching quickly higher pressures. Therefore, respecting this self-adaptive nature of GIN grouting, once a certain maximum pressure is defined, it should be kept constant. Changing systematically the maximum pressure in function of depth does not only unnecessarily complicate the whole grouting procedure, but it also carries the risk of stopping grouting before the natural equilibrium is actually reached, resulting in an incomplete execution of the works. The only zone where a certain pressure limitation might be acceptable is the upper 5 m, in order to avoid grout break-out to the surface, especially if grouting is not performed through a concrete slab or similar. To ensure an efficient grout result along the entire borehole length, it is common practice to increase in addition to the grouting pressure can be best confirmed by several representative grouting test sections.

Maximum grout take (target volume)

The maximum grout take does actually not present an absolute stop criterion. It rather defines a decision point on whether to

- Continue grouting
- Terminate grouting
- Pause grouting and restart later after setting of grout
- Abandon the hole & drill another one nearby
- Modify the grout mix

In contrast to the grouting intensity number and the maximum pressure, this parameter is mainly defined considering economical rather than physical aspects. A rough indication of commonly chosen maximum grout takes, $V_{\text{max}}$, for certain grouting intensities is given in Figure 3.

Mix design

One of the key aspects of the GIN concept is the use of a single stable grout mix. The mix should be formulated to achieve the specified performance criteria as efficiently as possible (i.e. the minimum number of boreholes, the minimum number of injection phases, and the optimum injection rate throughout each individual injection). Its selection and design is based upon a thorough understanding of the site rock conditions, including fissure widths. It stands to reason that one of the most important aspects actually limiting the groutability is the maximum cement grain size relative to the fissure width. As a general rule, for a fissure to be groutable, its aperture should be at least three times the maximum grain size of the cement. Finally, the mix is also of low water-cement ratio to ensure both long-term strength and durability, and the avoidance of bleed within the voids and fissures of the formation.

Figure 2. Grouting paths for different fissure openings, illustrating the self-adaptive nature of GIN grouting.

Figure 3. Typical range of GIN values, as well as corresponding maximum pressures and volumes.
Stable mix

Generally a stable mix is a grout consisting of a cement-based slurry, with additives if necessary, to ensure that no water is expelled from the suspension when injected at pressure (i.e. no pressure-filtration). The stability of the grout ensures that:

- the grout rheological properties remain constant throughout the injection to maintain the fluidity and penetration capability
- the progressively reducing absorption of grout can be clearly observed, understood, and measured, as the works progress
- no water filled zones are left

Consistent rheological properties ensure a realistic comparison of grout injection data between subsequent phases of injection, and during the course of a single injection. This is why the mix should not be fluidified with excess water. Water should be mainly considered as transport medium for cement grains not as physical component of the mix.

Current practice is to employ a grout of low water cement ratio (typically 0.6 - 1.1), so that once an individual injection is completed, the potential for bleed in-situ is minimised. It also ensures long-term strength and durability reducing the requirement for successive re-injections.

Single mix

For successful and efficient grouting, it is highly recommended to inject a single grout type with a consistent water/cement ratio for all injections and all phases of the works. Combined with the stability of the grout, a single mix enables the accurate verification and control of the increasing competence and water-tightness of the strata with the grouting works progress.

Recognizing the importance of using a single mix is one of the main aspects where the GIN approach differs from classical grouting practice of 30 years ago. Traditionally, the w/c ratio was lowered in steps (see Figure 4) to increase the cohesion, and in this way lower the normalized pressure, P/c. The introduction of the GIN concept can be said to present a turning point away from this traditional approach of thickening the mixes in steps.

For GIN, (as indicated by the blue line in Figure 4), it is recommended to:

- Use 1 unique stable mix throughout the grouting works
- Limit the grouting pressure with increasing volume take
- Reduce the normalized pressure (P/c) by progressively decreasing the pressure.

![Figure 4. Mix and pressure evolution -Traditional versus GIN grouting.](image)

The use of a single, stable, grout mix avoids many potential errors in mix formulation and in the interpretation of the most relevant injection data - the volume per linear meter injected. In the past, much effort has been expended in trying to accurately convert injected volumes into a dry weight of material per linear metre - a pointless exercise in terms of the specified objectives and technical management of the works, and only of interest for assessing payment.

Multiple mixes, changed during a single injection according to certain volumetric or pressure criteria, have resulted in a flawed understanding of the grout absorption due to the fact that insufficient consideration was taken of the distance over which the grout has been pumped, and/or the volume of grout in the system. There have been sites where mixes have been changed in a rigid succession, when one of the mixes in the sequence has been still wholly or partly within the delivery system, without ever reaching the point of injection. Consequently, the basis for changing the grout mix was flawed, and a calculation of the total dry weight of material injected into a grout stage at the time of refusal was incorrect, so that decisions on subsequent injections were based on a false premise and understanding.

The changing of mixes, in particular the thinning or thickening of the grout mix already in the system, is prone to errors of mix formulation and preparation, whether manually or automatically batched, and this has led to errors in calculating the effects of varying viscosity and head loss, the extent of pressure filtration and sedimentation, and hence in understanding the effective penetration of grout into the formation.

However, the real advantage of a single mix is that it is designed specifically for the rock conditions on site, and particularly for the finer fissures required to be injected to achieve the specified residual permeability.

Another real and valuable advantage is to enable a simple and direct comparison of injections from stage to stage, hole to hole, and between successive phases of grouting. This is invaluable in understanding and visualising in real-time the improving condition of the rock mass and reduction in mass permeability.

Further, providing care is taken with the mix design to control the evolution of the mix viscosity, the gel time, and the setting time, so that the mix remains rheologically consistent throughout the injection, the injection
can be used as a surrogate hydraulic or packer test. Real-time plotting of the Equivalent Lugeon can indicate visually the increasing ‘tightness’ and reducing permeability of the formation as the injection proceeds. Field experience has shown this value - the misnamed Equivalent Lugeon - to be a remarkably good and consistent indicator of the true residual permeability, expressed in Equivalent Lugeons.

In summary, a carefully designed single mix greatly facilitates the work of the grouting engineer and the operatives in the field, has real technical advantages, and provides an accurate and reliable basis for comparison of grout absorptions between different injections stages and different boreholes, and between successive phases of grouting.

**Use of multiple mixes, including accelerator and/or gelling agent**

When employing the GIN grouting, the flow rate is automatically controlled to ensure that the function P x V remains within the boundary curve. It follows that towards the end of a given injection, the injection rate may be approaching the limit of the pump, i.e. approximately 180 L per hour. Considering for example a grout curtain. Due to its geometry and the need to keep a constant length for the grout injection line to ensure constant head loss at a given flow rate, the total volume of grout in the injection system might be as high as 450 L (150 L in the grout line, 250 L in the grout agitation tank, and 50 L in the grout Packer and stage). Clearly, if the new mix is introduced into the system, whether with or without an accelerator, it could take up to 2 hours for this mix to arrive at the point of injection, particularly as flow rates are progressively reduced.

This suggests that the use of an accelerated mix, where the accelerator is added at the mixing station, is not compatible with the GIN idea when following the standard GIN procedure, as this could lead to premature sealing of the borehole before the required volume is injected. Therefore, accelerated mixes might only be applicable when either:

- a pre-injection stage water test indicates an exceptionally high Lugeon value
- there is a high hydraulic gradient across the injection zone, with risk of grout dissipation
- grout is being freely absorbed with minimal pressure increase at the point where the target volume has been injected

at which point a decision could be made to introduce an accelerated mix for a single one-off, non-GIN injection to deal with a significant local feature such as a major fissure or preferred seepage path. Whether an accelerator is added for a single on-off injection, or used systematically in poor or voided ground, the accelerator should be added at the point of injection, via the packer, using a separate supply line for the additive, an in-line mixer, and with a variable flow or proportioning pump to adjust the flow according to the rate of injection to maintain the correct additive proportion in the mix.

The same considerations should be made to changing the grout mix at any point within a GIN injection, since as the injection progresses, and the flow rate gradually reduces, it is highly likely that the new grout mix could still be advancing within the injection lines at the time that the injection is nearing completion. We would strongly recommend therefore the use of a single grout mix throughout any GIN injection, and wherever possible, the use of a single grout mix throughout the whole injection program for a given phase of the works.

**Grouting procedure**

**Tracking the GIN boundary curve**

Injection of an individual stage proceeds on the basis of pre-set injection rates, until the value of P x V reaches the limit of the boundary envelope defined by the GIN value. Once the product of P x V reaches the boundary envelope, it is necessary to progressively reduce the flow rate as the cumulative volume increases, in such a manner that the product of P x V remains constant at or just below the limiting GIN value. This operation could be, and has been in the past, carried out manually - but this might be extremely difficult. Current best practice is to employ piloted grout pumps which have the facility to be controlled by computer at all stages of an injection, utilising continuous real-time feedback of data on the pressure, cumulative volume, and flow rate to the grouting computer, in such a manner that in real time the computer can respond to the incoming data and can automatically slow down the rate of pumping to allow P x V to track the GIN curve until one of several criteria are reached.

These are

- maximum pressure - no further injection is possible without exceeding the allowable pressure
- maximum volume - the cumulative volume of grout injected has reached the target limit for the borehole / injection
- minimum flow rate - this is a condition where in order to maintain the plot of P x V coincident with the boundary curve of the GIN envelope, the injection rate falls to a level which is impractical, un-desirable on economic grounds, or poses considerable risk of blockage of the grout pump and/or injection lines.

**Consistent injection rate**

There is no inherent advantage, technically or commercially, to either client or contractor in injecting grout slowly. Provided that the limiting grout pressures are not exceeded, the aim should be to pump as quickly as practicable. The GIN technique ensures that the limiting pressure is progressively reduced as the total injected volume increases, and this limit is defined and enforced by the GIN boundary curve.
It is prudent to limit the injection rate over the first 15-50 L to avoid immediately reaching the maximum limit pressure, and modern control measures allow for an injection rate of, for example, 300 L per hour until this volume has been placed. Thereafter, the pump can be programmed to seamlessly and automatically increase injection rate up to its practical maximum, typically in the range 1'000-1'200 L per hour. This injection rate should ideally be constant for all injections, and each injection will continue at this rate until the plot of the GIN curve approaches to within approximately 1 bar below the GIN boundary curve.

Practical experience has shown that it is convenient to define a certain regulation zone, when approaching the GIN curve, for which a reduced flow rate is imposed. As shown in Figure 5, this zone is bounded by the GIN curve itself and by a parallel regulation curve typically at around 1-2 bars below the GIN value. Within the regulation zone the pump flow rate varies automatically according to the cumulative grout volume and the rock conditions, to maintain the GIN plot within the regulation zone until the injection terminates on minimum flow or maximum volume. The path of the GIN plot and the point at which the GIN plot intersects the boundary curve will be dependent upon the mix, the pump injection rate, and the rock characteristics. Once the cumulative volume injected reaches the target volume for the stage, or the pump reaches its minimum practicable and/or economic pumping rate, the injection terminates automatically. The target volume and the minimum flow rate are all pre-set into the software and cannot be accidentally exceeded.

Once automatic regulation commences, limiting the injection rate, for low grout quantities, for too long a time in this regulation zone, would make the grouting works unnecessarily complicated and uneconomic. There are mainly two options for the termination criteria – either continue grouting at a reducing flow rate until the flow rate reduces to a pre-determined rate (somewhat equivalent to a classical ‘refusal’ criteria), or the GIN curve is followed until the previously defined maximum volume is reached. Applying the same criteria to every single injection ensures that the graphical plot for each injection can be compared with that of every other injection, and can provide a great deal of information about progress and success of the individual injection and the progress of the works. It also, together with the constant GIN value and mix characteristics, adds greatly to the substance and accuracy of any numerical analyses.

A key element of this visual inspection is to see on completion of the injection whether the full target volume has been injected, or whether the injection is terminated too early. The grouting engineer can see at a glance what percentage of the target volume has not been placed, and, can make a judgement as to whether this is due to improving rock conditions and reduced transmissivity, or whether the grout mix is inappropriate for the formation, and it allows him to see whether the GIN value is appropriate or not. If he has any concerns on these issues then, of course, he must be prepared to modify the parameter accordingly. However, this should ideally be done for all remaining boreholes. Varying the injection parameters for each individual stage renders realistic and systematic analyses of the results extremely difficult, and prevents the application of some very valuable comparative analyses.

To avoid such an unnecessary complication of the grouting process, it is advisable, in the early stages of the project, to immediately drop back and carry out one or two secondary injections after the first 3-4 primary holes have been completed, to verify that the assumptions made in terms of target grout volume, GIN value, and the optimum injection parameters, are correct. The parameters should then, if required, be modified at this early stage and maintained unchanged wherever possible for the remainder of the works to keep the grouting works as clear and manageable as possible.

**Minimum flow rate**

The minimum flow rate set for the injection should be a pragmatic decision based upon the characteristics of the pump, technical and cost efficiency considerations, and understanding of the gel and set times of the selected grout, and especially upon examination of the GIN curve and the implied injection pressures at the point on
the curve where the maximum target volume has been placed. If, at the maximum target volume, either the minimum flow rate defined by the GIN curve is below the minimum desirable injection rate, or the injection pressure is too low for accurate regulation then the design GIN value may have to be increased accordingly.

These considerations need to take into account the experience of the grouting engineer in similar rock conditions and with the characteristics of the equipment being used. There is no technical or commercial advantage in continuing the injection to a point where any further minimal improvement in the rock condition is not justified by the cost of continuing injection, or beyond the point at which there is a risk of grout line blockage or inefficient injection due to a change in the rheology of the grout mix.

Successful completion of grouting

Decision for additional boreholes

In accordance with the rock mass conditions and project requirements, grouting might be systematically executed from primary or secondary boreholes, depending on the hole spacing. The decision for additional, i.e. tertiary or quaternary boreholes is then based on the final grouting pressure reached. According to the GIN concept, and as a result of the split-spacing borehole pattern, grouting is a self-adaptive procedure: first wide fissures are grouted at rather low pressures, before by the following higher order boreholes increasingly smaller openings are filled using higher pressures, as shown in Figure 6.

Consequently, when applying the GIN technique, it can be observed that in general the final grouting pressure does continuously increase from phase to phase, whilst the grout takes are generally decreasing. This development from the lower right to the upper left of the GIN curve, reflects in fact that for each phase the widest remaining joints, not injected during previous phases, are filled. Such grouting results are therefore considered much more meaningful in terms of the actual groutability than any water pressure tests.

Generally, the grouting works are said to be completed if the GIN curve is reached at 50 to 75% of the final pressure. If the grouting path intersects the GIN curve at lower pressures, for example as shown in Figure 16, this phase cannot yet be considered finished and additional boreholes or phases are to be executed. These additional boreholes do not necessarily need to be drilled to full depth. Instead, their optimum depth should be selected based on the grouting results of adjacent boreholes at certain depth intervals. This simple design consideration shows how, by proper integration of the observational method within the grouting procedure, the full benefit of the self-adaptive

Table 2. Guidelines for acceptable foundation permeabilities, according to Houlsby and ranges for typical allowable hydraulic gradients allocated to different dam types.

<table>
<thead>
<tr>
<th>Dam Type</th>
<th>Curtain</th>
<th>Recommended Lugeon</th>
<th>Typical allowable hydr. gradient Δ</th>
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</thead>
<tbody>
<tr>
<td>Concrete Dams</td>
<td>Single row</td>
<td>3 - 5 Lu</td>
<td>5 - 10</td>
</tr>
<tr>
<td></td>
<td>Multiple row</td>
<td>5 - 7 Lu</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Embankment dams with narrow core (earth / rockfill)</td>
<td>Single row</td>
<td>3 - 5 Lu</td>
<td>5 - 10</td>
</tr>
<tr>
<td></td>
<td>Multiple row</td>
<td>5 - 10 Lu</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Embankment dams with a wide core &amp; membrane faced dams</td>
<td>Single row</td>
<td>5 - 10 Lu</td>
<td>1 - 5</td>
</tr>
<tr>
<td></td>
<td>Multiple row</td>
<td>7 - 15 Lu</td>
<td>1 - 2</td>
</tr>
<tr>
<td>All dam types with foundation material prone to piping or wash-out by seepage in general</td>
<td>Single row</td>
<td>3 - 5 Lu</td>
<td>5 - 10</td>
</tr>
<tr>
<td></td>
<td>multiple row</td>
<td>2 - 4 Lu</td>
<td>5</td>
</tr>
<tr>
<td>All dam types, if water loss by seepage becomes relevant for the project, and thereby warrants considerable expenditure to stop it</td>
<td>Single and multiple row</td>
<td>1 - 2 Lu</td>
<td>&gt;25</td>
</tr>
</tbody>
</table>
nature of the GIN concept can be gained, thereby achieving a complete, efficient, cost-effective, and safe grouting job.

**Acceptable final permeability**

Before defining an acceptable final permeability for a grouting job, one should first think about what might actually be the consequence of the seepage and/or leakage caused by it. There should be a clear differentiation between seepage, which is defined as interstitial movement of water in the foundation, or the abutments, and leakage, which is flow of water through holes or cracks.

Taking a closer look, it quickly becomes clear that foundation permeability may directly affect the stability of the structures to varying degrees, mainly depending on the dam type and height. Whilst for rockfill dams, for example, a certain amount of leakage is common and is rather of little relevance, for concrete dams, in particular if they are large, the same leaks might already significantly impair their safety.

This distinction was already recognized by Lugeon in 1933, when he came up with first indications for allowable foundation permeabilities. He suggested a limiting Lugeon value of 3 for small dams and a Lu < 1 for large dams, respectively. Based on subsequent experience and critical expert reviews, this concept has been further refined over time, in particular focusing on the actual warranty for grouting. Today, engineers commonly refer to the guidelines proposed by Houlsby [3], which can be summarized as indicated in Table 2. In the same table also some typical ranges for allowable hydraulic gradient allocated to different dam types are given.

It is obvious that the highest hydraulic gradients in the rock mass occur in the contact zone at the dam foundation. In the treated zone they diminish with increasing distance from the dam rock mass contact surface at the foundation. Both, the recommended Lugeon and typical allowable hydraulic gradients as listed in Table 2 refer therefore to the zone close to the dam rock mass interface in the central foundation part. With depth corresponding less stringent values (i.e. higher Lugeon and lower gradients) might be acceptable.

These values are obviously intended for guidance only and their appropriateness must be reviewed and verified individually for each project in terms of the project-specific risks. To arrive at an appropriate value, it is important to identify the possibility of encountering particular features and peculiarities of the site by means of thorough geological and hydrogeological investigations, and to evaluate their influence on the permeability on a short and long term. If permeability and geological conditions on one site are highly variable, certain generalizations are necessary.

**Relevance of additional testing - pre-injection and post-injection**

The determination of permeabilities is essential both to justify the need for grouting, and to evaluate the success of the works executed. Thus, water pressure tests should be performed in exploratory primary holes before grouting and in check holes after completion of grouting in a certain section. These tests are required to compare the initial and the final permeabilities of the rock mass and to assess in this way the grout efficiency and success, respectively.

On the other hand, the execution of pre-injection water pressure tests in individual grout stages during the grouting programme, is not generally necessary, and might negatively affect the already treated rock mass. In addition, such tests during the injection works may not be representative, since there is no direct and/or consistent relation between the penetration of grout and that of water in a rock mass. As shown in Figure 7, a unique wide crack (A) may give the same Lugeon value as a high frequency of fine joints (B), while due to its binghamian rheology as well as the maximum cement grain size, the actual grout take might be much lower in the latter case.

This is why water pressure tests do actually not give any indication on the actual grout takes to be expected. The only reliable way to obtain information on the actual groutability is therefore by the grouting process itself, which should show a consequent pressure increase and volume reduction from stage to stage. The use of Equivalent Lugeon analyses can substitute for pre-grout tests in a given stage, and provide intermediate...
data on the progress and effectiveness of the grouting programme. For the determination of the actual fissure conditions, that is especially their aperture with reference to the situation shown in figure 7, a complementary inspection by a borehole camera provides important information and is therefore highly recommended.

**With the GIN method it is not the Engineer that defines the final pressure, but it is the rock, with its localized (stage) fissured status that decides what will be the final pressure to be reached.**

Therefore, water pressure tests before and again after grouting the grouting programme, are allowed and even recommended, in order to evaluate the success of the performed injection works, in terms of the final permeability conditions achieved. To give a true indication of the residual rock mass permeability, post and pre-injection water tests must be executed at significantly lower pressures (normally equal to the predicted groundwater pressures in service) than the grouting pressures. Failure to follow this procedure will mean that the water tests will effectively be testing fissures which have not been affected by the grouting, and at pressures exceeding the service groundwater head, rendering the results un-representative.

In the upcoming Groutline issue (March 2016), the successful implementation of GIN grouting and other above mentioned design concepts in several challenging cases will be presented.

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As promised, below, some of my comments, as a strong supporter of the GIN method.

Being Europeans the authors of this articles, I think they didn’t, in my opinion and correctly from their point of view, emphasize a very important point about the GIN method that, in my opinion, is essential. With the GIN it is possible to use higher grouting pressures than the grouting pressures normally used in North America. Also today, and for important projects, I am reading Grouting Specifications where the grouting pressures are still evaluated with the “infamous” (in my opinion) “Rule-of-thumb” of 1 psi/ft (23 KPa/meter). Parenthesis. [Talking one moment about the “Rule-of-Thumb” (expression still used in our industry), my question is; how Engineers, as we are, can use a “rule-of-thumb” criteria? Are we Engineers or magicians? With all the respect for the magician. Will you be comfortable going to the 54th floor of a high rise building built by a structural engineer with rule-of-thumb criteria?]. Close parenthesis.

With the GIN method it is not the Engineer that defines the final pressure, but it is the rock, with its localized (stage) fissured status that decides what will be the final pressure to be reached.

The article gives, additionally, a good approach to use and values of what should be the “consistency” of grouting flow.

Another point that I would like to emphasize is that with the GIN method we can have a better characterization of the status of the rock mass keeping constant as many parameters as we can; specifically flow and grout mix. We avoid consequently, for instance, fictitious “termination criteria” due to change of grout mix, thicker.

Interesting to hear some comments also from you, if any!

As usual, I make the same request, asking you to send me your grouting comments or grouting stories or case histories. My coordinates remain:
Paolo Gazzarrini, paolo@paologaz.com, paologaz@shaw.ca or paolo@groutline.com.

Ciao! Cheers!