Grouting design and control using the GIN principle

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The Grouting Intensity Number (GIN) method for cement grouting of rock masses is derived and presented. The main features unique to the method are: (1) a single, stable grout mix for the entire grouting process (water:cement ratio by weight of 0.67 to 0.81) with superplasticizer to increase penetrability; (2) a steady low-to-medium rate of grout pumping which, over time, leads to a gradually increasing pressure as the grout penetrates further into the rock fractures; (3) the monitoring of pressure, flow rate, volume injected, and penetrability versus time in real-time by PC graphics; and, (4) the termination of grouting when the grouting path on the displayed pressure versus total volume (per metre of grouted interval) diagram intersects one of the curves of limiting volume, limiting pressure, or limiting grouting intensity, as given by the selected GIN hyperbolic curve (a curve of constant pV, pressure times volume, a measure of energy expended). Experience in several countries at major hydroelectric projects indicates the method to be technically and economically effective.

The grouting of rock masses with cement slurries to improve their mechanical and hydraulic properties is a well-established practice in engineering. This practice, however, has long been dominated by rules-of-thumb and personal or institutional experiences, often leading to dogmatic beliefs. During this decade, at a number of major hydroelectric projects under construction in different countries, the authors have had the opportunity to work with designers, geotechnical engineers and geologists, and field control engineers in the development of a better understanding of the grouting process by a combination of laboratory, theoretical, and field investigations.

Information gained by laboratory studies of the cohesion (yield strength) and dynamic viscosity of different grout mixes, by theoretical studies of grout flow and penetration, and by field monitoring of grout pressures and absorptions (takes), has led to the concept of Grouting Intensity Number (GIN), as will be discussed in this paper.

For simplicity, this paper will deal only with cement grouting of rock masses, although some of the considerations presented may also be applied to granular soils and to grouting with other materials. More emphasis is given to grout curtains for dams than to consolidation grouting or underground works, in spite of the fact that the GIN method has also been used a few times for these types of works.

It is not the purpose of this paper to review the present state of the art in grouting, as a number of recent books have done that quite well. Rather, a brief theoretical background will be given, followed by both theoretical and practical concepts leading to the development of the GIN grouting procedure. The proven effectiveness of the concept in achieving better grouting results and simpler and more economical grouting operations has suggested to the authors that the method should be presented to a larger audience.

Theoretical concepts of grout flow and penetration

Unlike Newtonian fluids, such as water or oil, where rheological behaviour can be characterized solely by the parameter viscosity, a "stable" grout slurry behaves as a Bingham fluid during flow, possessing both viscosity and cohesion (yield strength). While both are flow-resistance parameters, the viscosity governs the rate of flow, while the cohesion governs maximum travel distance (for a given applied grouting pressure and a given aperture of rock fissure). Equations have been developed and presented elsewhere. For computing the maximal travel distance, the maximum volume of injected grout, and the maximum total hydroprojecting force exerted on the grouted area.

It is sufficient here to note that the maximum travel distance achieved by the grout slurry is directly proportional to the applied grouting pressure and to the aperture of the fissures, and is inversely proportional to the cohesion of the grout slurry. Thus, for enhancing grouting penetration into the fine rock fissures, it is necessary to increase the grouting pressure or to reduce the grout cohesion, or both.

Perhaps the greatest value of the Bingham flow equations is in providing insight into the grouting process, with respect to the factors that influence the penetration of grout into a rock fissure and the extent of the splitting forces created by the grouting process. While stable grouts (defined as those that exhibit in 2 h less than 5 per cent of decantation of clear water at the top of a 1000 ml cylinder) may approximate the behaviour of a Bingham fluid, it is not reasonable to apply the equations to thin, watery grouts. Such thin mixes or slurries are unstable suspensions of cement particles in water that, during grout flow through rock fissures, may be expected to show erratic sedimentation, erosion, re-suspension, and re-sedimentation behaviour. This behaviour is impossible to predict and characterize with the Bingham flow equations or any others.

In the following section, additional factors that enter into the selection of a design grout mix are presented.

Selecting the grout mix

The controversy over thick-versus-thin grout mixes (slurries) will certainly continue for several more years. The authors, since 1985, have expressed their preference in the literature for thicker mixes . The practice of adding 1 to 2 per cent of bentonite, for stabilizing the mix and for reducing sedimentation, is progressively being replaced by the use of mixes of higher cement contents but with superplasticizer additives. These latter mixes are stable, and because they possess less cohesion, they are more penetrable, they also have greater strength upon setting.

Traditionally, advocates for thicker mixes have noted the several advantages that thick mixes exhibit, both during the grouting process and during the service life of the grouted rock mass after the grout has hardened.

During grouting, a moderately thick, stable grout has the following advantages compared with a thin grout:

- less sedimentation of cement grains during low-flow conditions;

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• less bleed water to accommodate as a result of squeeze-out or filtration at narrow zones in the flow pathways, with less premature blockage;
• greater stability over time and distance as a predictable fluid (Bingham fluid with a given cohesion and dynamic viscosity);
• less risk of hydrofracturing (also termed hydrospalling, or hydrojetting) and uplift of geological strata, because of fast pressure drop away from the grout hole as a result of the grout cohesion (and the filling of the fracture with a high quality grout in the case of such an occurrence).

During the service life of a hardened grout in rock fissures, the thick grout has the following advantages as compared with a thin grout:
• less shrinkage during setting, and thus a greater bond along the rock fissure walls and less risk of re-opening;
• greater density and higher mechanical strength because of greater cement content, and thus a greater resistance to physical erosion and piping;
• less porosity, lower permeability, and greater bond strength, and thus a greater chemical resistance to leaching and a greater durability of the grout curtain over the lifetime of the dam.

Stable grout, because of its cohesion, requires higher grouting pressures to reach the same distance of travel compared with a thin grout. However, by the use of a small amount of superplasticizer, both its cohesion and viscosity-parameters can be dramatically lowered.

Current practice at a number of major projects is to use a mix ratio of 0.67:1 to 0.8:1 (water: cement by weight) to obtain the desirable higher density and strength of the hardened grout, and a superplasticizer to reduce the cohesion and viscosity during grout placement. Laboratory tests are used to determine the flow, sedimentation, settling and strength properties of different grout mixes for different cements and different superplasticizers.

Cohesion and viscosity values may be obtained in the laboratory using a rotary viscometer with concentric cylinders. However, the simple plate cohesion meter may also be used. This is a piece of roughened steel plate, 100 mm by 100 mm by about 1.5 mm in thickness, which is weighed before and after dipping it for a few seconds into the grout mix. The difference in weight divided by the area of the two sides gives the cohesion parameter in shear strength units. It is convenient to divide the cohesion C by the unit weight of the slurry γ, giving the relative cohesion C/γ, which is the one normally reported. It is commonly given in mm, and typical values are 0.2 to 0.35 mm for thick slurries without superplasticizers. With additives, the apparent cohesion drops to values of 0.08 to 0.15 mm, the recommended range. It is of interest to note that the C/γ value is in fact the thickness of the grout slurry clinging to each side of the cohesion plate. The cohesion plate must be sufficiently scored by the cutting of intersecting thin grooves on its surface, so that the adhesion between the steel surface and grout is greater than the cohesion between the surface layer of adhered grout and the remaining grout; otherwise all the grout will slide off.

Other typical laboratory values are: specific weight of the grout, 1.59 to 1.67 t/m³ (99.2 to 104.2 lb/ft³); Marsh funnel flow time, 29 to 32 s; and, 28 day compressive strength, 15 to 20 MPa (2250 to 3000 lb/ft²).

Another point to keep in mind is the potential loss of water in grouting dry rock above the water table. Were grout to be thickened for this reason, its cohesion would increase (and internal friction would build up) to the point where no more grout could be injected. A prudent practice is to inject water for a period of time, to obtain partial saturation of the rock mass just before grouting. Water-retaining admixtures may also be used in the grout.

In grouting fine fissures in rock, it should be remembered that penetration of the grout depends more on the size of the cement grains and flocks than on the dilution of the mix with excess water. Thus, instead of trying to obtain a higher penetrability by diluting the mix, a finer cement with superplasticizer, together with higher grouting pressures, should be used.

Once an acceptable mix has been determined by laboratory tests, with its mechanical properties in the desirable ranges, that mix should be used for all the grouting at a project; the use of a single mix greatly simplifies the grouting procedure.

Design of grouting works

The design of a grout curtain includes the selection of the following main features: the grout mix, the grout hole spacing and depth, the grouting sequences, the grouting procedure (including volume and pressure limitation) and the field control. A good knowledge of the site geology is required in selecting some of those parameters, in particular, the physical characteristics of the rock mass discontinuities to be grouted (types, frequency, fissure aperture, roughness, alteration or infilling, and extension). The in-situ state of stress and the existing groundwater conditions should also be considered.

In addition to a knowledge of the existing geological and geotechnical conditions, the changes induced by the project in the stress state, and hydraulic pressures and their variation with time (such as during impounding and drawdown of the reservoir) must be taken into account. Finally, the goal to be achieved in terms of consolidation or strengthening effects should be defined better than is generally the case.

This paper does not attempt to address all these points in detail, but concentrates on several of the more important ones.

Development of the GIN method

Grouting of wide, open fissures

Both practical observations and theoretical studies indicate that the wider, open fissures in a rock mass are those most readily grouted. The grout travel can also be considerable (a few tens of metres). There are both practical and economical reasons, therefore, to reduce the grout travel and the grout volume injected. There are three ways to accomplish this reduction: by using a less penetrable grout (thicker with greater cohesion); by limiting the grout pressure; or, by limiting the volume of grout injected.

Before selecting the limiting criterion, one should consider that finer cracks may also exist in the rock interval being grouted. These are more difficult to grout and probably will not be well grouted until a later stage, when the more open, wider cracks have been filled. Nevertheless, during the first stage of grouting, it is desirable to achieve some filling of these fine cracks. Thus, the grout mix should not be thickened, but should remain a moderately thick stable grout with the superplasticizer additive. The alternative of limiting the pressure is also not very attractive, as this would also discourage the grouting of fine fissures. The remaining alternative of placing a volume limitation appears to be the best approach*.  

*For example, 200-400 l of grout per metre of borehole (2.15-4.3 0" per ft) in the interval being grouted or, in terms of weight, assuming a water:cement ratio of 0.75 by weight, 185-370 kg cement per metre of borehole (1.34-2.68 sacks per ft with 94 lb sacks).
Grouting of fine fissures

After the wider fissures have been grouted, or, if open, wide-aperture fissures were not present originally in the zone being grouted, it is the grouting of finer fissures that becomes the priority. Such grouting can be enhanced either by using a thinner mix with a lower cohesion, or by grouting at higher pressures. It is more convenient to raise the pressure and to maintain the high-quality moderately thick grout mix with the superplasticizer. Because the finer fissures will have less grout travel, and because the grout pressure diminishes rapidly as it spreads away from the borehole, the total uplift force, even at high grout pressures, will, as a rule, be much lower than the overburden weight; hydrofracturing of rock joints and bedding planes is seldom a problem (except in the upper 5-10 m). Consequently, quite high grout pressures are acceptable, even up to 30 to 40 bar, that is 3 to 4 MPa (425 to 570 lb/in²) computed at the grouting interval, provided that the grout take is small.

In considering these factors, an upper limit of grouting pressure is suggested where the grout takes are small, in the range of 30 to 50 bar (3 to 5 MPa), depending on the geology (weathering, stratification, weak zones, in-situ state of stress, and so on), the future water pressure, and the desired intensity of grouting.

The first two elements of the GIN principle are thus beginning to emerge: a volume-limitation where the grout enters easily at low pressures, and a pressure-limitation where the grout enters only with difficulty. It remains to focus on the intermediate ranges. However, before pursuing this intermediate range, it is beneficial to review other grouting considerations.

Split spacing of grout holes in series

In usual practice, primary holes are grouted first, spaced fairly widely (such as 10-12 m) so that grouting at the first primary hole does not interfere with the next. Often, it is specified that every third or fourth primary hole be drilled and grouted before the other primaries, to serve as “exploratory” primary holes. These holes will often be cored holes, and will be water-pressure tested to a total depth of 0.75 × H (where H is the height of the future reservoir at the point in question). The remaining primary holes may be adjusted in depth according to the results of the exploratory primary holes.

The next series of holes, the so-called secondary grout holes, are grouted next in a split-spaced location between the primaries. Since these holes are only 5 or 6 m from the primary holes, they will often encounter hardened grout in some of the wider fissures. In general, their “takes” will be lower than the primaries. Tertiary holes are often called for, again at a split spacing (2.5 to 3 m), usually with even lower takes; eventually, even quaternary holes may be called for (1.25 to 1.5 m from each tertiary hole), resulting normally in acceptably low final absorption of grout.

Since the rock gets tighter with each phase of holes, the ungrouted fissures encountered in the later holes will mostly be finer fissures; higher pressures would thus be of benefit and would produce a more efficient grouting operation.

Thus, the third ingredient of the GIN procedure is identified: a progressively higher pressure as the rock tightens up, so as to grout the progressively finer fissures.

Water-pressure tests (Lugeon)

Water-pressure tests (Lugeon tests) have often been used at each grouting interval to help select the grout mix. However, experience and theory have indicated very poor corre-
Fig. 2 illustrates five suggested limiting envelopes for different intensities of grouting. The GIN value, the limiting pressure and the limiting volume are in fact three more or less independent parameters defining the limiting envelope for grouting. In the proposed definition, they are related to each other, but they need not be. The uppermost envelope represents a very high intensity of grouting with a GIN value of 2500 bar/l/m, a very high limiting pressure of 50 bar, and a very high limiting volume of 300 l/m. The lowest envelope represents a very low intensity, with a GIN value of 500 bar/l/m, a maximum pressure of 15 bar and a limiting volume of 100 l/m. For most conditions, the authors would recommend the moderate intensity envelope with a given value of 1500 bar/l/m, a limiting pressure of 30 bar, and a limiting volume of 200 l/m.

For geologically critical areas (near the surface and on steep slopes) the very low curve could apply. It is easily understood, from the combination of Figs. 1 and 2, that the grouting process will stop at different points depending on the value selected for the grouting envelope.

For curve 1 (Fig. 1) the grouting would be terminated at point a for a low intensity of grouting, because of the 150 l/m volume limit with a resulting pressure of 3 bar. However, if the designer had specified the moderate intensity envelope, the grouting would continue to point b, the 200 l/m volume limit, the final pressure again being about 3 bar. If high intensity grouting had been selected, the grouting would continue to point c, the 250 l/m volume limit, the final pressure being about 6 bar. Finally, if the very high intensity had been selected, the grouting would continue to point d. The path would not be terminated by the volume limit, but rather by intersecting the 2500 GIN curve. At this point, the total injected volume would be 285 l/m and the final grouting pressure would be 9 bar. Thus, there would be a range of volume injected of 150 to 285 l/m and a range of final grouting pressure of 3 to 9 bar depending on the specified GIN.

For curve 2 (Fig. 1) the volume injected at point a’ would be about 60 l/m, and the final grouting pressure would be 13 bar. Had the grouting continued to point d’, representing very high intensity (p-V=2500), the grout take would have increased only to 90 l/m, but the pressure would have attained 28 bar, considerably less than the limiting value of 50 bar. Similarly, for curve 3, grouting would be halted at any point between a” and d” depending on the previously selected GIN criteria and the pressure limitation. The portion x-y represents an example of a hydrofracturing or hydroplating event, where a joint or bedding plane is suddenly forced open, with a resulting pressure drop and an increase in the absorption rate. One could continue grouting at low rates to try to arrive at the selected GIN curve, but if the pressure increased, there would probably be another hydrofracturing event at about the same pressure or a little higher. It is questionable if grouting should be continued in such circumstances. Many times, however, it has been done without any major problems. In any case, the limiting curve is arrived at, sooner or later, and the grouting is stopped.

Selecting the GIN value

The dam designer and his geotechnical and grouting staff must select the GIN value for the projected grout curtain. While the authors recommend the moderate GIN value of 1500 bar/l/m as a starting, geological conditions, the value of future water losses, and uplift pressures after impounding, are points to be considered. The upper pressure limits and the upper volume limits may also be modified by the designers and field control engineers for special cases. Probably the best approach is to conduct one or two grout test sections before selecting the limiting grout envelope.

The upper pressure limit may be less in the abutments than that selected for the valley bottom, because of the difference in reservoir depths. A worthwhile goal is a limiting pressure of at least twice the reservoir pressure, but it may be difficult to achieve this without inducing undesirable water injection.

Computer controlled grouting

Since personal computers can nowadays be installed and easily operated at the grouting site itself, the possibility now exists of continuous real-time controlling of the grouting process. Only two values need to be continuously read by the system: the actual grouting pressure p and the flow rate q, from which the cumulative volume V per unit length (injected since the beginning of the grouting of the depth-interval in question) can be obtained by integrating. If desired, the volume V of grout injected can be measured directly, and the flow rate q obtained by derivation.

Starting from the two measured values of p and q, a number of time graphs can be shown on the monitor screen and plotted (for example, pressure, flow rate, cumulative volume, and penetrability versus time). Fig. 3 shows such a series of graphs. Attention is drawn to curve (d) which represents the specific flow (q/p) or penetrability (that is, the flow rate divided by pressure) versus time. This curve shows clearly the progressive filling of voids and fissures and the build-up of grouting resistance, caused primarily by the increasing total cohesive force as the grout flow extends.
Fig. 3. Grouting process of a single stage: (a) grouting pressure; (b) grout mix flow; (c) volume taken; and, (d) penetrability, all versus time. O = start of grouting; H = hydro-jacking; and, F = finalizing of the grouting.

Further along the rock fissures. A hydrofracturing or hydro-jacking event is readily observed from the presence of a sharp peak in the graph.

The \( g-in \) and penetrability-volume curves as practical grouting controls

Fig. 4 represents the main control plots that the computer may display. These curves may be used to control the grouting process. Fig. 4(a) shows the limiting grouting envelope that has been chosen for the project (or for a given area of the project), including the limiting pressure \( p_{max} \), the limiting volume \( V_{max} \) per unit length, and the selected g-in hyperbolic curve. This envelope may be written into the program and be displayed upon call. In general, these limiting envelope curves are referred to simply as the g-in curves.

The irregular curve 2 shown on Fig. 4(a) represents the actual grouting path, plotted at small increments of time, of the instantaneous grouting pressure versus the cumulative grout volume per unit length. The grouting-path irregular curve intersects the g-in curve at point F, and grouting is stopped at "zero" flow rate, with a final pressure \( p_f \) and a total cumulative unit volume of injected grout \( V_f \).

Fig. 4(b) is also an important real-time monitoring curve. The penetrability \( q/p \) is plotted versus cumulative grout volume rather than versus time as in Fig. 3(d), giving similar type curves, however. As the curve develops, one normally sees a decline in the penetrability, indicating that the grouting efficiency is decreasing. Thus, at a constant grouting pressure, the flow rate is decreasing or, if a constant flow rate is maintained (almost to the end), the grouting pressure is increasing. Which of these combinations applies is dependent both on the type of pump and the details of the grouting operation (piping, valving).

The decline of the penetrability-volume curve indicates that the grouting process is proceeding normally. The grouting pressure must be monitored and controlled to stop the process at the grouting limits of the g-in curve.

As noted in the previous section, the grouting path will meet the g-in curve at different points, a function of the aperture of the rock fissures (wide fissure near point B and fine fissures near point A, Fig. 4a). As the grouting path progresses toward the g-in curve, the pumping rates should be as low as practicable while still achieving grout penetration (for example, 500 l/h, that is 17.6 ft/h or 2.2 gals/min).

Experience has shown that these various plots aid greatly in controlling the grouting process in an effective and continuous manner.

Application to grout curtains

The g-in method as presented has dealt primarily with considerations for a single grouting interval or stage. The method also applies to all intervals of the grout hole, and to all the primary and split-spaced holes. The split-spacing procedure in a single-line grout curtain is a proven efficient method, with sound theoretical reasoning.

In certain highly permeable or cavernous rocks (lava flows, some limestones, fractured sandstones), 3-line grout curtains have been constructed. The downstream line is usually grouted first, followed by the upstream line, and finally by the central line. The two outer lines are considered to behave as barrier lines, and only primary and secondary holes are grouted, with the intent of filling the majority of the larger fissures or voids. The central line can then be treated as a normal single-line curtain, with primaries through to tertiaries, and even with quaternary or quinary holes if needed.

In the split-spacing method, the primary holes will partially or completely fill and plug only the widest of the rock fissures. The next series of secondary holes, again, will plug only the widest fissures not yet plugged in the first series, and so on. In Fig. 5, the likely final positions of the primary, secondary, tertiary, and additional holes (quaternary or check holes) are plotted on the g-in curve. The average grout volume absorbed will decrease from series to series, while, obviously, the average final grout pressure will increase accordingly from series to series. This happens automatically when the g-in procedure is followed.

With a primary hole spacing of 10 to 12 m, it is likely
that both secondary and tertiary series would be required. The tertiary holes would be at 2.5 to 3 m distance from the nearest adjacent hole; these holes could be shorter, depending on the geology and the results of the secondary holes.

Quaternary holes might or might not be needed. At least some would be required as check holes for performing Lugeon tests, to see if an acceptably low permeability of the rock mass has been achieved; for a tight curtain, requirements may be as severe as 90 per cent of all tests to be at or below one Lugeon (1 x 10^-2 cm/s), with no values greater than 3 Lugeons.

Relationship of hole spacing and GIN

It is obvious that a relationship must exist between the hole spacing and the GIN required. For instance, if the selected primary spacing is too wide and the selected GIN is too low, no significant decrease of grout take will result from the primary series to the secondary, or even to the tertiary. In such a case, no guarantee for a successful curtain can be given, even though considerable drilling and grouting costs have been expended.

If the primary spacing is too close or the GIN is too high after the first two series, the grout takes will be very low, and tertiary holes would be wasted essentially. The GIN is also related to the distance that the grout travels and, therefore, to the thickness of the grouted rock curtain or "wall".

A working rule-of-thumb is to select the values of GIN and the spacing so that the volume of injected grout per metre of stage grouted reduces from hole series to hole series by around 50 per cent (realistically in the range of 25 to 75 per cent). Such behaviour would provide confidence that progressive closing of the curtain is occurring. One or more test grouting sections can be utilized during the design phase or at the first part of the grouting contract to define better the optimal primary hole spacing and GIN value.

Criteria for closure

If the grout paths for the holes of the last series (say, the tertiary series) do not arrive at the upper limiting pressure line for the selected GIN (and preferably in the left-hand half of that line), additional holes should be grouted on either side of those holes not meeting the criteria. Thus, all parts of the curtain (although not all primary, secondary, and tertiary holes) will have been grouted at the maximum limiting grout pressure with reasonably low grout absorptions (less than 25 kg/m or 0.18 sacks/ft, for example).

If non-optimal selection of the hole spacing has been made, the proposed grouting method is, at least to some extent, a self-regulating procedure. This is as a result of the split-spacing techniques, the GIN curve, and the requirement for the last series of holes to reach the pressure limit with minimal unit takes.

In conclusion, it is believed that if one follows the concepts or rules presented, a fairly optimal distribution of the total grout volume along the grout curtain can be achieved. The procedure almost automatically takes into account the actual irregularities of the geological conditions in the rock mass. In doing so, the benefit-to-cost ratio of the grout curtain can be maximized.

Main points of the GIN method

Several concepts and procedures are basic in applying the GIN grouting method. These are summarized below under four headings.

**Basic concepts**

- Use only stable, moderately thick grout mixes: (a) to reduce sedimentation and premature blockage; and, (b) to obtain dense, resistant, hardened grout.

- Use, as far as possible, only a single mix for the entire grouting work: (a) to provide a single Bingham fluid with known properties; and, (b) to simplify the grouting procedure, thereby improving efficiency and reducing errors.

- Use the GIN curve to monitor the grouting pressure: (a) to allow high pressure to be applied where needed; and, (b) to avoid high pressure where it would be harmful or wasteful.

- Control the grouting process by field computer: (a) to follow in real-time the pressure and flow rate; (b) to plot the p-V grouting path on the selected GIN curve; and, (c) to indicate the completion of grouting using both the p-V grouting path and the penetrability-volume curve.

**Mix design**

- Use admixtures to obtain the desired grout characteristics: (a) superplasticizer to reduce the cohesion and viscosity of the mix, so as to increase grout penetrability; and, (b) possibly a water retarding agent to reduce water loss during squeezing.

- Conduct a comprehensive series of laboratory tests early on several grout mixes, with a water:cement ratio (by weight) ranging from 0.7:1 to 1:1. This is to: (a) test different available cements of varying fineness; (b) test different admixtures at varying percentages; and, (c) obtain test values of unit weight of grout slurry, Marsh Funnel apparent viscosity, 2 h sedimentation, cohesion, initial and final setting times, 7 day and 28 day compressive strengths, and water loss in squeeze test.

**Grout-hole layout**

- Adopt the normal split-spacing method of primary through to tertiary or quaternary holes: (a) to provide a minimal uniform coverage throughout; and, (b) to allow for closer spaced holes where the geological conditions and grouting results so indicate.

- Conduct grouting field tests either during the final design phase of the dam or during the first part of the construction phase: (a) to test different parts of the site having different geological or topographical conditions (for instance, valley bottom and each bench); (b) to select optimum primary hole spacing, so that later secondary and tertiary holes exhibit a continuing decrease of 25 to 75 per cent per series (consider a preliminary primary hole spacing of 10-12 m); and, (c) to allow for different GIN curves to be examined (for instance, by plotting the p-V grouting path for each grouting stage up to the anticipated grouting intensity or up to the first, or even second, hydrofracturing event).

**Field control**

- Define the controlling elements of the GIN curve from the...
results of the test grouting programme, as well as any special engineering, rock mechanics, or geological considerations: (a) to ensure that the volume and pressure limits are reasonable for the existing geological features; and (b) to assess the need for different GIN values at different site locations.

- Grout every fourth primary hole first, as exploratory grout holes, except in areas of previous test grouting: (a) to allow for better areal definition of geological and ground-water conditions (by rotary core drilling and Lugeon water-pressure tests to a depth equal to the future reservoir height above the ground point in question); (b) to permit final selection of the hole depth for the remaining primary holes (probably a depth range of 0.5 to 0.8 of reservoir height); and, (c) to ensure that the selected GIN curve is appropriate.

- Control the grouting process by field computer using the GIN curve and penetrability curve: (a) to allow for real-time monitoring of the grouting path; and, (b) to allow for the completion of grouting to be anticipated, from the declining penetrability curve, and from the approach of the p versus V grouting path towards the controlling GIN curve (including the volume limit and the pressure limit portions of the curve).

- Pre-inject water before the grouting of any stage above the water table, to part-saturate the rock, so as to reduce the risk of water loss from the grout with premature blockage.

- Use Lugeon water-pressure tests only in the exploratory primary holes and in the check grout holes to compare the initial and final permeabilities of the rock mass.

- Summarize the grouting results by appropriate statistical and graphical methods, to ascertain a progressive closing of the rock fissures with a resulting acceptably low residual permeability.

Example

During the last decade, this grouting procedure was introduced step by step at a number of sites in Argentina, Austria, Ecuador, Mexico, Switzerland and Turkey. In the near future, the method will continue to be used in various countries at planned projects.

The on-going grouting at the Aqumilpa dam in Mexico may be mentioned as an outstanding example. This 180 m-high dam, owned by the Comisión Federal de Electricidad, will be the highest concrete-faced rockfill dam in the world. Its impounding will start during 1993.

The GIN method is at present being used both for the rock consolidation below the foundation plinth of the concrete face and for the deep grouting curtain. After extensive laboratory and field tests, a single “normal” mix was selected. It has the following characteristics:

- Cement: fine pozzolanic cement, Blaine value about 5000 cm²/g
- Water-cement ratio: 0.9:1 (somewhat higher than usual because of the high Blaine value)
- Superplasticizer: 1.6 per cent of the cement weight
- Density of the mix: 1.5 to 1.55 g/cm³
- Decantation: 4 to 5 per cent in 2 h
- Marsh Funnel flow time: 28 to 32 s
- Relative cohesion (C/y): 0.08 to 0.2 mm, increasing to 0.2 to 0.3 in 2 h
- Strength of the hardened mix: 9 to 10 MPa at 7 days and 13 to 17 MPa at 28 days.

It corresponds to a stable but very fluid mix, with high penetration properties during the first hour, and excellent resistance both mechanically and against bleaching out.

For the grout curtain, the following are specified as a rule:

- Procedure: 5 m stages from bottom up;
- Splitting method, starting with primary holes at 24 m distance;
- Additional higher rank holes are drilled so long as the take is greater than 25 l/m;
- Saturation of the rock mass (above water table) during 1 h at a pressure of 2 bar immediately before the start of the grouting of each 5 m stage;
- Grouting intensity: 2500 bar, l/m (reduced to 1500 below the plinth);
- Maximum pressure limit: 40 bar (reduced near the surface to 10 bar and increasing to 40 bar at 20 m depth, and also, adequately reduced at geologically delicate spots);
- Maximum take limit: 400 l/m, in fact 2000 litres per 5 m stage (locally reduced to 300 l/m); and,
- Stopping criterion: flow rate less than 3 l/min for a 5 m stage at the final grouting pressure.

These specifications are easy to handle at the site, especially as only one single mix is used.

As an example, Fig. 6 shows the grouting path of one of the consolidation work below the plinth. Readings were taken intermittently at about 5 min intervals, as pc monitoring was not available. In the upper part, Fig. 6 (a), the paths of the pressure p as well as of the flow rate q are plotted versus the grain volume V injected. The pressure path may be compared with the GIN limiting boundary.

The grouting target was an intensity of 1500 bar l/m. However, an intensity of 2510 bar was arrived at, and the limiting volume of 300 l/m was slightly exceeded. This over-run was caused by a delay in transmission from the grouting spot to the pump operator, or by a slow reaction of the pump operator himself. (This indicates the desirability of real-time continuous monitoring and display by a pc, as well as of having automatic cutoff of the pump when the controlling GIN curve is reached.)

In the lower part, Fig. 6 (b), the penetrability is plotted against the volume taken V. At the beginning of the grouting process, the penetrability increases (from 0.2 to 0.5 l/min.m.bar) because of the progressive opening of the discontinuities of the rock mass. After a take of 200 l/m, the penetrability decreases quite regularly to zero for a volume of 320 l/m. Indeed, the grouting process was stopped just before reaching this value.

It is felt that some irregularities shown in the penetrability curve are caused by the rounding of some readings by the operators. Also, it is probable that two or more hydro-jacking events occurred that were not completely picked up by the intermediate monitoring.

Comparison with usual grouting

A “traditional” grouting process consists of defining a grouting pressure and the use of different types of grout, for example, grouts with successively lower water:cement ratios (4:1, 3:1, 2:1, 1:1, and so on). The change of the mix takes place at given volumes of grout taken by the borehole. It is obvious that the cohesion of these mixes increases from one to the next and that, at some point, the increased cohesion resistance to flow and penetration will stop the grouting process.

With the GIN method, only one mix is used; consequently, the cohesion is a constant. As the grout spreads out along fractures, its contact with the fracture walls increases and so does its total cohesion resistance to flow. Conse-
sequently, greater pumping pressures must be utilized to overcome the flow resistance. This is a normal and expected physical phenomenon. The GIN method allows for the grouting process to continue under gradually rising pressure, until one of three limiting values is reached: limiting pressure, limiting volume, or a combination of pressure and volume represented by the specified p-V curve.

Other differences exist between traditional methods and the GIN procedure: the GIN method always uses only the best possible mix with regard to strength, durability, resistance to leaching and shrinkage; GIN avoids injecting large water volumes in the form of thin mixes; the use of a stable mix avoids or significantly reduces the risk of damaging the rock by hydrofracturing; errors in the grouting process are greatly diminished; and, the grouting process is simpler and faster, as no time is lost in changing the mix.

Summary and conclusions
The grouting process involves steady pumping of the grout at a low to medium rate, with a slow building up of pressure as the grout penetrates further into the rock mass. Grouting is stopped when the volume injected attains a specified limiting value for a grouting interval, when the grouting pressure arrives at the previously selected limiting value, or when a given intensity of grouting has been achieved at an intermediate position, less than the limiting values of volume and pressure, as judged by the GIN curve previously selected.

The distance of the curve from the origin is a function of the energy expended in the grouting. A family of curves may be prepared for various intensities of grouting, ranging from very low to very high. One intensity curve may be selected for the project, or two may be used, for instance, a high intensity for the valley grouting, and a low intensity for the shallow, abundant slopes or in geologically weak areas.

The complete limiting envelope thus consists of the limiting pressure line (in the range 15 to 50 bar), the limiting volume line (in the range 100 to 300 litres per metre of grouted interval), and a selected GIN curve connecting the two limit lines (with GIN values ranging from very low to very high, for example, 500 to 2500 bar.L/m).

The GIN method requires close monitoring by residential graphics of real-time curves of pressure versus time, grout flow rate versus time, and total injected volume versus time, plus the derived curve of penetrability (flow rate divided by pressure, q/p) versus time. This latter curve is of particular value in signifying the approach of grouting refusal, or at least of diminishing absorptions.

The GIN method has been proven to be a very useful tool in designing and controlling grouting works. Its increasing use should improve the grouting works for hydraulic structures. Since the method is flexible with respect to the limiting pressure, the limiting volume injected, and the GIN value to be achieved, it is probable that experience gained in current and future projects will lead to additional refinements.

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Fig. 6 Aquamilpa dam, Mexico. Borehole 674.P, stage 17-22 m, grouted 3 December 1992: (a) pressure $p$ and flowrate $q$ versus volume taken and grouting intensity limiting line; and, (b) penetrability $(q/p)$ versus volume.

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