Volume 18 Number 3 September 2000

# GEOTECHNICAL NEWS

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# New Developments in Rock and Soil Grouting: Design and Evaluation

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## Abstract

*There are two major components in a soil grouting operation. The first step is the design of a site-specific grouting program. The second step is the execution of that program; this includes on site monitoring and assessment of the operation in real time. If these tasks are undertaken with state-of-the-art engineering methods, then the best achievable results will be predictably accomplished.*

Two recent developments are discussed in this paper; the first, an In situ Soil Injection Simulator (I.S.I.S.), developed for use during the design phase of a soil grouting program and the second, a Computer Aided Grouting Evaluation System (CAGES$^{TM}$), developed for utilization during the execution phase of a soil or rock grouting program.

The In situ Soil Injection Simulator (I.S.I.S.) was developed to assist during the design phase of soil grouting programs by improving on the present methods of determining and predicting the injectability limits of a given grout into a specific soil. The ISIS test cell was constructed with sufficiently large dimensions to reduce the effect of "boundary conditions" that distort the results of typical injectability tests. The soil in question is reconstructed by matching the soil gradation (sieve curves), silt content, moisture content, overburden pressure, density etc existing in the field. These reconstructed soils are injected with different grout types and/or formulations to determine the injectability, lateral grout spread, residual permeability (both horizontally and vertically), and grouted soil strengths for each grout type. Alternatively, different soil layers can be constructed to resemble a variety of conditions to test the performance of the various grouts in different field conditions. This type of laboratory test can be instrumental in determining the type of grouts and spacing of the grout holes and for predicting the characteristics of the grouted soils. Without the ISIS, these parameters are often determined by applying 'theories', mathematical models and 'rules of thumb with variable degrees of success.

A computer aided grouting evaluation system (CAGES) has been developed to allow for rigorous real-time monitoring, analysis and assessment of grouting operations. CAGES is a commercially available software/hardware package that permits practitioners to modernize to higher standards, by improving the method in which their grouting operations are monitored and evaluated. CAGES not only collects, displays, and stores relevant grouting data, but in addition these data are analyzed in real-time. CAGES then displays the raw grouting data, as well as calculated parameters, in an easy to interpret format so decisions pertaining to the grouting operation can be based on accurate information. CAGES can be configured for the simultaneous monitoring and analysis of up to eight holes for tight control of multiple-hole grouting programs.

## Design Phase - ISIS

### Limitations of Typical Soil Injectability Tests and Models

At present, there are no truly reliable small scale or laboratory methods which will accurately determine the injectability limits of soils characterized by grain size, permeability coefficient and silt content. Injectability tests currently being conducted in North America on a lab scale are usually fundamentally flawed. Current tests typically are conducted as follows; cylinders with a diameter of 100 mm are filled with soil and grouted from the top down. A similar method is the standard sand column test (French Standards NF 18-891) which involves the placement of sand into a transparent column. The grout is injected through a tube placed towards the bottom of the column under constant pressure. These methods do not take into account the impact of Aboundary conditions" on the ultimate injectability. The small scale of this test does not allow for grout mixing or injection to be performed in the same manner as is done in the field. These tests may be useful for comparing various grout mix designs against the same criteria but do not accurately determine injectability limits or injectability into site specific soil conditions.

Cambefort (Naudts, 1995) mathematically illustrated the important role of the thickness of the soil layers on their injectability. For this reason, it is necessary to determine injectability, using layers which are sufficiently thick (minimum 250 mm (8")) and extending laterally (from the injection point) at least 250 mm (8"). Equation 1 illustrates the importance of the soil layer thickness on the injectability.

Equation 1:

$$P_{effective} = \frac{Q\upsilon_i\delta_i}{2\pi k\upsilon e}\ln\frac{R}{r_0}$$

Where:

$P_{effective}$ = grout pressure
Q = grout injection rate
$\upsilon_i$ = kinematic viscosity of grout
$\upsilon$= viscosity of water
$\delta_i$ = specific gravity of grout
k = hydraulic conductivity of soil with water
e = thickness of soil horizon
R = constant depending on soil type (1-10)
$r_0$ = radius of borehole

The form of Equation 1 illustrates that thinner soil layers require higher injection pressures at a given injection rate, Q. The injectability of a soil layer is therefore indirectly proportionate to its thickness. The equation also indicates that by decreasing the injection rate the effect of the layer thickness can be somewhat compensated. Injecting at low flow rates however necessitates longer pump times, which allow the grout to increase in viscosity and cohesion (low shear rate superimposed on a time effect) prior to reaching the desired lateral spread. The maximum injection pressure to prevent hydrofracturing is limited by overburden thickness. The grout spread, which is directly proportionate to the grouting pressure, is therefore limited in "thin layers". Performing injectibility tests in small diameter cylinders results in distorted values of the actual injectability of a specific grout in a particular medium.

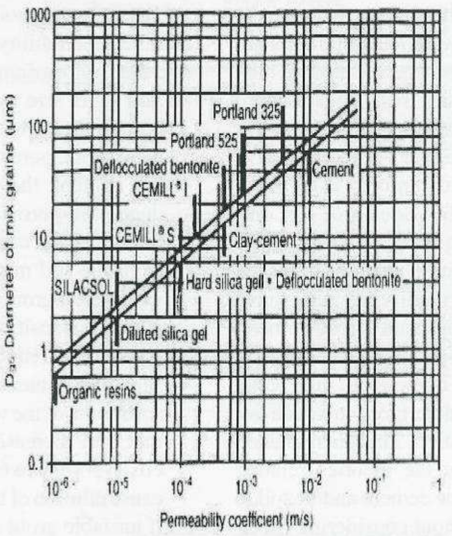


*Figure 1. (Naudts, 1995): Permeability limits of grouts - Cambefort (1977), lower line and DePaoli et al. (1992), upper line.*

In the past, researchers and practitioners have attempted to correlate the grain size of the suspension grout with the grain size of the soils to be injected. Mitchell (Mitchell, 1981) suggested that soils were injectable with a suspension grout if the $D_{15}$ soil >24 $D_{85}$ of the grout and definitely not injectable if $D_{15}$ soil >11 $D_{85}$ of the grout. Quite a few practitioners have found that this is a debatable rule of thumb. The rheological aspects, the pressure filtration coefficient and the solids content of the grout were not taken into account nor the fact that silts are picked up by the suspension grout as it runs through the pores and reduces penetrability.

Others, like Cambefort (Cambefort, 1977) and DePaoli (DePaoli et al. 1992) followed a sounder approach and suggested that the injectability of soils were governed by the $D_{50}$ (Cambefort) or $D_{95}$ (DePaoli) of the grout and correlated it with the permeability coefficient of the soils, as encountered in-situ. (See Figure 1 above.)

This approach to injectability in soil grouting however does not take into account the important role of additives and admixtures that enhance the rheological aspects and stability of grout mixes and affect ultimate penetrability in soils.

Hazen (De Beer, 1970) developed an equation for estimating the k value of soil based on the $d_{10}$ of the soil. Equation 2 is Hazens' equation.

Equation 2:

$$k(cm/s) = 116(0.7 + 0.34t)d_{10}^2$$

Where:

k = permeability coefficient
t = temperature in °C
$d_{10}$ = grain size in cm at which 10% of particles by weight are smaller

This equation has proven relatively accurate when dealing with soils that are dense and/or relatively undisturbed (N>20). For disturbed soils, the k value obtained with Hazens equation is usually underestimated. A very general rule of thumb used in conjunction with the permeability coefficient of soil has been that:

$k > 1 \times 10^{-1}$ cm/s are injectable with regular cement based suspension grouts

$k > 5 \times 10^{-3}$ cm/s are injectable with microfine cement based suspension grouts

$k > 1 \times 10^{-4}$ cm/s are injectable with solution grouts

Often unstable or marginally stable microfine cement based grouts are used resulting in high residual horizontal permeability, and in some cases, limited grout spread. Others have tried to make a case that low water/cement ratios are needed for optimum permeation. Whilst the latter approach results in a more stable grout formulation, its cohesion is typically much higher. A more cohesive Binghamian fluid can only flow as far as determined by Lombardi's (Lombardi, 1985) equation (Equation 3). Lombardi's equation also illustrates the effect rheology modifying admixtures can have on lateral grout spread or travel distance of a suspension grout. Reducing the cohesion of the grout mix, while maintaining a stable grout mix, can enhance its penetration. This phenomenon is overlooked in the theories relating particle size of the cement and/or soil to injectability without considering rheology and stability of the mix.

Equation 3:

$$L = \frac{pr}{2C}$$

Where:
L = grout travel distance
p = effective grout pressure applied
r = radius of a given cylindrical flow channel
C = cohesion of the grout

In most cases, the influence of "particle pick-up" has been ignored: the grout dislodges fine (silt) particles from the soil matrix, which in turn become part of the suspension grout and reduce penetration. It is important therefore to establish the upper limit of silt content in a given soil that will still enable acceptable penetration. A soil with a "suitable" $d_{10}$, $d_{50}$ or $d_{85}$ which would lead one to believe that it is perfectly injectable based on one of the theories mentioned above, may be found in the field to not be injectable with microfine or suspension grouts due to the silt content.

## Factors Affecting Injectability of Soils

A large number of factors control the injectability of a specific grout into a particular formation. Some factors pertain to the in-situ soils to be grouted while others pertain to the specific parameters of the grout to be injected.

The following soil characteristics affect the penetrability of a specific grout into that soil medium:

- Soil grain size and grain size distribution: contribute to permeability coefficient, pore size and spacing,
- Silt content: the presence of silt reduces the permeability of the soil; moreover, silt can become dislodged from the soil matrix and part of the suspension grout thus increasing apparent viscosity, suspended solids content and reducing penetration,
- Moisture content: dry soils will absorb some of the water from the grout mix and increase the apparent viscosity; very wet conditions may cause dilution of the grout, especially if unstable grout mixes are used,
- Density (or compaction of soil): will affect the hydraulic conductivity of the soil (a disturbed soil can be up to 100 times more pervious than can be derived with Hazen's equations) and pore volume,
- Hydraulic conductivity (preferably established in situ, utilizing Caron's equations),
- Chemistry of soil: contaminants and nature of soil particles: some contaminants may affect grout rheology or affect gel and set times,
- Thickness of soil layer: thinner soil layers require more injection pressure to obtain a desired grout spread, and therefore "choke off" more easily,
- Homogeneity of soil layer: non-injectable strata may block off layers that are amenable to permeation grouting.

In addition, the following grout characteristics affect the penetrability of that grout into a specific soil medium:

- For suspension grouts : the particle size and particle size distribution,
- Stability of grout mix: unstable grout mixes will easily pressure filtrate or form flocs and hereby increase the effective particle size if the blockage gets dislodged. Once the grout cures in the soils, bleed water separates from the solids, causing anisotropic characteristics in grouted soils (high residual permeability in the horizontal direction and low residual permeability in the vertical direction); as was originally determined by Krizek (Krizek, 1992),
- Pressure filtration coefficient of grout mix: if a grout mix is susceptible to pressure filtration (i.e. water is 'squeezed' from the grout) a rapid increase in viscosity occurs under pressure and reduces penetrability into smaller pores (as pore channels are smaller, particles tend to "dry pack" and block further flow of grout),
- Viscosity of the grout: lower viscosity will reduce the internal friction and enhance penetration,
- Internal cohesion of grout: cohesion affects the travel distance of the grout as illustrated in Lombardi's equation (discussed previously),
- Evolution of the internal cohesion of the grout: evolutive grouts are characterized by a gradual increase in gel strength and increase in viscosity prior to reaching initial gelation (C= 100 pa) which adversely affects its injectability. A properly formulated suspension grout has virtually non-evolutive gelation characteristics: low viscosity is maintained for at least 50% of its final gelation time to achieve the desired grout spread,
- Thixotropy of grout: a thixotropic grout is characterized by low viscosity under moderate to high shear conditions and high viscosity under low shear, useful for void filling when non-sag grouts are desired. As the thixotropic grout travels farther away from the injection point, shear on the grout is reduced and its viscosity will increase resulting in a gradual refusal,
- Initial gelation time of suspension grout or solution grout (Karol, 1982),
- Nature of the chemical reaction (solution grouts): foaming grouts have different penetrability compared to evolutive and non-evolutive (non-foaming) solution grouts,
- The mixing sequence and process by which the grout was produced: some additives need to be incorporated in the grout mix at a specific stage in order to provide the desired impact on the fluid characteristics of the grout. For cement based suspension

grouts, it is imperative that a high shear mixer is used to ensure complete mixing and that each particle is individually wetted to obtain optimum stability and benefit from additives or admixtures. Solution grouts often require special preparation or precautionary measures and mixing methods (often in line static mixers). Clearly, the soil and grout(s) form a complex interacting system which is not easily mathematically modeled. Therefore, in order to select and determine critical design and feasibility parameters such as: the hole spacing, the grout type and formulation required, the performance criteria that are economical or reasonably achievable, the refusal criteria required to achieve the performance criteria, etc. it is advantageous to perform injectability tests in simulated soils and assess the operation. Figure 2 depicts the ISIS (In-situ Soil Injection Simulator) apparatus.

### Soil Injectability Tests as Part of the Design Process - Determination of the Most Suitable or Economical Grouts

Based on the soil data gathered pertaining to the area to be grouted, site conditions are duplicated in ISIS with respect to soil compositions. A hydraulic jack located below the soil sample is used to compact the soil and reconstruct overburden pressure. Sleeve pipes properly embedded in casing grout are used for water testing followed by injection of the grout into the individual soil layers in the same way. The sleeve pipes are used to perform multiple injection passes into the same layer as performed during a soil grouting operation in the field.

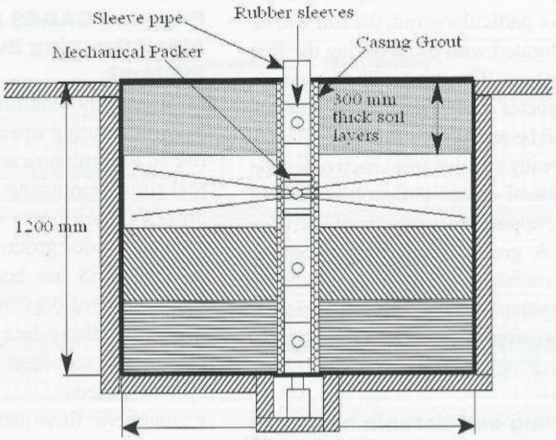
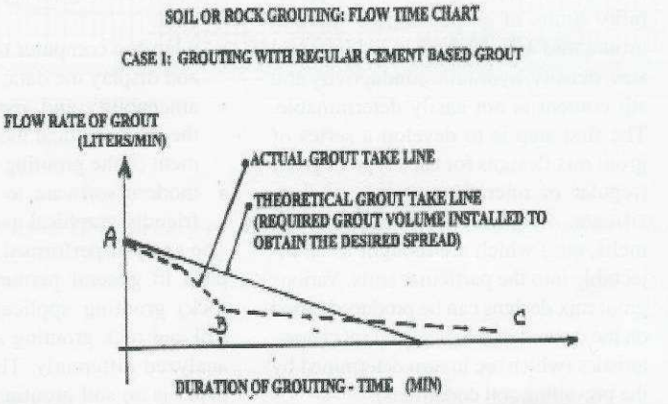


*Figure 2. ISIS Apparatus*



FROM POINT A TO B: INITIALLY THE AMENABILITY OF THE FORMATION FOR REGULAR CEMENT BASED GROUT IS EXCELLENT. THE APPARENT LUGEON VALUE IS GRADUALLY DECREASING. THE TRENDLINE INDICATES THAT THE THEORETICAL VOLUME CANNOT BE INJECTED WITH THIS FORMULATION. THE SOLIDS CONTENT IN THE MIX MUST THEREFORE BE LOWERED OR A CHANGE TO A MICROFINE CEMENT BASED GROUT MUST BE MADE.

FROM POINT B TO C: THE FORMATION RESPONDS POSITIVELY TO THE ADJUSTED OR CHANGED MIX: AMENABILITY INCREASES AND THE DESIRED VOLUME OF GROUT IS PLACED.

*Figure 3. (Naudts, 1995): Graphical Representations of grout takes in time, signaling measures to change formulations to obtain the desired grout spread*

The ISIS test chamber is constructed to reduce the effects of boundary conditions by creating soil layers with a minimum thickness of 300 mm (12") and a diameter of 1200mm (4 feet). The grout is injected through a sleeve pipe that has been encased in casing grout after the grout has been prepared in a high shear mixer. The flow and pressure are recorded continuously and assessed with CAGES (further described later in this paper). This provides a first insight into the injectability of the soil and the obtainable grout spread. Testing on the grouted soil mass is performed at a later stage after the grout is allowed to harden. The grouted soil is jacked (undisturbed) from the test chamber to determine the actual characteristics of the grouted soil:

- Unconfined compressive strength
- Residual horizontal and vertical permeability coefficient
- Lateral grout spread (determination of hole spacing)

ISIS tests provide details as to the injectability limits of various suspension grouts and solution grouts in soils with a large variety of compositions and densities. The advantages/disadvantages of rheology modifiers and admixtures can be directly analyzed. Much of the 'guess work' can be taken out of preparing grouting plans for soil grouting jobs by replicating the soil composition found on site and optimizing a grout plan which will achieve the project goals.

If a particular soil is completely amenable to a particular grout, the soil will be fully saturated with grout during the first grouting pass. The grout will permeate to the perimeter of the soil sample and refusal will be reached. Since the soil layers are generally isolated from each other, the actual lateral spread is therefore derived from the apparent Lugeon trend line (figure 3). A geotextile membrane can be placed around the soil layers, individually or all together, to allow the dissipation of water pressure while preventing grout from escaping.

### Designing and Establishing Injectability Characteristics of Grouts

ISIS can also be used to design and test the injectability of grouts. The injectability limits of suspension or solution grouts into soils characterized by grain size, density, hydraulic conductivity and silt content is not easily determinable. The first step is to develop a series of grout mix designs for each type of grout (regular or microfine cement, sodium silicate, acrylate, polyurethane hot melts, etc.) which are thought to be injectable into the particular soils. Various grout mix designs can be produced based on the desired rheological and set characteristics (which are in turn determined by the prevailing soil conditions).

Once several grout mix designs are developed, ISIS can be used to investigate soil layers with varying characteristics according to the criteria previously listed. These soil layers can be constructed to systematically reduce the soil permeability and adjust the silt content to determine the injectability limits for each optimized grout formulation. After extracting the test sample from the test chamber, direct analysis of the following can be conducted: penetrability, lateral grout spread, percentage of pores permeated, highest allowable silt percentage still enabling permeation, residual permeability coefficient and unconfined compressive strength on grouted soils.

### Execution of Grouting Program: CAGES (Computer Aided Grouting Evaluation System)

To accurately monitor and record a soil or rock grouting operation it is imperative to use pressure and flow meters for real-time monitoring (Baker, 1982). A powerful tool in this regard is CAGES: computer aided grouting evaluation system. CAGES has been developed not only to record pressures and flows, but in addition these data are analyzed, displayed and recorded in real-time. This system utilizes:

- magnetic flow-meters, and pressure transducers to acquire analog injection data;
- an analog-to-digital converter for real-time digitization of incoming data;
- a lap-top computer to store, analyze and display the data;
- amenability and aperture theory as the mathematical models for assessment of the grouting operation;
- modern software to provide a user friendly graphical user interface.

The analysis performed by CAGES applies to general permeation (soil and rock) grouting applications, although soil and rock grouting applications are analyzed differently. The focus of this paper is on soil grouting, and therefore the discussion will focus on soil grouting.

For soil grouting projects, without prior in situ testing, the theoretical grout spread for a given formulation is calculated with the equations of Cambefort-Naudts (Naudts, 1995), based on the initial permeability of the soil (either determined with Hazens' or preferably by in-situ permeability testing). The accessible pore volume in turn determines how much grout is needed to obtain the theoretical spread. This in turn determines the slope of the line governing the evolution in apparent permeability (with reference to figure 3) as a function of time.

If an ISIS test has been performed to develop a grouting plan, then accurate data on spread, grout volumes and apparent permeability as a function of time are already developed.

The surface area below the apparent Lugeon line indicates (after multiplying with a scale factor) the amount of grout that is needed to obtain the target grout spread (1 Lugeon corresponds to a permeability coefficient of $1.13 \times 10^{-5}$ cm/s). If the apparent Lugeon value decreases too quickly, the target grout spread cannot be obtained with this type of formulation. This in turn means that the formulation needs to be adjusted ("on the flight"-without interrupting the operation) in order to reach the desired grout spread.

This allows real time analysis and changes to the grouting operation as described in the two figures above.

During a typical grouting application CAGES can be used for the following:

1. To conduct the initial permeability tests prior to grouting to determine the initial grout formulation to be injected and to establish pre-grouting baseline data.
    - The Newtonian fluid water is injected into the formation via the holes or sleeve-pipes used for grouting.
    - The effective pressure and flow-rate are monitored and the permeability coefficient or Lugeon value ($Lu_{water}$) is calculated.
    - For rock grouting: the total width of the apertures intersected by the borehole that are still accessible to water is calculated (utilizing Littlejohns aperture theory).
2. To monitor grout injection parameters during grout injection.
    - The effective pressure, flow rate, apparent Lugeon value (grout) and cumulative take are continuously displayed.
3. To continuously assess the grouting operation allowing for appropriate (the most economical and durable grout that is still injectable) grout selection and real-time evaluation and optimization of the grouting operation.
    - The entire grouting operation is conducted as an extended permeability test and the permeability (with grout as the test fluid) or apparent Lugeon value ($Lu_{grout}$) is calculated in real time. A correction factor is applied when calculating this apparent Lugeon

value to compensate for the difference between the apparent viscosity of the grout being injected and the viscosity of water. It is important to note that cement based suspension grouts are Binghamian fluids while water is a Newtonian fluid.

- The ratio of the initial apparent Lugeon value to the Lugeon value with water (Initial Lu $_{grout}$/Lu $_{water}$) or the amenability coefficient (A$_C$) is calculated. The amenability coefficient is a measure of the ratio of apertures accessible to grout that are accessible to water (Ac = Lu $_{grout}$/Lu $_{water}$). A low amenability coefficient (in rock grouting) is an indication that the grout being injected is only penetrating the widest fissure and is not suitable to penetrate the finer apertures that are still accessible to water. A low amenability coefficient, in soil grouting, indicates that only the largest pore channels are being permeated and that the zone will choke of prematurely. If no immediate changes are made to the formulation the result will be a high residual permeability.
- The theoretical radius or lateral grout spread is continuously displayed (based on user inputs of the accessible porosity and real time measure of the volume injected).
- The apparent Lugeon value is displayed graphically in real time. By observing the trend of apparent Lugeon value it is possible to determine the response of the formation to the grout being injected:
  - a flat line is typically indicative of void filling or washout of grout;
  - a sudden sharp increase is typically indicative of hydrofracturing;
  - a gradual increase is typically indicative of mud washing (rock grouting only);
  - a slow gradual decrease indicates that the hole is coming to a gradual refusal (Figures 4);

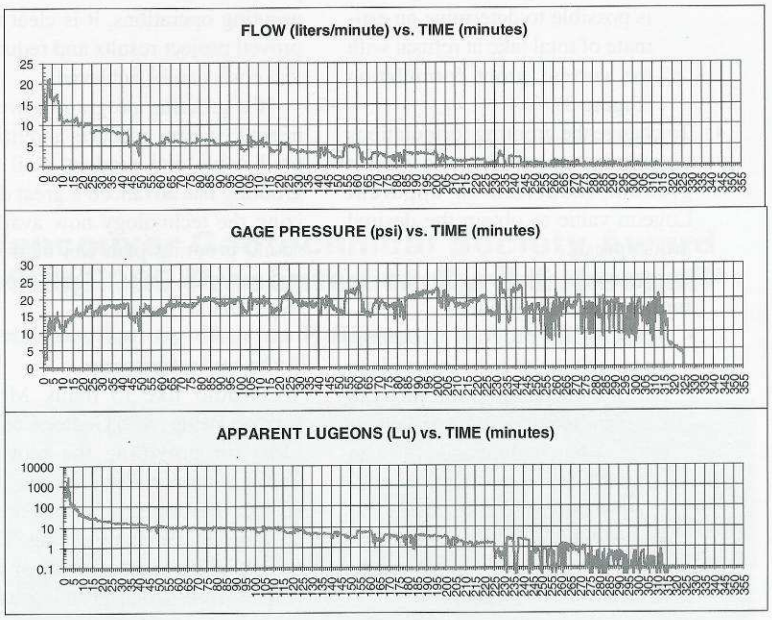
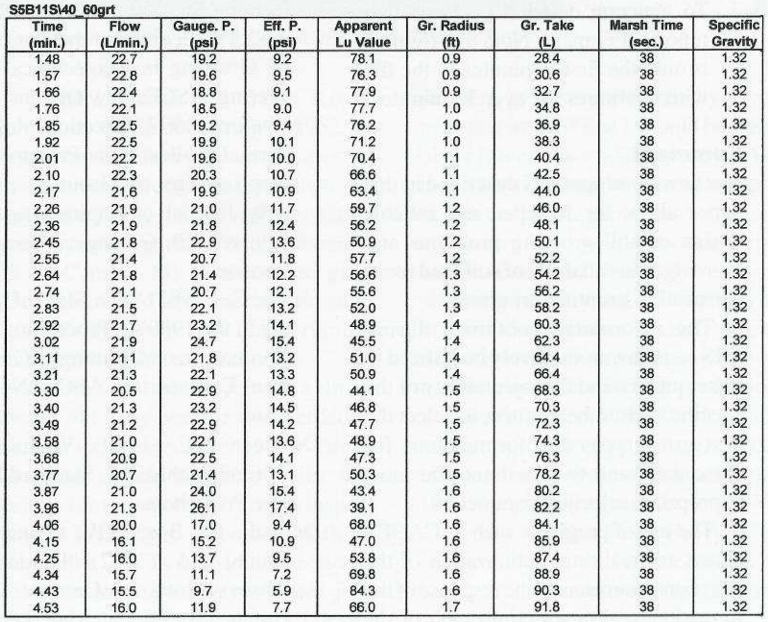


*Figure 4. Ideal Hole Behavior - High Apparent Lugeon slowly reduced during grouting.*



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| Time (min.) | Flow (L/min.) | Gauge. P. (psi) | Eff. P. (psi) | Apparent Lu Value | Gr. Radius (ft) | Gr. Take (L) | Marsh Time (sec.) | Specific Gravity |
|---|---|---|---|---|---|---|---|---|
| 1.48 | 22.7 | 19.2 | 9.2 | 78.1 | 0.9 | 28.4 | 38 | 1.32 |
| 1.57 | 22.8 | 19.6 | 9.5 | 76.3 | 0.9 | 30.6 | 38 | 1.32 |
| 1.66 | 22.4 | 18.8 | 9.1 | 77.9 | 0.9 | 32.7 | 38 | 1.32 |
| 1.76 | 22.1 | 18.5 | 9.0 | 77.7 | 1.0 | 34.8 | 38 | 1.32 |
| 1.85 | 22.5 | 19.2 | 9.4 | 76.2 | 1.0 | 36.9 | 38 | 1.32 |
| 1.92 | 22.5 | 19.9 | 10.1 | 71.2 | 1.0 | 38.3 | 38 | 1.32 |
| 2.01 | 22.2 | 19.6 | 10.0 | 70.4 | 1.1 | 40.4 | 38 | 1.32 |
| 2.10 | 22.3 | 20.3 | 10.7 | 66.6 | 1.1 | 42.5 | 38 | 1.32 |
| 2.17 | 21.6 | 19.9 | 10.9 | 63.4 | 1.1 | 44.0 | 38 | 1.32 |
| 2.26 | 21.9 | 21.0 | 11.7 | 59.7 | 1.2 | 46.0 | 38 | 1.32 |
| 2.36 | 21.9 | 21.8 | 12.4 | 56.2 | 1.2 | 48.1 | 38 | 1.32 |
| 2.45 | 21.8 | 22.9 | 13.6 | 50.9 | 1.2 | 50.1 | 38 | 1.32 |
| 2.55 | 21.4 | 20.7 | 11.8 | 57.7 | 1.2 | 52.2 | 38 | 1.32 |
| 2.64 | 21.8 | 21.4 | 12.2 | 56.6 | 1.3 | 54.2 | 38 | 1.32 |
| 2.74 | 21.1 | 20.7 | 12.1 | 55.6 | 1.3 | 56.2 | 38 | 1.32 |
| 2.83 | 21.5 | 22.1 | 13.2 | 52.0 | 1.3 | 58.2 | 38 | 1.32 |
| 2.92 | 21.7 | 23.2 | 14.1 | 48.9 | 1.4 | 60.3 | 38 | 1.32 |
| 3.02 | 21.9 | 24.7 | 15.4 | 45.5 | 1.4 | 62.3 | 38 | 1.32 |
| 3.11 | 21.1 | 21.8 | 13.2 | 51.0 | 1.4 | 64.4 | 38 | 1.32 |
| 3.21 | 21.3 | 22.1 | 13.3 | 50.9 | 1.4 | 66.4 | 38 | 1.32 |
| 3.30 | 20.5 | 22.9 | 14.8 | 44.1 | 1.5 | 68.3 | 38 | 1.32 |
| 3.40 | 21.3 | 23.2 | 14.5 | 46.8 | 1.5 | 70.3 | 38 | 1.32 |
| 3.49 | 21.2 | 22.9 | 14.2 | 47.7 | 1.5 | 72.3 | 38 | 1.32 |
| 3.58 | 21.0 | 22.1 | 13.6 | 48.9 | 1.5 | 74.3 | 38 | 1.32 |
| 3.68 | 20.9 | 22.5 | 14.1 | 47.3 | 1.5 | 76.3 | 38 | 1.32 |
| 3.77 | 20.7 | 21.4 | 13.1 | 50.3 | 1.5 | 78.2 | 38 | 1.32 |
| 3.87 | 21.0 | 24.0 | 15.4 | 43.4 | 1.6 | 80.2 | 38 | 1.32 |
| 3.96 | 21.3 | 26.1 | 17.4 | 39.1 | 1.6 | 82.2 | 38 | 1.32 |
| 4.06 | 20.0 | 17.0 | 9.4 | 68.0 | 1.6 | 84.1 | 38 | 1.32 |
| 4.15 | 16.1 | 15.2 | 10.9 | 47.0 | 1.6 | 85.9 | 38 | 1.32 |
| 4.25 | 16.0 | 13.7 | 9.5 | 53.8 | 1.6 | 87.4 | 38 | 1.32 |
| 4.34 | 15.7 | 11.1 | 7.2 | 69.8 | 1.6 | 88.9 | 38 | 1.32 |
| 4.43 | 15.5 | 9.7 | 5.9 | 84.3 | 1.6 | 90.3 | 38 | 1.32 |
| 4.53 | 16.0 | 11.9 | 7.7 | 66.0 | 1.7 | 91.8 | 38 | 1.32 |

*Figure 5. Sample of CAGES output.*

  - by extrapolating the slope of the apparent Lugeon value grade it is possible to determine an estimate of total take at refusal with the current grout formulation (Figure 3).
4. To change the grouting formulations to optimize amenability and cause a gradual reduction in apparent Lugeon value to obtain the desired grout spread.
5. To increase productivity by allowing for multiple-hole grouting.
   - The CAGES program will allow up to eight holes to be injected via one or more pump(s) and each can be monitored and assessed at once. A batch plant and crew can be maintained productive even when some of the holes are taking grout at a low injection rate (approaching refusal) by injecting several holes simultaneously.
6. To establish real hydrofracturing pressures (characterized by sudden increase in apparent Lugeon value). Traditionally the maximum grouting pressure is established by applying an empirical rule of thumb. By increasing the maximum grouting pressure to the actual hydrofracturing pressure, it is possible to increase grout spread.
7. To generate detailed post-grouting reports (Figure 5). Note that figure 5 is only the first 3 minutes of the file with continues for over 30 minutes.

## Summary

The new developments described in this paper allow for a better and reliable design of soil grouting programs and more rigorous analysis of soil (and rock) permeation grouting programs.

The information obtained during ISIS tests can productively be utilized to better understand the injectability of the specific soils to be grouted, to select the best grout types and formulations for these soils and to determine the most appropriate injection parameters.

The use of programs such as CAGES allows for real-time optimization of the injection parameters to the response of the formation, real-time optimization of the grout formulation to the response of the formation and multiple hole grouting.

Through the implementation of improved designs and better assessment of grouting operations, it is clear that improved project results and reduced project costs can be achieved.

If a grouting program is well engineered, it can produce a reliable and predictable end product. Soil or rock grouting has advanced a great deal utilizing the technology now available. A sound grouting plan can be developed and executed to predictably produce the required end product.

## Acknowledgments

We would like to thank Mr. Doug Heenan P.Eng (with Geotec Contracting Ltd.) for providing the plots of the CAGES output from a rock grouting project performed at Penn Forest Dam designed by Gannet Fleming. The Penn Forest Project is an example of a project where professional grouting was demonstrated to result in a better quality end product and a considerably lower overall cost. The authors would like to acknowledge the contribution of Gannet Fleming pertaining to the successful introduction of CAGES on a major project.

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