The GROUT LINE

Grout Line

Paolo Gazzarrini

Overture

At this, the ninth appointment with the Grout Line, I am still a long way from John Dunnicliff's 52 episodes of the GIN-Geotechnical Instrumentation News-, (it is better to clarify this acronym to distinguish it from the "other" GIN below), but the Grout line is still alive and well.

This issue I received a response from Dr. Dawn Shuttle, Grant Bonin and Vafa Rombough to Dr. Lombardi's comment about the GIN (Grouting Intensity Number).

I have not received any other comments, for the moment, to Dr. Lombardi's comment about the GIN, and this seems to me strange: is it possible that nobody has an opinion regarding this discussion? Or is it only a problem of time?

During several usual West Coast rainy June weekends (in Vancouver, BC- where is the summer?) I finally had the time to read Dam Foundation Grouting written by Kenneth Weaver and Donald Bruce. The book was presented at the February GeoDenver 2007 and advertised in the last issue of Geotechnical News. I, personally, found the book very interesting, providing a complete panorama of materials, testing, procedures, equipment and case histories. In my opinion the book is a "must have" for every "grouter".

The Grout Line Web Page

Have any of you had the chance to visit the Grout Line web page? I have not received any feedback and I encourage you visit it and comments!

Closure

As I wrote in the overture, the material for the publication in my possession is not very abundant and I would like again to ask your help to keep the Grout Line alive.

Send your grouting papers, articles or comments to:

Paolo Gazzarrini, fax 604-913 0106 or paolo@paologaz.com, paologaz @shaw.ca or paolo@groutline.com.

Ciao!

GIN Distilled

Dawn Shuttle
Vafa Rombough
Grant Bonin

Introduction

In the June 2007 issue of The Grout Line Dr. Lombardi commented on our recent paper (Rombough et al. 2006). Our paper discussed a limitation of GIN, in that for realistic grout properties and injection rates, the GIN approximation may overestimate the achievable penetration. In his discussion Dr. Lombardi suggests that we misunderstand GIN. This is not the case – GIN indeed overestimates the penetration length. To resolve Dr. Lombardi's misunderstandings we shall address the points raised in the previous article (using the same headings as the discussion), and include previously published site data to illustrate an instance in which GIN misled.

To facilitate this discussion The Grout Line has kindly arranged for the Rombough et al. (2006) paper to be available for download from their web site (see the Other Articles section at *www.groutline.com*).

Mathematical Model

The Rombough et al. paper used the standard Bingham fluid model as the grout idealization. The full solution of parallel plate flow equation was provided to enable non-mathematicians to use the equations without resort to texts on solutions of cubics (and which was not provided in Lombardi, 1985). However, Lombardi clearly misread our description. This model was never referred to as the "Chhabra Richardson" formula, although we did cite this reference. This theoretical derivation is not new, predating both Lombardi (1985) as well as the Chhabra & Richardson reference. And as Chabbra & Richardson did not give the original citation we referred to simply as the Bingham solution.

Dr. Lombardi also berated us for not including radial flow – using only a constant width strip. We disagree that radial flow is always more realistic than a constant width strip. Real fractures have variable apertures. Hakami (1995) suggests that fluid can flow over less than 60% of the fracture surface, a process most refer to as channeling. With channeling the true flow area with increasing injection typically falls between the limits of 1-D and 2-D flow, or even larger for short distances. Adapting the 1-D numerical model to 2-D is straightforward, and we present 2-D results later for completeness. However, although Lombardi makes reference to a radial flow solution in his 1985 paper, we could only find an example of its use, not the numerical method needed to develop the solution, despite careful reading. And to our knowledge no analytical solution for the 2-D situation exists.

Grouting Process

Now to the crux of the matter. Lombardi states "the 'Intensity number' (GIN) refers to the final status of the process, so it corresponds to the target (penetration distance) and applies thus to a flow rate nil; it does not refer to the actual grouting path." We agree that this is how GIN must be used. We showed on Figure 4 (reproduced below as Figure 1) that the GIN and Bingham solutions converge as the injection rate reduces, with only a 4.4% error as the flow velocity reduces to 0.01 L/m (corresponding to a flow velocity of only 1 cm/min). But at higher flow velocities GIN is shown to markedly overestimate grout penetration. For example, at the higher injection rate of 1 L/min, corresponding to a velocity of only 1m/min, GIN overestimates actual grout penetration by 58.8%. Our comment on the importance of injection rate is not a misunderstanding of GIN - this is in fact exactly the practical limitation of GIN that the paper by Rombough et al. set out to highlight!

In a typical GIN grouting project you pump at a constant rate. To obtain your required GIN you continually update the volume and monitor pressure – until the desired PV is obtained. You then stop pumping, and it is usual to have a cut-out on the pump to achieve this. Using GIN there is no way that you can determine in advance that the velocity will be at, or close to, zero. And if the velocity is non-zero then multiple penetration lengths exist for a single GIN. Importantly, the GIN method provides no guidance on the pumping rate required to approximate zero flow – hence in practice GIN becomes unreliable to control practical grouting.

Figure 2, adapted from Ritchie et al (2003), illustrates this problem at the Antamina Dam in Peru. Figure 2a plots pressure versus injected volume and illustrates that the required GIN was obtained four times at differing pressures and volumes. The corresponding injection rates are presented in Figure 2b. For the initial flow rate of about 18 L/min the GIN criterion was reached at A at an injected volume of 150 L/m. By Point C over 250 L/m has been injected, using only 50% of the initial injection rate (i.e. about 9 L/min). And by reducing the injection rate still further to a very low value of 5 L/min an additional 50 L/m could be injected before the GIN curve was intersected again. How slow an injection rate should be used ?

For this site the suggestion to "overpass somewhat (let us say by 10%) for a short time interval said intensity and then to return to it checking that the flow rate is actually nil" as suggested in Lombardi's article (and shown graphically in Figure 3) is very poor guidance. Figure 2a indicates the location of a GIN curve 10% lower than the original. Even for this lower GIN – and which was exceeded by 10% to reach the specified GIN – the injected volume intersects the GIN criterion multiple times between 150 L/m and 300 L/m injected volume. The problem for the site engineer remains how slow an injection rate is slow enough – and this is the question that our paper sought to answer.

The Model and Reality

That both GIN and the complete Bingham solution are over-simplifications of reality is unarguable. In this both Dr. Lombardi and ourselves appear to be in complete agreement. The individual fracture roughness, the interconnectivity of fractures in a full 3-D fracture network, and the number of fractures intersecting a single grout interval, among many other factors, are important and will influence grouting effectiveness. But as both computer

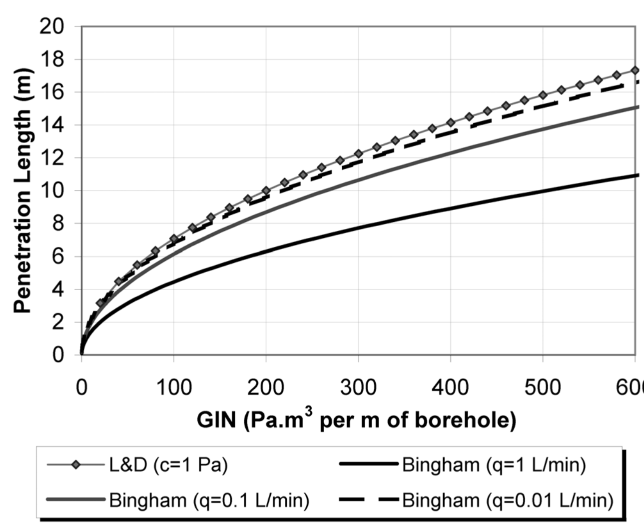

Figure 1: 1-D Penetration length versus GIN with varying injection rate: c' = 1 Pa, μ = 11 mPa.s (from Rombough et al., 2006).

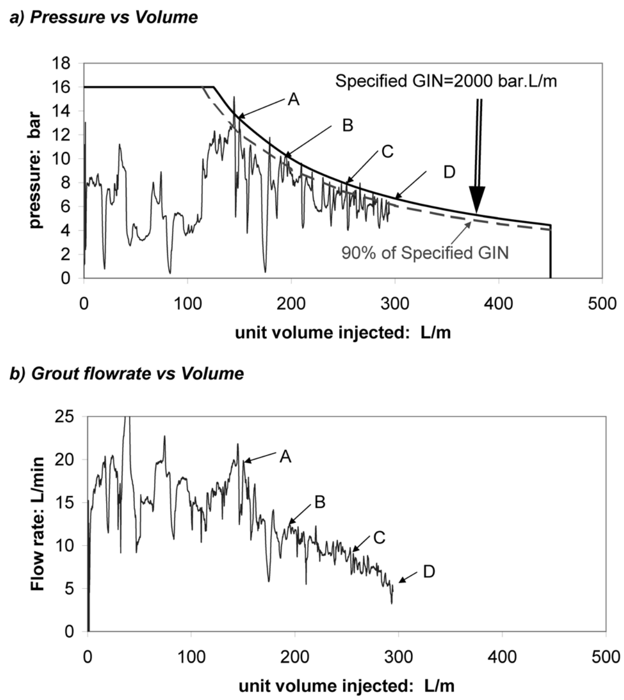

Figure 2: Example grout injection data from Antamina Dam showing multiple GIN "closures" [234BP 27.6-32.6m] (adapted from Ritchie et al, 2003).

power and our understanding of fracture networks increases, so does the benefit to be gained from using more realistic flow models.

One important point highlighted by Lombardi in his discussion of real fracture grouting is that most grout intervals contain more than one intersecting fracture. This is a good example of where using the Bingham solution, rather than simplified GIN, provides a more realistic outcome. Take the very simple example of two horizontal fractures intersecting one grout interval (see schematic of Figure 4). For simplicity we have assumed fracture transmissivity, T, may be computed using the "cubic law" – although modification to account for differences between the hydraulic and void-filling aperture is straightforward. The first fracture has an aperture of 0.5 mm (T = 1.55 x 10^{-5} m^2/s). The second fracture has an aperture of 0.175 mm (T = 6.66 x 10^{-7} m^2/s). Assuming typical grout properties from Rombough et al. (2006) of density ρ = 1671 kg/m^3, dynamic viscosity μ = 0.011 Pa.s., and yield stress (or cohesion) c' = 1 Pa, the Bingham and GIN penetration distances can be computed for any prescribed GIN. The penetration versus injection rate for 2-D flow is plotted on Figure 5 for a GIN of 140 bar.L. The Bingham theoretical penetration does not reach the predicted GIN penetration of 13m for both fractures, even for extremely low injection rates. This is exactly the point of Rombough et al., although now presented for 2-D radial flow.

It may be argued that this degree of precision is not required due to other unknowns. We disagree. This analysis is simple to perform, and provides the grouting engineer with more reliable penetration distances. Clearly using the Bingham solution will not remove all of the difficulties linked to grouting. But the wide availability of ever faster and faster computers has made real time solution of more complex systems possible. It is also straightforward to adapt the full Bingham approach in 2-D, or even a 'partial dimension' idealization of the channeling, to real-time electronic grout monitoring providing the grouting engineer with instantaneous and reliable practical guidance. Accounting for the grout injection rate avoids placing the grouting engineer in the ambiguous situation that arose at Antamina (as illustrated on Figure 2).

The Merits of GIN?

Lombardi argues in conclusion that the main merit of the GIN-concept is to know the penetration at the end of grouting. If this is indeed the case, GIN has severe limitations. For a single fracture the approximation will give the Bingham solution if very slow injection rates are used – but these "slow" rates are impractical for real grouting. At the injection rates required to match GIN predicted penetration, Figures 1 and 5 suggest that the grout mix would need to be designed to accommodate injection over an extended period of time. Not an easy proposition, as with time the properties of typical GIN grouts (without retarding admixtures) tend to both increase in yield strength and viscosity as the process of hydration begins to influence the Bingham properties of the grout mix. Moreover, if more than one fracture is to be grouted in a single stage – the usual state of affairs - then Figure 5 indicates that GIN will

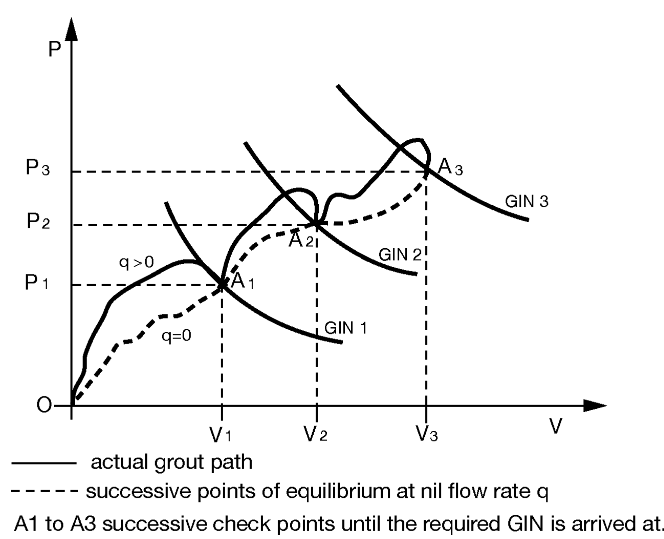

Figure 3: Actual grouting path and Grouting Intensity (GIN).

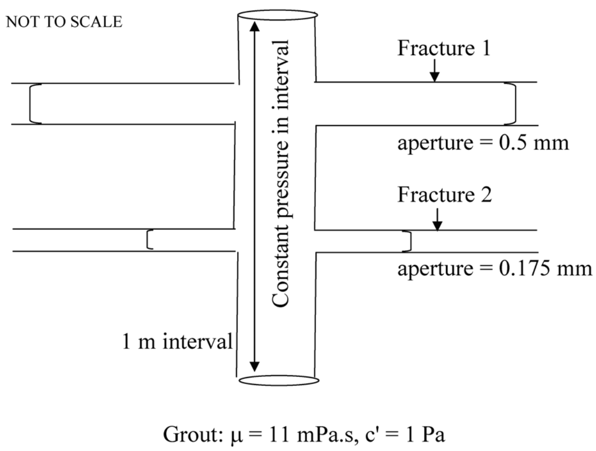

Figure 4: Schematic of constant pressure injection into two radial flow fractures.

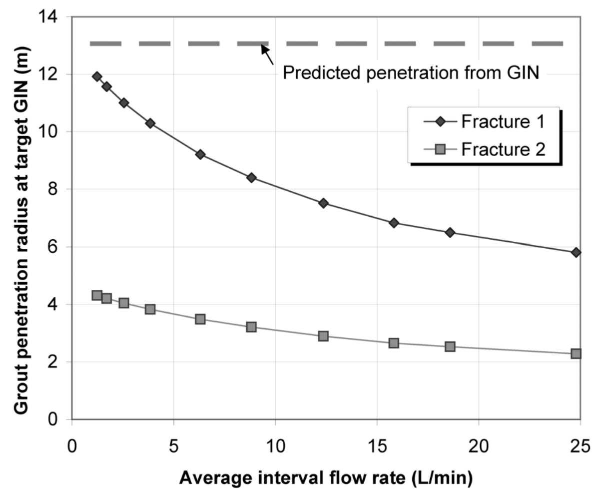

Figure 5: Grout penetration into two horizontal fractures at target GIN – P.V = 140 Bar.L.

give the wrong penetration distance even for infinitely slow injection rates. The reality is that grout injection rate does matter.

In contrast to GIN, allowing for the actual grout injection rate using the Bingham solution provides more reliable penetration predictions. The effects of fracture roughness are easily included, much reducing the uncertainty in the volume of grout to needed penetrate the desired distance. The grouting engineer can now judge whether or not curtain closure is being achieved. Why not give Bingham a try?

frame is

27,6 x 18

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