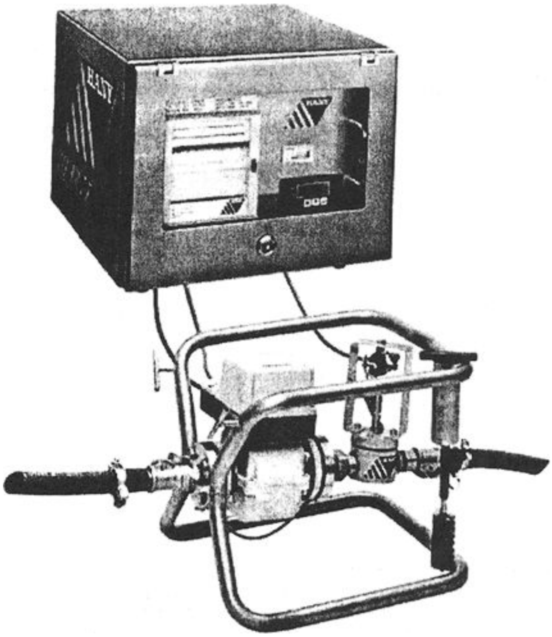

Figure 17. Simple pressure and flow recording unit.

monitoring equipment must be designed to cope with typical site conditions, and must be operated and maintained by skilled operators as opposed to computer specialists. New units are capable of recording pressure and flow data from up to six grout lines simultaneously. Signals from flow meters and/or stroke impulses are collected, and limits on grout volume pressure and flow rate can be preset for each group pump. Data are recorded on standard memory cards and later processed under a Windows-based program or can be processed and displayed in real time.

Weaver (1991) described proprietary automated injection systems wherein the outputs from drilling parameter recorders are "married" to automated plants to cause "the proper grout mix to be injected at the proper pressure for a given soil condition". Similar electronic recording and analytical equipment can also

- Obtain, record, and interpret in situ permeability tests.
- Design grout patterns and quantities.
- Identify anomalies and produce various tables, graphs, and documents.
- Record and display surface movement data in relation to the grouting progress (for compensation grouting).

5. *Combined Units*

Depending on the application for the grouting, and the project requirements and constraints, it is often found that all the equipment components are combined into one portable unit. Thus for anchor, micropile, soil nail, or tunnel contact grouting, compact integrated units are available, comprising a high shear mixer, holding tank, grout pump and power pack. In addition, a water flow meter or grout injection parameter instrumentation is usually mounted on the same steel frame. Outputs of 1 to 8 m^3/hr are commonly available, with the pump capacities, depending also on choice, rated at 2 to 10 MPa. For projects such as deep mixing or diaphragm walling where large volumes of slurry are required, larger, containerized units are produced, usually fed by screw conveyors. Figure 18 provides a view of a typical 2-pump set up. Such plants can produce 12 to 45 m^3/hr depending on the type and composition of the mix, have a weigh batch accuracy of ± 3% and can weigh up to 8500 kg.

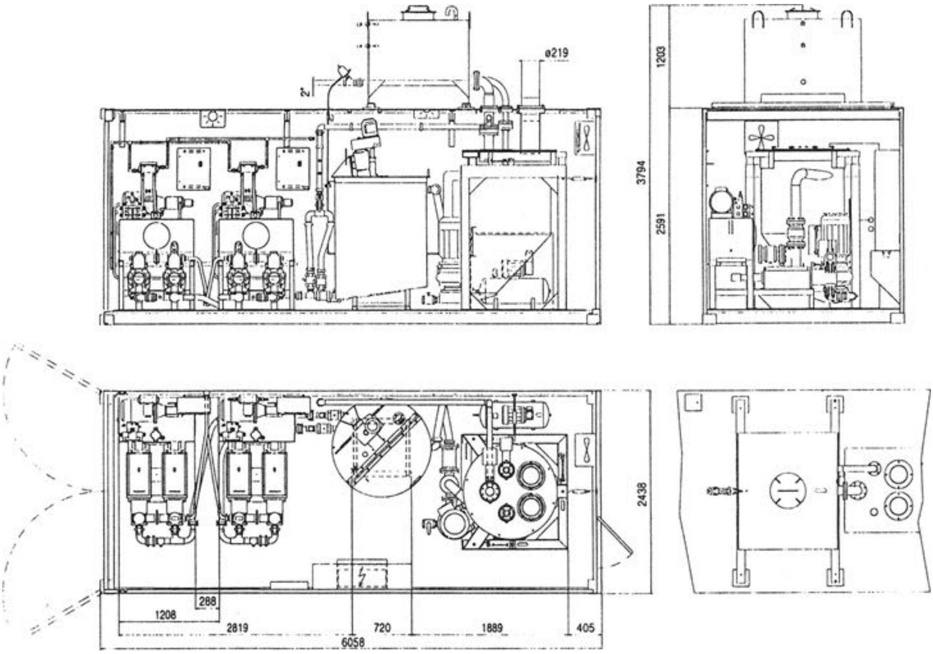

Figure 18. Plan of a typical containerized combined unit.

6. *Final Remarks*

Practice in cement grouting technology is spread across a wide variety of applications, and employs a similarly extensive range of materials, grouts, and parameters. The correct choice of the most appropriate batching, mixing, pumping, and recording systems plays a vital role in the potential success of any grouting project. The growing use of multicomponent grout formulations, often using microfine cements, requires equipment that can accurately batch and efficiently mix the components so that the intrinsic benefits of these materials can be fully exploited: the use of high shear mixing equipment is therefore essential to produce fully hydrated, homogeneous "colloidal" suspensions. Pumps are available which are capable of pumping grouts with a wide range of rheological properties under closely controllable pressure and flow rate limits, and which can satisfy the different national injection philosophies. Regarding data recording and display, the ability to view and process such information in real time is integral to the management of a successful project. Aided by modern computer technology this goal is readily and economically achievable.

References

1. Bruce, D.A., G.S. Littlejohn, and A. Naudts. (1997). "Grouting Materials for Ground Treatment: A Practitioner's Guide," *Grouting – Compaction, Remediation, and Testing*, Proc. of Sessions Sponsored by the Grouting Committee of the Geo-Institute of the American Society of Civil Engineers, Logan UT, Ed. by C. Vipulanandan, Geotechnical Special Publication No. 66, July 16-18, pp. 306-334.
2. Gause, C.C. and D.A. Bruce. (1997). "Control of Fluid Properties of Particulate Grouts: Part 1 – General Concepts." *Grouting – Compaction, Remediation, and Testing*, Proceedings of Sessions Sponsored by the Grouting Committee of the Geo-Institute of the American Society of Civil Engineers, Logan UT, Ed. by C. Vipulanandan, Geotechnical Special Publication No. 66, July 16-18, pp. 212-229.
3. Houlsby, A.C. (1990). *Construction and design of cement grouting*. John Wiley & Sons, 442 p.
4. Jefferis, S. (1982). "Effect of mixing on bentonite slurries and grouts." *Grouting in Geotechnical Engineering*, Proceedings of the conference sponsored by the Geotechnical Engineering Division of the American Society of Civil Engineers, New Orleans, LA, February 10-12, pp. 62-76.
5. Littlejohn, G.S. (1982). "Design of cement based grouts", *Grouting in Geotechnical Engineering*, Proceedings of the conference sponsored by the Geotechnical Engineering Division of the American Society of Civil Engineers, New Orleans, LA, February 10-12, pp. 35-48.

6. Mongilardi, E. and R. Tornaghi. (1986). "Construction of large underground openings and use of grouts," Proceedings of the International Conference on Deep Foundations, September, Beijing, 19 p.
7. Müller, R. (1993). "Geräte für die moderne Injektionstechnik." *Grouting in Rock and Concrete*. Proceedings of the International Conference on Grouting in Rock and Concrete, Salzburg, Austria, October 11-12. pp. 185-193.
8. Schwarz, L.G., and R.J. Krizek. (1992). "Effects of mixing on rheological properties of microfine cement grout." Proceedings of the conference sponsored by the Geotechnical Engineering Division of the American Society of Civil Engineers, New Orleans, LA, February 25-28, pp. 512-525.
9. Weaver, K.D. (1991) *Dam Foundation Grouting*, ASCE Publication, 178 p.
10. Wilson, D. and T. Dreese. (1998) "Grouting Technologies for Dam Foundations", Proceedings of the 1998 Annual Conference Association of State Dam Safety Officials, October 11-14, Las Vegas, Nevada, Paper No. 68.

A Critical Look at Use of "Rules of Thumb" for Selection of Grout Injection Pressures

Kenneth D. Weaver[1], Aff. ASCE

Abstract

The quite different "rules of thumb" used by American and European grouting practitioners for selection of grout injection pressures have for many years been a subject of great controversy between the two groups. Practitioners who are not "married" to either rule have long suspected that each may be an artifact of the respective systems of measurement used. Although use of the "American rule" commonly is rationalized on the basis of protection against possible uplift of horizontal strata, application of the pressures that this rule seems to dictate may not be sufficient to cause grout to adequately penetrate and fill small openings in potentially permeable fractured rock. Conversely, these same pressures may be excessive for use in very weak rock. "European rule" pressures would, of course, be potentially damaging to weak rock, but they have been widely and successfully used in "average" bedrock foundation conditions. Nonetheless, even higher pressures than would be allowed by that rule also have been widely and successfully used. Therefore, it should seem evident that - rather than mindlessly following either "rule" - grouting practitioners should base their selection of grout injection pressures on site-specific factors, including - to the maximum extent feasible based upon grout hole logging and water test data - the conditions at each specific hole into which grout is to be injected.

Introduction

Two "rules of thumb" for selection of grout injection pressures are widely known and used, and have been a subject of controversy for many years. The American "rule of thumb" indicates that the injection pressure should be 1 psi per foot of depth of the interval being treated, and the European "rule of thumb" indicates that the injection pressure should be 1 kg/cm^2 per meter of depth. It seems evident that these "rules" probably are artifacts of the respective systems of measurement. The applicability of the American "rule of thumb" appears to be particularly subject to question. To the extent that it relates to overburden pressure, the American "rule" is inappropriate because rock has strength as well as weight; for typical rock, the

---

[1] Grouting Consultant, 40442 Valencia Court, Fremont, California 94539

strength can be a very significant factor in enabling the "average" rock to remain intact under injection pressures well in excess of overburden pressure.

Adherence to the American "rule" may have contributed to, or may even have been largely responsible for, the findings of Professor Arthur Casagrande (1961) regarding the effectiveness of grout curtains. Following an examination of the piezometer data from a number of dams, he concluded that grout curtains typically have no observable effect on the piezometric gradient through the dam. At the very least, Professor Casagrande's findings should have led to a more rigorous and critical reexamination of American grouting practice than actually has occurred. Ideally, his findings also should have led to an examination of European and other foreign grouting practices, so that an assessment could be made as to whether some of them should be adopted for use in the U.S. (Grout injection pressure is, of course, only one element of the respective practices.)

European Grouting Philosophy

Some European grouting practitioners advocate using sufficient injection pressures to enlarge fine fractures so that they will admit grout. For example, the author of the world's first comprehensive book on grouting, H. Cambefort (1977), made the following statement: *"If we do not wish to bungle the injection of a fissure, the refusal pressure must be sufficiently high to enlarge the fissure."* Another French authority on grouting, P. Rigny (1974), presented a list of reasons for using relatively high grouting pressures. This list included the following opinion, which supports that which was expressed by Cambefort: *"During the injection process, pressure causes the fissures in the rock to open, the cement particles are deposited on the walls of the fissure during grouting and, when the pressure is released, there is a tendency of the fissure to close against this cement thereby producing a very tight bond between cement and rock."* A noted Yugoslavian authority on grouting, E. Nonveiller, had earlier published a similar statement: *"Some elastic deformation and the resulting opening of additional fissures is beneficial because it facilitates grout penetration from the borehole into the existing fissure system of the rock, resulting in a wider grouting range and a better saturation of the rock around the grouted hole."* However, Nonveiller (1989) also has stated that the injection pressure ordinarily should be lower than that which would initiate new fractures.

Some investigators either fail to make a distinction, or blur the distinction, between dilation of preexisting fractures or other rock discontinuities and hydrofracture. Ewert (1992), for example, commented that *"Hydraulic fracturing in a near-surface seam is controlled by the pressure caused by the weight of the overlying* *rock; ... Further below the critical pressure causing fracturing is determined by the strength of the rock,..."* Somewhat incongruously considering those statements, he presents two groups of pressure / flow (P/Q) diagrams: one group in *which "hydraulic fracturing of ... latent bedding planes"* is seen to be initiated and another in which *"dilation of paths"* is demonstrated.

Ewert (1992) elaborated upon the subject of injection pressure and related factors, making the following additional statements that point up the fact that use of high (by U.S. standards) injection pressures is not universally applicable or appropriate: *"High pressures are required to grout fine openings, otherwise the suspension does not enter. In soft rock latent discontinuities, particularly bedding planes, can already be opened at relatively low pressures. At such pressures only wide openings can be grouted, the fine ones not. The pressure rises once the wide openings are filled. Before the rising pressure reaches that level required for penetration of the fine paths, latent discontinuities are pressed open and filled, the existing fine openings remain open. It depends on the geological situation (orientation of joints, isotropic or anisotropic permeability) whether the remaining permeability is smaller or larger and whether it becomes effective or not."*

The results of laboratory testing performed in Austria demonstrated that the minimum pressure required to initiate permeation of grout into a fracture may, without risk, be much higher than would be indicated by the various "rules of thumb" that have been used for selecting the allowable grouting pressure (Feder, 1993). The test results indicated that the pressure necessary to start grout flow into a joint depends not only on the width of the joint but also upon the shape of the intersection of the grout hole with the joint, the grout type and rheological properties, and the grain size of the particles in the grout. Feder (1993) suggested use of fine-grained cements to reduce the gradually increasing effect of development of filter cakes at the pressure required to continue the flow of grout with time. The laboratory tests described by Feder (1993) used grouts with w:c ratios of 0.5:1, 0.7:1, and 0.9:1.

European Grouting Theory

Dr. Giovanni Lombardi, a Swiss expert on grouting, developed a series of mathematical relationships regarding grout takes and distances of grout penetration. As indicated in the following formula that he developed, Lombardi (1985) concluded that the extent of penetration of grout beyond the borehole is directly proportional to the injection pressure and to the half-width of the fissure into which the grout is being injected:

$$R_{max} = [P_{max} \cdot t] \div c$$

where: R_{max}= Maximum radius of grout penetration
P_{max} = Maximum injection pressure
t = crack thickness ÷ 2
c = cohesion

It appears implicit from this theoretical relationship that elastic enlargement of fine fissures, as advocated by Cambefort, Rigny and Nonveiller, can enable stable, relatively thick, grouts (i.e., those with relatively high cohesion) to be injected so is potentially desirable. It also seems evident from the theoretical relationship that the potential effectiveness of grouting can be closely related to use of the highest acceptable injection pressure, whether or not this pressure is sufficient to enlarge the fissures.

Dr. Lombardi, working in conjunction with Dr. Don U. Deere, developed the so-called GIN principle, which entails evaluation of site-specific factors to select a "Grouting Intensity Number" that is then used in plotting graphic relationship between the maximum allowable injection pressure and the maximum volume of grout that will be allowed to be injected. Every point on the curve represents both a pressure and a volume that is not to be exceeded. According to Lombardi and Deere (1993) pressures as high as 500 bars may be appropriate in some cases.

European and Other Foreign Grouting Practice

Unlike many American grouting practitioners, European practitioners do not accept their "rule of thumb" as an article of faith. Not being bound by the strictures imposed by certain U.S. Government agencies, European practitioners are free to consider the rock conditions when selecting the appropriate injection pressure. For example, Nonveiller (1968) reviewed the grouting practices at a number of sites, finding that the most of the injection pressures used were in the range of 2 to 4 times the overburden pressure, and that there was no trouble with hydrofracture. However, he did point out that there were cases of surface uplift when grouting at shallow depth in weak, schistose or bedded rock.

Grout injection pressures based upon or comparable to those advocated in the U.S. "rule of thumb" have been used on various overseas projects, sometimes without noteworthy success. Nonveiller (1989) cited Dokan Dam, in Iraq, as an example of a dam that had to be regrouted because the injection pressures used during construction were too low. This experience appears to validate the ISRM Rock Grouting

Commission (1992, 1994) conclusion that application of the American "rule of thumb" increases the risk of incomplete filling of the joints. By contrast, experienced contractors reportedly have successfully and without risk applied the European "rule of thumb" at sites throughout the world. Grout injection pressures in China commonly are twice as high as would be indicated by application of the European "rule of thumb", without any reported disadvantages (ISRM, 1992, 1994).

Londe and Le May (1993) reported that *"there seems a trend toward consensus on the need to open the joints of finely jointed rocks by the action of grouting pressure."* They pointed out that higher pressures enable thicker grouts to be injected, but that use of higher pressures necessitate correlation of pressure with grout take.

Some Relevant Theory from U.S. Grouting Practice

The concept of "groutability ratio" is sometimes used in U.S. grouting practice. This concept recognizes the fact that the relationship between grout particle size and fracture aperture can become very important when assessing whether or not a particulate grout can be injected into a pervious medium. As presented by Mitchell (1970), that ratio is as follows:

$$\text{groutability ratio} = \text{fissure aperture} \div D_{max} \text{ grout}$$

For successful grouting, the groutability ratio should be greater than 3. The presumption is that clogging of the fissure, or development of a filter cake at the intersection of the grout hole and the fissure, occurs at lower ratios. Depending upon the grouting philosophy to which one chooses to (or is forced by organization policy to) adhere, either of two inferences may be drawn from this relationship:

1. Based upon the American "rule of thumb" practice in vogue at the time that the "groutability ratio" concept was first promulgated, grout particle grain size may make adequate grouting of fine fissures impossible; or
2. For any given grout particle size, widening the aperture(s) of fine fractures by judicious use of relatively high injection pressures can improve the groutability of fractured rock, hence may be essential to the effectiveness of some grouting operations.

Some Non-Conforming U.S. Grouting Practice

Grouting pressures higher than specified in the American "rule of thumb" have had at least a few advocates (in addition to the present author) among U.S. grouting practitioners. E. Graf (1993), a grouting consultant and a former grouting contractor, ventured the opinion that *"even the European practice can be overly conservative under certain conditions."* Among other related opinions, he also stated that *"Tightening of a formation by pressure dilation is often desirable."* Graf (1993) describes a case history in which he injected chemical grout into a dam foundation at shallow depth, using injection pressures up to 20 times overburden pressure without any observed surface heave. Close control of the grout travel distance by use of a very rapid set time is essential if such high injection pressures are to be attempted. Injection pressures 3 times overburden pressure were used successfully, under the present author's direction, to "stitch grout" steeply-dipping shear zones in a dam foundation in gneiss at the Merrill Creek Project, in New Jersey. Based upon the author's analysis of packer test data obtained from core borings for the East Dam at the Eastside Reservoir Project in Southern California, application of pressures approximately 2 to 3 times that of overburden fairly consistently produced elastic (i.e., reversible) enlargement of bedrock fractures in gneiss, and two stages of dilation were noted in some cases as the test pressure was increased.

Conclusions Regarding Selection of Grout Injection Pressures

Based upon a review of the considerations described above, it seems evident that pressures significantly in excess of the outdated and largely discredited American "rule of thumb" should be more widely accepted and used. It is essential that injection pressures higher than overburden pressure be applied judiciously, with full consideration being given to the geologic conditions and the surface configuration at and adjacent to each boring in which they are being applied. Recognizing the potential for uplift or lateral displacement and possible damage to the foundation, it likewise is essential that the pressure and injection rate be closely monitored during injection.

Recommendations

Ideally, the injection pressures initially used for construction of a grout curtain (until the effects can be assessed) should be based upon the results of packer tests performed in borings made during the design exploration studies. Each test should be made at several different pressures, using a Lugeon test procedure similar to those described by Houlsby (1990). Houlsby's approach uses only three test pressures, two of which are duplicated, with each pressure being applied for ten minutes. This relatively small range of pressures will not necessarily make it possible to ascertain the dilation pressure. Four pressures, each being applied for at least 5 minutes, is more appropriate for that purpose. (Repetition of tests at the lower pressure following the peak pressure test is desirable but not essential.) The highest and